BIODETERIORATION OF HERITAGE BUILDINGS REPRESENTATIVE OF COSTA RICAN CARIBBEAN ARCHITECTURE

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1. Introduction

In Limón, Costa Rica, Central America, there are buildings with historical value and distinctive structural and aesthetic characteristics which are differentiated from other typologies and styles used in the rest of the country. Costa Rican Caribbean architecture is characterized by vernacular buildings based on models imported by the United Fruit Company with adaptations to the climate conditions of Limón [1]. Although there are similarities with other expressions developed in the Caribbean islands and coastal areas of some Central American countries, Costa Rican Caribbean architecture represents a unique case of adaptation to the context [2]. These representative features are part of the urban landscape of Limón city and are the cultural heritage and identity of this region, but very few of them have legal protection. Furthermore, since research in this area is limited, preservation initiatives need to be implemented to protect this valuable cultural and historical heritage. Limón is a city of port origins that was developed at the beginning of the 20th century. Its history is directly linked to the railroad and banana production because of the United Fruit Company enclave in this Caribbean region in Costa Rica [3]. The main city and the entire province of Limón are characterized by climatic conditions with predominantly high temperatures (21.8 - 29.7°C) and humidity (75.7 - 99.9%) [4]. Limón is also a coastal city, where many of the buildings were built on what was once marshland.

The original buildings representative of Costa Rican Caribbean architecture are rapidly disappearing as a result of biodeterioration, limited resources for building maintenance, and poor recognition of their historical significance. The age of these buildings, their materiality, proximity to the Caribbean Sea, and constant exposure to high temperature and humidity, make these buildings very susceptible to biodeterioration. Biodeterioration can be described as the process in which living organisms damage or

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degrade organic substances or materials such as wood; this process is the result, mostly, of the growth and metabolic activity of microorganisms such as fungi and bacteria [5]. Wood is a common material used in Caribbean buildings due to its hardness, light weight, and availability [6], but its degradation is rapid in houses and buildings in the tropics. The objective of this research was to characterize biological agents responsible for the biodeterioration in two heritage buildings identified as Costa Rican Caribbean architecture: the Casa Misionera de la Iglesia Bautista (the Missionary House of the Baptist Church) and the Antigua Capitanía de Puerto (the Former Port Captaincy), both of which are protected by the Law of Architectural Historical Heritage of Costa Rica (Law 7555 of the Republic of Costa Rica). This research included the architectural characterization of the buildings, an inventory of existing buildings, identification of the areas with damage, isolation, and the molecular identification of possible biodeterioration agents (fungi), through a multidisciplinary approach.

2. Materials and Methods

2.1. Definition of the characteristics of Caribbean architecture

The project focused on buildings located in the oldest sections of Limón City; the historical center and the neighborhood called Jamaica Town, which is considered the first extension of the city.

The main characterization of Caribbean architecture was based on construction materials, and architectural and constructive elements described in the literature [1, 2, 7-10, 11]. These criteria were used to identify the buildings to use for the preliminary phase of the study. A basic template of the characteristics was used to establish an initial list of buildings with a minimum number of architectural elements. The initial list included the geo-localization and photographic documentation of the buildings of interest that were also used to create a map using the free and open-source software QGIS 16.6 (GNU and OSGeo). Buildings were classified into four typologies based on the presence and clarity of the characteristics of Costa Rican Caribbean architecture in each building [7]. The following set of typologies was established: Type 1 (building not modified, minimally modified, and preserves most characteristics); Type 2 (building slightly modified and preserves many characteristics); Type 3 (greatly modified and preserves few characteristics); Type 4 (not eligible for the study, extremely modified and does not preserve any characteristics). Buildings that were not accessible or for which there was a lack of information, were considered “Unclassified”.

Based on the typology, a more detailed description of the basic characteristics was conducted. Recurrent and new architectural elements were identified that had not been reported as common characteristics [12] and added to the profile. Additionally, we included each characteristic in an eBook of Costa Rican Caribbean architecture, in which each of the elements identified was defined and illustrated [13].

2.2. Inventory of Costa Rican Caribbean architecture buildings

Based on the typologies that showed more prominent characteristics of Costa Rican Caribbean architecture (Type 1 and 2) an inventory was elaborated to include registration code, location, coordinates, street name, and number/neighborhood name, materials, original and current use, building typology, identification of main architectonic and constructive elements, as well as a general assessment of the preservation state. Any damage present in the building was also described. The elaboration of the inventory required the design of inventory tabs for the compilation of field data including photographic documentation. A database on Excel (Microsoft, USA) was elaborated using all the information in the inventory tabs. Each one of the buildings was designated with a code that denoted the block in which the structure is located (letter), typology (Type 1 or 2), and the number of buildings in the block. The inventory tabs, the classification using typologies, data gathered on-site, and the database were constantly revised for accuracy and to refine the established inventory.

2.3. Multi-criteria evaluation

A multi-criteria evaluation was conducted and is a method that enables the selection of specific decisions by taking into account a vast amount of information, relationships, and objectives, as explained by Munda [14 -15]. A first evaluation was developed with five criteria [16] to evaluate and select the buildings that better represent and preserve the characteristics of Caribbean architecture and are at a higher risk of deterioration due to the presence of biodegrading agents. After the demolition of some of the buildings during the development of this project, a review of the multicriteria evaluation was conducted and a sixth criterion was added to include the current use of the buildings (Table 1). Each one of these criteria was used to calculate a final score by adding the assigned percentages to each criterion. A point scale ranging from 0 to 4 was assigned (Table 1) to evaluate each criterion.

Table 1. Criteria, percentage, and point scale used in the multi-criteria evaluation of the 23 buildings inventoried in Limón City, Costa Rica.

Criteria	Percentage (%)	Point scale
Presence and clarity of characteristics of the Caribbean architecture (Lc)	30	Type 1: 2 points Type 2: 1 point
Declaration of architectural historical heritage (Law 7555) (Dp)	10	Has declaration: 1 point Does not have declaration: 0 points
Preservation condition (Ep)	20	Bad condition (presents a lot of damage, deterioration, and many modifications to the structure): 3 points Regular (presents some damage, deterioration and/or few modifications): 2 points Good condition (presents little to no damage, deterioration, or modifications): 1 point

Accessibility to the building (Da)	20	Access approved to the interior of the building and availability to conduct research work: 3 points Access to the interior of the building: 2 points Access only to the exterior of the building: 1 point
Current use (Ua)	10	Abandoned (more vulnerable): 3 points Non compatible with original use: 2 points Compatible with original use (less vulnerable): 1 point Demolished: 0 points
Property status (Cp)	10	Abandoned (more vulnerable): 4 points: For sale: 3 points Rented: 2 points Occupied by owner (less vulnerable): 1 point

To obtain the final score, the following formula was used:

$$Final\ Score = [(Lc2 * 0.3) + (Dp1 * 0.1) + (Ep3 * 0.2) + (Da3 * 0.2) + (Ua3 * 0.1) + (Cp4 * 0.1)] * 100 \quad \text{(Eq. 1)}$$

Where:

- Lc is the presence and clarity of characteristics of the Caribbean architecture
- Dp is the declaration of architectural-historical heritage
- Ep is the preservation condition
- Da is the accessibility to the building
- Ua is the current use
- Cp is the property status

Once all the scores were obtained, we prioritized the evaluation and sampling of the buildings with higher scores.

2.4. Damage documentation, sample collection, and microbial isolation

From the inventory and the multi-criteria evaluation, two properties considered with higher architectural heritage were selected, the Antigua Capitanía de Puerto (AAA - Type 1 - 01) and the Casa Misionera Iglesia Bautista (W -Type 1 - 01). Visual observations of areas with aesthetic damage, such as the presence of holes or tunnels, dust, sawdust, cracks, and color changes were made and recorded. In addition, structural lesions including any softening of the wooden surfaces, presence of rot, molds, or other organisms were also noted. A written record was made of the location of each identified lesion inside the building, as well as details present in the site regarding the presence of vegetation, proximity to the Caribbean Sea, and climatic conditions such as temperature and relative humidity; the information was recorded using data loggers (Testo 174H, Instruments Testo S.A., Spain). Selected areas were sampled for isolation of potential microorganisms responsible for wood damage. Inside the properties of interest, each wood segment with visible damage caused by microorganisms was cleaned using 70% ethanol. Two sampling methods were used: a) smaller samples between 0.1 g and 1 g were taken by scraping the surface with a scalpel or, if possible, by taking a small piece of wood containing the damage, the sample was wrapped in sterile aluminum foil, and b) rubbing a sterile swab in the affected area where microbial growth was visible. The collected samples were placed in a cooler until they were transferred to the Laboratory of Forest Pathology of the Forest Innovation Research Center at the Costa Rica Institute of Technology where they were stored at 4°C for further use. For the isolation in laboratory conditions, the wood samples were first disinfected with 1% sodium hypochlorite a. i. for 30 s, washed with 96% alcohol for 30 s, and finally with distilled water for 1 min [17]. Then, the wood pieces were placed on three different solid media to grow fungi present in the samples. Media included potato dextrose agar (PDA), Sabouraud dextrose agar (SDA), and nutrient agar (NA). Then the plates were incubated at 25°C in the dark for 7 days. After 7 days, all colonies from each plate were transferred to obtain single colony cultures. Cultures were stored in 10% saline solution at room temperature and 50% glycerol solution at -20°C [18] for further use.

2.5. Molecular characterization

A QIAGEN DNeasy Plant Kit (QIAGEN, Germany) was used for DNA extraction following the manufacturer's instructions. Polymerase chain reaction (PCR) was conducted using a Promega PCR Master Premix (Promega, Wisconsin), a final reaction with MilliQ water, PCR master mix 2X (Promega M7502, Wisconsin), 5 μM forward primer ITS1F [19], and reverse primer ITS4 [20], BSA 1% and fungal DNA (40ng/μl) [21]. For negative controls, PCR water was used instead of the fungal DNA.

For visualization of PCR products, an agarose gel was made of TAE X1. It was run in an electrophoresis chamber at 150 V for 45 min and then visualized with UV light. Samples that showed a strong band without contamination with limited smears were selected for sequencing. A second PCR was made for LSU, using the forward primer LR3 [22] and reverse primer LROR [22] to compare results and to better identify the fungal isolates. PCR products were sequenced using Sanger sequencing by GENEWIZ (South Plainfield, New Jersey).

The same PCR primers (ITS and LSU) were used to obtain forward and reverse sequences. Sequences were trimmed and edited using Sequencher 4.0 (Genes Codes Corporation, Michigan) and compared via nucleotide blast with the NCBI and UNITE databases for both ITS and LSU sequences. For both programs parameters were E-value 0, score higher than 700, query cover between 80% and 100%, and a percent identity higher than 95%.

3. Results

3.1. Definition of characteristics of Caribbean architecture

Based on the bibliographic review [1, 2, 9-11], a basic profile of main Caribbean architectural characteristics was established [16]. The main features of these buildings include the use of wood as the main construction material in external and internal structures. The presence of one or more of the following architectural elements was required to be included in the study: wooden or concrete piles, galleries, attics, socles, porticos, wooden rails, wooden grilles or *petatillos*, wide eaves, and similar structures in other areas separated from the roof, balconies, corridors and galleries, thermal control chambers for insulation and skylights. Fieldwork was conducted in Limón City using the basic profile and a list of 101 buildings was established; each building was geo-localized (Figure 1).

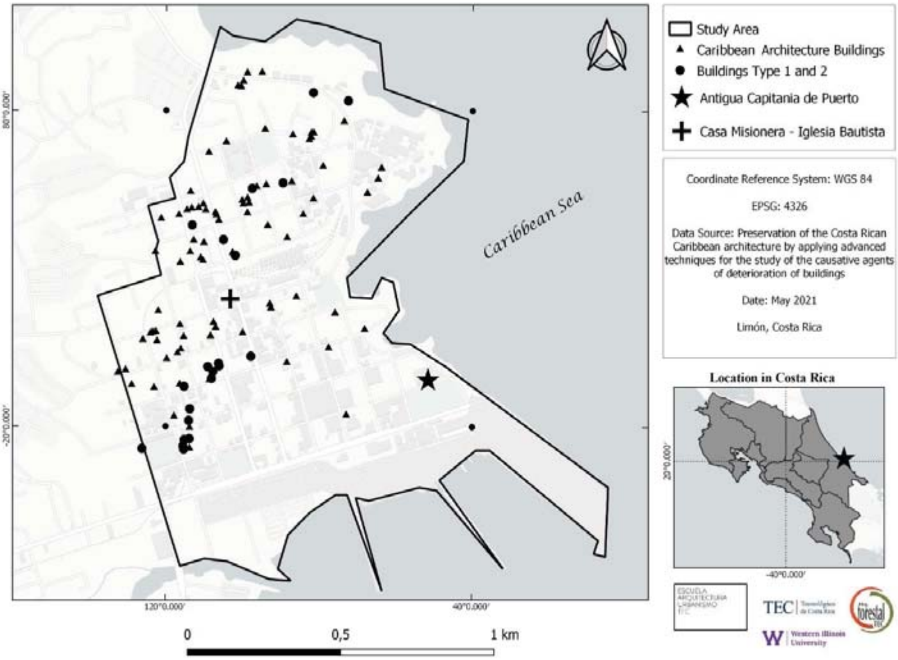

Figure 1. Location of buildings with Caribbean architectural characteristics in Limon City, Costa Rica.

Characterization of the buildings started with the identification of the features described in the basic profile, as well as the identification of the new common elements that were not previously reported in the literature.

For example, buildings in the area presented structural systems, “balloon framing”, passive strategies for climate comfort, a variety of vibrant colors, and different spatial configurations.

A classification based on typology was implemented for the initial list of buildings (101 in total) and buildings were classified using the information in the inventory from the text by Hernández-Salazar, I. et al including the newly identified characteristics and verified field data [7] resulting in 16 buildings in Type 1 category, 7 in Type 2, 37 in Type 3 and 22 in Type 4 (Table 1, Figure 2A-D).

Nineteen buildings were not considered due to lack of information or restricted access to the properties and 11 buildings were listed as demolished following the owner's decision.

Figure 2. The basic facade of typical housing buildings of Costa Rican Caribbean architecture classified according to typology. A) Multi-family dwelling type 1 (TT - Type 1 - 01); B) Attached dwelling type 2 (P - Type 2 - 02); C) Two storey house with concrete base type 3 (JJ - Type 3 - 01); D) Single family house with many modifications type 4 (I - Type 4 - 01). All buildings were located in Limón, Costa Rica.

3.2. Inventory of Caribbean architectural buildings

Additional information was obtained for the 23 buildings classified as Type 1 and Type 2. Location, owners' contact information, state of preservation, architectural, structural, and material characteristics were determined, as well as the main aesthetic and structural damage and possible degradation caused by biological agents or damage caused by the building's advanced age. In some cases, more than one visit was necessary to verify the information gathered in the first visit, then the database was updated. The inventory showed that most Type 1 and 2 buildings are in poor condition, putting at high-risk key elements of Limón city's heritage. According to García-Baltodano et al. [23], Limón City has a total of 22 declarations for buildings of heritage importance, of which only three are listed as Costa Rican Caribbean architecture, two of the three are still standing, while the other was lost due to a fire in 2016 (The Black Star Line). The two buildings of heritage importance were registered in this study inventory as Type 1.

3.3. Multi-criteria evaluation

Based on the information gathered in the inventory and the score assigned in the multi-criteria evaluation, an order of priority to select representative buildings of

Caribbean architecture and demonstrate the highest risk of deterioration and loss was developed (Table 2).

Table 2. Order of priority based on the final score assigned in the multi-criteria evaluation of the 23 buildings classified as Type 1 and Type 2 of Costa Rican Caribbean architecture present in Limón City, Costa Rica.

Inventory Code	Property Name	Use	Coordinates	Score	Ranking
W-Type1-01	"Casa Misionera de la Iglesia Bautista"	Unoccupied	9.99554, -83.03121	100.0	1
FF-Type1-02	N/A	Unoccupied	9.99364, -83.0319	83.3	2
AAA-Type1-01	"Antigua Capitanía de Puerto"	Institutional	9.99319, -83.0253	72.5	3
A-Type1-01	"Antigua Casa Dr. Argüello"	Unoccupied	10.00117, -83.0309	70.0	4
MM-Type1-01	N/A	Housing	9.99199, -83.03244	65.0	5
M-Type1-01	N/A	Housing	9.99881, -83.02962	62.5	6
TT-Type1-03	N/A	Unoccupied	9.99118, -83.03257	60.0	7
FF-Type1-01	N/A	Housing	9.99325, -83.03177	58.3	8
FF-Type1-03	N/A	Housing and services	9.99367, -83.03161	58.3	9
FF-Type1-04	N/A	Housing and services	9.99359, -83.03157	58.3	10
J-Type1-01	"Casa del Coco"	Housing and commercial	9.99763, -83.03236	58.3	11
L-Type1-01	N/A	Demolished	9.99871, -83.03044	58.3	12
MM-Type1-02	N/A	Housing	9.99215, -83.03249	58.3	13
TT-Type1-1	N/A	Housing	9.99144, -83.03259	56.7	14
TT-Type1-2	N/A	Demolished	9.99147, -83.0325	56.7	15
GG-Type2-01	N/A	Unoccupied	9.99388, -83.03055	51.7	16
P-Type2-02	N/A	Housing	9.99719, -83.03143	50.0	17
EE-Type1-01	N/A	Housing	9.99307, -83.03274	49.2	18
SS'-Type2-01	"Casa Familia León"	Housing	9.99123, -83.03386	47.5	19
FF-Type2-03	N/A	Housing and services	9.99325, -83.03177	43.3	20
P-Type2-01	N/A	Housing	9.99675, -83.03119	43.3	21
TT-Type2-1	"Casa Garvey"	Demolished	9.9913, -83.03263	43.3	22
B - Type 2 - 01	N/A	Housing	10.00144, -83.02877	36.7	23

According to the ranks obtained, buildings with scores higher than 60 (six buildings) were selected for additional sampling and analysis.

Nonetheless, it was only possible to work with four of these buildings due to restricted access to two of the properties. In this study, we focused on the two buildings with the highest heritage importance as mentioned above: Casa Misionera de la Iglesia Bautista (W-Type 1-01) and the Antigua Capitanía de Puerto (AAA-Type 1-01) which were ranked as first and third in priority, respectively.

The Casa Misionera de la Iglesia Bautista (W - Type 1 - 01) belongs to the First Baptist Church in the province of Limón and was built in 1887; it was last restored in 2001 and declared architectural heritage in 2002 (Decree No. 30232-C, La Gaceta No. 65 - Thursday, April 4, 2002). Nowadays, the building is in poor condition and mainly used for storage, which further impacts its deterioration. The Antigua Capitanía de Puerto' (AAA - Type 1 - 01) was constructed in 1930.

It was declared architectural heritage in 1995 (Decree No. 24366-C, La Gaceta No. 121 — Monday, June 26, 1995). The building was last restored in 2014 and since then it has been used as a Cultural Center of the Municipality of Limón; despite its recent restoration, the building presents recurring deterioration that affects its overall preservation state.

3.4. Damage documentation and identification of biological agents in the properties

During the onsite visits, damage and tunnels made by insects, such as termites, were observed in both buildings (Casa Misionera and Antigua Capitanía). Nonetheless, it was not possible to find living insects for collection and identification, very likely representing previous infestations. Insect damage was observed in the interior as well as in the exterior of the buildings. In the Casa Misionera de la Iglesia Bautista, 24 damaged areas showed signs of biological activity, 67% of which showed fungal growth or characteristic deterioration caused by fungi and 33% by insects.

Structural damage such as loss of material, change in color, and presence of vegetation was also observed (Figure 3A-D). In the Antigua Capitanía de Puerto, 14 areas with damage caused by biological agents were identified, 79% of the areas that showed visible damage were caused by fungi, and 21% were caused by insects. Aesthetic damage such as a change in color and the presence of vegetation was also observed (Figure 4). In the Casa Misionera de la Iglesia Bautista a relative humidity of 87.4% and an average temperature of 25.5°C with a maximum of 32°C were recorded in one year. In the Antigua Capitanía de Puerto, an average of 25.7°C was recorded with a maximum of 34°C, and relative humidity of 87.34% was also recorded in one year.

3.5. Microorganism isolation

From the samples of the areas showing damage, 36 fungi were isolated from both locations, 19 of the isolates were obtained from the Antigua Capitanía de Puerto and 17 from the Casa Misionera de la Iglesia Bautista. Most isolates were obtained from the PDA medium (26 cultures) from both buildings including *Trichoderma*, *Fusarium,* and *Penicillium*. SDA medium isolates were dominated by the genus *Penicillium.*

Using an NA medium, we were able to obtain a culture of *Fusarium oxysporum* from the “Antigua Capitanía de Puerto” and one of *Penicillium citrinum* from the Casa Misionera de la Iglesia Bautista.

Figure 3. Casa Misionera de la Iglesia Bautista (W - Type 1 - 01). A) Front view. B) Damage caused by insects (termites) (indicated with black circles). C) Damage caused by humidity and fungi (indicated with a black circle). D) Presence of vegetation under the structure (indicated with a black circle).

Figure 4. Antigua Capitanía de Puerto (AAA - Type 1 - 01). A) South and East view of the façade; B) Damage caused by insects (termites) (indicated with a black circle); C) Damage caused by humidity and fungi (indicated with a black circle). D) Presence of vegetation under the structure (indicated with a white circle).

The isolated fungi were stored in either a saline solution or glycerol solution in a fungal collection of the School of Forest Engineering of the Costa Rican Institute of Technology for preservation and further use.

3.6. Molecular characterization

All isolated fungi belong to the phylum *Ascomycota*. The most common orders were *Eurotiales*, *Hypocreales*, and *Botryosphaeriales*, respectively. The most common genera identified were common environmental fungi including *Trichoderma*, *Fusarium, Penicillium,* and *Lasiodiplodia (*Figure 5). *Penicillium* was the most common genus found (21% of the cultures), followed by *Fusarium* with 19%.

The only fungi present in the two locations were *Aspergillus niger*, *Fusarium solani*, and *Lasiodiplodia citricola*.

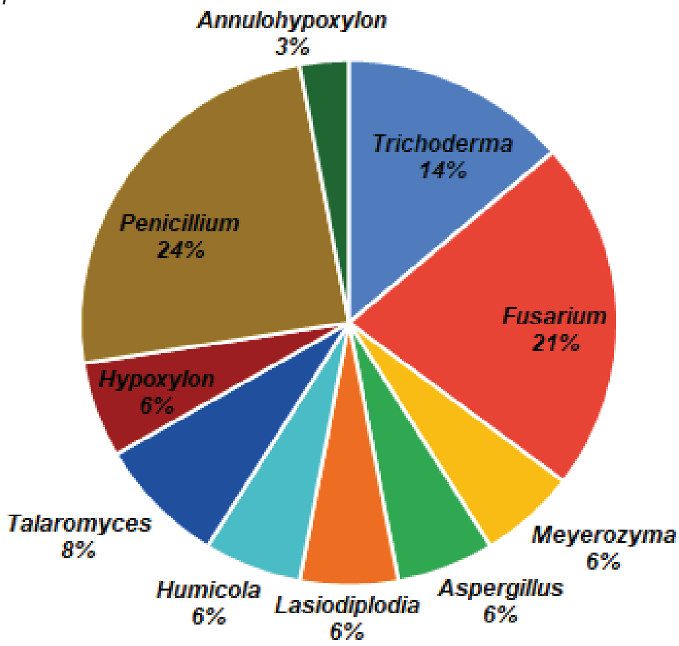

Figure 5. Genera identified from isolates obtained from wood samples from the two buildings (Casa Misionera and Antigua Capitanía) studied in Limón City.

A total of 19 different genera were isolated from Antigua Capitanía de Puerto, *Fusarium* was the most common isolate with seven of the 19 cultures in this genus (37%). The second most common genus found in this location was *Trichoderma* with four isolates (21%). Additional genera included *Humicola* with two colonies (11%) and lastly *Hypoxylon*, *Talaromyces*, *Lasiodiplodia,* and *Aspergillus*, all of which represented 5.3 % of the isolates.

From the Casa Misionera de la Iglesia Bautista, the most abundant genus was *Penicillium* with nine colonies out of the 17 isolated (53%), followed by *Talaromyces* with two colonies (12%) and lastly *Hypoxylon*, *Fusarium*, *Annulohypoxylon*, *Trichoderma*, *Aspergillus* and *Lasiodiplodia*, all of these with 5.9% each (one colony per genus).

4. Discussion

4.1. Costa Rican Caribbean architecture, heritage at risk

The buildings included in this study are examples of architecture adapted to a specific context of Costa Rica that have become a significant aspect of the historic urban landscape of Limón City. The Caribbean architecture of Costa Rica is part of the cultural and historical heritage of the city and country, being a key feature of the area.

Despite the heritage importance of these buildings, this type of architecture has not been studied, causing great difficulty on the part of the owners, researchers, and respective authorities to spread awareness of the historical importance and the need to preserve these structures.

The lack of documentation and studies regarding this topic have hindered the proper preservation of these buildings, an aspect that has also negatively impacted the documentation of traditional knowledge on the construction of this type of architecture and increased the risk of losing them completely.

Between 2018 and 2022, 11 buildings representing Caribbean architecture were demolished; eight of them were part of this study in the initial phases of this project and had already been demolished when the inventory was conducted, so it was not possible to further investigate them.

The remaining three, classified as Type 1 and included in the inventory, were demolished later. This represents a loss of 13% of the recorded buildings of Costa Rican Caribbean architecture in Limón city.

In this regard, there is an immediate need to fully understand the importance of this heritage to develop initiatives for the successful preservation of these buildings.

4.2. The need for interdisciplinary investigation for the preservation of heritage

According to Bertolin and Loli, the existence of a building of historic importance inside the cultural heritage field has an intangible meaning [24]. Cultural and architectural heritage is considered the legacy of our societies and must be managed through good preservation practices.

Heritage management must, moreover, be an interdisciplinary process with the intervention of many groups of experts in areas such as conservation, architecture, engineering, history, biology, chemistry, and other fields [25].

This study was carried out with an interdisciplinary perspective which included researchers from different areas such as architecture, forestry engineering, and biotechnology.

Tools implemented in the study, like multi-criteria evaluation, show the importance of joint efforts to determine risks and develop strategies to decrease the biodeterioration process.

Wood is the oldest construction material, the most used globally [26] and represents the most commonly used material in Costa Rican Caribbean architecture. It is, however, susceptible to deterioration and aesthetic damage caused by environmentally common fungi such as the ones detected in this study.

It is necessary to implement diverse multi and interdisciplinary studies to identify the potential causal agents of biodeterioration present in these buildings and provide possible solutions for their preservation.

4.3. Interaction of factors such as plants, insects, and climate conditions in wood structures

Wood is commonly treated before it is used in construction to improve its hardness and durability, including simple processes such as drying and treating the wood with varnish. These treatments are also used to reduce the deterioration of the wood known as weathering [27]. In the case of Costa Rican Caribbean architecture, the location of Limón City and the use of wood as the main construction material promotes the growth of wood-degrading microorganisms. Figures 3 and 4 show damage caused by humidity and rain on the outside of the buildings which leads to the attack of fungi, insects, and general wood decay.

Weathering is inevitable. Nonetheless, it is a slow process that normally takes many years to see significant damage in the wood, but if there are favorable conditions for the growth of biological agents, quicker and more severe degradation can occur in less time [28]. The main cause related to timber degradation is the presence of moisture in buildings, this leads to the attack of wood eaters such as termites and fungi [29]. This, alongside the poor maintenance of the buildings, aggravates the process of deterioration, such as in the case of the previously mentioned buildings in Limón City.

The outdoor structures constantly affected by humidity were more susceptible to damage (Figures 3 and 4) and there is a higher presence of fungi on the external surfaces than inside the structures.

Another important point is that fungi can be dispersed by wind or vectors and thus scatter their spores to colonize these buildings. The rate at which wood degrading fungi decompose these materials is majorly influenced by ecological interaction with wood-damaging vectors such as insects that facilitate the entry and penetration of fungi [30]. In many instances where there is damage by insects, like termites or beetles, there is also colonization by fungi. This is due to insects digging holes and permeabilizing the wood surface by removing paint and other protective layers like varnish and, in some cases, the insects may also vector communities of symbiotic fungi [31].

4.4. Ascomycota fungi as common colonizers of indoor and outdoor environments

Fungi from the *Ascomycota* phylum can also degrade wood components and damage buildings and structures. Any genera belonging to *Ascomycota* have the genes and enzymatic capabilities to degrade cellulose and other wood components [32]. All fungi isolated in this study are from the *Ascomycota* phylum and were present in the damaged areas where samples were taken. White rot and brown rot fungi were not obtained in culture, structural damage characteristic of these fungi was observed. Fungi from *Ascomycota* are normally recovered as environmental fungi, nonetheless, these fungi are more commonly found in anthropic areas, in cities, or villages with trees and wood structures [33] and can cause aesthetic damage, especially in conditions of high humidity.

This is the case in Limón City, where, due to high temperatures and high humidity, many of the buildings are made of wood and are surrounded by vegetation to lower temperatures inside the house. The genus *Hypoxylon* has been reported as very common in wood samples [34] and was present in the buildings of Limón City. *Trichoderma* was another genus that was fairly common in these buildings. This genus is capable of inhabiting wood and degrading its components [35].

5. Conclusions

Limón City represents a valuable and unique resource of Caribbean architecture. Many of the buildings that show these characteristics are in danger of disappearing or being destroyed due to damage caused by fungi, insects, climate, and other factors, including poor maintenance. The study and preservation of these buildings of heritage importance have included a multidisciplinary perspective to facilitate a better collection of information and a more complete analysis based on each specific situation. The present study shows the importance of this type of research and how the usage of multi-criteria tools optimized the decision-making to define priorities for the identification and preservation of specific properties. This is the first study on Caribbean architecture conducted in Limón City, Costa Rica, using a multi-criteria and interdisciplinary approach.

All the fungi isolated from the two locations in Limón City were from the *Ascomycota* phylum, with *Trichoderma*, *Fusarium*, and *Penicillium* being the most common genera. These results showed that fungi from the *Ascomycota* phylum are common inhabitants in damaged wood.

The wood also showed structural damage characteristic of white rot and brown rot fungi. Most of the isolated fungi could cause aesthetic deterioration of the structures considering the high temperatures, rain, and humidity experienced in this region. Molecular characterization was shown to be a reliable method to characterize genera and species of the samples isolated in tropical regions, but direct sequencing may be necessary for specific identification of fungi difficult to culture including many of the wood-degrading species not isolated in this study.

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Summary

The goal of this work was to characterize potential biological agents responsible for biodeterioration in heritage buildings identified as Costa Rican Caribbean architecture using a multidisciplinary approach. First, an inventory of buildings of Caribbean architecture from Limón City was elaborated. Then, a multi-criteria evaluation system was used to define priority scores to select buildings for sampling and analysis. Selected buildings were sampled for potential biological agents responsible for biodeterioration. Wood samples were taken from sections showing visual damage and fungi were isolated and characterized using Sanger sequencing. A basic profile of Costa Rican Caribbean architecture was established. A preliminary identification of 101 buildings that satisfied the basic profile of characteristics was conducted. Subsequently, these buildings were classified into 4 typologies from which 23 buildings belonging to Typologies 1 and 2 were chosen for the collection and registration of data. Applying the multi-criteria evaluation, 6 buildings with final scores higher than 60 points were selected from which the 1st (Casa Misionera Bautista) and 3rd (Antigua Capitanía de Puerto) in the classification were selected for further characterization of biological agents. From the sampling conducted on these two buildings. A total of 36 fungi were isolated. All fungi identified belonged to the fungal group *Ascomycota* phylum, the most common genera being *Trichoderma*, *Fusarium,* and *Penicillium*. The study shows how multidisciplinary studies can improve the process of decision-making in the preservation of heritage with the use of a ranking obtained for each building in the multi-criteria evaluation and the use of advanced techniques for the identification of biological agents.

Riassunto

L'obiettivo di questo lavoro è stato quello di caratterizzare i potenziali agenti biologici responsabili del biodeterioramento negli edifici storici identificati come architettura caraibica del Costa Rica utilizzando un approccio multidisciplinare. In primo luogo, è stato elaborato un inventario degli edifici della città di Limón. Successivamente, è stato utilizzato un sistema di valutazione multicriterio per definire i punteggi di priorità per selezionare gli edifici per il campionamento e l'analisi. Gli edifici selezionati sono stati campionati per individuare potenziali agenti biologici responsabili del biodeterioramento. I campioni di legno sono stati prelevati da sezioni che mostravano danni visivi e i funghi sono stati isolati e caratterizzati utilizzando il sequenziamento Sanger. È stata condotta un'identificazione preliminare di 101 edifici che soddisfacevano il profilo di base delle caratteristiche. Successivamente, tali edifici sono stati classificati in 4 tipologie tra le quali sono stati scelti 23 edifici appartenenti alle Tipologie 1 e 2 per la raccolta e la registrazione dei dati. Applicando la valutazione multicriterio, sono stati selezionati 6 edifici con punteggi finali superiori a 60 punti, tra i quali sono stati selezionati il 1° (Casa Misionera Bautista) e il 3° (Antigua Capitanía de Puerto) nella classificazione per un'ulteriore caratterizzazione degli agenti biologici. Dai campionamenti effettuati su questi due edifici, in totale sono stati isolati 36 funghi. Tutti i funghi identificati appartenevano al gruppo fungino *Ascomycota* phylum, i generi più comuni sono *Trichoderma*, *Fusarium* e *Penicillium*. Lo studio mostra come studi multidisciplinari possano migliorare il processo decisionale nella conservazione del patrimonio con l'utilizzo di una graduatoria ottenuta per ogni edificio nella valutazione multicriterio e l'utilizzo di tecniche avanzate per l'identificazione degli agenti biologici.