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Design of a two-stage air monitoring and filtration system for implementation in enclosed spaces

Diseño de un sistema para el monitoreo y filtración de aire en dos etapas para su implementación en espacios cerrados

HERNÁNDEZ-SÁNCHEZ, Uriel Alejandro†*, VÁZQUEZ-ROSAS, Sergio, CABALLERO-LÓPEZ, Emma Isabel and FLORES-SÁNCHEZ, Verónica

Universidad Tecnológica del Centro de Veracruz, Ingeniería en Mantenimiento Industrial, Av. Universidad 350, Cuitláhuac, C.P. 94910, Veracruz, México.

ID 1st Author: *Uriel Alejandro, Hernandez-Sánchez* / **ORC ID:** 0000-0003-1488-3601, **Researcher ID Thomson:** Q-2907-2018, **CVU CONAHCYT ID:** 482289

ID 1st Co-author: *Sergio, Vázquez-Rosas* / **ORC ID:** 0000-0002-3259-382X, **Researcher ID Thomson:** P-8011-2018, **CVU CONAHCYT ID:** 857794

ID 2nd Co-author: *Emma Isabel, Caballero-López* / **ORC ID:** 0000-0002-6486-9368, **Researcher ID Thomson:** ABH-3859-2020, **CVU CONAHCYT ID:** 660625

ID 3rd Co-author: *Verónica, Flores-Sánchez* / **ORC ID:** 0000-0001-7899-4592, **Researcher ID Thomson:** O-2622-2018, **CVU CONAHCYT ID:** 344279

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Abstract

The objective of this paper is to develop an air quality monitoring system implemented indoors. Our research is qualitative approach and a descriptive scope, since, the measurement of CO_2 levels will be performed from an automated system that will be monitoring this parameter and to determine whether the air quality is adequate or air recirculation is required. The study focused on the detection of carbon dioxide CO_2 over a 12-day period. The results obtained from the monitoring system show average values of 600 ppm for the dirty air sensor, while values of 488 ppm were obtained at the system output. Therefore, the performance of the system for air filtration is verified.

Air quality, CO_2 levels, Enclosed spaces monitoring, Programmable Logic Controller, Recirculation

Resumen

El presente trabajo de investigación tiene como objetivo el crear un sistema para el monitoreo y filtrado de aire en dos etapas para su implementación en interiores. La investigación se desarrolla mediante un enfoque cualitativo y un alcance descriptivo, puesto que, se realizará la medición de los niveles de CO_2 a partir de un sistema automatizado que estará monitoreando dicho parámetro y poder determinar si la calidad de aire es adecuada o se requiere de una recirculación del aire. El estudio se enfocó en la detección de dióxido de carbono CO_2, durante un periodo de 12 días. Los resultados obtenidos del sistema de monitoreo demuestran valores promedio de 600 ppm para el sensor de aire sucio, mientras que en la salida del sistema se obtuvieron valores de 488 ppm. Por consiguiente, se comprueba el funcionamiento del sistema para el filtrado de aire.

Calidad del aire, Controlador lógico programable, Monitoreo de espacios cerrados, Niveles de CO_2, Recirculación

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† Researcher contributing as first author.

Introduction

Most of the activities performed by humans take place in enclosed spaces, such as classrooms, homes and offices, the latter being an environment that may involve health risks, either because of the nature of the work or because this space does not have optimal conditions with respect to breathing air quality, i.e. the physical, chemical and/or biological factors that interact with each other (Bian *et al*., 2018). Indoor air quality refers to air pollution inside buildings, commercial premises, airports, offices, industries, etc. The study of indoor air quality is an environmental problem; therefore, it has been posited that indoor pollution implies negative health effects (Kelly & Fussell, 2019). Measuring air quality requires tools and methods that are special for measuring the concentration level of physical and chemical properties of pollutants present indoors, another of the most widely used methods is the monitoring of suspended particles which employ filters to calculate their proportion present in the air (Braniš *et al*., 2005).

Advances in air monitoring methods have made it possible to analyse long-term pollution phenomena (Li & Bi, 2023). The parameters that determine indoor air quality are classified according to their nature as physical (such as temperature, radiation), chemical (such as organic and inorganic substances and/or compounds present in the air and/or airborne dust) or biological (moulds, spores, bacteria or mites), and the qualification of these pollutants is expanded in table 1 (Fromme *et al*., 2008). In order to carry out a correct measurement of air quality it is necessary to know the levels of chemical and biological contamination, which are provided by temperature and humidity, on the other hand, these levels are provided by sensors.

Pollutant	Type of pollutant
Organic	Volatile organic compounds (VOCs).
Inorganic	Carbon monoxide, carbon dioxide, nitrogen oxides,
Allergens	particulate matter.
Contaminants of biological origin	Fungi, moulds, dust mites, dander and pet hair.
Mixtures	Viruses, fungi, bacteria, dust mites, pet hair and dander.

Table 1 Classification of indoor containing agents
Source: Own elaboration

Air quality sensors are devices that detect and measure changes in the concentration of specific pollutants (Concas *et al*., 2021). The quality of a measurement is dictated by the basic performance of the sensor, the way the sensor is operated and the way its measurements are analysed (Anjum *et al*., 2021). There are several types of sensors, including electrochemical (EC) and optical sensors. Electrochemical sensors allow the determination of CO_2 and volatile organic compounds present in the environment in PPM concentration, based on an electrochemical semiconductor that generates an output voltage proportional to the concentration of pollutant material. A disadvantage is that the accuracy of the measurement is affected by temperature and humidity. There are several types of EC sensors, such as the MQ-7 and the MQ135. The former can measure carbon dioxide gas (CO_2), which is ideal for detecting harmful concentrations of CO_2 in the air to avoid a harmful impact on health. It can detect concentrations in the range of 20 to 2000ppm (Basford *et al*., 2020).

On the other hand, the MQ135 sensor used for air quality monitoring equipment is suitable for detecting CO_2, NH_3, benzene, NOx, smoke and alcohol. These types of gases can be harmful to health (Stavroulas *et al*., 2020). The sensor is integrated by an electronic circuit which is interfaced to a development board and has an analogue and a digital output (Dominutti *et al*., 2020). Optical sensors are the method of choice for detection due to their low cost, power requirements and fast response time. In this technique, a light source illuminates the particles, which are then measured with a photometer. For particles with diameters larger than 0.3 microns, the amount of light scattered is roughly proportional to their mass/number concentration. Particles smaller than 0.3 microns do not scatter enough light and cannot be detected by this method (Lambey & Prasad, 2021).

On the other hand, the control of temperature (both surface and air), humidity, and air quality in an indoor space generates a higher control of air pollutants. The concentration of carbon dioxide (CO_2) is a new indoor air quality check as it is a clear indicator of the performance of the air renewal system (Pichat *et al*., 2000).

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Several projects have been carried out to purify the air, some of which are the photocatalysis on TiO_2, which was able to test the rate of photocatalytic degradation using a laboratory photoreactor, with these data obtained it was concluded that pollutants inside a room are reduced by 43% by photocatalysis of TiO_2 (Karagulian *et al*., 2019).

On the other hand, research has been developed where transparent indoor air filters are used, these filters are composed of polymer nanofibres, the attributes obtained by this filter is that they have high filtering efficiency, logical transparency, low air resistance and light weight. This filter can prevent PM from entering the interior of the room, it can be used as a stand-alone device or incorporated with other filters such as HEPA in order to achieve a more pleasant indoor living environment (Liu *et al*., 2015). The PCO air purification technique mostly uses nano semiconductor catalysts and ultraviolet light to convert organic compounds in the air into benign and odourless constituents (Zhou *et al*., 2019).

Existing devices with applications in industry, education and government institutions have high costs, large dimensions, operational requirements and complexity of application. The implementation of such devices is limited to the geographical and temporal conditions of the areas where they are implemented. In recent years, the importance of measuring and filtering air for the prevention of diseases in people in workplaces, schools and homes has been detected.

Methodology to be developed

The present project is developed using a quantitative approach, since data will be collected for the evaluation of air quality. The scope of the research is descriptive, where the characteristics, properties and profiles of individuals or processes that can be susceptible to collection, measurement, evaluation and information of the variables examined are examined (Hernández Sampieri *et al*., 2014).

Therefore, the research work is carried out through a descriptive scope, since, exposure levels of various pollutants will be collected to establish alert levels for the prevention of harmful effects on health.

Figure 1 describes the 3 methodological stages applied to the project. In the first stage, the relevant calculations were carried out to determine the volume of the space, air changes per hour, CO_2 concentration and to estimate the clean air in the study area. Then we proceeded to design the device, starting with the selection of a free platform to facilitate the management of the information, then the response algorithm was developed, then the components of the device were integrated. Finally, a pilot test was carried out to check the performance and functionality of the device.

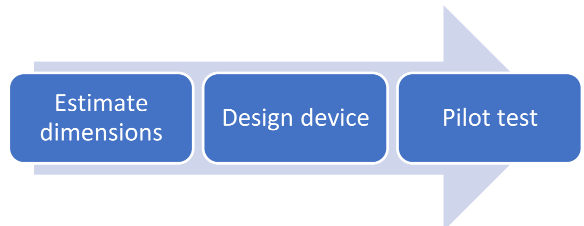

Figure 1 Methodology applied
Source: Own elaboration

Design of the device

The first step to develop the device is to select the platform that allows the development of the research work, therefore, the different platforms that will facilitate the transmission of information generated by the sensor were investigated. A free software platform was selected, which can be replicated as long as the equipment is available to carry out the monitoring. Then the elements that will integrate the air quality monitoring system were selected, which are shown in figure 2; two MQ-135 sensors for air quality control, an air extractor, UV-c lamp and a Logo 8.3 programmable logic control (PLC) that includes an LCD screen for data visualisation, power and ethernet ports for connection to the cloud.

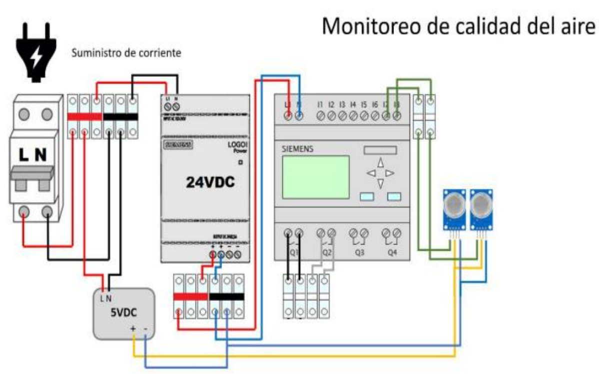

Figure 2 Wiring schematic and monitoring system components
Source: Own elaboration

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In order for the system to process the signals generated by the MQ-135 sensor, the flow diagram of the air quality monitoring system is shown (figure 3); The sensor is in continuous operation, therefore, it will detect measurements that exceed 500 ppm, when the levels exceed the concentration limit, a signal will be sent to activate an air extractor and an ultraviolet light lamp (UV-c), the extracted air will pass through a chamber in which a HEPA filter and an activated carbon filter are installed and ends up passing through the UV-c lamp. A second MQ-135 sensor is located at the air outlet to analyse whether the air being processed for filtration is below 500 ppm. Finally, when the sensor detects readings below 500 ppm a signal will be sent to determine the filtration system, however, the first sensor will continue to take real-time readings of the air quality levels.

The next stage is the development of the block diagram shown in figure 4. This programming code has 3 inputs, two analogue (AI1 and AI2) and one digital (I1). The input (AI1) captures the CO_2 concentration in the polluted environment.

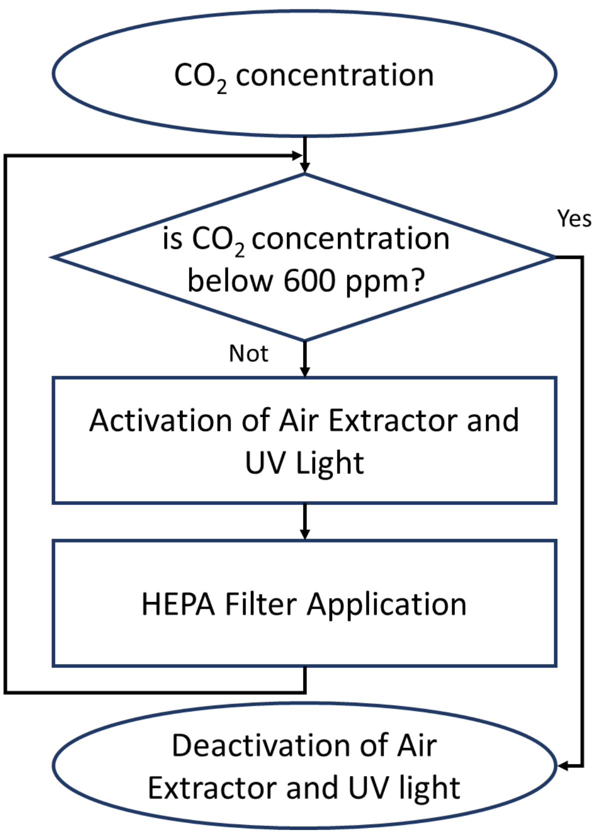

Figure 3 Algorithm flowchart
Source: Own elaboration

The signal is then processed in an arithmetic operation block to determine the carbon dioxide concentration values in ppm (parts per million). An analogue threshold value switch activates the outputs Q1 and Q2 (extractor and UV light) when the values are equal to or greater than 550 ppm. If values below 500 ppm are registered, the actuators (extractor and UV light) will remain off.

UV light) will remain switched off. The input (AI2) is connected to the filtered ambient sensor, which will perform the same signal conditioning process except that this input will only register carbon dioxide concentration values. The digital input is a push button that will force the system on and off the outputs.

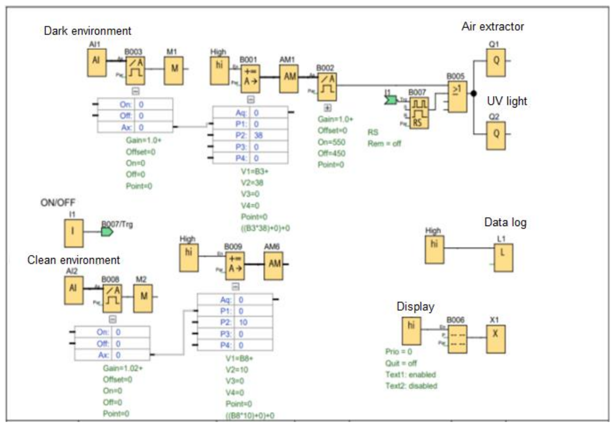

Figure 4 *Block diagram of the system*
Source: Own elaboration

The design of the air purification cabin was made using CAD SolidWorks 2018 software where: different projection views were developed, a breakdown of the components for assembly is observed. Figure 5 shows the arrangement of the purification filters used in the design, with a pre-filter of filter cloth (made with fiberglass mesh), a HEPA filter, an activated carbon filter and a UV sterilization system.

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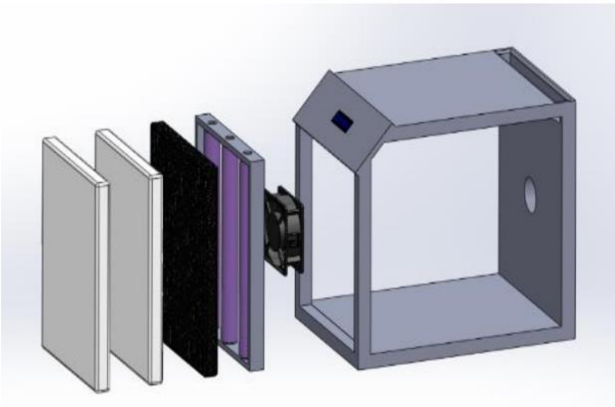

Figure 5 Exploded view of the system
Source: Own elaboration

Finally, a device was developed to place the MQ-135 sensors and the air filtration system, which can be seen in figure 6. The design of the filtration system starts with the extraction of the air inside the equipment to begin the filtering process. As a first stage, a fabric pre-filter is placed to remove dust particles, dirt and most of the pollutants found in the air. Afterwards, the air passes through an activated carbon filter that will remove odors, toxic solvents and chemical vapors and, if necessary, will retain cigarette smoke. Next, a HEPA H13 filter of 0.01µm to 0.3µm will reduce the presence of allergens by 99.95%; furthermore, the implementation of the filter is essential to trap most microscopic particles such as viruses and bacteria including SARS-COV2. Finally, the air will undergo UV sterilization to kill or inactivate viruses, molds, bacteria and micro-organisms that have not been filtered out in the previous process by destroying their genetic material (DNA or RNA). And thus, return clean air free of microorganisms to the room where the purifier is located.

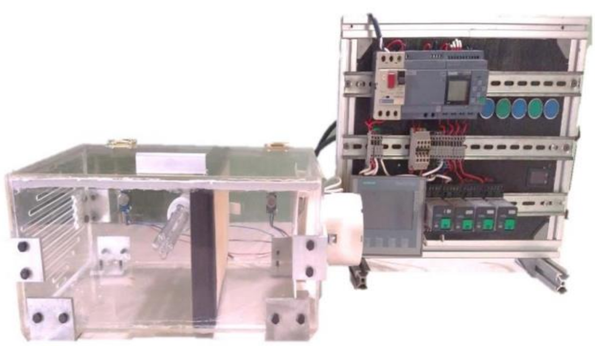

Figure 6 Measurement and filtration system
Source: Own elaboration

Results

In this section, the results of the proper functioning of the sensors, the processing and collection of information will be demonstrated. Subsequently, the behavior of the data generated by the system will be analyzed.

The dimensions of the equipment were determined based on the size of the classrooms, where V represents the volume of the classroom defined in Equation 1, where l is length, b is width and h is height, with a resulting volume of $30m^2$.

$$V = l * b * h = 2.5m * 4m * 3m = 30m^2 \quad (1)$$

According to DIN 1946, the recommended number of air changes per hour is 5-7 for the tertiary sector (classrooms), which when multiplied by the volume, gives the clean air flow specified in Equation 2, where Q is clean air flow, V is classroom volume and R/H is air changes per hour.

$$\mathrm{Q = V * RH} = 30m^3 * \mathrm{5hr} = 150m^3/hr \quad (2)$$

The ANSI/AHAM AC-1 standard is consistent with the method for verifying the performance of electric air purifiers in enclosed spaces. In this standard, the clean air flow rate is expressed in CADR (Clean Air Delivery Rate) and its unit is m3/h. Therefore, the exhaust fan must maintain a CADR of 150 m3/h. Also in the CSIC guide for classroom ventilation, it is recommended to include the number of people in the room, by means of Equation 3, where ACH is the air change per hour and is obtained by multiplying the volume of air contained in the purifier multiplied by the number of people and the adjustment constant, over the volume of the room.

$$ACH = \frac{(14liters)(25\ people\ )\ (3600s)\ (0.001m^3)}{30m^3} = 42 \quad (3)$$

Comparing the data obtained, it is established that a classroom with a volume of $30m^3$ requires a flow rate of $150m^3$/hr in a full day of classes (5hr), so that the activation of the purifier is adjusted to 42 renewals per hour. Figure 7 shows the behavior of the equipment, under controlled conditions of 24 students and one teacher.

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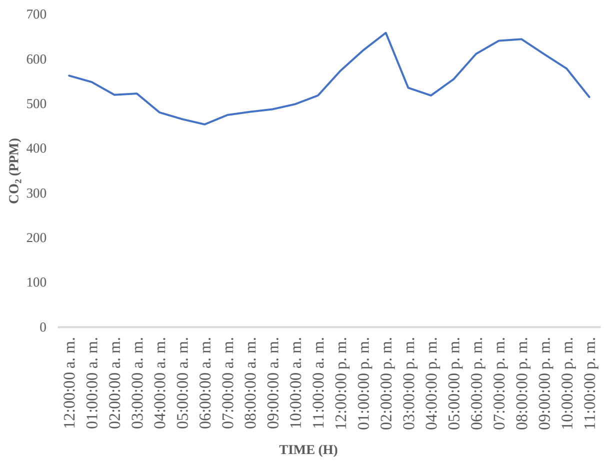

Figure 7 CO_2 behavior in an evening class day (5hr), 30m^3 classroom, 42 renewals/hr.
Source: Own elaboration

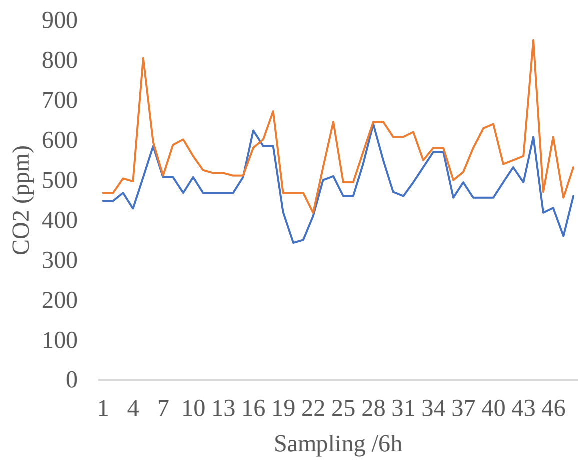

Figure 8 CO_2 behavior over 12 days, 30m3 classroom, 42 renewals/hr.
Source: Own elaboration

Figure 8 shows the behaviour of CO_2 over a period of 288 hours of analysis to generate precision in the data collected. Averages of 600 ppm were obtained in the polluted environment sensor. On the other hand, the clean air sensor obtained values between 343 ppm and 608 ppm. Consequently, it is possible to demonstrate that the device maintains the minimum values of CO_2 concentration in closed spaces, which are recommended not to exceed 800 ppm and do not represent a health risk.

One of the characteristics of carbon dioxide is that it is a gas that does not harm human health; however, in high concentrations it can have repercussions on people's integrity. For example, it can cause asphyxiation due to the reduction of oxygen in space. Due to the health contingency caused by the SARS-CoV-2 virus, which is transmitted through the air under certain conditions in enclosed spaces. Measuring carbon dioxide helps to reduce pollutants by monitoring air quality. Systems such as the one designed allow the accumulation of CO_2 in indoor spaces to be quantified and help to improve quality by activating an air renewal and purification system to achieve acceptable levels of this pollutant.

The values obtained during the 12 days of evaluation are within the parameters specified by the Occupational Safety and Health Administration (OSHA), which specifies reference values for 8 hours of CO_2, the indicator is 5000 ppm. To validate the effectiveness of the system, it is planned to implement it in certain areas in the future. In addition, sensors for the measurement of PM_{10} and $PM_{2.5}$ particulate matter will be implemented. Another aspect that will improve the monitoring of these parameters is the enabling of IoT for the visualization of results in real time in places with internet access.

Conclusions

A system was designed to assess indoor air quality based on the detection of indoor carbon dioxide CO_2. The system only allows real-time visualization and downloading of measurements collected during the period it is activated. The results show average values of 600 ppm for dirty air conditions and 488 ppm for filtered air. The results show that when CO_2 values higher than 550 ppm are detected, the filtering system is activated, then, at the air outlet, values in the range of 300 ppm lower than the inlet value are provided. Therefore, the creation of a system for monitoring and filtering air in two stages for indoor implementation was achieved, achieving its function and demonstrating that the objective of the research is fulfilled.

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It is important to carry out studies for the evaluation of the exposure times to which people are exposed to indoor and outdoor air pollutants, since this makes it possible to identify the relationship between the concentration of the pollutants in the air and the concentration of the pollutants in the air.

The existence of studies that focus on the concentration of pollutants and the possible effects on people's health is important. The existence of studies that focus on the air filtering process is vital to be able to prevent and predict the risks to which the population is exposed and, consequently, to be able to establish the necessary regulations for indoor air quality according to the conditions of the country.

To conclude, the concentration of carbon dioxide (CO_2) increases if a large number of people are gathered inside a room, which leads to a decrease in air quality and therefore, as there are more people in the same place, the spread of viruses and bacteria increases. And a cause of COVID-19 contagion is that there is an agglomeration of people, which is why it is necessary to have equipment in charge of purifying the air, mitigating the contagion not only of COVID but of all diseases derived from viruses and bacteria.

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