Design and implementation of an intelligent system for urban vertical agriculture in the framework of the Internet of Things (IoT)

Diseño e implementación de un sistema inteligente para la agricultura vertical urbana en el marco de internet de las cosas (IoT)

Projeto e implementação de um sistema inteligente para agricultura vertical urbana no âmbito da Internet das Coisas (IoT)

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Abstract

Introduction: This article is the product of research conducted on the Internet of Things and its application to urban agriculture, carried out at the Fundación Universitaria Juan de Castellanos in the year 2022. The goal is to create ideal conditions by controlling irrigation, temperature and humidity. Investigate the needs of the plants and seek to maximize production with vertical models, in addition to implementing an IoT interface to monitor the crop.

Problem: Growing in limited urban spaces is difficult due to lack of time and supervision. Importance: Impact on the availability of healthy foods.

Objective: Design an IoT system for urban gardens, efficient in resources, with online monitoring and analysis of environmental variables to improve cultivation in small spaces.

Methodology: The methodology involves investigating the needs of the plants and designing vertical cultivation models. IoT is used to capture data and the system is evaluated by analyzing environmental variables.

Results: The results demonstrate that the IoT system is effective in the monitoring, control and efficient use of water, promoting healthy growth of vegetables with remote supervision.

Conclusion: Urban vertical farming with IoT is an innovative solution to grow vegetables in limited spaces, improving resource efficiency and promoting technological agriculture.

Originality: It lies in the combination of urban agriculture with IoT technology, which allows for the precise monitoring and control of growing conditions in real time.

Limitations: Adapt the system to fast-growing seedlings and deliver prototypes with germinating seedlings, reliance on Internet connectivity, with limitations in some areas.

Keywords: Urban vertical agriculture, Internet of Things (IoT), vegetables, environmental monitoring, prototype, agricultural technology.

Resumen

Introducción: El artículo es producto de la investigación desarrollada en internet de las cosas y su aplicación a la agricultura urbana realizada en la Fundación Universitaria Juan de Castellanos en el año 2022. El objetivo es crear condiciones ideales mediante el control de riego, temperatura y humedad. Investiga las necesidades de las plantas y busca maximizar la producción con maquetas verticales, además de implementar una interfaz IoT para seguimiento del cultivo.

Problema: Cultivar en espacios urbanos limitados es difícil debido a la falta de tiempo y supervisión. Importancia: Impacto en la disponibilidad de alimentos saludables.

Objetivo: Diseñar un sistema IoT para huertos urbanos, eficiente en recursos, con monitoreo en línea y análisis de variables ambientales para mejorar el cultivo en espacios reducidos

Metodología: La metodología involucra investigar las necesidades de las plantas y diseñar maquetas de cultivo vertical. Se emplea IoT para capturar datos y se evalúa el sistema mediante el análisis de variables ambientales

Resultados: Los resultados demuestran que el sistema IoT es eficaz en monitoreo, control y uso eficiente del agua, promoviendo un crecimiento saludable de las hortalizas con supervisión remota

Conclusión: La agricultura vertical urbana con IoT es una solución innovadora para cultivar hortalizas en espacios limitados, mejorando la eficiencia de recursos y promoviendo la agricultura tecnológica.

Originalidad: Radica en la combinación de la agricultura urbana con la tecnología IoT, lo que permite un monitoreo y control precisos de las condiciones de cultivo en tiempo real.

Limitaciones: Adaptar el sistema a plántulas de rápido crecimiento y entregar prototipos con plántulas en germinación. Dependencia de la conectividad a Internet, con limitaciones en algunas áreas.

Palabras clave: Agricultura vertical urbana, internet de las cosas (IoT), hortalizas, monitoreo ambiental, prototipo, tecnología agrícola.

Resumo

Introdução: O artigo é produto de uma pesquisa desenvolvida sobre Internet das Coisas e sua aplicação à agricultura urbana realizada na Fundação Universitária Juan de Castellanos em 2022. O objetivo é criar condições ideais controlando a irrigação, a temperatura e a umidade. Investigar as necessidades das plantas e buscar maximizar a produção com modelos verticais, além de implementar uma interface IoT para monitoramento da cultura.

Problema: Cultivar em espaços urbanos limitados é difícil devido à falta de tempo e supervisão. Importância: Impacto na disponibilidade de alimentos saudáveis.

Objetivo: Projetar um sistema de IoT com eficiência de recursos para jardins urbanos, com monitoramento on-line e análise de variáveis ambientais para melhorar o cultivo em pequenos espaços.

Metodologia: A metodologia envolve investigar as necessidades das plantas e projetar modelos de cultivo vertical. A IoT é usada para capturar dados e o sistema é avaliado pela análise de variáveis ambientais

Resultados: Os resultados demonstram que o sistema IoT é eficaz no monitoramento, controle e uso eficiente da água, promovendo o crescimento saudável de vegetais com supervisão remota.

Conclusão: A agricultura vertical urbana com IoT é uma solução inovadora para cultivar vegetais em espaços limitados, melhorando a eficiência dos recursos e promovendo a agricultura tecnológica.

Originalidade: Está na combinação da agricultura urbana com a tecnologia IoT, que permite monitoramento e controle precisos das condições de cultivo em tempo real.

Limitações: Adaptar o sistema para mudas de crescimento rápido e entregar protótipos com mudas germinando. Dependência de conectividade à Internet, com limitações em algumas áreas.

Palavras-chave: Agricultura vertical urbana, Internet das Coisas (IoT), vegetais, monitoramento ambiental, protótipo, tecnologia agrícola.

1. INTRODUCTION

Urban vertical farming, an innovative strategy to address the challenges of vegetable production in urban environments [1], is based on the creation of optimal conditions for plant growth through environmental control systems. This article focuses on developing and implementing an urban vertical farming system supported by IoT with the purpose of generating a propitious environment for the cultivation of vegetables in urban spaces, optimizing the use of resources and allowing real-time monitoring. Detailed research into the environmental needs of plants provides a solid foundation for the design of vertical growing mockups that are strategically configured to maximize space [2].

The implementation of a graphical monitoring interface through IoT tools is essential in this project, as it allows users to monitor their crops in real time and make adjustments as necessary, bringing convenience and efficiency to urban crop management [3]. This study seeks to fill a gap in the literature by combining urban vertical farming with IoT technology, highlighting its relevance in promoting sustainable farming practices in urban households and its ability to address the growing demand for healthy foods in densely populated urban environments. The fundamental purpose of this research is to explore and develop a system that integrates IoT technology in urban vertical farming to improve resource efficiency and availability of healthy foods in urban areas [4][5].

1.1 Research background

In the 19th century, urban agriculture originated as a response to improve the dietary conditions of low-income populations, and has evolved throughout the world, including Asia, Africa and Latin America [6]. Today, urban agriculture has been transformed with IoT technology, focusing on sustainability and thriftiness [7][8]. The need to efficiently schedule irrigation and the application of drip irrigation systems is highlighted, considering factors such as humidity, temperature and others. Furthermore, the importance of efficient use of water and the uniformity in water delivery in drip irrigation systems is mentioned [9]. Interconnection and the use of web-based languages are proposed as crucial for interoperability in agricultural IoT systems [10]. The use of platforms such as Ubidots is mentioned for the visualization of sensor data in real time [11]. The application of MQTT protocol in agricultural IoT systems is also discussed [12][13]. The implementation of humidity and temperature control systems in greenhouses is highlighted [14] as well as the design of fertigation systems for the optimization of water and fertilizers in crops [15].

2. METHODS AND MATERIALS

In the context of this research, the historical evolution of urban agriculture has been observed since its beginnings in the 19th century as a response to improve the nutritional conditions of low-income populations. Currently, urban agriculture has been transformed with the application of Internet of Things (IoT) technologies, which has expanded its possibilities and benefits, focusing on the sustainability of gardens and optimizing the work of urban families [7].

In this research, a variety of interdisciplinary methods were used to address the problem posed. These methods included a comprehensive review of the scientific literature related to urban agriculture and IoT technology, providing a solid context. In addition, a prototype of a smart urban garden adapted to small spaces was designed, with emphasis on vegetable crops, which incorporates sensors for monitoring environmental variables and an automated irrigation system. IoT technology was implemented to allow communication between the prototype and a web platform, which enabled real-time monitoring of orchard conditions and remote activation of the irrigation system; temperature, humidity and luminosity data were also collected throughout the crop growth cycle, and analyzed to understand the behavior of these environmental variables in correlation to plant growth [16].

2.1 Agriculture

The United Nations Development Program (UNDP) defines urban agriculture as the activity that encompasses the production, processing and commercialization of food and other products on soils and bodies of water within urban and peri-urban areas, making efficient use of the natural resources and promoting their recycling [16].

2.2 Permaculture

Permaculture is an agroecological approach to the study of agricultural systems, based on the cybernetic model, which aims to conceive designs that allow agro-ecosystems to be sustainable in the long term. This discipline emerged in the 70s as a positive response to the growing environmental and social crisis that we face today[17].

Permaculture can be summarized in three fundamental aspects: care of the earth, care of people and the equitable distribution of surplus time and resources. In other words, this approach focuses on the preservation and regeneration of natural resources and ecosystems, while seeking to improve the quality of life of the communities that participate in these systems [18].

3.3 Urban Agriculture

Urban agriculture is developed in small areas in or around a city, known as peri-urban areas [19]. This practice gives people the opportunity to grow food for self-consumption, with the possibility of commercializing the surpluses, which contributes significantly to the family economy [20]. In addition to supplying locally and sustainably, urban agriculture, particularly in its agroecological version, provides environmental benefits by incorporating green spaces into urban design, shortening food transportation distances, reducing dependence on industrial inputs and mitigating CO2 emissions, thus collaborating in the fight against climate change [21].

The practice of urban agriculture encompasses various forms and advantages. It not only guarantees greater availability and quality of food for self-consumption, but also allows the use of household waste for fertilization, prevents the accumulation of waste and unwanted weeds and also controls exposure to pesticides and diseases. Likewise, it promotes the use of medicinal properties of plants and the creation of microclimates that maintain biodiversity, contributing to the well-being of the community and domestic animals [22].

In this activity, it is possible to grow a wide variety of crops as long as the climatic requirements of the environment are respected, including vegetables, medicinal plants, ornamental plants and more [23]. The combination of utilities, from food production to urban ornamentation and environmental improvement, makes urban agriculture a versatile and valuable practice for urban and peri-urban communities [24].

3.3.3 Techniques and types of urban agriculture.

Urban agriculture techniques

It refers to the practices and methods used to grow food and plants in an urban environment. These techniques can vary widely and are tailored to the specific limitations and characteristics of an urban environment. Some common urban agricultural techniques include growing in pots or containers, hydroponics, aeroponics, vertical farming, gray water recycling, urban composting, among others [25]. These techniques are used to maximize the limited space and resources available in urban areas.

Traditional method: involves planting in pots, where constant monitoring is required to guarantee the appropriate watering and maintenance of the plants throughout each day, Figure 1.

Figure 1. Use of pots for aromatics plants.
Source: Photograph taken from the El Moral farm, municipality of Chivata, Boyacá.

Hydroponics: through the use of channels designed for controlled water retention, a planned irrigation system is implemented that supplies plants with mineral solutions without the need to use soil, which ensures the prevention of insects and pests, [26] Figure 2.

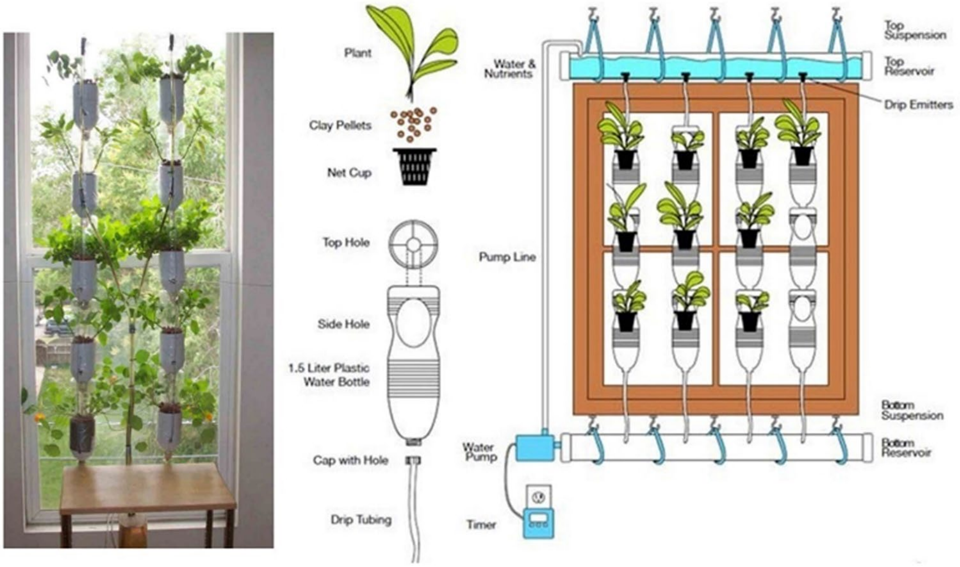

Figure 2. Hydroponic urban garden with window bottles.
Source: [27]

Types of urban agriculture

This term refers to the various ways in which agriculture is practiced in urban environments. The different types of urban agriculture can vary depending on their focus, scale and objectives. Some examples of types of urban agriculture include: community gardens where the community grows food on shared land, farming on rooftops of urban buildings, vertical farming using stacked structures in small spaces, home garden farming which is made on residents' patios or balconies, agriculture in public spaces such as parks and squares, cultivation in containers such as pots or boxes, agriculture in urban greenhouses as well as green roof agriculture, improving energy efficiency and air quality, in addition to producing food on the building's roof [28][29].

Vertical Farming: Vertical farming is an innovative way to grow food and plants in limited spaces, taking advantage of technology and environmental management to optimize plant growth [30]. This approach has the potential to play an important role in the future of food production, especially in densely populated urban areas and in response to the growing demand for fresh and sustainable food, [31] Figure 3.

Figure 3. Use of pyramidal structures with hydroponics in a vertical farming operation.
Source: Photograph taken from https://www.pthorticulture.com/es/centro-de-formacion/qu%C3%A9-debes-de-saber-acerca-de-la-agricultura-vertical/ [32]

3.4 Crop planning for an urban garden

Crop planning must take into account when, where and how many plants to grow, taking into consideration their needs for space, light, planting season, ripening time, tolerance between plants, tolerance to soil conditions, climate and other considerations.

The vegetables that should be planted are those that have high nutritional value, have good productivity, are easy to grow and are adequately adapted to the region. In addition, it is important to select varieties with different ripening times, both short and long, to ensure a constant supply of food throughout the year [33][34].

Vegetables are defined as herbaceous plants that are grown in gardens, generally in backyards, for self-consumption, semi-commercial or commercial purposes, intended for human consumption. To obtain a successful vegetable crop, it is essential to take into consideration factors such as temperature, humidity, oxygen and the light conditions necessary for optimal development. Information on the soil temperature required for vegetable germination, relative humidity, and light tolerance of each type of vegetable is found in Table 1 and Table 2. Likewise, another relevant aspect to take into account when planting is the relative tolerance of each variety to soil salinity [35][36], as shown in Table 3.

Table 1. Optimal soil temperatures for vegetable germination

Vegetable crop	Mínimum (°C)	Optimal Range (°C)	Optimal (°C)	Máximum (°C)
Celery	4	15-21	21	29
Chard	4	10-29	29	35
Cabbage	4	7-35	29	37
Lettuce	1	4-26	23	29
Onion	1	30-35	23	35
Parsley	4	10-29	23	32
Spinach	1	7-23	21	29
Cauliflower	4	7-29	26	37
Zucchini	15	21-35	35	37
Eggplant	15	23-32	29	35
Pumpkin	15	21-32	32	37

Source: Adapted from [37]

Table 2. Relative humidity values of some vegetables and aromatics

Group 1 *90 – 98% HR*	**Group 3** **85 – 95% HR**	**Group 4** **80-90%**	**Group 5** **Environment**
Cabbage	Pumpkins	Rosemary	
Broccoli	Tomato	Basil	Onion
Lettuce	Carrots	Mint	Potatoes
Turnip	Salsify	Peppermint	
Cucumber	Root Parsley		
Peppers	Beetroot		
Eggplants	Radish		
Zuchinni			
Artichoke			
Cucumbers			
Spinach			
Chard			

Source: Adapted from [37]

Table 3. Classification of vegetables according to their relative tolerance to soil salinity

Vegetables	**Maximum salinity of soil without loss of performance (limit value ds/m).**	**Decrease in performance at values of soil salinity higher than the limit value (% per ds/m)**
Sensitive crops		
Ejotero Bean	1.0	19
Strawberry	1.0	33
Onion	1.2	16
Carrot	1.0	33
Moderately Sensitive Crops		
Lettuce	1.3	13
Bean	1.5	11
Sweet potato	1.6	10
Corn	1.7	12
Cabbage	1.8	10
Celery	1.8	6
Spinach	2.0	8
Cucumber	2.5	13
Tomato	2.5	10
Broccoli	2.8	9

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Vegetables	Maximum salinity of soil without loss of performance (limit value ds/m).	Decrease in performance at values of soil salinity higher than the limit value (% per ds/m)
Moderately tolerant crops		
Beetroot	4.0	9
Zuchinni	4.7	9

Source: Adapted from [38]

Vegetable Planting

To grow vegetables in 40-50 cm deep pots, it is essential to provide adequate space between plants for optimal development. These vegetables need at least half a day of sun, and in areas with less than 4 hours of sun, such as in winter or shady places, only some vegetables such as lettuce, spinach or parsley will thrive. It is important to rotate the pots occasionally to achieve uniform growth. In addition, more frequent watering and fertilizing are required compared to vegetables grown in open soil [39][40]. For good drainage, holes should be made at the base of the pots. In the case of growing seeds Figure 4 (1/2), plates are ideal, filled with a mixture of 50% sand and 50% peat. It is recommended to cover them with glass or transparent plastic to create a mini-greenhouse and maintain the appropriate temperature and humidity, being appropriate for crops such as celery, lettuce, cucumber and tomato [41].

Germination

To evaluate seed germination, 10 to 100 seeds are generally used, which are placed in layers of moist paper, wrapped and kept at a temperature of 20-25ºC with sufficient oxygen for a week. It is important to prevent the paper from being too wet and to check the seeds daily, moistening them with lukewarm water if necessary. After a week, the seeds are counted and the germination rate is calculated, where, for example, 45 seeds germinated out of 50 indicate a 90% chance of germination. Figure 4 (3/4). In addition, it is essential to maintain a constant temperature, with 24ºC being sufficient for the germination of most horticultural plant seeds, although some, such as eggplants and peppers, prefer 27ºC, while lettuces do not germinate at higher temperatures. Regarding lettuce cultivation, they can develop with only four hours of direct sun, but longer exposure to the sun is recommended [42][43].

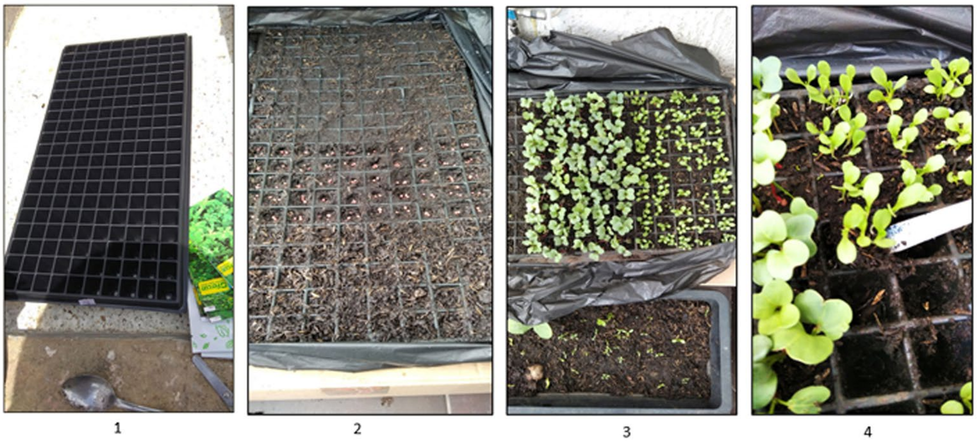

Figure 4. Germination process with seeds: 1. Germination tray, 2. Arrangement of seeds in radish and chard germination tray, 3. Germinated seeds, 4. Seedlings ready to transplant.
Source: own elaboration

On the other hand, when transplanting seedlings such as cabbage and lettuce, care must be taken to preserve the roots and to plant them at the appropriate depth and distance according to the reference table, Table 4.

Table 4. Planting density according to the biointensive method of vegetable production

Vegetables	Distance between rows (cm)	Distance between plants (cm)	Population in 10m²	Yield (kg/10 m²)	Vegetative cycle (Days)
Chard	20	20	320	320 plants	65
Chili pepper	35	35	80	10	180-190
Garlic	10	10	980	27	150
Peas	30	30	107	20	70-90
Onion	10	10	980	45	120-150
Bean	20	20	24v	10	180-150
Lettuce	20	20	245	60	60
Potato	30	30	107	35	90-120
Cucumber	30	30	107	70	120-150
Peppers	30	30	107	16	80 -100
Beetroot	18	18	303	91 roots	75
Cabbage	35	35	80	60	60-90
Tomato	25	25	156	200	80-90
Carrot	8	8	1531	45	80-120

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Vegetables	Distance between rows (cm)	Distance between plants (cm)	Population in 10m²	Yield (kg/10 m²)	Vegetative cycle (Days)
Cauliflower	20	20	245	60	120-150
Spinach	10	10	980	10	80-90
Corn	30	30	107	1.2	90-120

Source: Adapted from [43]

Fertilization

In an organic crop, the substrate is crucial, since it must be porous to facilitate root growth, allow good ventilation and store nutrients. To improve soil fertility, it is recommended to add organic material such as compost. If the soil is clayey and compact, it can be combined with compost and sand. Manure is essential to enrich the soil with nitrogen. Nutrients are divided into macronutrients and secondary nutrients, which affect plant growth and soil quality [44]. Humus protects the soil from erosion and regulates temperature. Rice husks improve physical quality and promote microbial activities. Coconut substrates offer porosity and moisture retention, and vermiculite is mixed with organic substrates such as peat moss to encourage plant growth.

3.5 Irrigation automation techniques

Automated jet irrigation involves the use of constant fluids and a water level sensor to keep a tank full, issuing alerts to the user when the level is low. On the other hand, the automated drip irrigation technique is efficient, sustainable and is based on the precise distribution of water through tubes near the plants, avoiding significant water losses compared to traditional flood irrigation techniques, which results in more productive crops [45][47] .

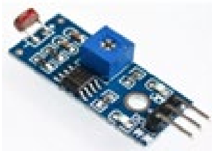
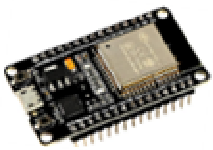
3.6 Data collection system

Telemetering is a technique that allows for the collection of data remotely, which is stored in a database in the cloud. Subsequently, this data is presented on a web page in real time, and the user can control it from a smartphone, tablet or computer [46].

3.6 Sensor technology

In urban vertical farming, sensors play a fundamental role. These devices are essential to monitor and control various environmental variables, such as temperature, humidity and light, in real time. This precise information allows plant cultivation to be optimized in limited urban spaces, guaranteeing ideal conditions for healthy and sustainable crop growth, [48] Table 5.

Table 5. Electronic devices for application in urban agriculture

SENSOR	PHYSICAL APPEARANCE	CHARACTERISTIC
Digital humidity and temperature sensor **DHT22**		It delivers a calibrated digital signal which ensures high quality and reliability over time.
Soil moisture sensor module Resistive Hygrometer **Sensor YL-69**		Controls humidity in the soil or topsoil
Soil Moisture Sensor Module Capacitive Hygrometer **Capacitive soil moisture sensor V1.2**		Allows you to measure moisture in the soil using the principle of capacitance between electrodes instead of resistance, which considerably increases the useful life of the sensor
Luminosity module/sensor with photoresist – LDR		Also called LDR It is a resistance that decreases as the intensity of light that affects her increases
Integrated LM39		Consists of two independent voltage comparators designed to operate with a single power supply over a wide voltage range
ESP32 board		This board is designed for mobile, electronics and Internet of Things (IoT) applications. It features all the cutting-edge features of low-power chips, including fine-grained clock gating, multiple power modes, and dynamic power scaling.

Source: taken from [47]

MQTT Protocol

MQTT (Message Queue Telemetry Transport) is a Client/Server message transport protocol based on publications and subscriptions to so-called "topics".

The MQTT protocol works over TCP/IP or other network protocols with bi-directional support and without data loss [48].

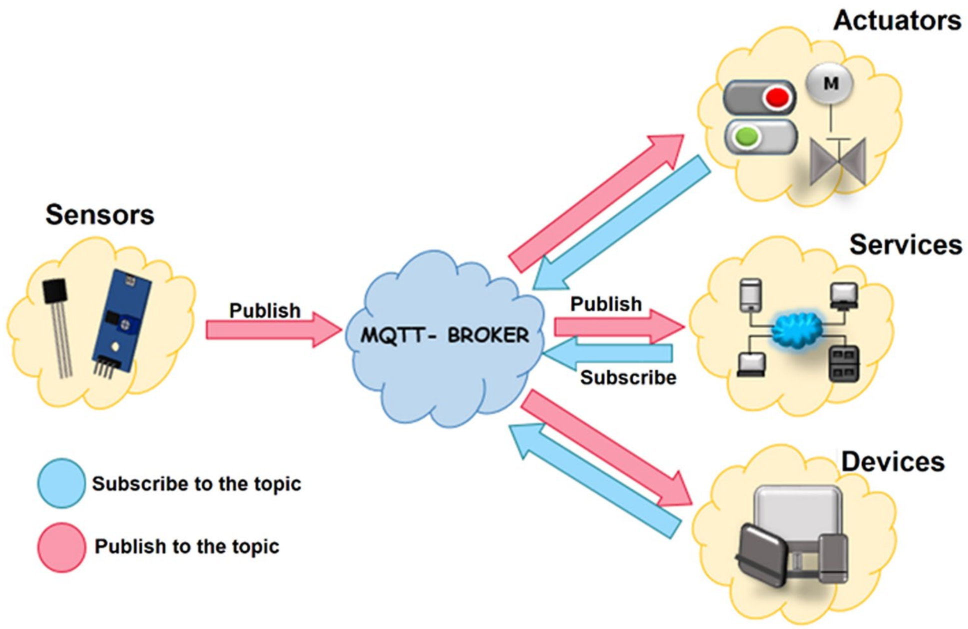


Figure 5. MQQT Protocol.
Source: Own elaboration.

Web server

Web servers are essential programs on the Internet, facilitating two-way communication between clients and servers. They act as intermediaries between the user and the server that hosts the requested information, using the HTTP protocol to transmit data. Additionally, they can also refer to the equipment that stores website files and software for web connection [48] [49].

Research Description

Figure 6 provides an overview of the organization of the key elements of the prototype. The monitoring and drip irrigation system of variables (soil moisture, ambient humidity, ambient temperature and luminosity index) involves hardware components such as the sensor network [45]. For the correct operation of these sensors, it is required to calibrate the two humidity sensors separately in relation to the soil moisture sensor [45][46]. Calibration involves acquiring data when the sensor is completely dry and completely wet. In the case of the luminosity sensor, the process is similar as with the other sensors, but data is taken when the sensor is in full shade and when it is exposed to sufficient light. With the data from each sensor, the code is configured to obtain data within a predefined range, which determines the maximum and minimum values detected. The ESP32 embedded data capture and communication device is powered by 5V DC, and a MOSFET module is used to control irrigation pressure, receiving a PWM signal generated by the device and sending it to the water pump, as shown in Figure 9. Both the sensor network and the MOSFET are supplied externally with 5V [51]. The design incorporates mechanical aspects to facilitate the flow of water in the form of drips [47] [48].

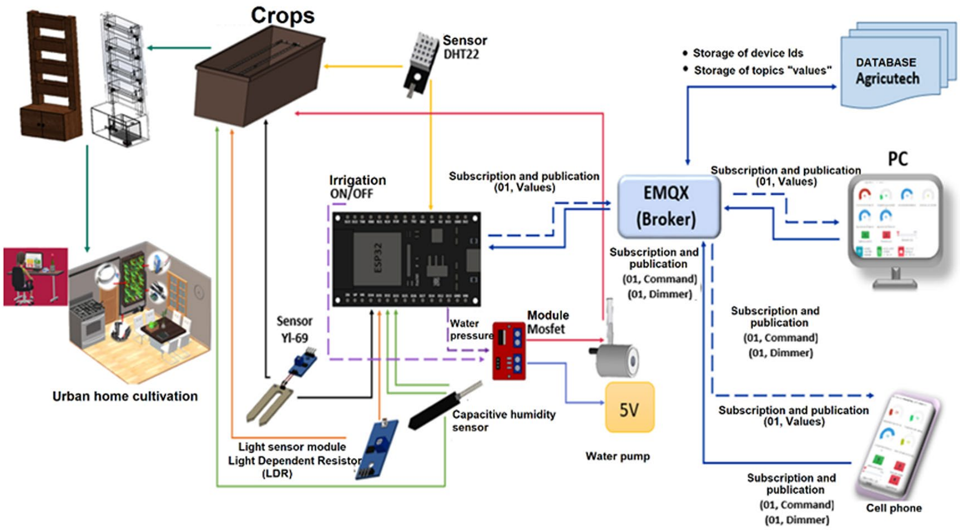


Figure 6. General diagram of the interrelation between the hardware and software system of the prototype to be developed.
Source: Own elaboration

In the software field, a web page was developed with monitoring functions, storage and ON/OFF controls. This interface allows you to supervise the crop's drip irrigation, providing real-time monitoring and facilitating data analysis through graphs that cover a range of dates of interest. To establish communication between the hardware and the website, the EMQX broker was used, which uses the MQTT protocol [50]. Topics were configured to send sensor data (01/Values), activate or deactivate buttons on the page (01/Command) and to manage a dimmer with values from 0 to 100 (01/Dimmer). The "01" refers to the ESP32 device and was used as an identifier. It should be noted that the website has the ability to store multiple crops with the same characteristics, including the same sensor variables for various types of crops such as lettuce, spinach, chard. This expands the functionality of the page to monitor and control several crops, although in this case it focused on a single crop prototype [52][53].

Schematic diagram of the census circuit

Figure 7 presents a schematic diagram of the monitoring circuit used in the prototype. This diagram is crucial to understanding how sensors are connected and configured, which is essential for effective and accurate monitoring of variables. Each sensor connection and arrangement is detailed in the diagram, ensuring the system operates optimally and ensuring accurate data collection [54].

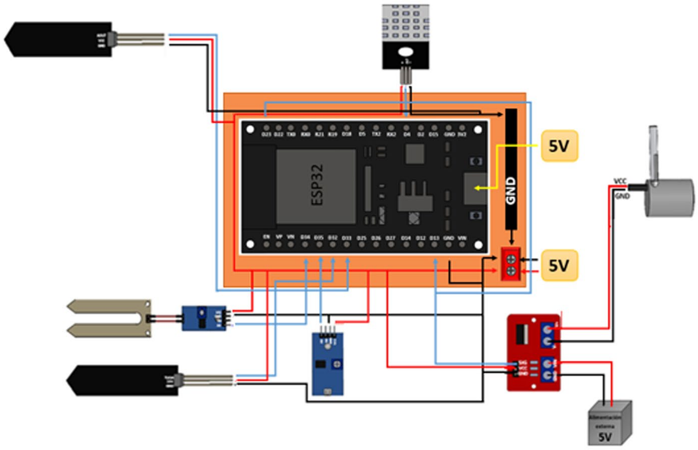


Figure 7. Monitoring circuit connection diagram.
Source: Own elaboration.

Investigation Development

Seedling study

At this stage, a study was carried out on the types of vegetables most suitable for vertical cultivation. The objective was to categorize them so that they all shared similar characteristics that favor their development, considering the local climate, temperature, humidity and luminosity needs of the crop. As a result, the data shown in the research were obtained, Table 6.

Table 6. Vegetable classification

Seedling	Climate in which it develops	Temperature	Humidity	Luminosity
Lettuce	Mild weather	12° to 24°C	90 – 98%	Gloomy places
Spinach	Mild weather	15° to 26° C	90 – 98%	Gloomy places
Chard	Mild weather	15° to 25° C	90 – 98%	Gloomy places

Source: Own elaboration

IoT crop development

The creation of the web page is essential to enable IOT intercommunication between devices that meet specific hardware requirements to transmit and receive information [55]. This general objective involves the visualization and control of the cultivation system, which includes the management of specific environmental variables.

Creation of the instance/server

It is essential to have a server that offers the necessary services for the creation and design of the website. It was decided to use an Amazon server with the following specifications: 1 CPU, 1 GB of RAM, 30 GB of storage and a network speed that varies between low and moderate. Additionally, a free server with a viewing duration of 1 year was chosen. These features are essential to guarantee the proper functioning of the website and IOT intercommunication between devices [56].

Domain Settings

A domain was created on the internet through freenom.com, which establishes a validity of 12 months for the page that was created with the following name http://agricutech.tk/.

Ports enabled for the operation of the website and protocols.

Various ports have been configured for various functions on the server, such as Port 22 for SSH connection through external software such as PUTTY, Port 443 for establishing HTTPS certificates, Port 21 for FTP connections, Port 8083 for enabling web -Vesta hosting, Port 3306 as default port for MYSQL, Port 8093 for non-secure WS web socket, Port 80 for web browsing, Port 8080 as standard EMQX listener, Port 18083 enabled for configurations in the EMQX broker panel, Port 8090 as a port enabled for EMQX listener, Port 1883 for the MQTT protocol that works over TLS, and Ports 12000-12100 enabled for passive FTP and making changes to the website from the ATOM software, along with Port 8094, which is enabled for WSS secure web socket. These configurations allow effective and secure operation of the different applications and services on the server.

Vertical cultivation structure design

Vertical farming, a growing method in urban areas, highlights the importance of physical design for effective operation and proper plant growth. Although there are no standard parameters for the design of vertical crops, it is essential that the structure provides a conducive environment and is strong enough to support plants, sensors and actuators. Figure 8 illustrates the structural design in cm made in Solidworks software.

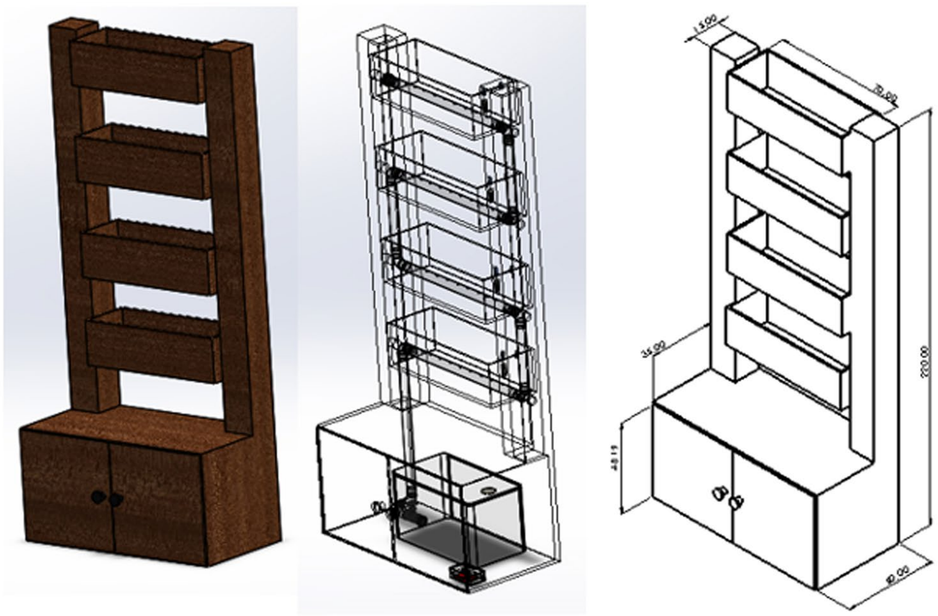


Figure 8. Structural design in Solidworks
Source: Own elaboration

2. ANALYSIS AND RESULTS

3.1 Tests

As shown in Tables 7, Figures 9, 10, 11, the tests are initially carried out every four days. These tests gather data related to system humidity and ambient temperature, as well as the detection of soil moisture and light index of the entire crop [57].

Table 7. Data taken with the sensors arranged in the prototype in week 1

Week 1				
date:		September 6		
	Ambient humidity	Ambient temperature °C	Soil Humidity	Luminosity
Letucce	79%	19°C	20%	19%
Spinach	79%	19°C	20%	19%
Chard	79%	19°C	20%	19%

Source: Own elaboration

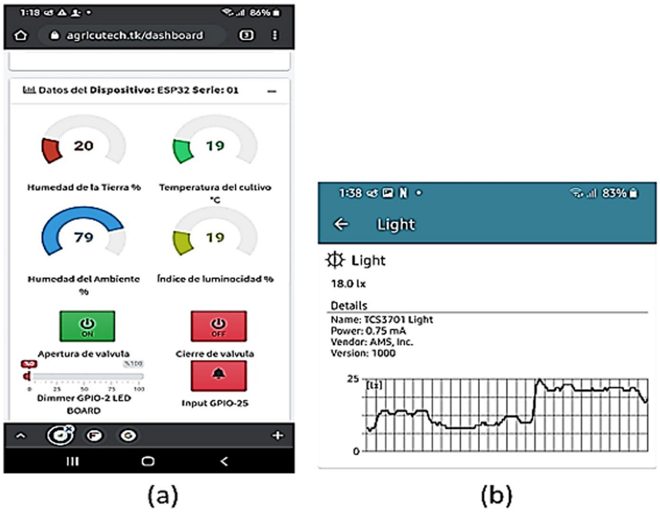
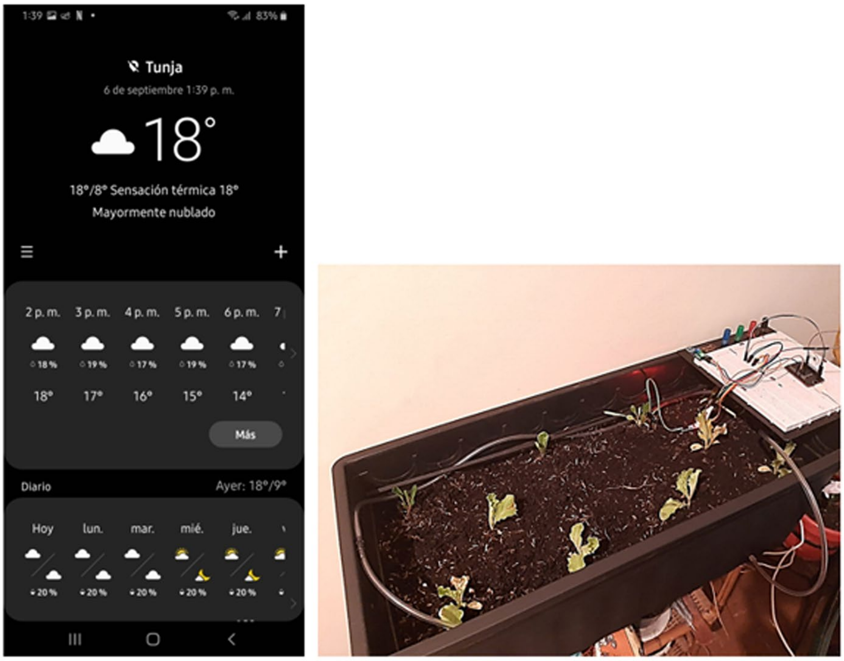


Figure 9 (a). Shows week 1 data on the web page in a mobile device and Figure (b). Shows luminosity data. The application (sensors) is installed on the cell phone to compare the data taken by the sensor arranged in the prototype and displayed on the week 1 information on the web page.
Source: Own elaboration.

In Figure 9(a)., data taken with the weather application on the mobile device is compared with the data taken by the sensor arranged in the prototype and displayed on the web page. Figure 9(b). Prototype first test, data collection week 1.



(a) (b)

Figure 9(a). Humidity and ambient temperature data, (b). First prototype
Source: Own elaboration

Data collection week 2

The ambient temperature and humidity data were taken with the weather application on the mobile device, the luminosity data are taken through an application (sensors) installed on the cell phone to compare with the data taken by the sensor arranged in the prototype and displayed on the website.

Table 7. Data taken with the sensors arranged in the prototype in week 2

Week 2				
Date:		September 11		
	Ambient Humidity	Ambient temperature °C	Soil humidity	Luminosity
Letucce	82%	19°C	19%	19%
Spinach	82%	19°C	19%	19%
Chard	82%	19°C	19%	19%

Source: Own elaboration.

(a) (b)

Figure 10 (a). Shows the data on the web page for week 2 in a mobile device and Figure (b). Shows luminosity data. The application (sensors) is installed on the cell phone to compare the data taken by the sensor arranged in the prototype and displayed on the week 2 information on the web page.
Source: Own elaboration

For the analysis and comparison of the first tests, the data sensed by the prototype were compared with data acquired from applications installed on the mobile device, to display the ambient temperature and humidity and also in the same way for the luminosity index.

Figure 11. Prototype Week 2
Source: Own elaboration

Analysis

To evaluate the effectiveness and impact of urban vertical farming implemented through the Internet of Things (IoT), a comparative study was carried out with a traditional crop Figure 12. The latter, although rooted in conventional agricultural practices, faced the persistent threats of pests, fungi and weeds, which limited its yield and required frequent fumigations. However, when contrasted with the innovative approach of IoT-enabled urban vertical farming, striking differences emerge. Technology and constant monitoring make it possible to completely eliminate these problems (Figure 13), which translates into optimal plant growth and a significant reduction in the need to use chemicals. This comparison highlights the radical transformation that vertical urban farming with IoT is bringing to the agricultural world and how it is revolutionizing food production in urban environments.

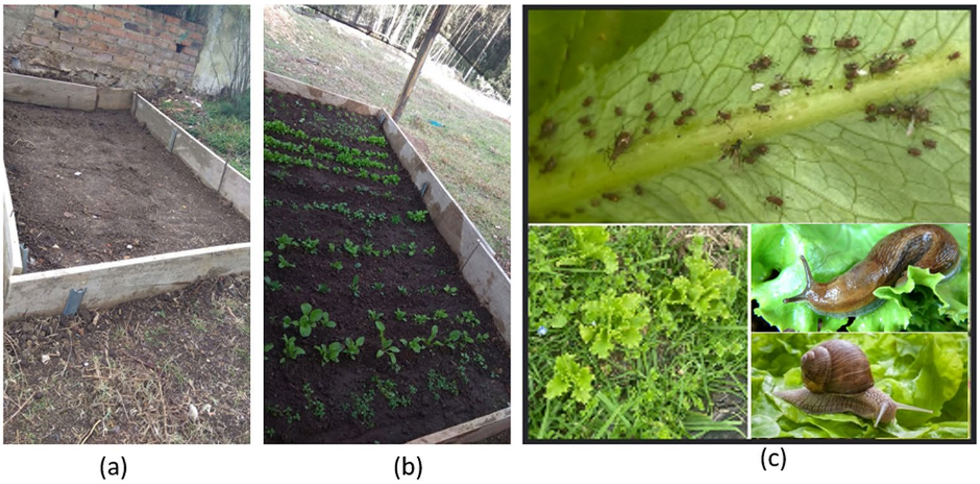
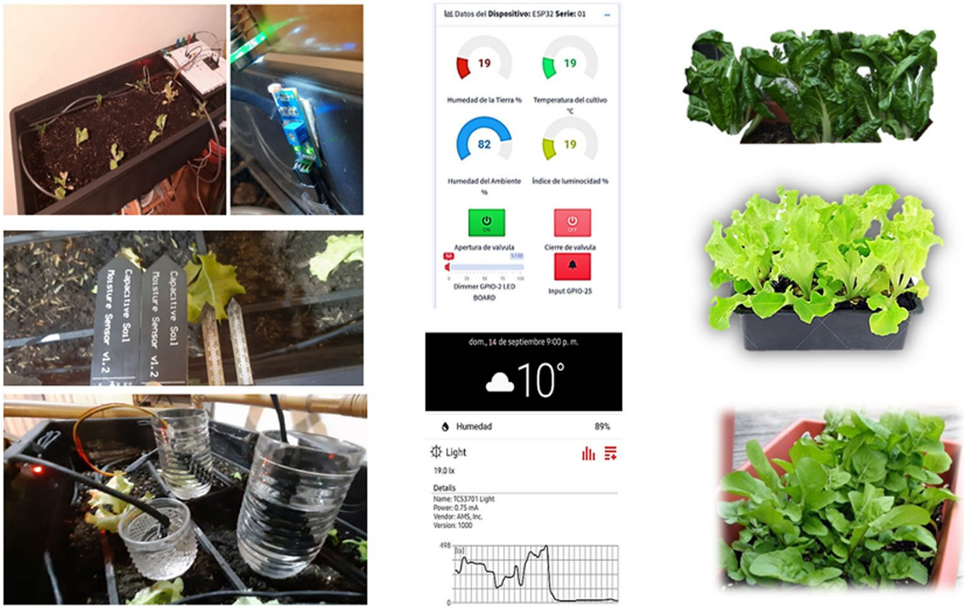


Figure 12. Traditional cultivation; (a) layout of the bed for planting, (b) bed with lettuce, spinach and chard "sowing by seed", (c), crop damage with aphids, slugs, snails and weeds.

Source: Own elaboration

Monitoring in vertical urban agriculture prototype mediated by IoT



(a) (b) c)

Figure 13. (a) Implemented prototype of vertical farming with IoT, (b) Web Monitoring, (c) final product (spinach, chard, lettuce).
Source: Own elaboration

3. DISCUSSION AND CONCLUSIONS

Discussion

Electronic systems applied to the field are generating a new trend and support for the various processes that exist in monitoring and control. In this sense, we proceeded to observe the change and development that the seedlings experienced with the drip irrigation actuator, since the latter had a significant impact on the proper development of the seedlings.

Regarding the monitoring of variables, it was observed that none of them were outside the ranges allowed for the optimal growth conditions of lettuce, spinach and chard seedlings. This finding is supported by the data collected in the database. The irrigation actuator operated three times a week: Monday, Wednesday and Friday. It was determined that this frequency was more than sufficient and provided adequate humidity to the system throughout the week.

The calibration of the sensors was carried out based on the desired parameterization, which means, that characteristic ranges of the environment were defined for the different values of the sensors, such as the percentage of humidity and light indices. This allowed us to determine if the system maintained the necessary humidity and if the required light levels were met.

Conclusions

Nowadays, the implementation of IoT-based urban vertical farming systems has become an achievable reality. The availability of technological advances and abundant detailed information allow us to conceive innovative and concrete ideas. Beyond the installation of technology in specific areas, the design and implementation of IoT systems requires the identification of the needs of the environment and the development of services that provide direct solutions to the population that requires these IoT services.

The main objective of this research is to revolutionize vertical farming in limited spaces. The aim is to design an automation system that monitors specific variables. These variables are accessible to the user through an application and the system has the ability to take actions in response to parameters set in relation to these variables. All data is recorded in a database that provides real-time information on the behavior of the system. This allows people to monitor cultivation from their workplaces, all within the context of the Internet of Things (IoT).

It is essential that the devices and platforms used for these IoT services are interconnectable and interoperable with each other to guarantee their correct functioning. The availability of free IoT services from many manufacturers significantly contributes to reducing implementation costs. IoT represents not only a business opportunity, but also a fundamental tool for the design and implementation of urban vertical agriculture, with a positive impact on the environment. The need to promote this technological culture in the long term is evident, especially considering the challenges that climate changes present to agriculture in the countryside and the growing demand for technological tools like this to guarantee crop production for the population.

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