Ge-conservación
Conservação | Conservation

Incidence of environmental factors on travertine façade of heritage buildings in the historic center of Cuenca-Ecuador. A test scenario through Digital Imagen Processing

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Abstract: The problem of architectural heritage conservation in a consolidated historic urban context is of worldwide relevance. In Ecuador, and specifically in Cuenca, there are no specific approaches to evaluate the environmental impact on the heritage deterioration, therefore, an alternative diagnostic of travertine facades is proposed to define the levels of deterioration based on climatic factors through a case study. Two research stages are developed; 1) preliminary diagnosis of the architectural, environmental and anthropic components, using architectural cards and Leopold's Multivariable Matrix; and 2) quasi-experimental analysis with a mixed approach (quantitative and qualitative) based on real-time data collection of potential environmental variables to generate deterioration, which focuses on image processing. This technique is gaining momentum because it offers the possibility of studying the characteristics of surfaces through a non-invasive procedure. This paper describes the application of the Normalized Difference Vegetation Index (NVDI) algorithm applied to RGB images known as False-NVDI in order to obtain the deterioration caused by the incidence of environmental factors on the travertine facades. In particular, images of two buildings belonging to the Historic Center of the City of Cuenca were used. The results indicate that this technique has a great potential to determine three levels of deterioration; good, fair and bad. At the same time, it is confirmed that the proposed methodology is an effective and low-cost tool with high potential for short-term application in previous studies and more extensive research prior to intervention.

Keywords: environmental incidence, digital image processing, heritage buildings, heritage deterioration, state of conservation, NVDI

Incidencia de factores ambientales en fachadas de travertino de edificios patrimoniales del centro histórico de Cuenca-Ecuador. Un escenario de prueba mediante el Procesamiento Digital de Imágenes

Resumen: El problema de la conservación del patrimonio arquitectónico en un contexto urbano histórico consolidado es de relevancia mundial. En Ecuador, y específicamente en Cuenca, no existen enfoques específicos para evaluar la incidencia medioambiental en el deterioro patrimonial, por ello, se propone una alternativa de diagnóstico para definir los niveles de deterioro en fachadas de travertino en función de factores climáticos a través del estudio de caso. Se desarrollan dos etapas de investigación; 1) diagnóstico preliminar de los componentes arquitectónico, ambiental y antrópico, utilizando fichas arquitectónicas y la Matriz Multivariable de Leopold; y 2) análisis cuasi-experimental con enfoque mixto (cuantitativo y cualitativo) basado en la recolección de datos en tiempo real de las variables ambientales potenciales para generar deterioro, el cual se enfoca en el procesamiento de imágenes. Esta técnica en particular está tomando fuerza ya que ofrece la posibilidad de estudiar las características de las superficies a través de un procedimiento no invasivo. En este artículo se describe la aplicación del algoritmo Índice de Vegetación de Diferencia Normalizada (NVDI) aplicado en imágenes RGB conocido como Falso-NVDI con el fin de obtener el deterioro causado por la incidencia de factores ambientales en fachadas patrimoniales de travertino . En particular, se utilizaron imágenes de dos edificaciones pertenecientes al Centro Histórico de la ciudad de Cuenca. Los resultados indican que una técnica con un gran potencial que permite determinar tres niveles de deterioro; bueno, regular y malo. A su vez, se confirma que la metodología planteada es una herramienta efectiva y de bajo coste con alto potencial para aplicación a corto plazo en estudios previos e investigaciones más amplias antes de la intervención.

Palabras clave: incidencia ambiental, procesamiento de imágenes digitales, edificios patrimoniales, deterioro patrimonial, estado de conservación, NVDI

Incidência de fatores ambientais na fachada de travertino de edifícios patrimoniais no centro histórico de Cuenca-Equador. Um cenário de teste através do Processamento Digital de Imagens

Resumo: O problema da conservação do património arquitetónico num contexto urbano histórico consolidado é de relevância mundial. No Equador, e especificamente em Cuenca, não existem abordagens específicas para avaliar a incidência ambiental na deterioração patrimonial, portanto, propõe-se uma alternativa de diagnóstico para definir os níveis de deterioração nas fachadas de travertino, em função de fatores climáticos, através de um estudo de caso. São desenvolvidas duas etapas de pesquisa: 1) diagnóstico preliminar dos componentes arquitetónico, ambiental e antrópico, utilizando fichas arquitetónicas e a Matriz Multivariável de Leopold; e 2) análise quase-experimental com uma abordagem mista (quantitativa e qualitativa) baseada na recolha de dados em tempo real das variáveis ambientais potenciais para gerar deterioração, focando-se no processamento de imagens. Esta técnica em particular está a ganhar força, pois oferece a possibilidade de estudar as características das superfícies através de um procedimento não invasivo. Neste artigo, descreve-se a aplicação do algoritmo Índice de Vegetação da Diferença Normalizada (NVDI) aplicado em imagens RGB conhecido como Falso-NVDI para obter a deterioração causada pela incidência de fatores ambientais nas fachadas patrimoniais de travertino. Em particular, foram utilizadas imagens de dois edifícios pertencentes ao Centro Histórico da cidade de Cuenca. Os resultados indicam que é uma técnica com grande potencial que permite determinar três níveis de deterioração: bom, regular e mau. Por sua vez, confirma-se que a metodologia proposta é uma ferramenta eficaz e de baixo custo com alto potencial para aplicação a curto prazo em estudos preliminares e investigações mais amplas antes da intervenção.

Palavras-chave: incidência ambiental, processamento de imagens digitais, edifícios patrimoniais, deterioração patrimonial, estado de conservação, NVDI

Introduction

The evaluation of the state of conservation of a monument, building or work of art is one of the most important aspects in the conservation of heritage, the application of non-invasive techniques to detect the state of the same are key elements when it is not possible to physically access the resource. In Latin America, since the middle of the twentieth century, an arduous task has been undertaken to ensure that State policies introduce the concept of conservation and rehabilitation of historic centers. This work, which began with the physical-spatial delimitation (Carrión 2001), today brings together the joint efforts of civil society, municipal governments, and academia. The results are significant, and optimism for the future is even greater. So much so that there are 31 historic centers declared as Cultural Heritage of Humanity for their architectural, artistic, social, and historical value (Carrión 2001), that is, for their Outstanding Universal Value (OUV). However, the policies' elaboration and application by returning un-touchable monuments to buildings with value are neither enough to achieve adequate conservation nor promote social development.

Thus, the entrenchment of the conservationist concept entails the severe risk of turning historic cities into cold, empty, indifferent museums, lacking vitality, displacing the inhabitants and their productive activities (Carrión 2001). In contrast, the historic center should be understood as a public space par excellence and, therefore, an element around which the city is articulated, making it, above all, a major urban project (Carrión 2005). In this sense, the problem of their conservation and management has become the focus of debates and discussions of current urban policies. Three facts impact: 1) the deterioration of the historic areas of the cities, 2) the formation of awareness about the conservation of historic-cultural centers that almost always modify urban agendas and, 3) urbanization tendencies (Carrión 2020). In other words, the need for appropriate technical responses for its conservation is ratified, despite the evident building renovation (Mutal 2003) that it is experiencing worldwide and that even falls into the so-called urban vandalism (Carrión 2005).

When they added the Historical Center of Cuenca (HCC) to the World Heritage List (WHL), it was agreed to comply with a series of guidelines for its conservation and care, framed in the 1972 Convention on the Protection of the World Cultural and Natural Heritage, which has been developed with ups and downs. The most relevant issues, such as stopping and treating the deterioration of its real estate, have not been considered beyond the abandonment and associated negligence and the implementation of the legal and administrative measures in force. In other words, the applicability of scientific, technical, and financial measures capable of protecting, conserving, enhancing, and rehabilitating the heritage is not guaranteed (UNESCO 1972). Despite this, at least in the last two decades, it is recognized that the deterioration of the architectural heritage is associated with urban dynamics such as inefficient transportation and other polluting emissions.

The most forceful reference goes back to 1998 in the context of the declaration of Cultural Heritage of Humanity, it indicates that one of the most severe problems of the HCC is the environmental pollution and abundant rainfall, especially between January and May (Municipio de Cuenca and Universidad de Cuenca 2017). At the same time, the drastic reduction of the number of problems through the renewal of the public vehicle fleet remains a pending task. As an iconic example, the Cuatro Rios Tramway in Cuenca planned to transport 65 thousand passengers per day (PNUD and UNOPS 2017) has barely reached 10 thousand on average, before a 2.5 month of free of charge. That is, the adaptation of the system and the citizen still present difficulties that lead to permanent emissions with increasingly significant effects.

On the other hand, faced with the difficulty of implementing structural measures, the vulnerability and risk of environmental and anthropic architectural heritage increases in the most exposed elements, such as facades more and more frequently (Perez-Monserrat *et al.* 2016). In polluted urban areas such as Venice, Florence, Athens, among others, but also as HCC, building materials tend to darken due to the accumulation of pollutants, present black crusts as a result of damage or loss of matter, sulfation, moisture, oxidation and other types of deterioration (Hambrecht and Rockman 2017), which over time form strata without historical relevance. Therein lies the importance of considering the external environment as much as the internal one in the deterioration of the assets and in the search for alternatives for their conservation.

In the first scenario, the most common, other experiences of interest are the studies developed by Žarnić, Rajčić and Moropoulou (2012) regarding the implementation of the EU Project European Cultural Heritage Identity Card to expose that, the interaction and joint action of environmental factors generate a great impact on cultural heritage in the long term. In other words, increasingly comprehensive studies allow tuning environmental requirements on architectural envelopes at first, and then on the integrity of heritage assets to perform compatible actions and the generation of a data structure (EU CHIC Iceberg) containing is relevant to cultural heritage (Žarnić Rajčić and Moropoulou 2012).

Against this background, in cities, what is considered heritage is facing increasing problems. Thus, risk and vulnerability assessment has rapidly become a global priority (Aguirre Ullauri *et al.* 2019; Ortiz *et al.* 2014). Research by Campiani *et al.* (2019), Ortiz and Ortiz (2016), Ortizet *et al.* (2014) or Galán Huertos, Bernabé González and Ávila Ruiz (2006) confirms the direct impact of environmental and anthropic variables on conservation at the individual and territorial scale. Furthermore, the positioning of valuation methods such as The ABC Method: a risk management approach to the preservation cultural heritage (Purdy 2010), which uses the ISO 31 000 (2009) standard (Purdy 2010), confirms the importance of risk assessment considering the context and types of risks in order to make appropriate decisions and effectively conserve heritage.

The previous problems are not foreign to HCC, Argudo *et al.* (2015), Rueda (2014) and Arizaga (2012), who from different professional levels and legal competencies, position the need to identify injuries in significant architectural elements and components, risk assessment and vulnerability as heritage conservation resources, despite not being a priority of application in national public policy (Aguirre Ullauri 2021). Through frequency instruments, derived from inventories, it has not been possible to generate progress, but some local research allows progress, such as the use of image processing techniques and data collection with digital tools that have been applied to evaluate conservation at the urban level based on heritage values and the required long-term control (Heras, Briones and Sinchi 2018). Another proposal includes the application of the supervised classification method called Support Vector Machines (SVM) to determine the heritage elements to monitor at a territorial scale (Heras *et al.* 2019). As is clear, there is no systematized tool that allows diagnosing the state of conservation of heritage real estate continuously, but rather generic actions for its control.

In this context, this work aims to evaluate the suitability of using the NDVI theory applied on an RGB image as a low-cost tool to assess the condition of the facades of heritage buildings, in conjunction with other technical inputs. The NDVI is calculated from the combination of red and infrared spectral bands of an image, which provides a quantitative measure of the health of vegetation in an area, in an RGB image, these bands are assigned to the red, green and blue channels, respectively, which allows to visualize the NDVI along with the basic visual information of the image showing tonality according to the state of the facade being able to identify and monitor possible damage.

Nowadays, the use of digital image processing to evaluate the state of conservation is a real option as a popular option, with the same can identify various aspects such as pigments, repairs, cracks, etc. Multispectral imaging has become very important due to its portability and ease of use, but their use is limited due to their cost (Cosentino 2015; Del Pozo *et al.* 2017; Meroño *et al.* 2015; Valença *et al.* 2013). Thus, the present research promotes the systematization of a low-cost route for the automated diagnosis of pathological damages and their state of conservation on the façade of the HCC's heritage assets. It also seeks to demonstrate in an agile way the relationship between the deterioration of travertine facades in heritage buildings through the proposed tool, as a case study; this is relevant, since usually this affectation goes unnoticed due to the geological nature of the material and its wide variation. Therefore, it is desirable to apply an image-based method for damage assessment, which also covers inaccessible parts of the building surface. It should also provide data for further analysis and classification of the existing damages; this approach offers good preconditions for an automation of damage detection. Thus, due to its technological vocation, it is a practical tool for professionals and citizens. In addition, it intends to offer a feasible technical vision whose implementation is expected in the short term.

Background: Historical Center of Cuenca, dynamics, and state of conservation of architectural heritage

Cuenca is a city that, throughout its history, has had a remarkable growth that impresses from any point of view. It combines the Cañari, Inca, Hispanic and Republican influences, and the inscription of the HCC in the WHL responds to this architectural, cultural, and natural richness. The criteria established by UNESCO for such designation in 1999 focus on the successful implementation of checkerboard cities and their harmonious articulation with the ecosystem as an outstanding representation of the Spanish colonial city *entroterra* (Municipio de Cuenca and Universidad de Cuenca 2017). In other words, there is a sort of balance between the environment and its actors, which has been progressively transforming and reporting negative impacts. That is, either by the loss of native forests, the mutilation of the habitat immediately surrounding the HCC, the disrespect of the natural vocation (Mannoni 2006) and the pre-Hispanic cosmovision (Alulema Pichasaca 2018), or in contemporary settings, the ever-increasing emissions of the automobile fleet (EMOV EP 2021).

Long before being aware of these alterations from the first moments of occupation, although to a greater extent since the foundation, there has been the successful fusion of different societies and cultures. Therefore, they have externalized their identities through architecture and significant urban context and landscape nuances. This intermingling exposes sumptuous colonial buildings, such as the Monastery of the Conception and Carmen de la Asuncion, tiny adobe houses covered with tile, typical of the vernacular building tradition of the Ecuadorian Austro, portentous buildings of the Republican period (Municipio de Cuenca and Universidad de Cuenca 2017) and even national references of architectural modernity, such as the Teatro Casa de la Cultura or the Municipal Palace. That is to say, architecture as a human manifestation has been influenced by social, cultural, and economic events of each era, which in turn has demanded the development of a vital capacity for adaptation.

A crucial factor in the morphology of the city of Cuenca in terms of architecture has been the natural topographic layout in the form of terraces; three are recognizable in the immediate context, although it is possible to identify others. The highest one is located in the north of the city; the intermediate one is in the center and houses the HCC, and the last one is in the lower part on the south bank of the Tomebamba River. The last one also receives the name of El Ejido and has historically been a point of communication with the surrounding parishes (Minchala 2019).

In the extent of such terraces, urbanization and modernization have been subject to a political transition. Therefore, the bonanza of the export of cascarilla plant and toquilla straw as a catalyst for implementing the French Neoclassical and other events such as intellectual production or the insertion of technical instruments of administration and urban planning (Aguirre Ullauri *et al.* 2018). It is also known that the financial excess and foreign cultural influence led to the architectural transformations through the elite from Cuenca. They also financed the new architecture to project the fashion of the world's great cities (Aguirre Ullauri, Sanz and Vela 2018). Correspondingly, over the years, the implementation of materials and construction systems in HCC buildings have been amalgamated while still evidencing alterations in construction customs and structures in general (Roura Burbano and Ochoa Arias 2014). Despite these possible detriments, the coexistence of forms, styles, typologies, and construction practices are primarily favorable. In such a way, the application of materials remains in people's memory despite changes, assuming a form of attachment to the OUV of HCC, but also enhances social construction and generates an understanding of those elements that hold collective meaning (Roura Burbano and Ochoa Arias 2014).

On the other hand, and aware of this historical reality (Gallardy 2014; Revelo 2011), there is a growing concern to find the causes that provoke the sometimes-accelerated deterioration of buildings with heritage values, and by extension, of the urban image and landscape. This image is associated with the group of façades that make up the block and constitute the fundamental protective layer against the incidence of aggressive agents present in the environment (Hernández 1997; Revelo 2011), climatic elements, and human beings.

Air pollution is one of the parameters that has had much relevance in recent years due to the particles present in it, which represent a high risk to health, among the components that affect the quality of it are Ozone (O_3), Sulfur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), Particulate Matter less than 10 microns (PM_{10}) and Particulate Matter less than 2.5 microns ($PM_{2.5}$), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), Particulate Matter smaller than 10 microns (PM_{10}) and Particulate Matter smaller than 2.5 microns ($PM_{2.5}$), most of which come from the incomplete combustion of fossil fuels, mostly from the automobile fleet. According to data provided by EMOV EP (2021), $PM_{2.5}$ air quality levels in Cuenca are within the Ecuadorian national standard (FAOLEX 2015.) but outside the limits established by the World Health Organization (WHO) in 2005 and with its subsequent update in 2021 (WHO 2005; 2021). This has led the city to implement policies to reduce pollution, the best known of which is the technical vehicle inspection, which began in 2008. By the year 2020, the number of vehicles has multiplied exponentially and, although they pass the review, they emit pollutants into the HCC ecosystem, according to the Mobility Plan report which details that the streets of the historic center circulate between 10,000 to 20,000 vehicles per day (DGM 2015). In other words, the approach was born and maintained within the framework of health conservation without articulation with heritage. The same is true for other examples, such as the effects of climate change. It will lead to thermal increases such as heat islands in historic cities in Latin America and the Caribbean (Markham, *et al.* 2016), capable of causing general damage to materials (Bustamante Campoverde 2021).

In this scenario, although there is a framework of knowledge of environmental deterioration and physical recovery of the architectural heritage, research on pathological damages associated with the characteristic materials of the HCC architecture is incipiently developed. The approach remains in the qualitative denominations of good, regular, and bad, limiting the proper formulation of a prior judgment and consequent practical actions.

Methodology

This research has several approaches and therefore includes a set of processes associated with the three fundamental pillars described below.

a) Preliminary evaluation of a case study **[Figure 1]** *is based on the collection of information in the field regarding pathological damages of the materials of the front face or façade*

As a starting point, we consider the case of a heritage building located in an emblematic road artery of the HCC,

Figure 1.- Test case study and its context.

such as Simón Bolívar Street, according to coordinates 721502.64; 9679747.9157 and 721490.43; 9679696.8338. In addition, the property belongs to the category Architectural Value B (VARB) (2) [Figure 1]. That is, to those buildings whose role is to consolidate a coherent fabric with the aesthetics of the city or the area in which they are located and may be enriched by historical attributes or essential meanings for the local community. From the point of view of their spatial organization, they expressways of life that reflect the community's culture and use of space (Consejo Cantonal de Cuenca 2010).

In architectural terms, it is a four-story property whose façade faces south, with a slight slope to the west. The constituent material of heritage interest is yellow travertine (A18); however, there are other materials such as lime, sand, and cement mortar (A10), handmade glass (A6), cement mortar (A9), earth mortar (A8), and wood (A12 and A13). These materials report a diversity of pathological damages. According to previous studies, there are significant incidences, that is, the environment and human action generate moderate effects in the conventional range of the Leopold Multivariable Matrix.

In addition, it is inserted in a road axis whose level of incidence is also moderate and reflects the general urban and productive condition of the roads in an east-west direction.

In urban terms, under considerations of the selected test case, the analysis focuses on the HCC First Order Area, which was described as such after the Declaration of National Heritage in 1982 and ratified through the Declaration of Cultural Heritage of Humanity in 1999. In other words, the selection of the pilot case and its location is based on the intrinsic characteristics of the building, its heritage value, and proximity to significant areas within the perimeter of the First Order Area, whose radius of influence covers approximately 50% of the HCC. Thus, the comparative case maintains similar conditions to the pilot case, despite the distance and location conditions, so the analysis and results are consistent.

b) Study of environmental variables based on a quasi-experimental analysis with a mixed approach (quantitative and qualitative)

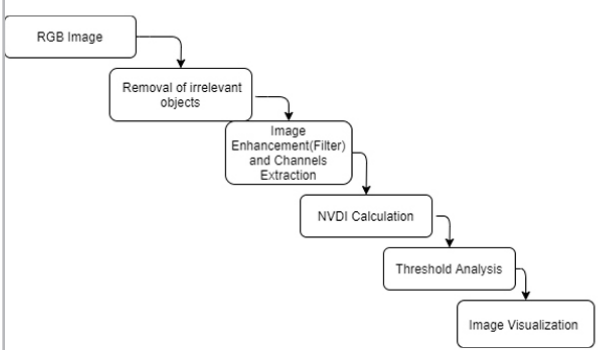
Field data collection is contemplated. That is, real-time readings of the environmental variables could cause deterioration in the building, such as atmospheric pressure, precipitation, relative humidity, diffuse solar radiation, global solar radiation, ambient temperature, wind direction, gust, and wind speed. The meteorological data was taken every hour, during the months of March -May 2021, it was installed in a nearby building, obtaining more precise data that reflects the conditions faced by the building studied. Meteorological data is taken every hour, the three months it changes from summer to winter, to see the environmental characteristics in those crucial months. Finally, the average for the simulation processes is obtained in one month, the station has the following characteristics: Ane-mometer (accuracy +/- 5%, resolution 1 m/s), Temperature (Outstanding Uni-versal Value accuracy +/- 0. 1°C, Resolution 0.1°C), Humidity (accuracy +/- 2% RH, resolution 1% RH), Barometric Pressure (accuracy +/- 0.5hPa, resolution 1 hPa), Precipitation (accuracy +/- 2%, resolution 0.254 mm/h), as well as a pyranometer (accuracy +/- 5%, sensitivity 280-2800nm). Also, an air quality report was obtained from EMOV EP (2021) for the months in which the study was carried out.

c) Digital Image Processing

The use of the Normalized Difference Vegetation Index (NDVI), which is widely used around the world in vegetation applications, has been proposed to perform image processing. This index takes advantage of the contrast of the characteristics of two bands of a multispectral dataset: in vegetation, green leaves usually present a better reflection in the near-infrared wavelength range than in the visible wavelength range. When leaves are diseased or dead, they become more yellow and reflect significantly less in the near-infrared wavelength range (Kim, Jung and Seo 2016). In this paper, the NDVI theory is applied to RGB (red, green and blue) images to obtain the state of the facade material by analyzing the reflectance in the image. The diagram in Figure 2 indicates the process used to obtain the different characteristics of the facade using the Matlab software (Kazemi & Ghanbari Parmehr 2023; Suárez *et al.* 2021).

As the first step, many image elements are removed, like windows, doors, and other reflectance elements that cause inconsistencies during processing. Then, it is necessary to apply the decorrelation filter to make an improvement in the colors scale on the image and perform the separation of colors in a better way, obtaining a false-color infrared composite image (False CIR) because is obtained from RGB image and not from a multispectral image (Ammaiappan & Manoharan 2012; Miller 2024).

Then, the color components of the false CIR image are extracted, specifically the near-infrared band (NIR) and




```
\\ Main module
IMAGE_PREPROCESSING( removing windows,doors,etc)
START
READ RGB_Image;
NORMALIZE (Input_Image) ;
DECORRELATION_STRETCH (Input_Image) ;
GET CHANNELS FROM IMAGE:  NIR,RED,GREEN ;
COMPUTE_NVDI();
DEFINE threshold levels FROM NVDI IMAGE;
FOR {levels} in {threshold level} DO
    {
       APPLY threshold levels AND GET PERCENTAGES OF PIXELS EXCLUDING
        PERCENTAGES OF PIXELS CORRESPONDING TO PREPROCESSING(windows, doors) ;)
       }
ENDFOR
DRAW PERCENTAGES FROM BINARY IMAGE OBTAINED;
COMPUTE_STATS { COMPUTE SUMMARY PERCENTAGES VALUES FOR FACADE STATE;}
SAVE {OUTPUT_IMAGES}
END
```

Figure 2.- Flowchart and Pseudo-code of image processing in Matlab.

the red color band to perform the analysis, then the formula of NDVI is applied as shown in equation (1) to the image and with the help of the false CIR image we proceed to apply the umbral. As a result, the material in good condition is shown in red, the material with severe damage is shown in green, and the material in fair condition is shown in yellow (Hemmleb *et al.*, 2005; 2006).

$$NVDI=((NIR-Red)) /((NIR+Red)) \quad (1)$$

It is important to emphasize that when the NDVI formula is applied, the pixels take values from -1 to 1. So, different thresholds are applied per observation to obtain pixels that match the different conditions of the architectural material (Huang *et al.* 2021). Also, as the calculation was made with an RGB image, the NDVI image obtained is known as false NDVI, so for the rest of the document, when mentioning the NDVI image, it will be referring to the false NDVI image.

Results and Discussion

a) Architectural diagnosis

The heritage building presents different pathological processes; that is, there is increasing damage at different levels. The primarily identified injuries are humidity, graffiti or drawings (including marks, stripes, and other similar anthropogenic actions), small detachments of material in scattered areas, and dirt by deposit.

This pathological chart includes exhaustively [Figure 3]; 1) loss of cohesion in joints, which describes a decrease in the binding capacity of existing mortars (A10 y A8); also accentuates the mobility channels and water stagnation, 2) high porosity of the predominant stone material (A18), 3) constructive discontinuities (A18) and possible changes in the material (A12 y A13), 4) predominance of rough surfaces (A18) that promote the accumulation of suspended particles which causes hints of exterior water stains on the cornice, sills, and discontinuities

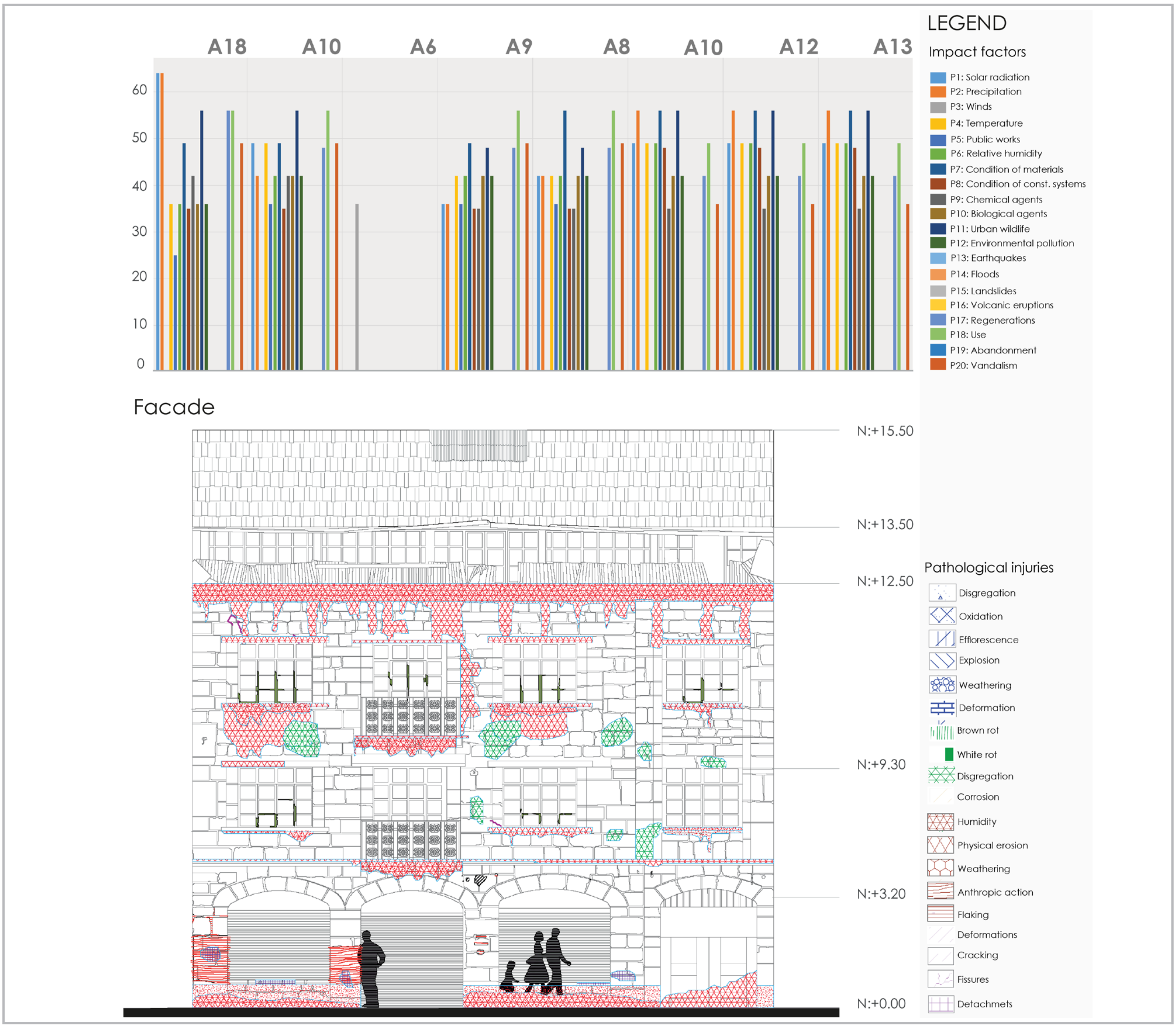


Figure 3.- Synthesis of the state of conservation: materials and associated damages.

(change of masonry), that is depositional fouling, 5) lack of consolidation surface treatment (A18) for areas in which advertising elements have been inserted, and 6) lack of citizen empowerment resulting in physical aggressions. Likewise, it is also associated with the extrinsic or physical features of the place of location, such as the rainfall, insolation, pollution, relative humidity, and others, which are later detailed.

It is, then, established that there is significant damage, even more advanced than the moderate initial assessment, which could also be found in any other building in the HCC. In fact, it is well known that by the end of the year 2021, 170 damaged patrimonial assets were identified; 85.29% were in bad condition, and 12.35% were in ruins (Sánchez Mendieta 2021), which evidences a high level of deterioration in heritage buildings in general. If the intrinsic conditions (constructive materials and systems) and the extrinsic conditions (environment and context) meet, quick damage on the façade of the patrimonial asset is possible, also having in mind that this damage could be extrapolated to the whole building. This scenario is of interest due to the abundant use of local travertine since at least the late 19th century; that is, several heritage buildings in the HCC could exhibit similar deterioration regardless of their style, typology or form, as material and surrounding conditions converge.

On the other hand, it is convenient to state that the enclosure or façade indicates monumental preservation, and frequently, it is the leading cause of renovation actions (Balaras *et al.* 2005). Further degradation can occur in the damages with the pass of time, resulting in social rejection, detriment to the urban image and the historical landscape without losing its capacity to meet functional requirements (Bassily, Abufarag and Goubran 2022). Therefore, although the factors of maintenance and usage play a fundamental role, the intrinsic characteristics of the material, the construction process, the technique, and the environment are catalysts for the appearance of symptoms, which show qualitative changes in values and singularities (Iñigo *et al.* 2022; Douglas-Jones *et al.* 2016).

b) Field environmental measurements

The report of environmental variables is shown in Figure 4, it corresponds to an average of the study months obtained from the installed meteorological station and the air quality measures from study period.

• Atmospheric Pressure: there is an average value of 756.11 hPa. This value is not used in the architectural study because it represents the air's weight on a surface and is negligible in this analysis (Brandariz 2022). Nevertheless, the authors (Rivas Kluber 2023; Simancas 2003) assert that precipitation and atmospheric pressure are other factors determining the climate, so the incidence of the latter can arise through the set of climatic parameters. Likewise, it is known that in 2021 in Cuenca, the atmospheric pressure fluctuated between 750 and 760 hPa (EMOV EP 2021), which validates the collection of information on the parameter from its relationship with the Cuenca Air Quality Monitoring Network.

• Precipitation: In Cuenca, there is an approximate value per the year of 1612 mm (Sellers Walden 2023; Climate-Data n.d), that is an average value of 134mm per month; in the study period, an average of 42mm was obtained, this parameter is of utmost significance due to its quantity, it can cause severe damage to buildings. If this parameter joins with wind and radiation, a set of cyclic processes that

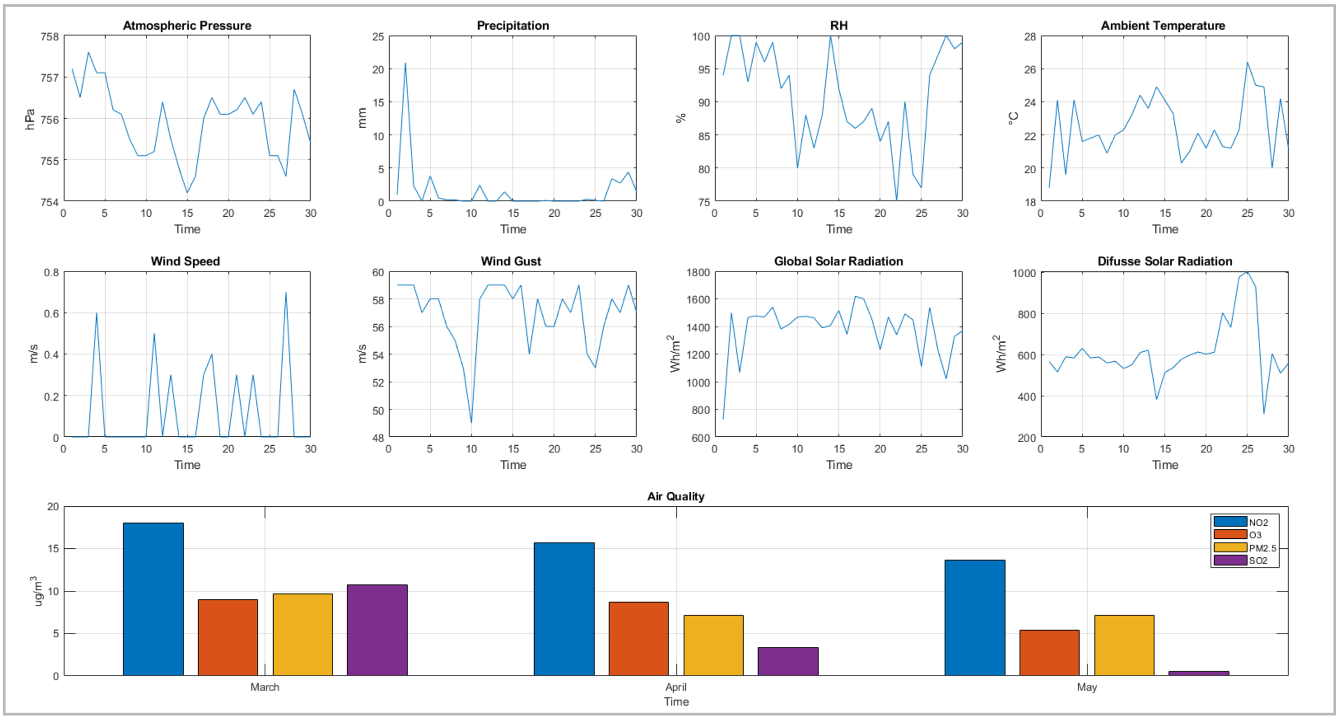


Figure 4.- Monthly average of measured meteorological variables (March to May)

generate an essential group of pathological processes can be provoked (Revelo 2011). Some particular cases are when the action of wind on the surfaces of the elements, erosive action, and others, make the fluorides, chlorides are settled (Rabal Saura and Castejón Porcel 2023; Arencibia Iglesias and Cortiñas Abrahantes 2015), and others.

• Relative Humidity (RH): it is understood that as the amount of water that the air contains as a result of the evaporation of water, according to historical data– the relative humidity in Cuenca is around 84% monthly (Sellers Walden 2023; Climate-Data n.d). In the case of this study period, the average value is 90%; hence, it exceeds the average. According to Franco (2016) and Rivas Kluber (2023), it is a macroclimatic parameter, which can be modified due to micro-climatic variations. The variation experienced guides such definition, as well as its association to biodeterioration processes (Rodríguez *et al.* 2023; Rodríguez García 2016) or other plant growth, and even the deterioration of artworks (Muñoz González *et al.* 2020) if any.

• Diffuse Solar Radiation: according to the data collected, we have an average of 611 Wh/m^2. The high values shown occur due to high cloudiness in the study period and, therefore, a lower incidence of direct sunlight on the building (US Department of Energy n.d), which implies a high potential for deterioration associated with discoloration, but not with all pathological processes such as biodeterioration.

• Global Solar Radiation: the average value of the data collected is 1378.1 Wh/m^2, a lower value than the average of 3791 Wh/m^2 estimated by Delgado and Orellana (2015), emphasizing that metric is the sum of direct, diffuse, and reflected radiation, it plays an essential value in the degradation of materials due to its absorption (US Department of Energy n.d; Rosas-Lusett and García 2023).

• Ambient Temperature: In Cuenca, there is an average temperature of 15.44 °C (Campoverde 2021; Kottek *et al.* 2006; IERSE n.d). However, an average of 22 °C was obtained in the study period. This metric is vital in the analysis because solar radiation, wind, and humidity play an essential role in the deterioration of architectural surfaces (Athauda *et al.* 2023).

• Wind Gust: is defined as the sudden and short-term increase in wind speed. This metric is vital in the analysis because it would damage the architectural surface. In the study period, there is a maximum speed of 59 m/s, which can carry dust and smock from vehicles against the building promoting the deposit, since, when considering the morphology of the area and the scale of the building, there are no obstructions to limit the effect of the wind (Cuadrat *et al.* 2022; Rajagopalan, Lim and Jamei 2015), as in other cases such as Rafael María Arízaga St. (Bustamante Campoverde 2021).

• Wind Speed: in some cases of the study period, the values are practically zero, and in the rest of the cases, the values are minimal, reporting an average of 0.11 m/s for the architectural study. This variable can be discarded since it does not represent a damage factor. Even so, it should be recognized that the predominant wind direction in the HCC follows the alignments of the trace, with particular accentuation at 15h00 from the east, which in turn indicates the influence of the local landscape on the behavior of climatic variables such as wind (Bustamante Campoverde 2021).

• Air Quality: in the study period, a high level of $PM_{2.5}$ particles can be appreciated, exceeding the threshold established by WHO in 2021 of 15 ug/m^3, this variable represents a potential damage to the façade due to the long-term accentuation of the particles.

The climatic factors changes, and its destructive nature determine the various consequences on the façade and the roof as highly exposed architectural elements. Research about this last topic should mainly be developed and, is not detailed in this research, however, it is recognized that the type of roof and its operation affect the conservation of the facades. Significantly, in the case of the façade, such factors and their variations modify the distribution of the molecules causing changes in shape or appearance. An example is rain and solar radiation, which causes the humification and drying process, respectively, causing the volume of the material to increase and decrease. If this process occurs repeatedly, the presence of cracks or fissures becomes evident (Albatayne *et al.* 2018), but in the case study, it is not. Also, the wind, with variable conditions of direction and speed, influences the action of the rain, causing more deposited dirt on the material since it can drag larger particles that will be placed on the surface (Vera *et al.* 2022), causing exterior water stains as the case study shows. In general, these environmental factors cause different types of degradation; some of the common and visible (total or partial) on the study case can be summarized as:

• Depositional fouling: occurs when the particles are stored superficially on the material, creating a layer of black color in its worst case when the particles are introduced into the pore of the material, but in most cases, the wind and rain drag the particles easily when the atmospheric conditions are Good (Vera *et al.* 2022).

• Fouling by exterior water stains: occurs when there are distortions in the path of the water sheet due to the existence of reliefs that will change their direction; thus, the particles will be carried to other material locations entering the pores of the material, which occurs because the particles are dragged slowly, it receives the name of churretones or runoffs, which are common in urban façades (Vera *et al.* 2022; Casas Figueroa 2019).

• Discoloration and staining: this action occurs due to the presence of sunlight on the surface which, added to the accumulation of dust, tends to stain and discolor the surface of the material (Vera *et al.* 2022).

• Erosion: this phenomenon occurs due to temperature variations that expand and contract the material's surface, breaking its sheets (Jiménez López 2020).

c) Digital Image Processing

With the environmental data sampled, we proceed to contrast the façade condition as determined in the preliminary diagnosis by digital image processing [Figure 5]. This processing allows us to perform mathematical analysis to propose maintenance actions according to time, which leads to having a technical tool in the activities of façade conservation according to the impact of the environment, so there is correspondence between the two processes. It also guides the architectural elements that require immediate action, such as cornice, sills, apron, lintels, and framing with relief. In other words, some elements increase vulnerability (Emergency Management Australia 2000) by generating discontinuity of the vertical and horizontal plane of the façade, even though they are determining elements of the Neoclassical architectural style of the asset.

In the same way, to verify that the algorithm works as expected, another heritage building is taken within the area of influence (500 meters) at the intersection of Luis Cordero and Mariscal Sucre streets. The denominated Superior Court of Justice Building, listed as Architectural Value A (AVA), was studied with the image processing, and the same results are obtained [Figure 6] according to damage distribution.

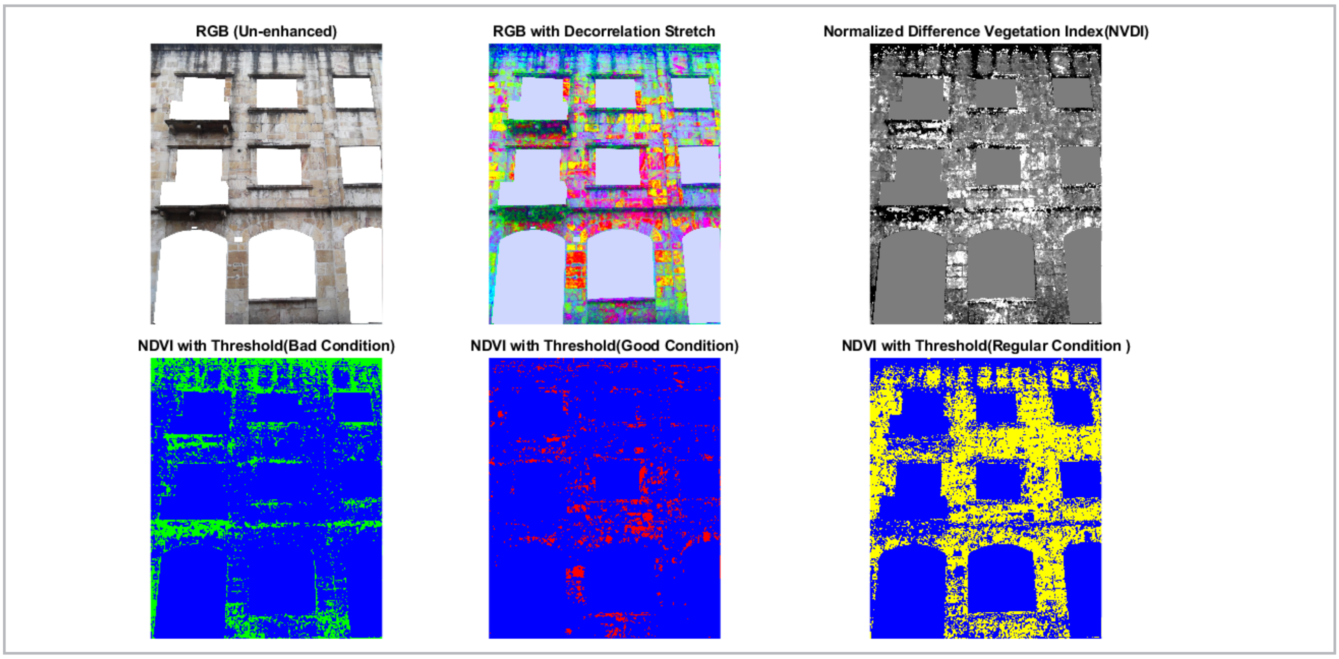


Figure 5.- Imagen Processing to identify the state of the material of the building's façade using NVDI analysis of the studied building.

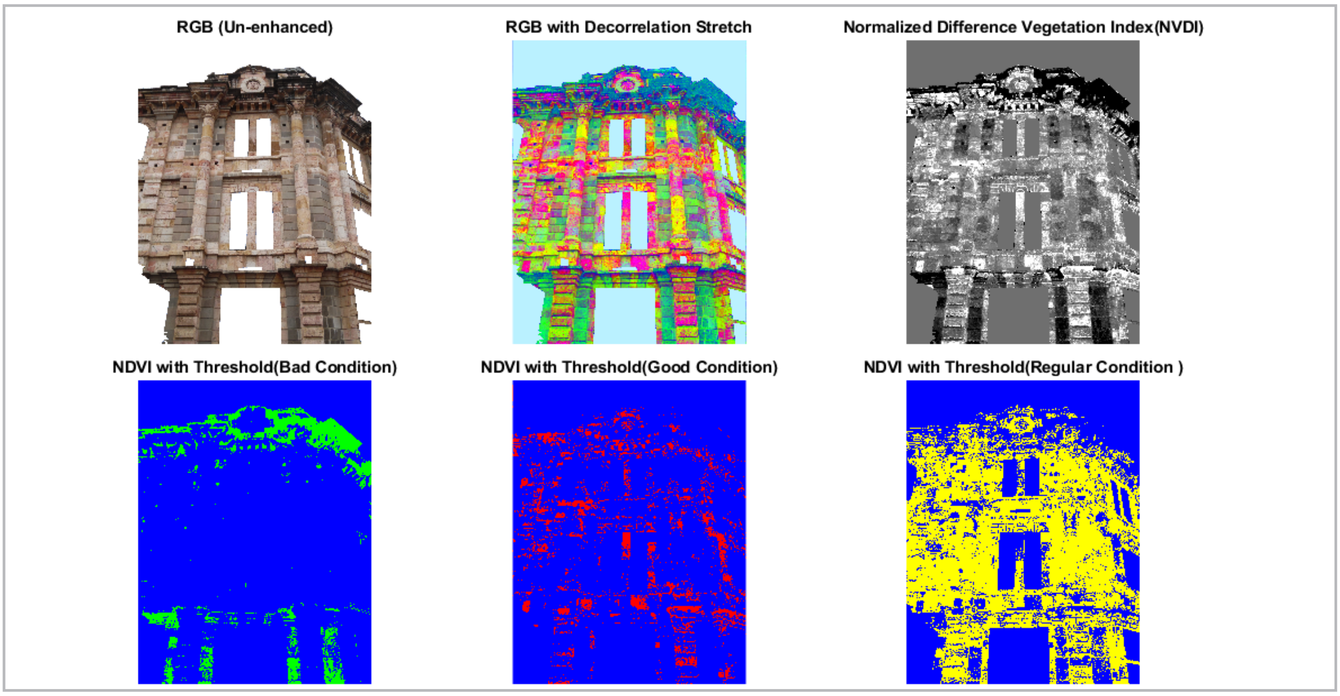


Figure 6.- Imagen Processing to identify the state of the material of the building's façade using NVDI analysis

Finally, by applying the thresholds and adding the number of pixels that comply with its range, an estimate of the percentage of damage on each façade can be obtained, summarized in Table 1:

Levels		Building #1 (Studied Building)	Building #2 (Inside influence zone)
		NVDI (% Pixels)	**NVDI(% Pixels)**
Bad condition	Green	28.1288	12.3899
Good condition	Red	11.3483	14.5362
Regular condition	Yellow	56.8782	67.7524
Not determinate	None	3.6447	5.3214
Total		100%	100%

Table 1.- Classification in percentage of the state of the facade found by digital image processing

It is convenient to indicate that the percentage of error shown occurs due to the deviation of the levels between thresholds established in 0.1 pixels within this deviation range are not considered for the analysis to achieve better spectral separation, as can be seen [Figure 5 and Figure 6].

On the other hand, according to the data obtained from the image processing, in the case study [Figure 5], 28.12 % of the façade of the building shows a bad state of conservation, that is, severe conditions in its integrity. Also, together with an analysis by observation in situ, the presence of corrosive material covering this area is evidenced due to the high relative humidity present causing fouling by exterior water stains on the architectural elements denominated as vulnerable. In the same way, only 11.34% of the façade of the building is in good condition supported by the meteorological conditions of the area, while the remaining 56.87% is in regular condition, that is, worn, but the latter is not severe due to the level of solar radiation received. However, the same could weaken the material's structure, causing it to fade. At the same time, in the comparative case study [Figure 6], the state of deterioration is ratified, the image processing is able to segment the three states of the facade, it should be noted that the percentage in poor condition is lower than the building studied, this is due to the fact that the location of the building is located at an intersection adjacent to the central park, therefore the particles spread over a larger area, depositing to a lesser extent in On the façade of the building, it should be noted that according to data from the municipality, an average of between 10,000 and 20,000 vehicles circulate daily[1], although municipal regulations prohibit the presence of public transport within the historic center, vehicle traffic is high, increasing the particles that settle in nearby buildings (Ilustre Municipalidad de Cuenca, 2015).

Finally, Figure 7 shows the input image of the building façade with three regions marked by visual inspection in situ and with NVDI applied. Comparing the regions with the different results obtained from NVDI images shows many similarities, and the algorithm correctly separates the material's states. The image shows the presence of erosion and discoloration in the yellow area, which is travertine. Also, there is fouling by external water stains in the green area and the area that is travertine, too. Furthermore, a good state of conservation is framed in red, where the material is travertine again. In this way, it is shown how, regardless of the material, the constructive discontinuities associated with the style itself or later interventions show the greatest affections, even if the material presents low intrinsic vulnerability, as in the case of the stones.

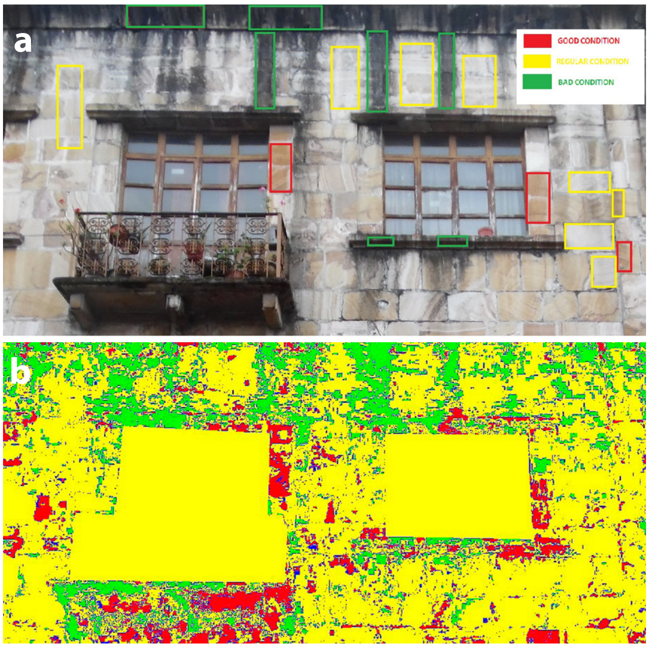


Figure 7.- Input Image Damage Compariso. Figure a) Image with marked regions by visual inspection. Figure b) Image with NVDI applied.

Conclusions

The preliminary diagnosis is a relevant approximation to the state of conservation of the façade of the case study, which is enriched through digital image processing. The purpose has shown that it is possible to use NDVI to analyze the state of the façade of a building using only RGB images that can be easily obtained with a mobile phone or, as in this case, using a regular photographic camera. That is a crucial tool to professional development as it helps in low-time investment and avoids effects associated with the purchase of sophisticated equipment and even the hiring of several professionals to formulate a preliminary diagnosis. Also, when obtaining the percentage of affectation towards the environmental variables, the need to plan the technical actions for short-term maintenance to avoid the current condition to advance to an irreversible situation is clear.

With the implementation of the algorithm, it is possible to analyze how environmental conditions impact the façade condition. Through the images it can be seen how rain and particles are deposited in specific places of the buildings at the top and on the edges of the balconies, this is contrasted with the rest of the building where a low level of exposure to weather variables shows a better condition of the facade.

Concerning other levels of damage, it is necessary to define significant retrieval actions and to do so, the implications of technical and financial resources stand out. In other words, some cases where the best majority of the population presents limitations that lead to the loss of heritage should be faced.

On the other hand, it is possible to determine a high vulnerability of damage of the architectural heritage when considering the aggressiveness of the location as a general feature of the First Order Area of the HCC and the whole city, even without taking into account other determining factors such as natural hazards or unforeseen catastrophic events like fires. Indeed, there is the imperative necessity to broaden the scope of heritage diagnostics and the development of emerging risk and vulnerability management policies that would support resilience building.

One of the technical limitations of the work carried out implies that pre-processing of the images has to be done to remove visual elements that affect the identification of the pixels since they generate reflection and are poorly identified by the algorithm.

In future applications of the method, it is expected to expand the case studies considering different materials representative of the HCC heritage buildings. The current findings show optimistic conditions for this. Thus, the results are not decisive, but they show the usefulness of the method for the diagnosis of travertine facades. Another future research field is to test the effectiveness of the algorithm against restored buildings, in addition it is necessary to contrast the percentage of particles that impact the façade versus those found in the nearby environment, in order to establish a link between the quality of the air and the impact on buildings.

Notes

[1] Refers to roads in which the concentration of particles per million is between 50 and 100. There is constant vehicular traffic, although there is no flow of public transportation; there is permanent commercial activity.

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