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Abstract:

An innovative solar-powered meteorological station will utilize an IoT-based approach to provide reliable solutions for remote areas lacking electricity and conventional or reliable communications infrastructure, as well as for agricultural facilities to enable early prediction of weather changes. The primary purpose of this project is to collect essential climate information (such as temperature, humidity, air pressure, wind speed and direction, precipitation, and air quality) with minimal or no human intervention. The station's solar energy and intelligent power management system will allow it to operate effectively for several months in extreme environmental conditions.

This station is built around an ESP32 low-power microcontroller. A solar panel, a lithium battery, and an MPPT (Maximum Power Point Tracking) charge controller to enable charging even in overcast conditions will power each station. For communication with agricultural facilities and isolated areas, different technologies will be used based on the available local infrastructure: Wi-Fi, LoRaWAN, NB-IoT, or satellite communications.

This project provides integrated solutions for climate monitoring in challenging locations using solar energy, smart power management, and long-range communication technologies. Despite the problems associated with operating in harsh conditions, the difficulty of system maintenance, and frequent communication outages due to the remote location, the design features and advantages—such as local data storage, data transmission via dedicated applications, and self-monitoring—make this project practical and reliable. This type of remote sensing will greatly assist farmers and users in monitoring their land and making immediate decisions based on accurate, real-time data.

Keywords:

Internet of Things (IoT), Autonomous Weather Station, ESP32 Microcontroller, LoRaWAN, MPPT Charge Controller, Smart Agriculture, Remote Climate Monitoring, Local Data Logging, Energy-Harvesting IoT, Remote Sensing.

ملخص:

ستستخدم محطة أرصاد جوية مبتكرة تعمل بالطاقة الشمسية نهجًا قائمًا على إنترنت الأشياء لتوفير حلول موثوقة للمناطق النائية الخالية من الكهرباء والتي تفتقر إلى البنية التحتية التقليدية أو الموثوقة للاتصالات والمنشآت الزراعية لتنبؤ مسبقا بتغير الأحوال الجوية. الهدف الأساسي من هذا المشروع هو جمع معلومات مناخية أساسية (مثل درجات الحرارة، الرطوبة، الضغط الجوي، سرعة الرياح واتجاهها، هطول الأمطار، وجودة الهواء) بأقل تدخل بشري أو بدونه. سيمكن نظام إدارة الطاقة الذكي والطاقة الشمسية المحطة من العمل بكفاءة لعدة أشهر في ظروف بيئية قاسية.

هذه المحطة عبارة عن ترتيب مبني حول متحكم دقيق ESP32. سيتم تشغيل كل محطة بواسطة لوح شمسي، بطارية ليثيوم، ومنظم شحن بتقنية تتبع نقطة الطاقة القصوى (MPPT) لشحن اللوح حتى في الظروف الغائمة. بالنسبة للاتصال بالمنشآت الزراعية والمناطق المعزولة سيتم استخدام تقنيات مختلفة حسب البنية التحتية المحلية المتاحة (Wi-Fi ؛ LoRaWAN ؛ NB-IoT ؛ الأقمار الصناعية).

يوفر هذا المشروع حلولاً متكاملة لمراقبة المناخ في المواقع الصعبة باستخدام الطاقة الشمسية، الإدارة الذكية للطاقة، وتقنيات الاتصال بعيدة المدى على الرغم من المشاكل المرتبطة بالتشغيل في الظروف القاسية، وصعوبة صيانة النظام، وكثرة الأيام التي ينقطع فيها الاتصال بسبب المنطقة، فإن خصائص ومزايا التصميم التخزين المحلي للبيانات وارسالها عبر التطبيقات الخاصة، والمراقبة الذاتية تجعل من الممكن لهذا المشروع أن يكون عمليًا وموثوقًا. هذا النوع من الاستشعار عن بعد سيساعد كثيرا الفلاحين والمستخدمين بمراقبة أراضيهم واتخاذ قرارات فورية مبنية على بيانات دقيقة ولحظية.

الكلمات المفتاحية: إنترنت الأشياء (IoT)، محطة أرصاد جوية مستقلة، المتحكم الدقيق ESP32، تقنية LoRaWAN، منظم شحن MPPT، الزراعة الذكية، مراقبة المناخ في المناطق النائية، تجميع البيانات

DEDICATION

To those who granted me life and hope....

To the heartbeat of my soul and the light of my eyes...

To my dearest parents,

I dedicate this humble work to you, in appreciation and love for your invaluable efforts and sacrifices. You have always been my source of support and inspiration, and without you, I would not have reached this stage. Every moment of your hard work and every sincere prayer from you was a reason for this achievement.

I hope I have made you as proud of me as I am proud to be your child.

To the one who has been my steadfast support...

To the one who provided me with guidance and encouragement with heartfelt sincerity...

To my esteemed professor and mentor ***Dr.LABIOD CHOUAIB,***

I dedicate this humble work to you, in deep gratitude and appreciation for your crucial role in the completion of this thesis. You have always been my source of inspiration and motivation, generously giving your time, effort, and invaluable advice. It is through your wise guidance and unwavering support that I was able to achieve this success.

I hope that I have made you as proud of your efforts and dedication as I am proud to be your student.

Thank you from the depths of my heart.

To my companions and lifelong friends...

To those who have been my support, my laughter, and my comforting hand...

I would like to express my sincere gratitude to ***Dia Zakaria*** *for their invaluable support and guidance throughout the development of this thesis. Their insightful advice and continuous encouragement played a significant role in overcoming challenges and completing this work successfully. I am deeply thankful for their contribution.*

***To my dear friends**,*

I dedicate this humble work to you, in appreciation and gratitude for every moment we spent together and for all the support and encouragement you provided me throughout this journey. You have always stood by my side, in difficult times and joyous moments, and without you, this journey would not have been as beautiful or successful.

I hope I have succeeded in achieving what you wished for me, and that we can all take pride in this accomplishment just as I take pride in our friendship.

Thanks, and Appreciation

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To my brothers, thank you for your continuous encouragement, understanding, and moral support, which helped me stay motivated and focused.
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We are deeply grateful to the esteemed members of the jury for their participation in the evaluation of this work, an honor that we deeply

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List of abbreviations

- **η :** Efficiency (as a decimal or percentage)
- **Vin :** Input Voltage
- **Iin :** Input Current
- **Vout :** Output Voltage
- **Iout :** Output Current
- **USB :** Universal Serial Bus
- **HMI :** Human Machine Interface
- **UART :** Universal Asynchronous Receiver/Transmitter
- **COM :** Communication Port
- **HTTP :** Hyper Text Transfer Protocol
- **ID :** Identifier
- **PPM :** Parts Per Million
- **IoT :** Internet of Things
- **AI :** Artificial Intelligence
- **GPS :** Global Positioning System
- **RFID :** Radio-Frequency Identification
- **CCL :** Cold Chain Logistics
- **EEG :** Electroencephalogram
- **EMG :** Electromyogram
- **ECG :** Electrocardiogram
- **NDIR :** Non-Dispersive Infrared
- **VOCs :** Volatile Organic Compounds
- **CO_2 :** Carbon Dioxide
- **CO :** Carbon Monoxide
- **NO_2 :** Nitrogen Dioxide
- **SO_2 :** Sulfur Dioxide
- **MARL :** Multi-Agent Reinforcement Learning
- **ATSC :** Adaptive Traffic Signal Control
- **LoRa :** Long Range (Wireless Protocol)
- **NB-IoT :** Narrowband Internet of Things
- **ADC :** Analog-to-Digital Converter
- **WIFI :** Wireless Fidelity

- **SDA :** Serial Data Line (I^2C Protocol)
- **SCL :** Serial Clock Line (I^2C Protocol)
- **MOS :** Metal-Oxide Semiconductor
- **PM :** Particulate Matter
- **LDO :** Low Dropout Regulator
- **ESD :** Electrostatic Discharge
- **PSRAM :** Pseudo-Static Random Access Memory
- **CPU :** Central Processing Unit
- **SPI :** Serial Peripheral Interface
- **PWM :** Pulse Width Modulation
- **OTG :** On-The-Go (USB standard)
- **PCB :** Printed Circuit Board
- **GPIO :** General Purpose Input/Output
- **SSR :** Solid State Relay
- **I^2C :** Inter-Integrated Circuit
- **V :** Volt
- **A :** Ampere
- **°C :** Degree Celsius
- **% :** Percentage
- **Ω :** Ohm
- **mV :** Millivolt
- **kHz :** Kilohertz
- **MHz :** Megahertz
- **W :** Watt

General Introduction

Introduction

The rapid development of agriculture in remote and semi-arid regions has created a strong need for accurate, local meteorological information. Farmers and decision makers increasingly depend on climate variables to understand crop behavior, estimate water needs, anticipate unfavorable weather, and organize daily operations. A meteorological station is therefore a decision-support tool that transforms the surrounding atmosphere into usable information. In isolated areas, where official stations may be far away and microclimates differ from one field to another, local monitoring becomes especially important because a small change in temperature, humidity, wind, or rainfall can influence irrigation, crop stress, and yield quality.

This graduation project focuses on the design and implementation of an IoT-based, solar-powered meteorological station dedicated to isolated areas. The subject is motivated by three practical constraints: the absence of a stable electrical grid, the difficulty of maintaining wired communication infrastructure, and the need to obtain reliable field data without frequent human intervention. Conventional weather stations provide high-quality measurements, but their cost, installation requirements, and maintenance needs limit their use in dispersed agricultural zones. The proposed system offers a more accessible solution by combining embedded electronics, autonomous power supply, wireless communication, and cloud-based data visualization.

Technically, the station is built around an ESP32 microcontroller, which is appropriate for embedded IoT applications due to its processing capability, interfaces, wireless connectivity, and low-power modes. The sensing subsystem acquires the main meteorological variables required for agricultural monitoring: air temperature, relative humidity, atmospheric pressure, wind speed, wind direction, rainfall, solar radiation, and optionally air quality. These variables were selected because they are directly linked to plant growth, evapotranspiration, irrigation scheduling, and environmental safety.

The project also emphasizes measurement reliability. Outdoors, sensors are exposed to solar heating, dust, rain, wind, and vibration. Therefore, the design includes protective elements such as a ventilated radiation shield for temperature and humidity sensing, proper mounting for wind sensors, a stable support for the rain sensor, and a weather-resistant enclosure for the electronics. Using a barometric sensor like the BMP280 or BME280 is crucial, as the DHT21 or AM2301 only measures temperature and humidity. This distinction improves the scientific consistency of the final system.

Energy autonomy is another central aspect. Since the station is intended for isolated locations, it cannot depend on grid electricity. The solar power subsystem includes a photovoltaic panel, a charge controller, a rechargeable battery, and voltage regulation circuits. The objective is to maintain operation during the night and during days with reduced solar radiation. Low-power firmware strategies, such as scheduled measurements, transmission intervals, and sleep modes, complement the hardware design and reduce unnecessary energy consumption.

Communication and software complete the system by making data accessible to the user. Depending on coverage, the station may use GSM/GPRS, NB-IoT, Wi-Fi, or another suitable wireless technology. Transmitted data is stored in a cloud platform and displayed through a web or mobile dashboard. This remote monitoring is essential because it allows the user to observe real-time values, compare historical measurements, detect abnormal situations, and receive alerts without being physically present at the station.

The overall aim of this work is to develop a practical, autonomous, and scalable meteorological monitoring solution adapted to agricultural fields. The project integrates scientific knowledge about meteorological variables with engineering choices related to sensors, microcontrollers, power management, communication, and software. By doing so, it contributes to smart agriculture, where decisions are supported by local data rather than general assumptions.

This dissertation follows the logical progression of the project. The first chapter presents the fundamentals of meteorological monitoring and the importance of climate variables in agriculture. The second chapter introduces IoT technologies, sensors, and communication solutions. The third chapter describes the design of the proposed solar-powered station, including the sensing, power, communication, PCB, and enclosure subsystems. The fourth chapter presents the practical implementation, software development, calibration, field testing, and analysis of results. The conclusion summarizes the main contributions and proposes future improvements, such as soil moisture sensing, AI-based forecasting, and multi-station networking.

Chapter I

Fundamentals of Meteorological Monitoring in Isolated Areas.

I.1 Introduction:

Meteorological monitoring consists of the regular measurement of physical variables that describe the state of the atmosphere near the Earth's surface, such as air temperature, relative humidity, atmospheric pressure, wind speed, wind direction, rainfall, and solar radiation. In agricultural applications, these variables are not collected for descriptive purposes alone; they are interpreted as indicators of crop stress, evapotranspiration, disease risk, field accessibility, and exposure to extreme events. The scientific quality of weather monitoring therefore depends not only on the sensor itself, but also on siting, sampling frequency, shielding, calibration, logging strategy, and data validation [1].

A station deployed in a remote area must provide a balance between three requirements: measurement reliability, operational continuity, and field practicality. High precision has little value if the system stops operating after a short period, and continuous operation is not enough if the measurements gradually drift away from reality because of poor maintenance or exposure. For that reason, modern smart weather stations are increasingly designed as complete systems in which sensing, energy management, communication, and self-monitoring functions are considered together rather than as isolated technical blocks [1], [10], [11].

I.2 Importance of Meteorological Monitoring in Agriculture and Remote Areas:

Agriculture is one of the economic activities most strongly controlled by atmospheric conditions. Germination, flowering, fruit set, plant growth, evapotranspiration, disease development, pollination quality, and harvest timing are all influenced by short-term weather variability and seasonal climate behavior. A farmer may know from experience that heat increases water demand or that high humidity encourages fungal diseases, but a monitoring station transforms that qualitative experience into measurable evidence. In this sense, meteorological data act as an operational support for daily and seasonal decisions rather than as background information only [3], [4].

The need for local observation becomes even more evident in remote or heterogeneous agricultural landscapes. In oases, center-pivot irrigation systems, terraced fields, and semi-arid production zones, the microclimate observed at crop level may differ from official regional observations because of altitude, soil moisture contrasts, vegetation density, irrigation practices, sheltering structures, and local topography. A field located a few kilometers away from a reference station may experience different wind behavior, night cooling, or rainfall distribution. Depending exclusively on distant measurements can therefore lead to irrigation errors, late response to frost events, or inappropriate spray scheduling [1], [3], [4].

Meteorological monitoring in remote areas also contributes to risk reduction and early warning. Timely ground data make it easier to identify potentially dangerous situations such as rapid temperature drops, abnormal wind episodes, intense rainfall, or prolonged dry conditions. The World Meteorological Organization emphasizes that risk knowledge, monitoring and forecasting, warning dissemination, and preparedness are interlinked pillars of an effective early warning system [2]. Without ground observations, especially

in poorly covered territories, hazard assessment remains incomplete and the connection between forecast products and local reality becomes weaker.

From an agricultural management perspective, weather data support more precise irrigation scheduling, more rational use of water and crop-protection products, and a better understanding of crop vulnerability over time. They also help build historical local databases that can later be used to study climate variability, drought recurrence, or the behavior of a given production zone from one season to the next. The practical value of a weather station, therefore, is not limited to the instant reading displayed on a screen; it lies in the accumulation of trustworthy local evidence that can guide decisions in the present and inform planning in the future [3], [4], [5].

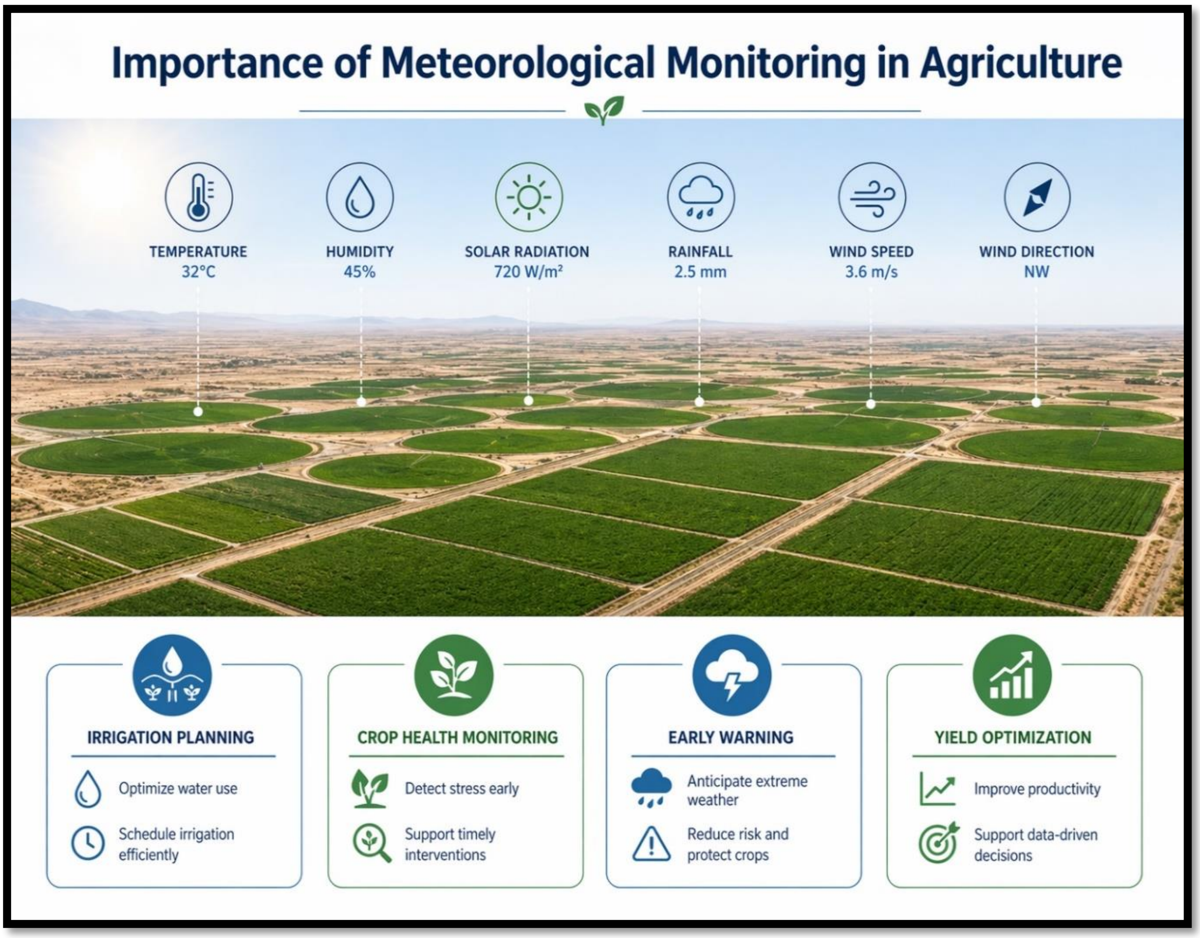

Figure I.1: Large agricultural production areas illustrate the need for localized climate measurements inside the actual zone of cultivation.

I.3 Main Climate Variables to Be Measured:

The set of variables measured by a weather station depends on the intended application, the cost constraints, and the expected environment. Nevertheless, there is a core group of atmospheric variables that forms the minimum scientific basis for most agrometeorological and early-warning uses. Measuring several variables together is essential because agricultural interpretation usually depends on their interaction rather than on isolated values. Table 1-1 summarizes the main variables commonly considered in a field weather station and their operational meaning in agriculture [1], [3], [6].

Variable	Typical Unit	Measurement Device	Practical Agricultural Significance
Air temperature	deg C	Thermal sensor	Germination, growth rate, heat stress, frost risk
Relative humidity	%	Humidity sensor	Disease risk, transpiration, dew formation
Atmospheric pressure	hPa	Digital barometer	Weather trend detection and disturbance tracking
Wind speed	m/s	Anemometer	Evapotranspiration, spray drift, structural exposure
Wind direction	Degree / cardinal	Wind vane	Air-mass movement, dust transport, pest movement
Rainfall	mm	Rain gauge	Irrigation balance, runoff, flooding potential
Solar radiation	W/m2	Pyranometer or radiation sensor	Photosynthesis, ET estimation, solar energy assessment
Air quality	ug/m3 or ppm	Gas / particulate sensors	Environmental quality, worker and plant exposure

Table I.1: Core meteorological variables and their agricultural significance.

I.3.1 Air Temperature:

Air temperature is among the most influential variables in crop development because it controls biological rates such as germination, respiration, photosynthesis, vegetative growth, flowering, and ripening. Many crops respond not only to average temperature, but also to daily maxima, minima, and the duration of extreme episodes. High temperatures can accelerate development while reducing quality, whereas low nighttime temperatures can delay growth or expose the crop to chilling and frost injury. Accurate temperature measurement is therefore central to crop monitoring, seasonal management, and the interpretation of local climatic suitability [1], [3].

In practice, The AM2301 temperature measurement device must be protected from direct radiation and the effects of poor ventilation. This is why the sensor is usually placed inside a shield that allows airflow while limiting solar heating. For remote smart stations, the temperature sensor must also combine stability with low power consumption, because it is expected to operate continuously in an autonomous system. Once collected over time, temperature data become especially useful when transformed into indicators such as hot-day counts, frost alarms, or cumulative thermal conditions for crop development [1], [10].

I.3.2 Relative Humidity:

Relative humidity expresses how much water vapor is present in the air compared with the maximum amount the air could hold at the same temperature. It is therefore closely related to temperature and helps explain the atmospheric demand for water. In agriculture, humidity influences plant transpiration, dew formation, canopy wetness, and the likelihood of fungal and bacterial disease development. Periods of high humidity combined with weak ventilation are often favorable to pathogens, while very low humidity together with high temperature can intensify plant water stress [1], [3], [4].

For monitoring purposes, humidity becomes more informative when it is observed as a time pattern instead of a single isolated reading. Nighttime saturation, early morning dew, or sustained afternoon dryness can reveal different field conditions with direct agronomic implications. Since humidity sensors may drift in dirty or hot environments, their long-term use in isolated areas also requires attention to shielding, contamination, and periodic quality control [1], [11].

I.3.3 Atmospheric Pressure:

Atmospheric pressure may appear less directly agricultural than temperature or humidity, yet it remains an important variable for understanding the evolution of weather conditions. Pressure tendencies are linked to the approach of disturbances, wind changes, and shifts in atmospheric stability. In compact smart stations, pressure is usually measured by a digital barometric sensor that is small, energy efficient, and easy to interface with a microcontroller. Including this variable improves the station's ability to describe the weather system as a whole rather than monitoring only surface comfort conditions [1].

From an operational perspective, pressure data can also reinforce data interpretation and quality control. When pressure falls while wind and humidity begin to change, the station can identify a coherent meteorological transition. If pressure remains stable but a single variable behaves abnormally, this may point to a local disturbance or sensor anomaly rather than to a real weather event. In isolated stations, such cross-checking adds robustness to field interpretation [1], [11].

I.3.4 Wind Speed:

Wind speed has direct consequences for evapotranspiration, spray drift, the drying of plant surfaces, dust transport, and the mechanical stress exerted on structures or light agricultural equipment. It is therefore an essential variable in both crop management and station design. Under hot and dry conditions, stronger wind usually increases atmospheric demand and can intensify water loss from both soil and canopy. During pesticide application, excessive wind can cause off-target drift and reduce treatment efficiency. It can also affect the orientation and stability of solar panels, poles, or shields mounted on the station [1], [10].

Wind speed is commonly measured with an anemometer, which may use rotating cups or other sensing mechanisms. In remote deployments, the measurement quality depends strongly on exposure: obstacles such as buildings, trees, or walls can distort the local airflow and produce misleading readings. For this reason, correct siting is as important as the sensor itself. When time series of wind speed are stored continuously, they become useful not only for daily operations but also for long-term analysis of site exposure and for the identification of recurrent hazardous episodes [1], [11].

I.3.5 Wind Direction:

Wind direction complements wind speed by indicating the origin and movement of air masses affecting the site. In agricultural environments, this helps interpret the pathways of dust, saline air, airborne pests, smoke, and spray droplets. It can also assist in deciding the positioning of structures such as greenhouses, ventilation openings, or protective barriers. A wind vane is the common device used for this purpose, and its value increases when direction is analyzed together with speed and frequency over time rather than as isolated instantaneous observations [1], [10].

Direction statistics may reveal prevailing seasonal patterns that are relevant to local planning. In a remote field, a dominant dry hot wind from one sector may justify different protective actions than a humid coastal flow from another direction. Thus, wind direction is not a decorative parameter in a weather station; it is part of the spatial interpretation of the atmospheric environment affecting the crop and the station itself [1], [3].

I.3.6 Rainfall:

Rainfall is fundamental for irrigation management, water balance analysis, runoff estimation, and the identification of hazardous events. In agriculture, the total amount of rain is important, but the temporal pattern of rainfall is often just as important. A moderate amount distributed over several hours may benefit infiltration and reduce water demand, while the same total delivered in a short intense storm may increase runoff, erode the soil surface, or damage the crop. This is why rainfall data should ideally be interpreted in relation to event timing and intensity, not only monthly totals [1], [4].

Rainfall is commonly measured with a rain gauge, often of the tipping-bucket type in automatic stations. Although the principle is simple, long-term field reliability depends on maintenance because dust, insects, leaves, or poor leveling can disturb the measurement. In isolated regions, where field visits are infrequent, rainfall measurement must be supported by protective design and logical data checking so that false pulses or missing events can be detected as early as possible [1], [11].

I.3.7 Solar Radiation:

Solar radiation is a key driver of photosynthesis, crop energy balance, and evapotranspiration. It also has a dual importance in the present project because it directly affects the performance of the photovoltaic subsystem powering the station. Measuring radiation can therefore serve both agronomic interpretation and system energy analysis. From the agricultural point of view, radiation helps explain plant growth and atmospheric demand; from the technical point of view, it helps assess the energy resource available to the solar panel during different seasons or weather situations [1], [8].

Radiation can be measured by a pyranometer or by simpler radiation sensors depending on the desired precision and cost level. In all cases, the sensor must be mounted in a position that minimizes shading and contamination. In remote smart stations, radiation data can later be combined with temperature, humidity, and wind information to support more advanced indicators such as crop stress interpretation or approximate evapotranspiration analysis [1], [3], [8].

I.3.8 Air Quality:

Air quality is an optional but increasingly relevant variable for environmental monitoring stations, especially in dusty, peri-urban, or traffic-influenced agricultural environments. Particulate matter and gaseous pollutants may affect worker comfort, plant surface deposition, visibility, and, in some cases, broader ecosystem health. The World Health Organization's air quality guidance underlines the significance of pollutants such as particulate matter, ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide for public health [6]. While not all agricultural weather stations need these measurements, the inclusion of an air quality module can expand the environmental relevance of the platform.

In practical terms, the decision to add air quality sensing depends on project objectives, budget, required accuracy, and maintenance capacity. Low-cost gas or particulate sensors can provide useful trend information, but they often require careful interpretation and are more sensitive to environmental drift than standard meteorological sensors. For this reason, air quality modules should be considered an extension of the system, not a substitute for robust core weather monitoring [6], [11].

I.3.9 Integration of Atmospheric Variables in Field Interpretation:

A common mistake in weather analysis is to interpret each variable in isolation. A high temperature value does not carry the same agricultural meaning when it is accompanied by high humidity and weak wind as when it occurs under dry air, strong wind, and intense radiation. Likewise, a rainfall event cannot be judged only by the total millimeters recorded: event duration, wind, antecedent humidity, and solar recovery afterward can strongly influence its effect on the field. The analytical value of a station therefore increases when it allows the user to combine measurements into interpretable patterns or indicators rather than viewing each sensor as a separate universe [1], [3], [11].

This integrated reading also supports quality assurance. If temperature rises sharply without a corresponding change in radiation or daily cycle context, a sensor exposure problem may be suspected. If the rain gauge records repeated pulses on a fully dry day while humidity and cloudiness remain stable, mechanical vibration or clogging may be the real cause. Cross-variable interpretation is thus useful both for agricultural understanding and for the diagnosis of data credibility in remote operation [1], [11].

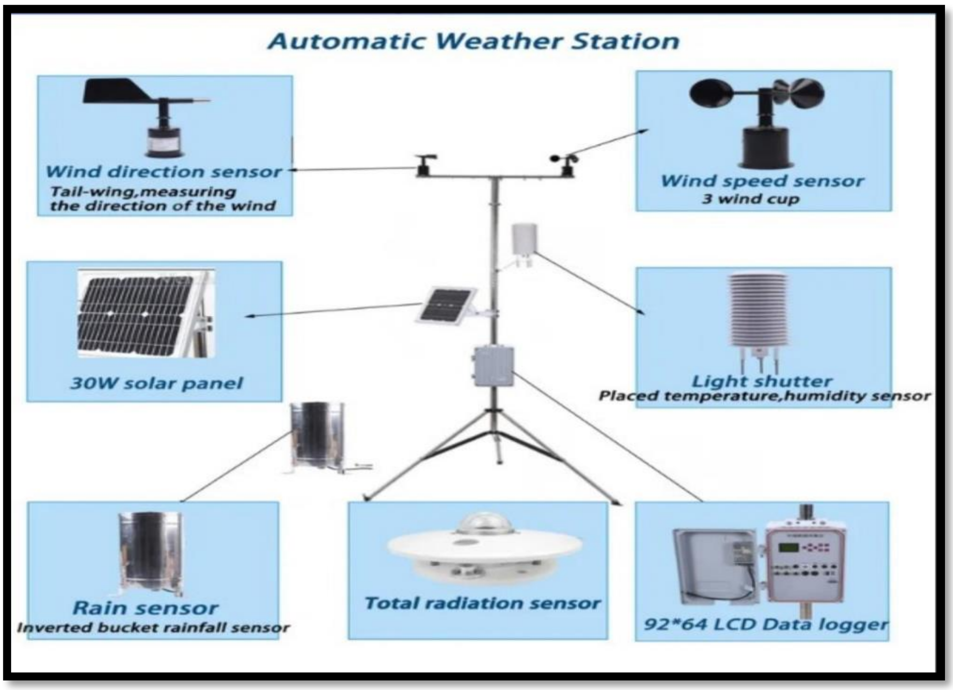

Figure I.2: Example of an automatic weather station integrating wind, rainfall, radiation, temperature, And humidity measurements with a data-logging unit.

I.4 Conventional Weather Stations and Their Limitations:

Conventional weather stations operated by national services, research centers, or specialized institutions remain fundamental references because they are generally installed according to strict standards and supported by established calibration procedures. They provide high scientific value and are essential for climatology, forecasting, and long-term observation networks. However, their importance does not automatically mean that they provide sufficient spatial coverage for all local agricultural needs. A limited number of high-grade stations distributed over large territories leaves wide observation gaps that cannot always be resolved through interpolation alone [1], [11].

In many rural regions, conventional stations are too sparse, too expensive to densify, or too dependent on existing infrastructure to be deployed exactly where the data are needed. They may also rely on centralized acquisition practices, longer reporting cycles, or organizational constraints that reduce their ability to provide field-level responsiveness. For local farm management, what matters is often not a national average but an immediate reading of the conditions actually affecting the crop at a precise site and time [10], [11].

The objective of smart low-cost stations is therefore not to replace official reference stations, but to complement them by increasing spatial density, improving immediacy, and enabling operational use in remote contexts. This complementarity is particularly useful when a project seeks local decision support, experimental field monitoring, or distributed climate observation over wide agricultural landscapes. In such cases, scalability, cost, autonomy, and connectivity become as important as measurement itself [10], [11], [12].

Comparison Aspect	Conventional Weather Station	Proposed Smart Station for Isolated Areas
Cost	Relatively high	Lower and more scalable
Energy source	Often depends on fixed infrastructure	Solar panel plus battery
Data transmission	Periodic or centralized	Real-time or near real-time
Spatial flexibility	Limited	Flexible and rapidly deployable
Suitability for isolated areas	Operationally constrained	High when properly engineered
Maintenance model	Specialized and often costly	Simpler in principle but must be designed for reliability

Table I.2: General comparison between a conventional weather station and a smart station intended for isolated-area deployment.

I.5 Challenges of Station Deployment in Isolated Areas:

Deploying a weather station in an isolated area is not merely a matter of placing sensors on a mast. It is a systems-engineering problem shaped by energy, communication, environment, maintenance, and data-quality constraints. A station that performs well in a laboratory or on an urban campus may fail rapidly in a dusty agricultural field or semi-desert site if these constraints are underestimated. For this reason, remote deployment must be approached from the beginning as a long-duration autonomous operation problem [8], [9], [11].

I.5.1 Lack of Electrical Infrastructure:

The first and most obvious challenge is the absence of reliable grid power. In isolated farms, rangelands, mountain sites, or desert perimeters, permanent electrical infrastructure may be unavailable, unstable, or too expensive to extend. This means that the station must generate and manage its own energy while keeping consumption low enough to survive cloudy periods, nighttime operation, and seasonal fluctuations in solar availability. Energy is not an accessory problem in such systems; it is the condition for every other function to exist [8], [9].

I.5.2 Communication Instability:

Remote sites also face communication uncertainty. Cellular coverage may be weak or intermittent, packet loss may occur, and some areas may only support limited technologies. As a result, the station must be capable of buffering data locally, retransmitting when the network returns, and separating sensing continuity from communication continuity. In other words, a temporary loss of network should not mean a loss of observation history. This requirement influences the architecture of the system as much as the sensor choice does [9], [10], [11].

I.5.3 Harsh Environmental Conditions:

Isolated deployments often expose electronics and sensors to severe heat, dust, sand, humidity variations, intense radiation, rain, corrosion, insects, and occasional animal interference. Such conditions can shorten sensor life, alter calibration, clog the rain gauge, or degrade connectors and enclosures. Outdoor reliability therefore depends heavily on weatherproof housing, suitable materials, cable protection, mounting stability, and the ability to keep sensitive sensing elements properly exposed while protecting the rest of the system [1], [9].

I.5.4 Maintenance Difficulty:

The farther the station is from technical personnel, the more important maintenance-friendly design becomes. Frequent field visits may be slow, costly, or impossible during part of the season. A good remote station must therefore simplify cleaning, replacement, inspection, and diagnosis. Modular components, status indicators, error logging, and protective design reduce the need for emergency intervention and improve the service life of the platform under real conditions [9], [11].

I.5.5 Need for Operational Autonomy:

Operational autonomy means more than being powered by a battery. It involves coordinated low-power strategies, scheduled data acquisition, standby or sleep modes, watchdog protection, restart resilience after outages, and local storage that preserves records during communication interruptions. The station must be able to continue its basic mission even when conditions are temporarily unfavorable. This requirement strongly favors microcontrollers, sensors, and communication schemes that have been selected with energy and reliability in mind from the start [10], [11].

I.5.6 Data Quality and Calibration in Remote Sites:

A less visible but highly important challenge is data quality over time. A station can continue sending numbers regularly while those numbers slowly drift away from reality because of sensor aging, contamination, misalignment, or environmental change around the site. The growth of nearby vegetation, the appearance of new obstacles, or the aging of the battery may all influence the reliability of what is being measured. This is why a remote monitoring project must include a quality strategy rather than assuming that continuity automatically guarantees validity [1], [11].

Recommended quality practices include range checking in firmware, coherence tests between related variables, logging of anomalies and communication outages, periodic comparison with reference instruments when possible, and maintenance procedures that preserve the siting conditions required by observation standards. Long records are valuable only if they remain traceable, interpretable, and sufficiently accurate for the decisions they are supposed to support [1], [10], [11].

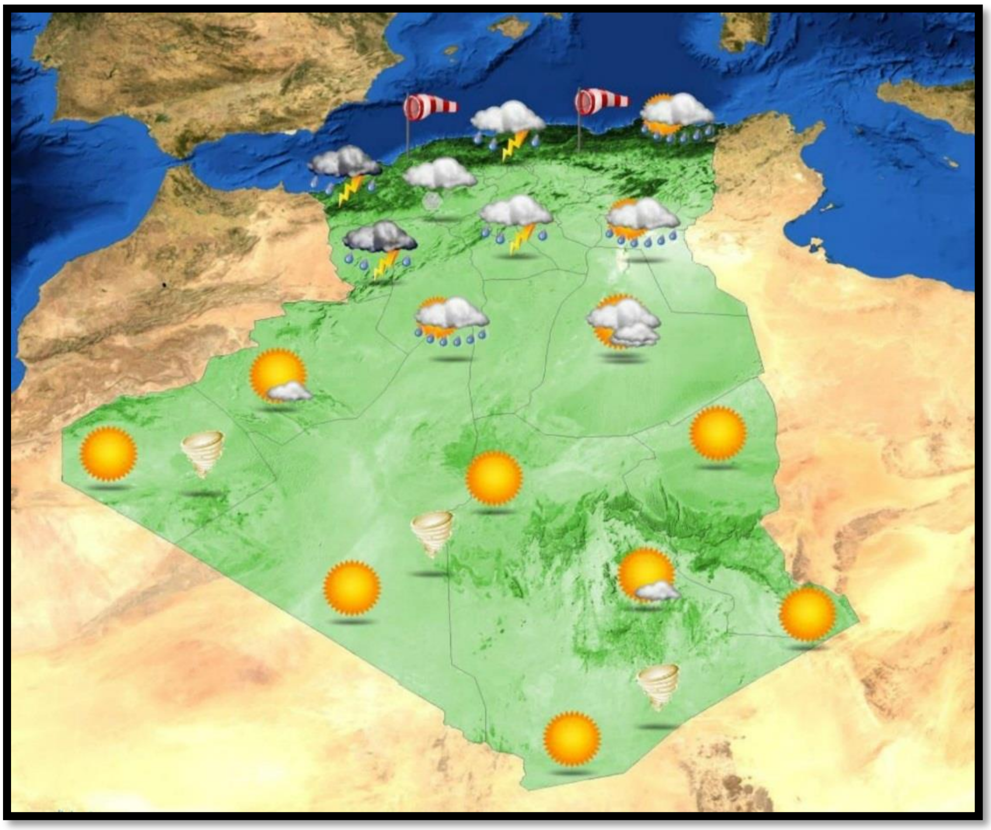

Figure I.3: Visual illustration of spatial diversity in weather conditions across Algeria, supporting the need for denser local observation networks.

I.6 Solar Energy as a Suitable Solution for Remote Monitoring Systems:

Solar energy is one of the most suitable solutions for powering monitoring systems in isolated areas because it offers a renewable and geographically widespread resource that can be harvested without a permanent grid connection. This makes it especially attractive for low-power stations that only need modest energy when sensors, microcontroller, and communication cycles are chosen carefully. In the context of meteorological monitoring, solar power also fits the logic of environmental autonomy: the station becomes capable of observing the climate without depending on fragile external infrastructure [8], [9].

A properly engineered solar subsystem is based on a daily energy budget, expected solar resource, desired days of autonomy, and the characteristics of the battery and charge controller. Stand-alone photovoltaic guidance stresses that system performance must be assessed at the level of the integrated whole rather than by examining components separately [8]. In practice, this means that panel sizing, storage sizing, load scheduling, and protection functions must be designed as a coordinated subsystem. Oversimplified sizing can lead to data loss during cloudy periods, while poor regulation may shorten battery life and compromise field operation.

Solar power also strengthens scalability. Once a reliable energy architecture is defined, similar stations can be replicated at multiple sites without the major logistical burden of extending electrical infrastructure. This is particularly important for agricultural monitoring, where the value of the project often increases with the number of sites observed. International work on off-grid and edge-of-grid photovoltaic systems highlights reliability, resilience, and operational security as central issues for such deployments, which directly aligns with the needs of an autonomous field weather station [9].

For the proposed project, solar power is therefore not a secondary convenience but a core design choice. It supports the feasibility of deploying the station in isolated agricultural areas, reduces operating dependence on the grid, and reinforces the long-term practical value of the system. When combined with low-power electronics and robust energy management, it becomes possible to build a monitoring node that is both technically realistic and economically meaningful [8], [9], [10].

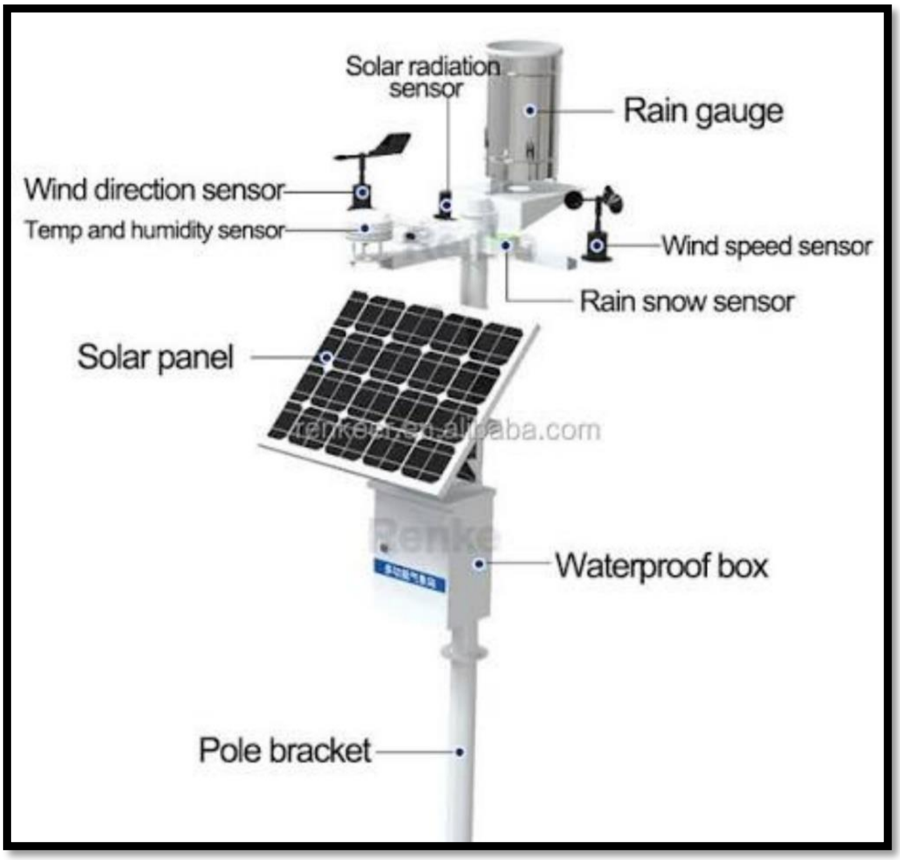

Figure I.4: Example of a solar-powered field weather station, a configuration well suited to isolated deployment conditions.

I.7 Role of Smart Stations in Early Weather Prediction and Agricultural Decision-Making:

The real value of a smart station does not lie in measuring variables for their own sake, but in transforming measurements into usable knowledge. Once data are sampled in real time, transmitted to a digital platform, and organized into trends, indicators, or alerts, the station becomes part of a decision-support chain rather than an isolated measuring device. At this point, the practical questions become explicit: should irrigation be postponed or advanced, are wind conditions unsafe for spraying, is there an increasing risk of disease, or are the signs of a heat episode becoming visible [2], [4], [10].

Ground observations are also a necessary complement to wider-scale forecasting and remote sensing. Weather models and satellite products provide indispensable regional coverage, but local measurements reveal what is actually happening at the site where the crop grows. This local truth is essential in heterogeneous landscapes, where small spatial differences may matter greatly. WMO early-warning guidance recognizes monitoring, analysis, communication, and preparedness as connected elements; good observation at the local level improves the quality of that chain and strengthens the relevance of warnings for vulnerable communities [2].

In agriculture, the usefulness of smart stations increases further when local climate data are combined with vegetation indicators and geographic interpretation. FAO programs such as GIEWS integrate ground-based information with Earth observation to assess crop conditions and food-security risks [5]. NASA Earthdata explains that vegetation indices such as NDVI use the contrast between red and near-infrared reflectance to evaluate vegetation health, with higher values generally associated with greener and healthier plant cover [7]. Linking station data with such indicators opens the door to practical applications such as irrigation targeting, crop-stress mapping, and seasonal comparison of field performance.

Recent research on low-cost IoT-enabled agrometeorological stations shows that these systems can expand access to localized weather data, strengthen climate-smart agriculture, and improve the ability of users in resource-constrained settings to act on site-specific information [10], [11], [12]. At the same time, the literature also reminds us that cost reduction alone is not enough: calibration, interoperability, and long-term field validation remain essential if the station is expected to support real decisions rather than generating attractive but unreliable numbers.

From the viewpoint of the final user, the best station is not necessarily the most complex one, but the one that translates climate behavior into understandable information. If the system can tell the user that frost risk is increasing, that atmospheric demand for water is high, that rainfall did not effectively reduce crop stress, or that wind conditions are unfavorable for spraying, then the station has moved from observation to utility. This is the conceptual transition that justifies the design of a smart meteorological platform for isolated areas [2], [4], [10].

I.7.1 from Measurement to Digital Alert:

The path from raw measurement to useful warning involves several stages: sensing, checking, filtering, threshold comparison, and user-oriented communication. A farmer or field manager does not necessarily benefit from a list of raw numbers alone. The system becomes more useful when it converts those values into actionable messages such as "possible frost overnight," "high evaporative demand today," or "spraying is not recommended under current wind conditions." The quality of this transformation depends on both good data and clear interpretation rules [2], [4], [10].

Time series are especially important in this context because many agricultural decisions depend on trends rather than on isolated observations. A gradual increase in temperature, repeated afternoon wind peaks, or a sustained decline in humidity can be more informative than a single instantaneous value. For this reason, dashboards and mobile interfaces are not mere visualization accessories; they are part of the knowledge layer that turns continuous observation into usable field intelligence [4], [5], [10].

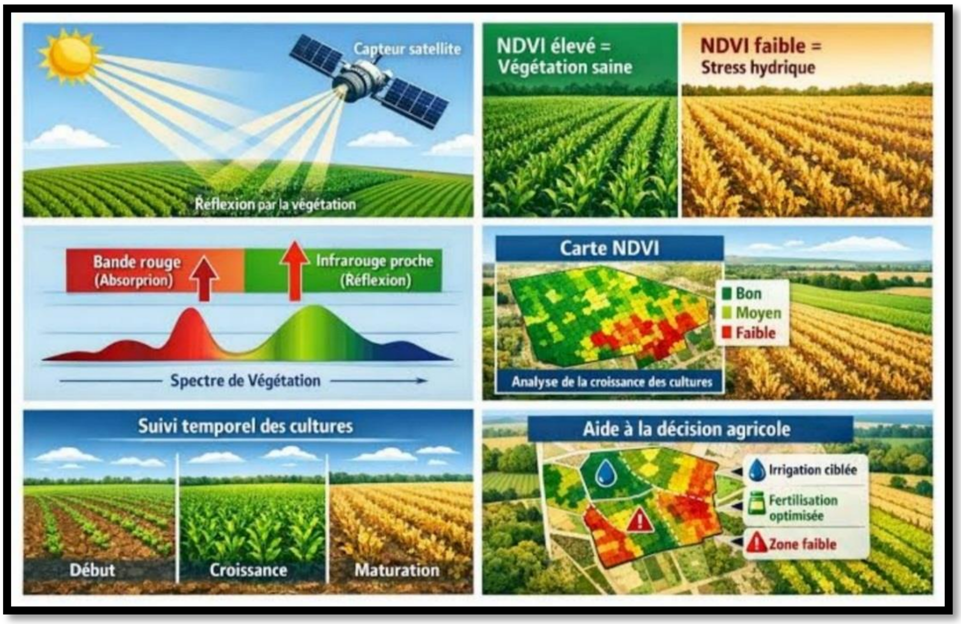

Figure I.5: Example of how meteorological data can be interpreted together with vegetation indicators such as NDVI to support agricultural decisions.

I.7.2 Integration with Cloud Platforms and Mobile Services:

Connecting the station to a cloud platform or mobile service gives the measurements operational continuity. Data become archived, searchable, comparable over long periods, and accessible from multiple locations rather than being trapped in a local logger display. This benefits supervisors, researchers, and farmers alike, especially when direct field presence is difficult or when several plots must be monitored simultaneously. The platform also allows data visualization, historical analysis, threshold-based notification, and the creation of simple indicators understandable by non-specialist users [4], [10], [12].

As the database grows, seasonal patterns can be identified more clearly, and the station starts contributing to local climatic memory rather than only current monitoring. This cumulative perspective is highly valuable for remote agricultural systems, where management improvement often depends on comparing one season to another. A cloud-connected station thus functions as both a live observation node and a long-term knowledge source [4], [5], [10].

I.7.3 Prospects for Multi-Station Networks:

A single station can characterize the immediate environment where it is installed, but a network of stations opens much broader analytical possibilities. Microclimatic differences inside an agricultural territory may become significant over relatively short distances because of elevation, irrigation pattern, soil texture, vegetation density, or exposure to prevailing winds. In such situations, a network of coordinated smart stations can reveal spatial gradients that a single node would never detect by itself [5], [11].

This network logic is strategically important for future development of the proposed project. One well-equipped reference station can be combined with several lighter nodes to balance cost, coverage, and reliability. Over time, such an architecture may support real-time thermal maps, humidity comparisons, local warning clusters, or broader territorial decision tools for farms, oasis systems, or irrigated perimeters. The current project can therefore be understood not only as a stand-alone device, but also as the foundation of a future distributed observation network [9], [11].

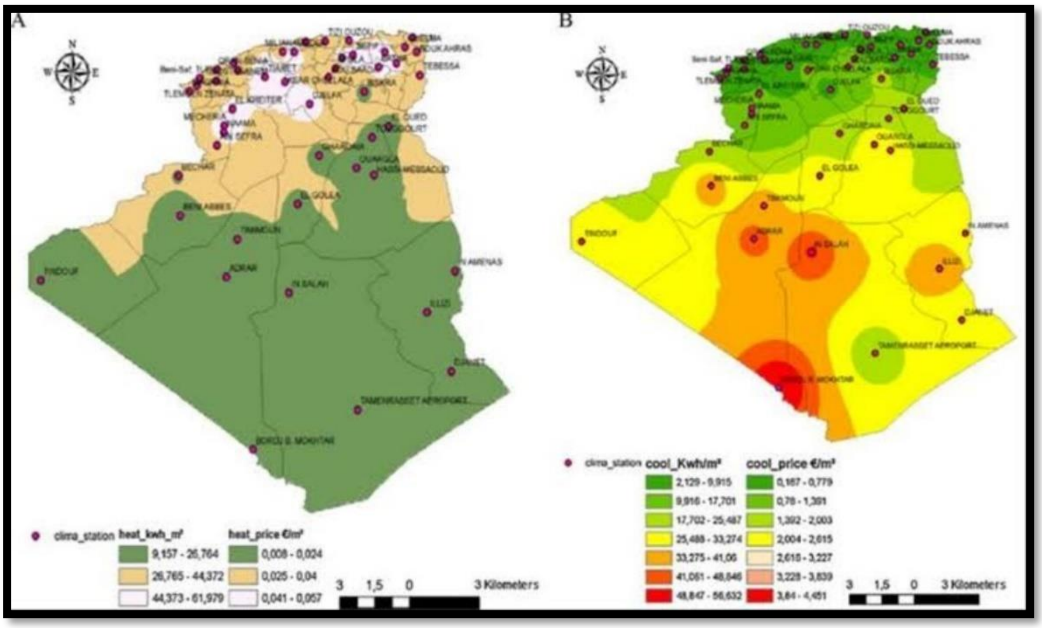

Figure I.6: Example of spatial agroclimatic variability, illustrating the value of territorial interpretation and future multi-station analysis.

I.8 Conclusion:

This chapter established the scientific rationale for an autonomous weather station in isolated areas by explaining the agricultural importance of local meteorological measurements, the core climate variables that should be monitored, the main constraints of remote deployment, and the relevance of solar power and smart data services. It also showed that the true value of such a station lies not only in sensing, but in transforming local observations into useful information for early warning and field decision-making. This foundation naturally leads to the next chapter, which presents the IoT technologies, sensors, communi- cation solutions, and monitoring platforms required to implement the proposed system.

CHAPTER II

IoT, Sensors, and Communication Technologies for Smart Meteorological Stations.

II.1 Introduction

The success of an autonomous meteorological station does not depend on the sensing elements alone. A modern station becomes truly useful only when measurement, local processing, communication, storage, visualization, and energy management operate as a coherent system. In remote agricultural zones and isolated sites, this integration is even more important because the station must continue working without permanent grid power, without constant human presence, and sometimes with unstable network conditions. For that reason, the second chapter focuses on the technological foundation of the proposed project: the Internet of Things architecture, the embedded controller, the meteorological sensors, the communication options, the cloud layer, the mobile interface, and the strategies that preserve autonomy [15].

In practical terms, an IoT-based weather station is a chain of functions. First, physical variables such as air temperature, relative humidity, atmospheric pressure, wind, rainfall, and solar radiation are converted into electrical signals. Second, the microcontroller samples, filters, and formats these signals. Third, the station sends the data through a suitable wireless link, such as GSM/GPRS or NB-IoT. Finally, the measurements are stored in a remote platform where they can be visualized, interpreted, and transformed into alerts or decision-support indicators. This chapter explains each of these technical building blocks and clarifies why they are appropriate for a solar-powered station intended for isolated areas [16].

II.2 Internet of Things in environmental monitoring:

The Internet of Things can be defined as a distributed digital ecosystem in which physical objects are equipped with sensing, processing, identification, and communication capabilities that allow them to exchange data with local or remote platforms. In environmental monitoring, the value of IoT lies in continuity and accessibility. Instead of visiting a field station to read values manually, the operator can receive continuous measurements in near real time, archive them automatically, and examine historical behavior through charts and reports. This changes the weather station from an isolated instrument into an information service that supports observation, traceability, and rapid response [14], [28].

A typical IoT monitoring architecture is organized in layers. The perception layer contains the sensors and the signal conditioning stage. The edge layer includes the microcontroller, local memory, timing logic, and elementary data treatment such as calibration correction, averaging, outlier rejection, and packet preparation. The communication layer transfers the data toward a gateway or directly toward a cloud platform through a cellular or LPWAN link. Above that, the platform layer is responsible for storage, dashboards, alarms, data access, and integration with other services. Finally, the application layer transforms raw meteorological values into operational information for farmers, technicians, or researchers [14], [25].

For isolated weather stations, IoT brings four major advantages. The first is temporal continuity, because measurements can be taken at a fixed interval day and night. The second is spatial reach, because data can be supervised from distant locations without travelling to the site. The third is automation, since the platform can generate warnings when a threshold is exceeded, for example abnormal heat, high wind, or lack of rainfall. The fourth is scalability, because the same architecture can later be extended from a single station to a network of stations covering several farms or regions. Nevertheless, these benefits are achieved only if the designer selects a controller with low consumption, reliable sensors, and a communication technology adapted to the site constraints [14], [27], [28].

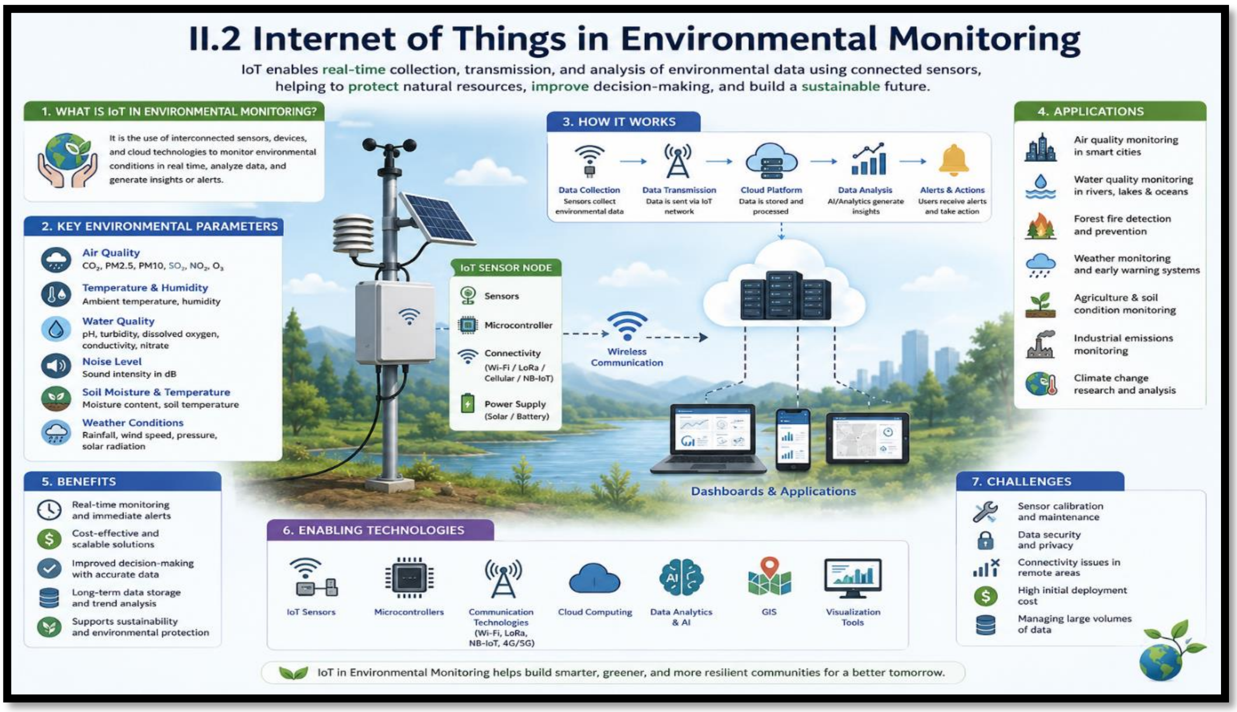

Figure II.1: Internet of Things in environmental monitoring.

II.3 ESP32 microcontroller in embedded IoT systems:

Among low-cost embedded platforms, the ESP32 has become one of the most practical solutions for environmental monitoring nodes. It combines processing capability, wireless functions, flexible peripheral interfaces, and low-power modes in a compact and affordable system-on-chip. According to Espressif documentation, the ESP32 family integrates a dual-core architecture in many variants, analog and digital peripherals, Wi-Fi and Bluetooth connectivity, GPIO lines, timers, PWM resources, ADC channels, and standard serial buses such as UART, I2C, and SPI [15]. These features simplify the design of a weather station because most meteorological sensors can be interfaced directly without adding an external controller.

From a functional perspective, the ESP32 is well suited to a smart meteorological station for several reasons. It can acquire analog or digital sensor data, manage local time scheduling, store configuration parameters, supervise battery-saving modes, and communicate with external modules such as GSM or NB-IoT modems. In addition, it offers enough memory and computational capacity to execute filtering routines, payload encoding, fault detection, and basic local intelligence. For example, the controller can reject a clearly invalid reading, store measurements when the network is temporarily unavailable, or reduce the transmission rate at night to preserve energy [15], [16].

Another decisive advantage is power management. The ESP32 supports light-sleep and deep-sleep modes, and only the subsystems required for wake-up can remain active. This is crucial in a solar-powered station, where autonomy depends not only on the battery size but also on the consumption profile of the controller. In a well-designed scenario, the ESP32 wakes up, powers the sensors if necessary, performs the acquisition, sends or buffers the data, and then returns to sleep. Such duty-cycled operation drastically reduces average current consumption and increases the operating time available during periods of weak solar charging [16], [27].

The designer must still be aware of certain practical limits. The quality of the ADC can be affected by noise and board layout, Wi-Fi transmission consumes much more energy than sleep operation, and outdoor systems require robust input protection, proper grounding, and careful routing between sensor lines and RF sections. For this reason, the microcontroller should be considered not only as a programming target but as the core element of a complete embedded system in which PCB quality, enclosure design, and energy strategy directly influence the reliability of the final station [15], [16].

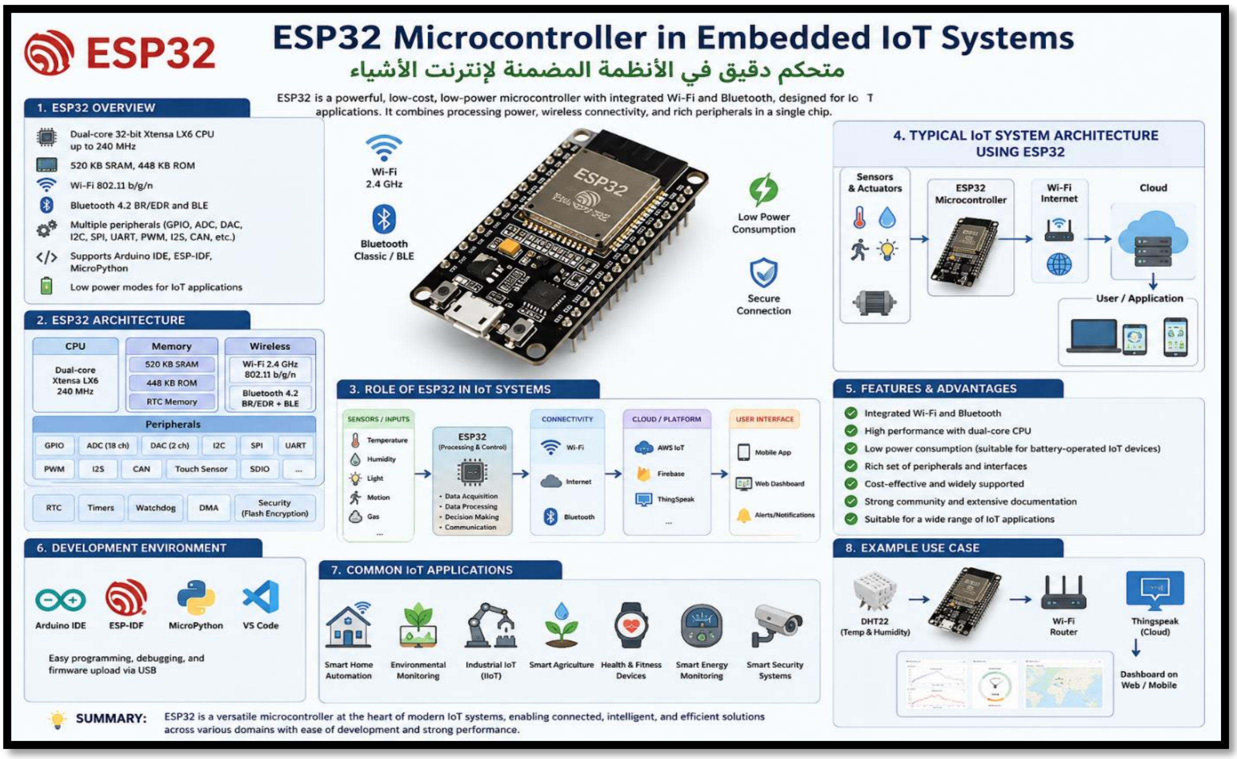

Figure II.2: ESP32 microcontroller in embedded IoT systems.

II.4 Meteorological sensors used in the proposed station:

The scientific usefulness of the station depends on the relevance and quality of the sensors selected. A meteorological sensor is not merely a component that produces numbers; it is the physical interface between the environment and the digital system. Therefore, sensor choice should consider measurement range, accuracy, resolution, long-term stability, interface type, supply voltage, outdoor durability, maintenance needs, and compatibility with the controller and power budget. WMO guidance remains fundamental in this domain because it explains the measurement principles and installation constraints associated with the main atmospheric variables [1].

In the context of a low-cost smart station, the design objective is usually not to reproduce the complexity of a full professional synoptic observatory. Instead, the goal is to obtain reliable local measurements that are sufficiently accurate for agricultural monitoring, microclimate observation, irrigation support, and early warning. This means that the designer must balance cost and performance carefully. The following subsections describe the principal sensors that can be used in the proposed station and explain their role in the overall architecture [13], [27].

II.4.1 Temperature and humidity sensor:

Air temperature and relative humidity are among the most important variables in agrometeorological monitoring because they influence evapotranspiration, plant stress, disease risk, and local comfort conditions. In low-cost prototype stations, the AM2301/DHT21 family is often selected because it provides calibrated digital output, simple single-bus communication, and a low implementation cost [17]. However, from a more professional perspective, sensors such as the Sensirion SHT3x family provide better stability, faster response, and improved precision, especially when measurements are repeated continuously over long periods [18].

Regardless of the chosen model, the installation conditions are essential. Temperature and humidity should not be measured in direct solar exposure or too close to the heat generated by the electronics box. For this reason, the sensing element is commonly placed inside a radiation shield that allows airflow while reducing the effect of direct radiation. If this rule is ignored, the station may report enclosure temperature rather than true ambient conditions. Thus, in an academic and practical sense, the quality of the support and exposure can be as important as the nominal specification written in the datasheet [13], [17], [18].

Characteristics AM2301:

- **POWER:** 3.3-5.2VDC
- **HUM:** 0..99.9%RH
- **TEMP:** -40..80℃
- **PRECISION:** ±3%RH ±0.5℃
- **OUTPUT:** DIGITAL (1 WIRE)
- **SERIE NO:** 18053E400

Figure II.3: Temperature & humidity sensor.

II.4.2 Pressure sensor:

Atmospheric pressure is a key variable for weather tendency analysis and for the interpretation of local meteorological evolution. Digital barometric sensors such as the BMP280 or the BME280 are widely used in embedded weather nodes because they offer compact size, low power consumption, and simple I2C or SPI interfaces. The Bosch BME280 is especially attractive because it combines pressure sensing with temperature and humidity channels in a single compact device while maintaining very low sleep current [19].

In the proposed project, pressure data can complement temperature, humidity, and wind measurements by indicating the arrival of local disturbances or rapid weather changes. Nevertheless, the pressure sensor must be protected from liquid water and condensation while still being exposed to ambient air pressure. This usually requires a vented but protected enclosure strategy. The designer should also remember that pressure values used for interpretation may need correction or normalization depending on whether the platform displays absolute pressure, local station pressure, or a reduced value referenced to sea level [12], [19].

Figure II.4: Pressure sensor.

II.4.3 Anemometer for wind speed:

Wind speed is generally measured by a cup anemometer or a propeller-based sensor. In low-cost automatic weather stations, the cup anemometer is preferred because of its mechanical simplicity and its straightforward electrical interfacing. Each rotation, or a known fraction of a rotation, generates pulses that can be counted by the controller during a sampling window. The microcontroller then converts pulse frequency into wind speed using the calibration factor supplied by the manufacturer [13].

For agricultural and remote monitoring, wind speed matters for irrigation scheduling, spray application, mechanical stress on crops and structures, and storm awareness. The main practical challenge is not only the electrical connection, but the exposure. Wind sensors must be mounted above nearby obstacles and sufficiently far from structures that disturb the flow field. If the mast is too short or the sensor is placed near the solar panel or enclosure, the measured speed may be lower than the real free-stream wind speed. Therefore, site geometry has a direct influence on data credibility [13].

Characteristics:

- **OUTPUT:** 0-3.3V
- **WIND SPEED:** OUTPUT VOLTAGE*14M/S
- **MODEL:** HWFS1

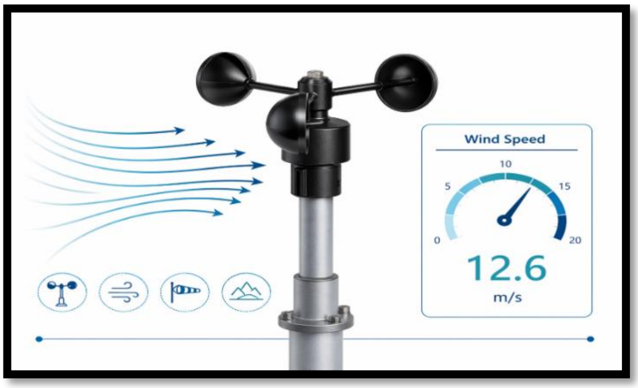

Figure II.5: Example of a wind-sensing element used to capture local wind behavior.

II.4.4 Wind vane for wind direction:

Wind direction is commonly measured by a vane aligned with the air flow. In low-cost stations, the vane often contains a resistive network or a coded output corresponding to discrete angular sectors. The controller reads the analog voltage or the encoded state and transforms it into direction classes or angular degrees. Although this sensor seems simple, it is very useful because direction adds context to wind speed. A strong wind from the north may have different operational implications than a moderate wind from the east, especially near exposed infrastructure or specific crop layouts [13].

Good installation practice requires the vane to be referenced to geographic north during mounting. Without this alignment step, the directional data become misleading even if the sensor itself operates normally. In practice, the calibration and physical orientation of the vane are just as important as its wiring. For long-term outdoor use, the moving axis should also resist corrosion and dust accumulation, since mechanical friction can degrade direction tracking over time [13].

Figure II.6: Wind Direction Sensor.

II.4.5 Rain gauge for precipitation:

In this project, the selected device is the rain detection sensor shown in Figure II.6 rather than a classical tipping-bucket rain gauge. The sensing plate changes its electrical response when water droplets fall on its surface, while the companion electronic module provides analog and digital outputs that can be read directly by the ESP32. This type of component is useful for detecting the onset of rainfall, identifying wet conditions, and providing a qualitative indication of surface wetness. For a smart prototype, it is attractive because it is inexpensive, compact, simple to interface, and well suited to rapid alert logic or protective actions inside the proposed system.

From a technical point of view, however, this component should be described as a rain detection sensor rather than a standardized rain gauge. It is suitable for indicating whether rain is present and for triggering reporting or protection actions, but it does not provide accumulated rainfall depth in millimeters with the same metrological validity as professional tipping-bucket instruments. In the context of the proposed invention, this choice remains coherent because the main objective is low-cost field monitoring, real-time event awareness, and practical decision support, rather than high-precision hydrometeorological.

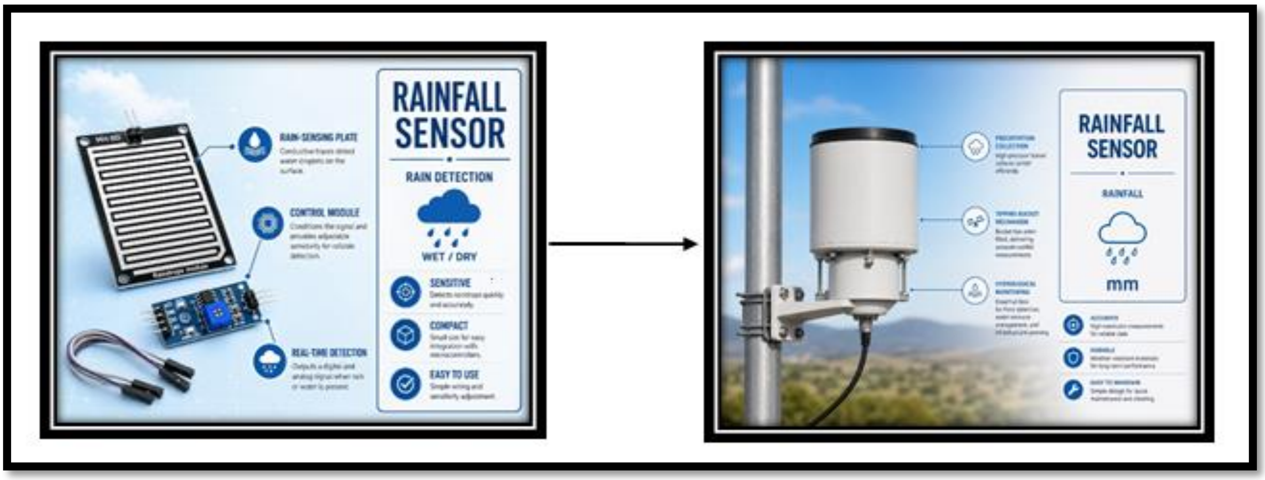

Figure II.7: Rainfall Sensor.

II.4.6 Pyranometer for solar radiation:

Solar radiation is one of the variables that justify the solar-powered nature of the station itself. It influences crop development, evapotranspiration, thermal behavior of the environment, and photovoltaic charging performance. A pyranometer is used to measure global solar irradiance. Professional instruments such as the CMP3 pyranometer from Kipp & Zonen are designed for routine shortwave radiation measurements and comply with recognized radiometric standards [14], [21].

In an engineering project, radiation sensing can serve two simultaneous purposes. The first is meteorological: to quantify the solar energy received at the site. The second is energetic: to interpret whether the available radiation is sufficient to sustain panel charging under different seasons or weather conditions. The installation of a pyranometer requires careful leveling and avoidance of local shading. If mounted near a mast, panel, or enclosure casting a shadow, the measured irradiance becomes biased. Hence, radiation measurement is technically simple at the signal level but demanding at the installation level [13], [20].

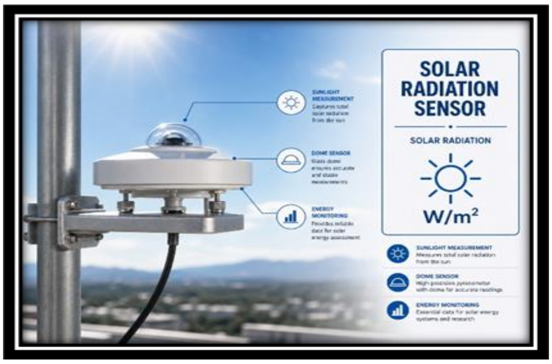

Figure II.8 : Solar Radiation Sensor.

II.4.7 Air quality sensor:

Although air quality is optional in the initial scope of the project, adding such a sensor increases the value of the station, especially near greenhouses, farms, roads, or semi-urban transition zones. A practical approach is to integrate a carbon dioxide or pollutant sensor as an auxiliary channel. For example, the Telaire T6713 is an NDIR-based CO2 module designed for integration with microprocessor systems and provides digital interfacing suitable for monitoring applications [22].

The usefulness of the air quality channel depends strongly on the application. In open rural fields, it may support broader environmental characterization. In protected agriculture or greenhouse conditions, CO2 levels can be directly linked to ventilation and plant performance. However, the designer must distinguish between optional environmental enrichment and the core meteorological mission of the station. In other words, air-quality sensing should enhance the platform without compromising autonomy, cost, or reliability of the primary climate measurements [21], [28].

Figure II.9 : Air Quality Sensor.

II.5 Communication technologies :

Communication is the element that transforms a local measurement unit into a remote monitoring service. In remote areas and agricultural facilities, this choice is particularly sensitive because it determines not only the connectivity but also the energy consumption, deployment cost, data latency, and long-term maintenance. A station may include excellent sensors and a powerful controller, yet still fail operationally if the chosen communication channel is poorly suited to field conditions. For this project, the most relevant cellular options are Wi-Fi; LoRaWAN; NB-IoT; GSM/GPRS; Satellites [22] [23] [24].

II.5. 1. Wi-Fi Communication:

- **Function:** Transmits data over very short distances (inside a building or small field) between sensors and a router connected to the internet.
- **Characteristics:**
- **High speed,** suitable for cameras or devices needing large data transfer.
- **High power consumption,** not suitable for battery-powered devices lasting years.
- **Short range** (typically 30–100 meters).
- Only suitable for farms near a building with internet.

II.5 .2. Lora WAN network Communication:

- **Function:** Transmits very small amounts of data (e.g, temperature, humidity) over long distances with minimal power consumption.
- **Characteristics:**
- **Very long range** (2–5 km in cities, 10–15 km in open fields).
- **Very low power consumption** (battery can last years).
- **Very slow speed,** not suitable for images or video.
- Ideal for private networks on large farms.

II.5. 3. NB-IoT Communication:

- **Function:** A cellular technology designed specifically for stationary devices that send small amounts of data infrequently.
- **Characteristics:**
- **Uses existing mobile towers,** but requires coverage from a telecom provider in your area.
- **Low power consumption** (lower than GSM/GPRS).
- Good signal penetration inside buildings and underground.
- Low latency for time-sensitive applications like remote valve closure.

II.5. 4. GSM/GPRS (2G/3G) Communication:

- **Function:** Connects to standard mobile networks to send data over the internet (like an older phone).
- **Characteristics:**
- Wide coverage in most populated areas.
- Relatively high power consumption, reducing battery life.
- Near real-time operation.
- Major drawback: Older networks (2G/3G) are being phased out in many countries.

Figure II.10: Example of a SIM800L cellular communication module.

II.5.5. Satellites Communication:

- **Function:** Direct connection from an earth device to a satellite orbiting the planet (e.g, Starlink or Inmarsat).
- **Characteristics:**
- The only option for very remote areas with no mobile or internet coverage.
- Global coverage (anywhere in the world).
- High cost for both the device and monthly subscription.
- Medium to high power consumption.
- Slightly higher data latency due to the distance.

Figure II.11: Communication technologies.

II.6 Comparison of communication solutions for isolated areas:

When the station is installed in an isolated area, the communication choice must be based on the intended traffic profile. If the device only uploads periodic measurements, alarms, and a few maintenance parameters, a low-data technology is sufficient. Under these conditions, NB-IoT is often preferable because it is designed for low power, good coverage, and massive IoT operation. By contrast, GSM/GPRS remains interesting when hardware simplicity, module availability, or local 2G service make it the most accessible option [22], [23], [24].

The selection can therefore be summarized as follows: GSM/GPRS is practical, familiar, and inexpensive for prototypes, whereas NB-IoT is more modern and better optimized for long-life sensor deployments. The final decision should consider energy budget, subscription cost, network maturity at the site, expected data frequency, and the maintenance strategy of the project. In some contexts, the best engineering choice is not the most advanced technology, but the one that can continue operating reliably over the longest period with the least human intervention [22], [23], [24], [27].

II.7 Cloud platforms and real-time dashboards:

Remote transmission has little value if the data cannot be stored and interpreted properly. For this reason, cloud platforms occupy a central place in smart meteorological stations. A good platform accepts telemetry from the node, stores time-series data, displays the latest values, provides historical charts, manages alarm rules, and exposes the information through dashboards and APIs. Platforms such as Things Board are designed precisely for this purpose and support telemetry ingestion, historical queries, visualization widgets, and rule-based processing [25].

In practical monitoring, dashboards should remain clear and operational. The user does not only need a long list of numbers; he needs organized information. A useful dashboard can show the latest temperature and humidity, daily rainfall accumulation, battery voltage, communication status, and warning flags on a single screen. Historical graphs help detect trends, seasonal behavior, or abnormal events. In addition, storing the data in the cloud makes it possible to compare periods, export datasets, and later apply predictive or statistical methods without modifying the field hardware [25], [28].

II.8 Power-saving strategies in IoT weather stations:

Energy autonomy is a fundamental requirement of remote meteorological monitoring. Even if the station uses a solar panel, the available energy remains limited because charging conditions vary with season, cloud cover, dust deposition, and battery state. Therefore, the station must be designed to consume energy only when the task justifies it. The first principle is duty cycling: the controller and the communication modem should remain inactive most of the time and wake up only for scheduled measurements, local checks, or alarm transmission [16], [27].

The second principle is local intelligence. Not every raw sample has to be transmitted immediately. The node can average several fast measurements, reject clearly abnormal values, and upload only the meaningful result. It can also buffer data when the network is unavailable and send them later in compact batches. This reduces the number of radio activations, which are often the most energy-intensive events in the system. In practice, careful scheduling often yields greater energy savings than simply increasing the solar panel size [16], [22], [23].

The third principle is subsystem optimization. Sensors that require warm-up time or continuous excitation should be selected carefully. Voltage regulators, modem idle current, LED indicators, and poorly designed PCB traces can waste energy continuously even when the station appears to be sleeping. The quality of the hardware architecture therefore matters as much as the firmware. The custom PCB must separate power domains when possible, allow switching of nonessential loads, and protect the controller from unstable supply conditions [16], [27].

Finally, a robust energy strategy should include self-monitoring. The station ought to measure at least battery voltage and, if possible, charging behavior. This diagnostic information helps the user detect abnormal consumption, aging batteries, or insufficient solar harvesting before the system collapses. In a research or dissertation context, this point is important because it proves that autonomy is not assumed theoretically but monitored as part of the system's operational intelligence [16], [27], [28].

II.9 Conclusion:

This chapter presented the technical foundation of the proposed smart meteorological station by examining the IoT architecture, the role of the ESP32 controller, the main meteorological sensors, the cellular communication options, the cloud and mobile supervision layers, and the power-saving strategies required for autonomous outdoor operation. The analysis showed that the effectiveness of the station depends on balanced integration: accurate sensing is not sufficient without suitable communication, and remote transmission is not sustainable without disciplined energy management.

It also became clear that the most appropriate technologies are those that match the field constraints of isolated areas. The controller must be versatile and efficient, the sensors must be technically meaningful and properly exposed, the communication technology must fit local coverage conditions, and the software platform must convert raw telemetry into readable operational information. On this basis, the next chapter can move from technological study to system engineering by presenting the detailed design of the proposed solar-powered meteorological station.

CHAPTER III

Hardware Design of the Unit.

III.1 Introduction:

The hardware design of the smart unit represents the core of the system designed to track climatic conditions. It isn’t merely about assembling a working circuit; instead, it’s a process of picking and fusing together just the right electronic parts based on how well they perform, their efficiency, and low power use – and all the while making sure the setup stays steady and reliable even when the environment gets harsh with high humidity, dust, and uneven power supplies [29].

Hardware drives this part of the system. You get an unscripted look at how the main parts come together—the microcontroller, communication modules, power units, and safety circuits all find a place in the mix. Instead of fixing sensors straight onto the board, we decided— generally speaking—to leave open ports for inputs, welcoming various sensor types whether they're analog or digital. That choice, as it turns out, gives the system room to adapt and grow, fitting the user’s evolving needs [30].

The selection of Each part gets picked based on a mix of tech demands—low power use, solid processing, plenty (of I/O) ports, user-friendly programming, and dependable long-term performance. At the same time, the board’s layout is arranged with care to boost overall performance while keeping things compact and keeping production costs down [31].

In addition, the PCB routing was carefully configured to minimize electromagnetic interference (EMI) as well as preserve signal integrity—for factors which are essential in ensuring system stability as well as accurate data acquisition. Based on these considerations, The hardware design lays a solid foundation for creating a smart and reliable weather station solution [32] [33].

III.2 Component Selection Criteria:

In any electronic system design, the careful selection of components plays a critical role in ensuring functionality, efficiency, reliability, and cost-effectiveness. Choosing the appropriate electronic parts is not solely based on their electrical specifications, but also on a set of design-oriented and practical considerations that impact the overall system performance and production viability [31].

The selection process typically considers several key factors, including:

- Electrical efficiency to minimize power loss, especially in voltage regulation stages.
- Compatibility with required voltage and current levels for both supply and load sides.
- Cost-effectiveness to balance performance and budget constraints.
- Market availability to ensure ease of sourcing and replacement.
- Physical size and packaging suitable for PCB layout and space optimization.
- Stability and noise characteristics to guarantee reliable operation of sensitive components.
- Ease of integration and programmability, especially for microcontroller-based systems.
- Built-in protections and long-term reliability under expected environmental and load conditions.

These criteria form the basis for selecting each component used in the design, from power regulators and microcontrollers to passive filtering elements. The following sections explain how these factors were applied in the context of the implemented circuit.

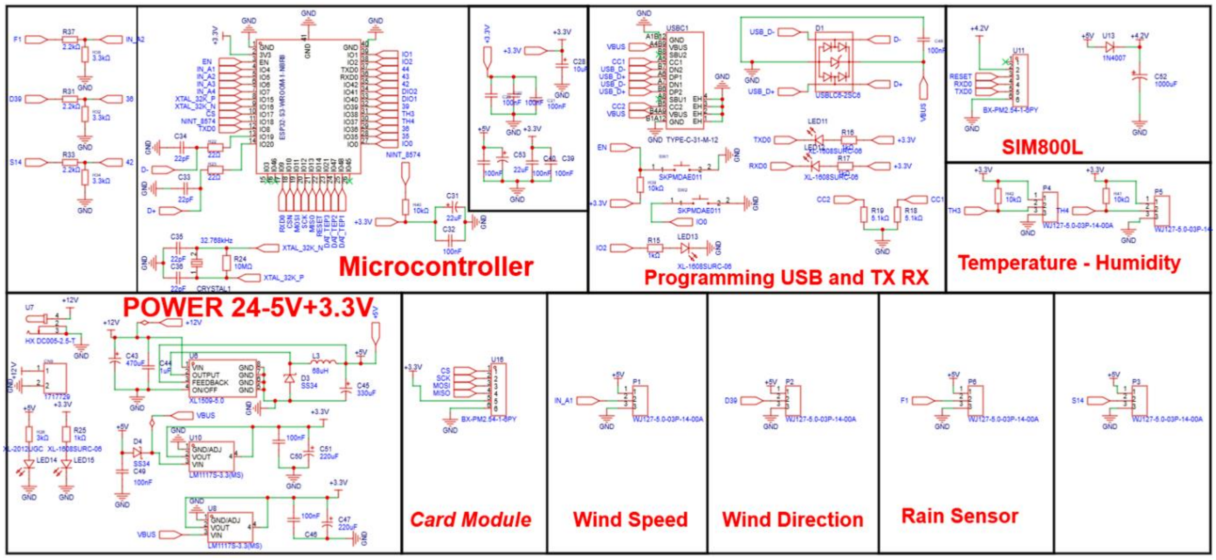

Figure III.1: Schematic Interface in EasyEDA Software.

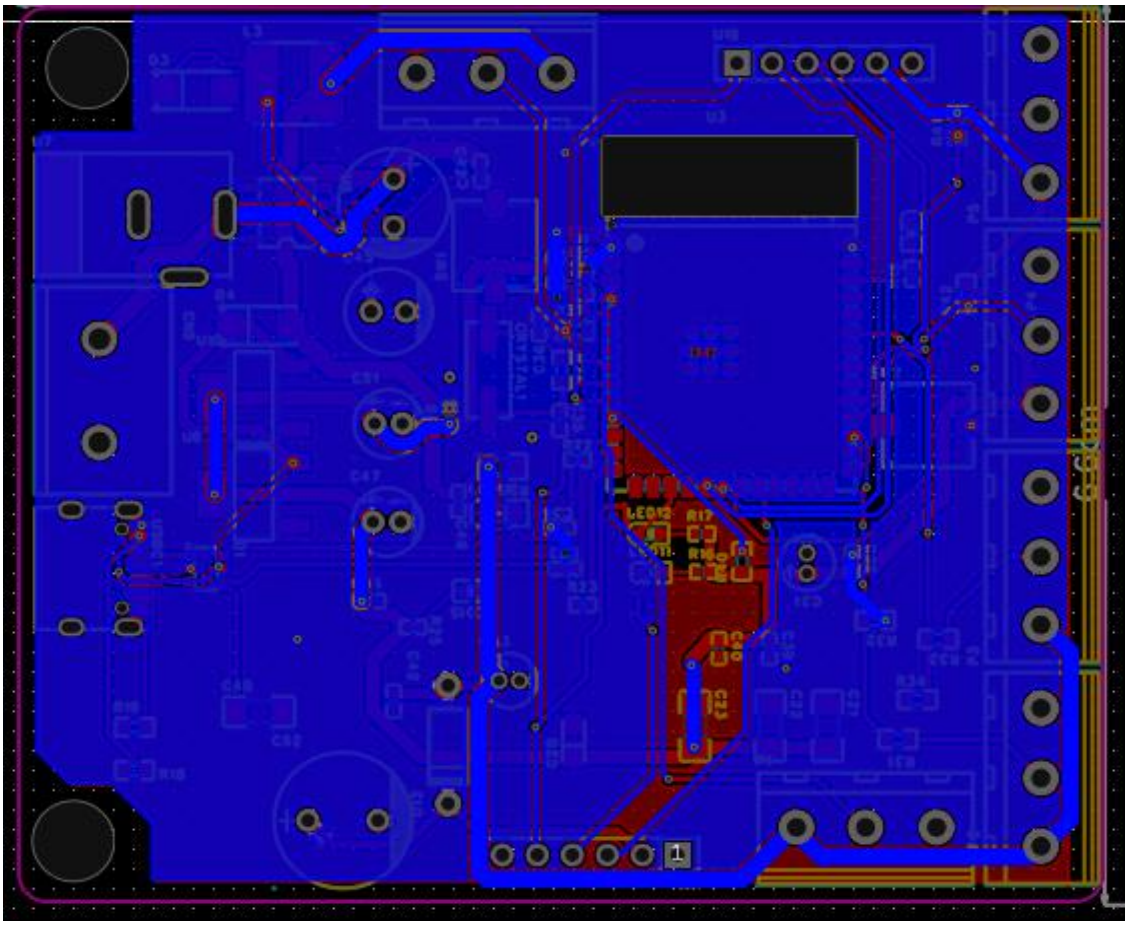

Figure III.2: Bottom Layer View of the PCB Layout in EasyEDA.

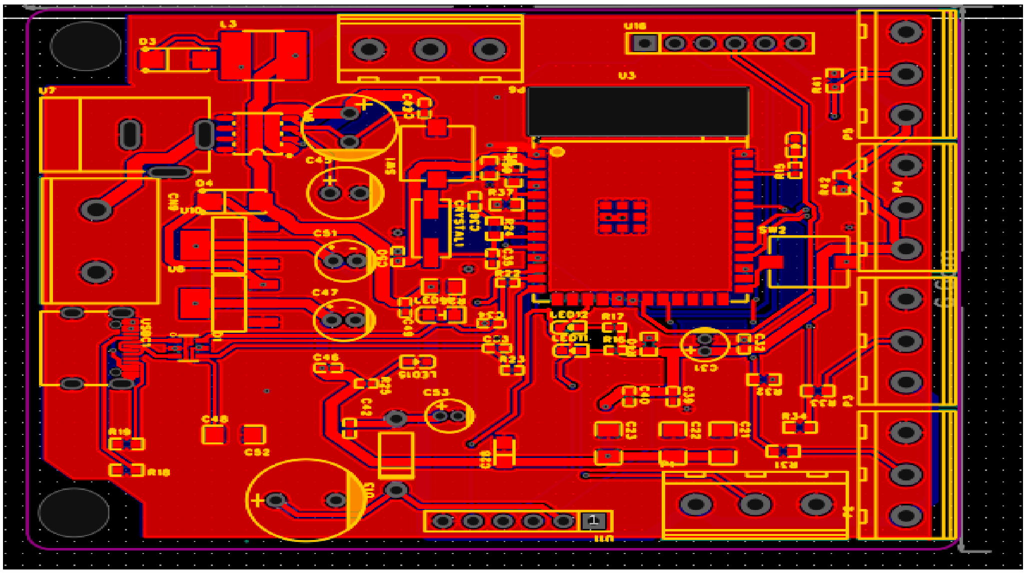

Figure III.3: Top Layer View of the PCB Layout in EasyEDA.

III.3 Circuit Design Explanation:

III.3.1 Power Circuit Design Explanation:

The circuit section functions as a DC-DC buck converter. It relies on the XL1509-5.0 voltage regulator. This converter decreases a 12V source to a stable 5V output. The 5V output is appropriate for providing power to digital or analog subsystems. Operation is in switching mode. The design includes a 68µH inductor, an SS34 Schottky diode along with filtering capacitors. This combination sustains voltage stability plus reduces output ripple. The resulting

Design is small. It has thermal protection and good performance. This makes it appropriate for embedded and systems with limited power [35] [36].

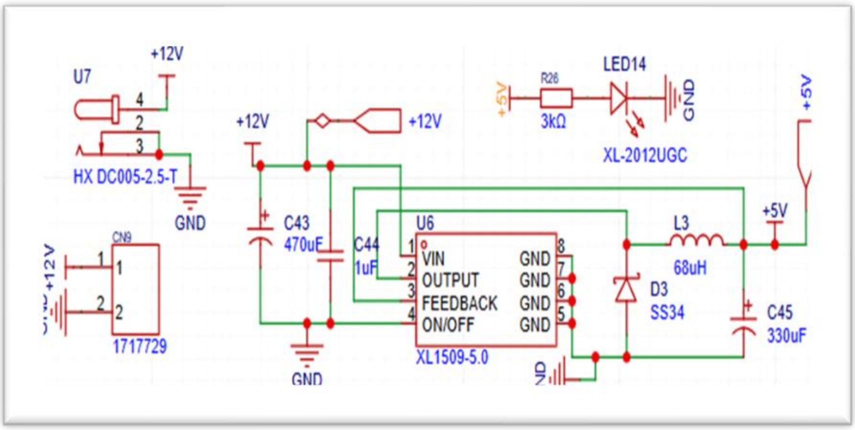

Figure III.4: Schematic of DC-DC buck converter based on the XL1509-5.0.

III.3.1.1 Why XL1509-5.0:

High Efficiency

$$\frac{V_{out} \times I_{out}}{V_{In} \times I_{In}}$$

$$\eta = \frac{V_{out} \times I_{out}}{V_{In} \times I_{In}} \ (1) \qquad \eta = \frac{5 \times 2}{12 \times 0.87} = \approx 0.957 \qquad \eta \text{ x } 100 \approx 96\%$$

Where:

- V_{in} = 12V - V_{out} = 5V - I_{out} = 2A - I_{in} = 0.87A [34].

*** Fixed Output**	*** Thermal Protection**	*** Wide Input**
5V regulated, no adjust needed	Overheat shutdown	4.5V–25V supported
*** High Current**	*** Compact Design**	*** Low Ripple**
Up to 2A load	Fewer external parts	Stable for digital

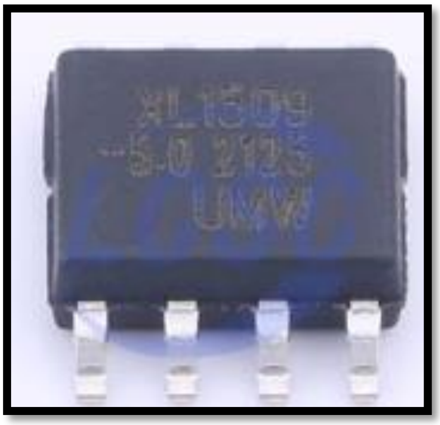

Figure III.5: XL1509-5.0.

III.3.2 Linear Regulation Stage 3.3V:

The circuit section achieves linear voltage regulation through the LM1117-3.3 low dropout regulator (LDO). It takes a 5V input from USB plus changes it to a steady 3.3V output. The 3.3V output works with low-voltage digital components [35] [36] [37].

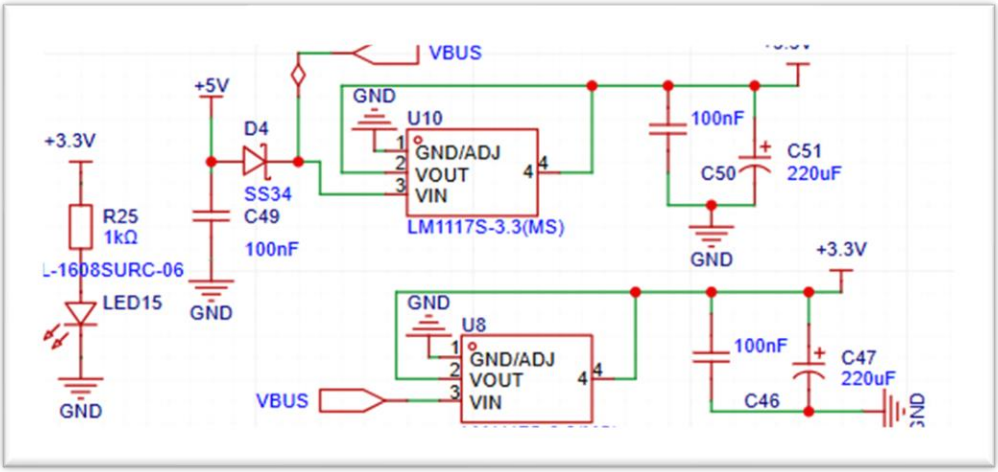

Figure III.6: Circuit and PCB of DC-DC buck converter based on the LM1117-3.3.

III.3.2.1 Why LM1117-3.3:

- **Simple Design:** The design is basic It has a fixed output plus requires few parts.
- **Low Dropout:** It has a low dropout it operates with an input voltage near ≈ 4.5V.
- **Stable Output:** It offers clean power to microcontrollers and sensors.
- **Cost Effective:** The cost is low. It is commonly available besides inexpensive

Efficiency Note:

- $Vin = 5V$ – $Vout = 3.3V$ – $Iout = 0.8A$ - $Iin = 1A$ [37].

$$\eta = \frac{3.3\text{x}0.8}{5\text{x}1} = \approx 0.527 \qquad \eta \text{ x } 100 \approx 53\%$$

(Not ideal for high-current loads, better for simplicity & low noise).

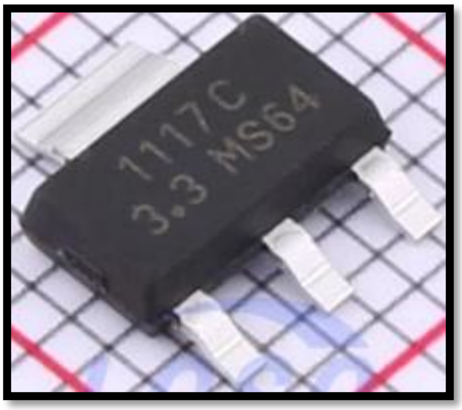

Figure III.7: LM1117-3.3.

III.4 Microcontroller Circuit Design Explanation:

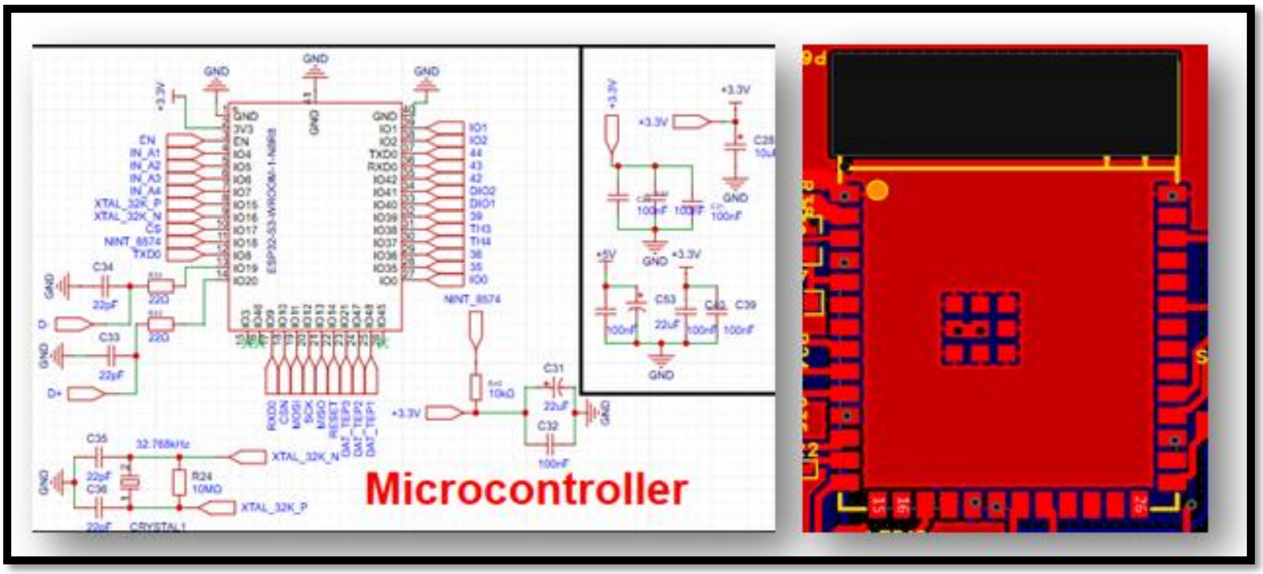

Figure III.8: Circuit and PCB of Microcontroller Unit (ESP32-S3-WROOM-N8R8).

The core processing element of the system is the ESP32-S3-WROOM-N8R8, which is this neat 32-bit microcontroller from Espressif. It features a fast Tensilica Xtensa LX7 CPU with a max operating speed of 240 MHz, and is ideal for use in power-saving applications, with Wi-Fi integrated as standard [38][39].

Key features relevant to this design:

- **Wi-Fi 802.11 b/g/n** – Suitable for IoT communication.
- **8MB PSRAM + 8MB Flash** – Ample memory for complex applications.
- **Rich Peripheral Set** – ADC, SPI, I2C, UART, PWM, USB, OTG.
- **Security Features** – Hardware encryption, secure boot, flash encryption.
- **Ultra-Low Power Modes** – Ideal for battery-powered applications.

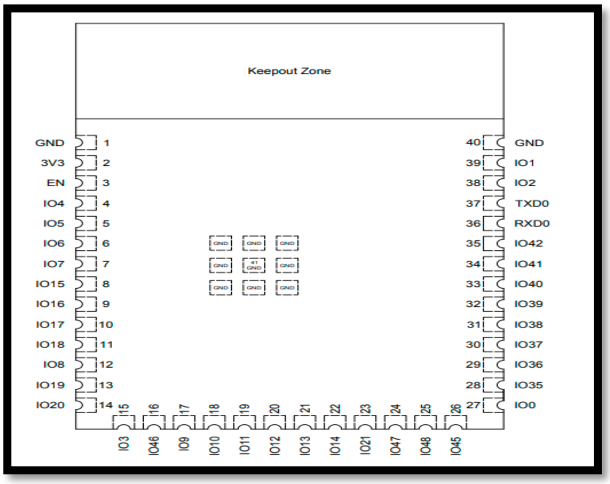

Figure III.9: Unit (ESP32-S3-WROOM-N8R8).

In this design, the ESP32-S3 uses a stable 3.3V power supply which is maintained by the LM1117-3.3 LDO. They also added in bypass capacitors near the power pins to stabilize the voltage and reduce noise, so that the microcontroller is able to function as it should [39].

III.5 USB Interface and ESD Protection:

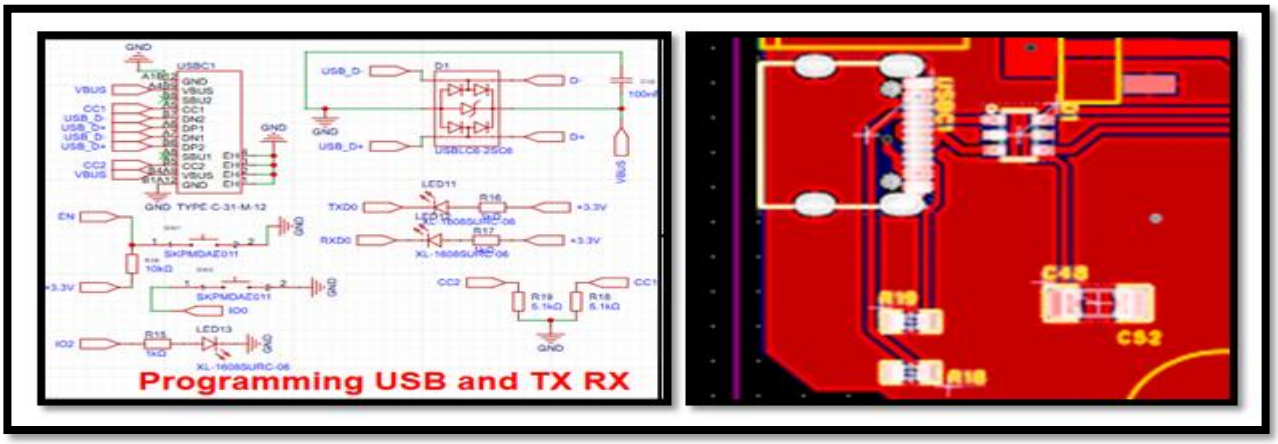

Figure III.10: Schematic and PCB of USB Interface and ESD Protection using (USBLC6-2SC6).

The USB connection in the circuit is designed to interface with the USB OTG functionality integrated in the ESP32-S3. In order to ensure smooth data flow and to protect the microcontroller from voltage spikes or static shock, two important components are added:

☒ **Pull-down Resistors:**

There are two 5.1 kΩ resistors connected to the OC1 and OC2 lines. These resistors must be present for proper enumeration and signaling according to the USB 2.0 standard, particularly relating to full-speed device mode operability [40].

☒ **USBLC6-2SC6 (ESD Protection Diode Array):**

The device being offered is an array of low-capacitance TVS diodes, which is used to protect USB data lines from electrostatic discharge events and voltage spikes. The array works by clamping dangerous voltage transients, along with adhering to IEC 61000-4-2 specifications in regard to ESD immunity [41].

Together, these components improve the robustness and reliability of the USB interface, enabling safe and stable communication between the ESP32-S3 and host devices (e.g., PC or USB power source).

III.6 Digital 3V Input Interface:

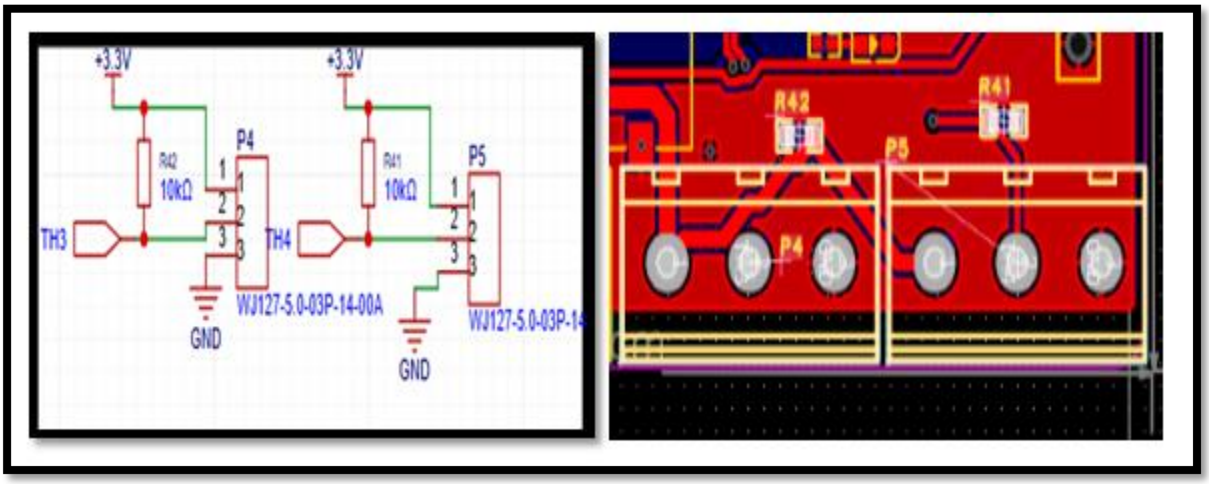

Figure III.11: Schematic and PCB of Digital 3V Input Interface.

As shown in Figure III.11, this stage is used to securely connect 3V digital sources from sensors or external units to the inputs of the signal converter of the ESP32-S3 microcontroller. It is a specially optimized negative resistor arrangement for the purposes of signal initialization and line protection.

☒ **Pull-down Resistor:**

The 10 kΩ resistor ensures that the signal wire never remains randomly "floating", but always has a known state (3.3V) when the sensor is silent, while maintaining low power consumption.

III.7 Digital Input Sensing Subsystem 5V:

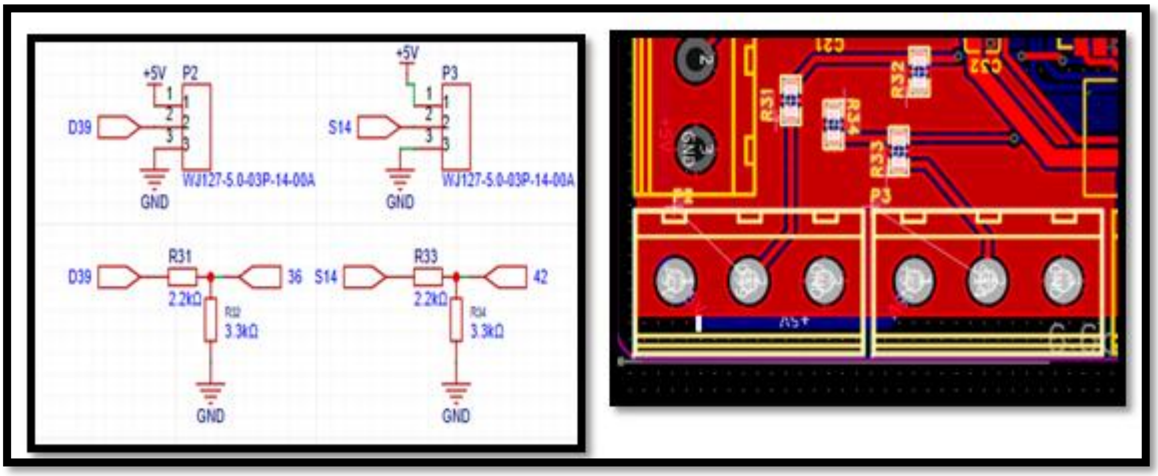

Figure III.12: Schematic and PCB of 5V Digital Input Sensing Subsystem.

As shown in Figure III.12, the ESP32-S3 microcontroller operates at a maximum input voltage of 3.3 V and is generally considered to operate safely at approximately 3.0 V; therefore, it is necessary to reduce the digital signal voltage from 0 to 5 V to an acceptable level. This stage achieves this goal using passive and active resistors.

III.7.1 Voltage Divider Network:

- Two resistors are used to reduce the sensor output from 0-5V to ~0-3.3V:

$R_1 = 2.2k\Omega, R_2 = 3.3k\Omega$

$V_{out} = V_{In} \times (R_2 / (R_1 + R_2)) = 5V \times (3.3k / 5.5k) \approx 0.6 \times 5V = 3V$

This ensures that the input voltage of the digital signal does not exceed the limits allowed under normal conditions.

III.8 Analog Signal Conditioning for 0–5V ADC Input:

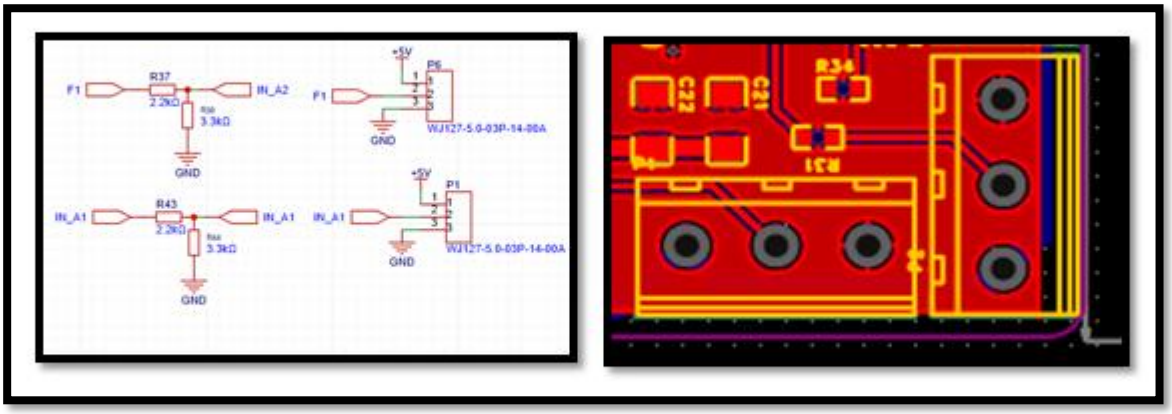

Figure III.13: Schematic and PCB of ADC Input 0– 5V.

Like the figureIII.10 showing since the ESP32-S3 microcontroller operates with a maximum ADC input voltage of 3.3V and is typically considered to be safely operating at around 3.0V for linear ADC functionality; hence, it is necessary to scale down 0–5V analog signals to an acceptable level. This stage accomplishes that goal via the use of passive and active components [42].

III.8. 1Voltage Divider Network:

- Two resistors are used to reduce the sensor output from 0-5V to ~0-3.3V:

R1 = 2.2kΩ, R2 = 3.3kΩ

Vout = Vin × (R2 / (R1 + R2)) = 5V × (3.3k / 5.5k) ≈ 0.6 × 5V = 3V

This ensures ADC input voltage does not exceed limits under normal conditions.

III.9 Card SIM:

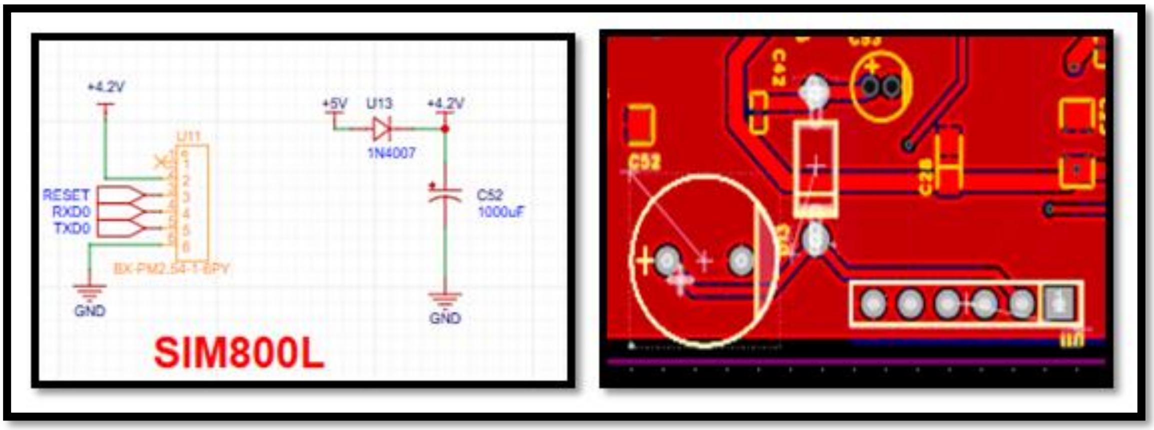

Figure III.14: Schematic and PCB of SIM.

Regarding the connection details, a six-pin connector was used, which includes:

- **RXD and TXD** (for serial communication).
- **RESET** (for controlled restarts).
- **3.9V and GND** (for power input).
- **A 1000 µF** capacitor is added to stabilize the voltage during startup.
- **A S2M diode is used**: for input voltage protection and isolation.

As illustrated in Figure III.14, this system allows the SIM module to be connected, in addition to general-purpose inputs and outputs, via standard female connector heads.

III.10 Card Module:

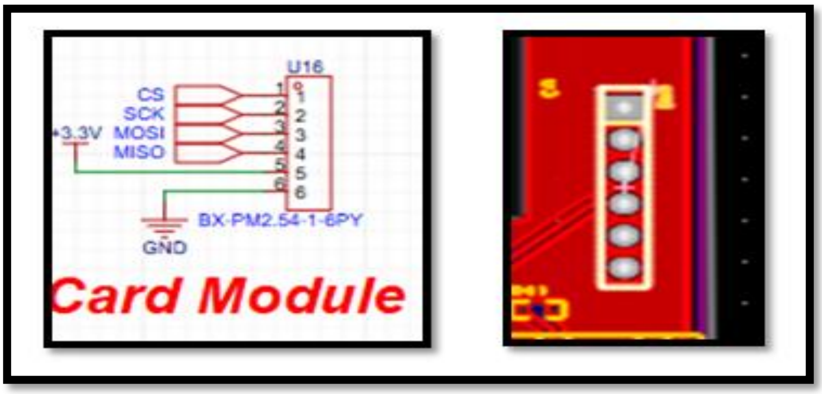

Figure III.15: Schematic and PCB of Card Module.

- Regarding the connection details, a six-pin connector was used, which includes:
  - **RXD and TXD:** (for serial communication).
  - **RESET:** (for controlled restarts).
  - **3.9V and GND:** (for power input).
  - **A 1000µF capacitor is added:** to stabilize the voltage during startup.
  - **An S2M diode is used**: for input voltage protection and isolation.

As illustrated in Figure III.15, this system allows the connection of the Card Module in addition to general-purpose inputs and outputs via standard female connector heads.

III.11 PCB Board Dimensions:

The final PCB layout was carefully designed to optimize component placement, minimize trace lengths, and ensure mechanical compatibility with the target enclosure. As shown in the Figure III.16, the board has a total length of 7.9 Cm and a width of 6.5Cm.

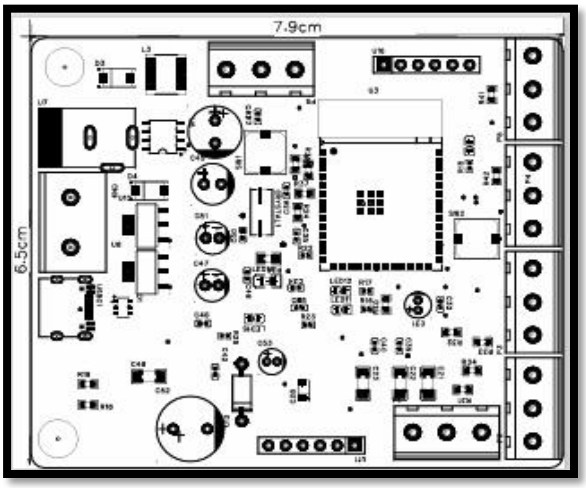

Figure III.16: General PCB Board Dimensions.

III. 12PCB Board After manufacturing:

This Figure shows the printed circuit board (PCB) of the smart system after the manufacturing process is completed. The board has been carefully designed to integrate all the essential electronic components. A high-quality manufacturing process was chosen, using a 2-layer PCB to ensure electrical performance and stability.

Figure III.17: PCB Board After manufacturing

III.13 Conclusion:

This chapter describes the hardware architecture of an intelligent climate monitoring and tracking module. The design features carefully selected components, such as the highly efficient XL1509-5.0 DC-DC low-voltage converter, which efficiently reduces the voltage from 12V to 5V with excellent voltage regulation and thermal protection, and the LM1117-3.3 linear voltage regulator, which ensures a smooth 3.3V supply from the USB port to power the microcontroller and low-voltage sensors. The main processing unit used in this system is the ESP32-S3-WROOM-N8R8 microcontroller, equipped with USB and analog and digital interfaces. Signal conditioning networks are also used to protect the inputs of the analog-to-digital converters, ensuring quality and accuracy. The precision printed circuit board design strategies optimize component placement, minimize interference, and ensure compatibility with the chassis and sensors. Overall, the design achieves a balanced integration of performance and safety, providing a reliable and scalable platform for climate tracking.

This design foundation serves as a direct reference for Chapter 4, which will delve into the practical implementation phase, including microcontroller programming, hardware assembly, cloud platform integration, and finally, testing the station under real-world operating conditions and analyzing the results.

Chapter IV

Implementation, Software Development, and Results

IV.1 Introduction:

After completing the theoretical study, analyzing the electronic components, and designing the printed circuit board in the previous chapters, the practical implementation phase of the proposed smart weather station was initiated.

This chapter focuses on the implementation of the embedded system based on the ESP32-S3 microcontroller, the integration of environmental sensors with Internet of Things (IoT) technologies, and the development of a communication system using the GSM network, with the aim of providing real-time environmental monitoring in agricultural and remote areas.

The chapter also discusses the development of the embedded software, environmental data processing and transmission to the cloud server, as well as the design of the solar power system and energy management using Deep Sleep techniques. Finally, the system performance is practically validated through field testing.

IV.2 Solar Power System Design:

Since the smart weather station operates outdoors and independently, a solar power system was adopted to ensure continuous operation and reduce dependence on external power sources.

- The power supply system consists of:
  - Solar panel.
  - Rechargeable battery.
  - MPPT charge controller.
  - Power management system.

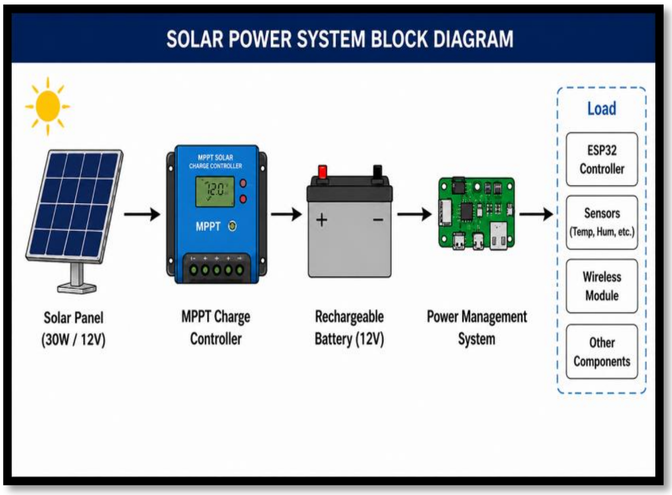

Figure IV.1: Solar Power System Design.

- The system was designed to provide sufficient power for all sensors, the ESP32 unit, and wireless communication modules.

IV.2.1Solar Panel Size Determination:

The solar panel capacity was calculated based on the daily energy consumption and the number of effective sunlight hours.

- The calculations showed that the total system consumption is approximately:
  - 31.19 Wh/day.
- Assuming an average of:
  - 5 effective sunlight hours per day.
- The following was selected:
  - 30W / 12V solar panel.

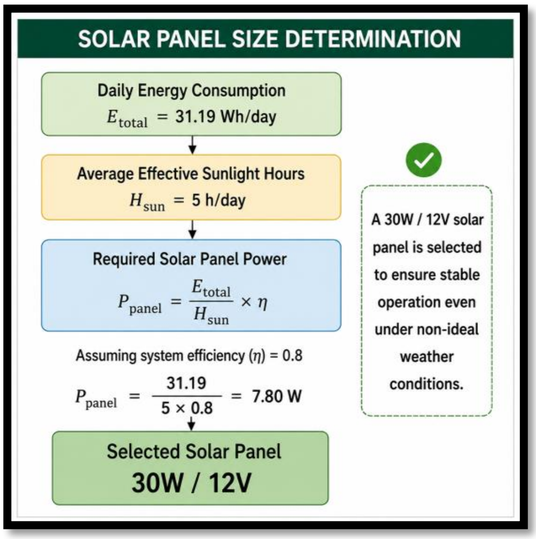

Figure IV.2: Solar Panel Size Determination.

This selection ensures stable operation even under non-ideal weather conditions.

IV.2.2 Battery Size Determination:

To ensure continuous operation during nighttime or cloudy days, the battery capacity was calculated based on the required system autonomy.

- The following assumptions were adopted:
  - **Battery voltage:** 12V
  - **Operating autonomy:** up to 5 days
- Based on the practical calculations, the following battery was selected:
  - 12V – 7Ah battery

This battery provides sufficient energy reserve for reliable system operation.

Figure IV.3: Battery Size Determination.

IV.2.3 MPPT Charge Controller:

An MPPT charge controller (Maximum Power Point Tracking) was used to improve battery charging efficiency and maximize solar energy utilization.

- The charge controller provides:
  - Improved power conversion efficiency.
  - Protection against battery overcharging.
  - Protection against deep discharge.
  - Regulation of charging voltage and current.
  - Increased battery lifespan.

This system contributes to improving weather station stability and reducing power loss, especially under varying solar radiation conditions.

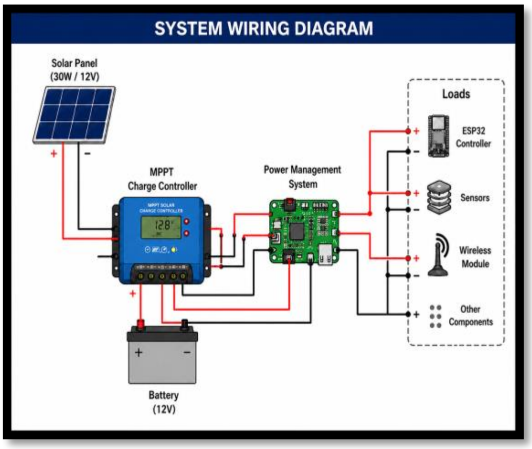

Figure IV.4: MPPT Charge Controller.

IV.3 System Assembly and Prototype Integration:

The prototype of the smart weather station was assembled using the PCB designed in the previous chapter, while integrating the sensors, communication modules, and power units into a complete and integrated system.

Figure IV.5: Prototype of the Smart Weather Station after Final Assembly.

IV.4 ESP32 Firmware Development:

The embedded software was developed using the Arduino IDE platform, where the ESP32 microcontroller operates as the main control unit responsible for managing all system functions.

- The program performs the following tasks:
  - Reading environmental sensor data.
  - Processing and filtering the data.
  - Managing communication through the GSM network.
  - Sending data to the cloud server.
  - Monitoring system and power status.
  - Executing tasks simultaneously.
  - Reducing power consumption.

☒ **Used Software Libraries**:

Used Software Libraries: Specialized software libraries were integrated to facilitate seamless communication between the system components. Their key functions include:

- **Programming Simplification:** Providing easy-to-use APIs to interact with the hardware without the need to code complex communication protocols from scratch.

- **Sensor Support**: Interpreting the electrical signals from the rain sensor and converting them into readable digital data for the microcontroller.
- **GSM Module Management:** Handling the required AT commands to interface with cellular networks, ensuring reliable and prompt delivery of alert messages (SMS) or calls.
- **Reliability and Efficiency:** Minimizing programming errors and accelerating development time by utilizing pre-tested and optimized code.

☒ **GSM Communication Configuration:**

The serial communication with the GSM module was established using designated TX/RX pins and a synchronized baud rate. This configuration serves as the central reporting hub for the entire multi-sensor network, ensuring that:

- **Multi-Sensor Data Transmission**: It acts as the primary gateway to dispatch alerts triggered by any of the integrated sensors (e.g., rain, temperature, humidity, gas, etc.), not just a single sensor.

- **Stable Serial Link:** Dedicated transmit (TX) and receive (RX) lines were configured to ensure a continuous and reliable two-way data stream between the microcontroller and the GSM module.

- **Baud Rate Synchronization:** A specific transmission speed (e.g., 9600 bps) was set to prevent data loss or corruption during the execution of AT commands.

- **Dynamic Alert Formatting:** Enables the system to automatically format and send customized SMS alerts based on the combined logic and specific threshold breaches of the various connected sensors.

☒ **Sensor Initialization:**

The GPIO pins assigned to the sensors were configured as follows:

- **Pin Mapping &Modes**: GPIO 4 (Wind) and GPIO 5 (Rain) were configured as INPUT for analog readings, while GPIO 37 was designated as the data pin for the DHT21 digital sensor.
- **ADC Configuration:** The Analog-to-Digital Converter was set to 12-bit resolution (analogReadResolution)with 11dB attenuation (analogSetAttenuation), enabling a full 0-3.3V measurement range for the analog weather sensors.
- **Initial State Stabilization:** To prevent erratic or false readings at startup, the wind sensor's exponential smoothing variable (windSmoothADC) was seeded with its first raw ADC reading, and the rain sensor's averaging array (rainSamples) was pre-populated with initial values.
- **Digital Sensor Setup:** The DHT21 object was initialized using dht.begin() to establish the digital communication protocol required for reading temperature and humidity.

☒ Sensor Data Acquisition:

- The system periodically reads environmental data from different sensors.

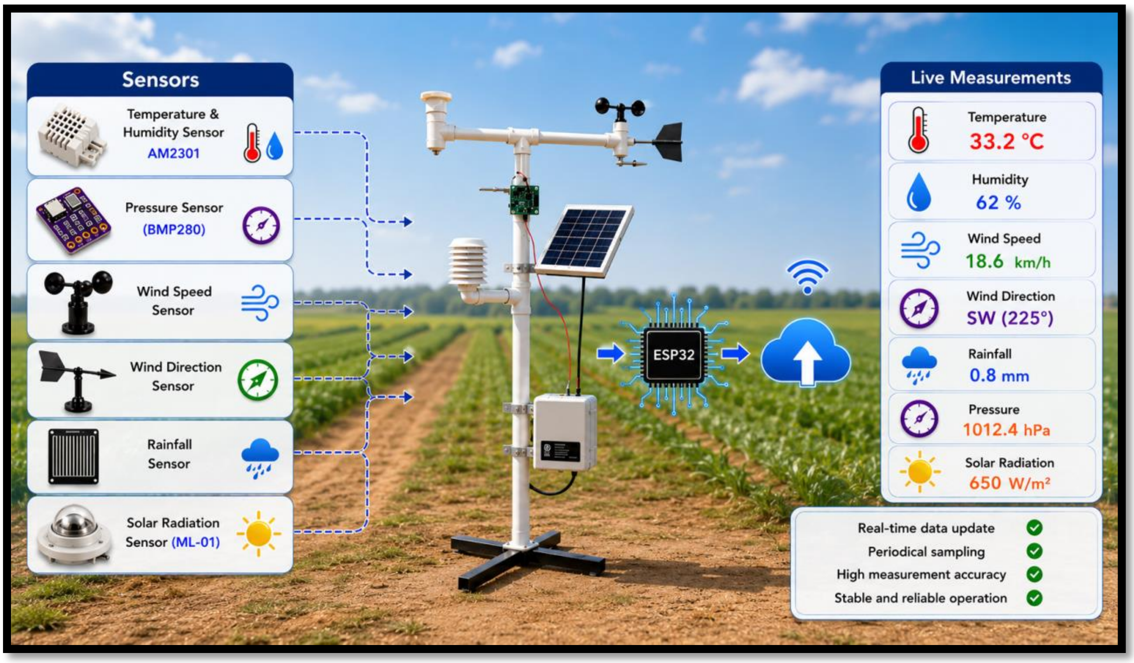

Figure IV.6: Sensor Data Acquisition.

A periodic timing mechanism was adopted to ensure stable sampling and accurate real-time monitoring.

☒ Data Processing and Measurement Filtering:

To improve measurement quality and reduce the effect of electrical noise, several filtering and processing techniques were applied before transmitting the data to the server.

- The processing includes:
  - Moving average filtering.
  - Exponential smoothing.
  - Ignoring invalid readings.
  - Measurement range validation.

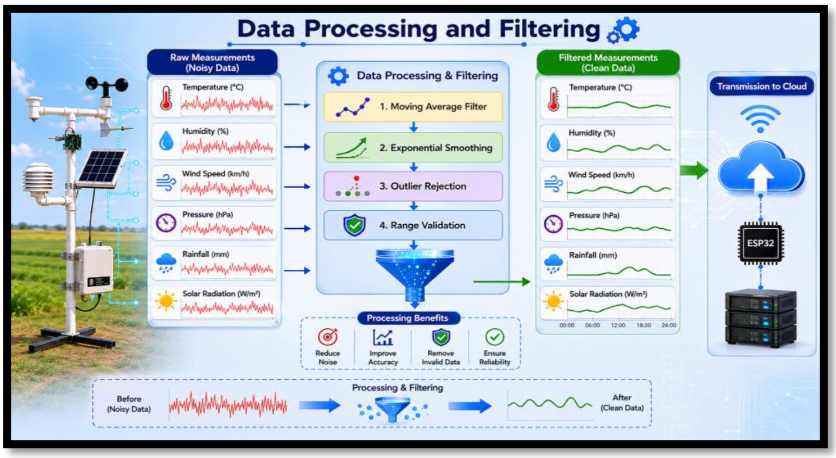

Figure IV.7: Data Processing and Measurement Filtering.

☒ Sending Data to the Cloud Server:

The system sends environmental data to the cloud server through the GSM network using the HTTP POST protocol.

- Data format:

```
String httpRequestData =
"s=" + String(temperature, 1) + "," +
String(humidity, 1) + "," +
String(pressure, 1) + "," +
String(windSpeedKmh, 1) + "," +
String(windDirectionDeg) + "," +
String(rainPercent, 0);
```

Figure IV.8: Sending Data to the Cloud Server.

- Example of transmitted data: s=(T,RH,P,WS,WD,R)

```
s=33.1,60.0,1012.5,22.0,180,12
```

Figure IV.9: Example of transmitted data.

☒ Task Scheduling:

The program relies on the **millis ()** function instead of **delay ()** to ensure non-blocking task execution.

- The timing intervals used are:

```
const long intervalAnalog = 1000;
const long intervalDHT = 2500;
const long intervalPost = 5000;
```

Figure IV.10 : Task Scheduling.

- Where:
  - Analog sensors are updated every second.
  - Temperature and humidity are updated every 2.5 seconds.
  - Data is transmitted to the cloud every 5 seconds.

☒ Monitoring Through the Serial Monitor:

- The Serial Monitor was used during field testing to monitor system performance and display data in real time.

```
╔══════════════════════════════════════════╗
║ Wind : 6.25 m/s | 22.5 km/h              ║
║ W.Dir: 180° (S)                          ║
║ Rain : 12.0 % | Status: Drizzle          ║
║ Temp : 33.1 °C                           ║
║ Humi : 60.0 %                            ║
║ Pres : 1012.5 hPa                        ║
╚══════════════════════════════════════════╝
```

Figure IV.11: Monitoring Through the Serial Monitor.

- This greatly facilitated calibration and error detection during development.

☒ Deep Sleep and Power Optimization:

Since the smart weather station operates using an independent power source, advanced techniques were adopted to reduce power consumption and improve operational efficiency.

Deep Sleep mode was implemented in the ESP32 microcontroller to minimize current consumption during idle periods.

- This approach provides:

  - Reduced power consumption.
  - Extended battery life.
  - Improved long-term operational stability.
  - Reduced load on the solar power system.
  - Support for autonomous operation in remote environments.

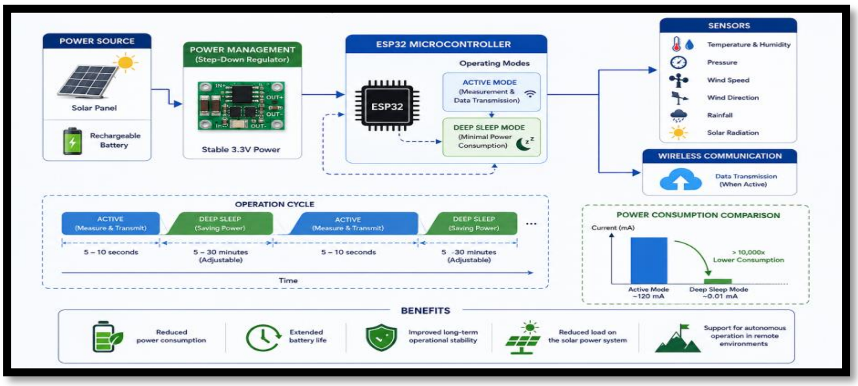

Figure IV.12: Deep Sleep and Power Optimization.

This strategy significantly contributed to achieving low power consumption suitable for long-term operation.

IV5 Cloud Integration and Database:

The weather station communicates with the cloud server through the GSM network.

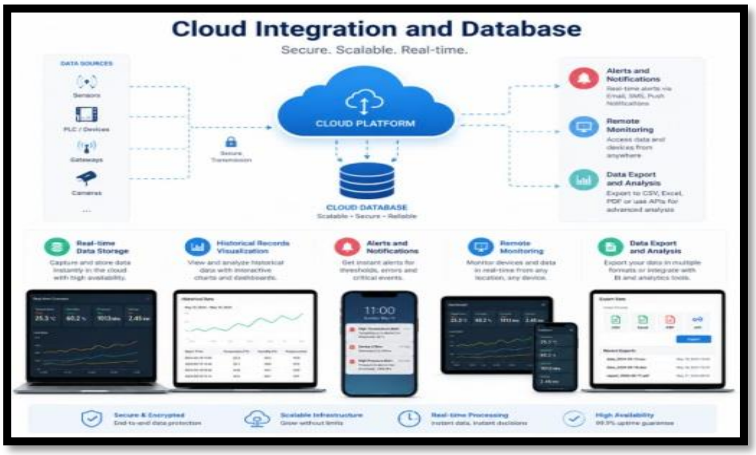

Figure IV.13: Cloud Communication Architecture of the Smart Weather Station.

- The cloud platform provides:

  - Real-time data storage.
  - Historical records visualization.
  - Alerts and notifications.
  - Remote monitoring.
  - Data export and analysis.

A time-series database was used for efficient storage of climatic data.

IV.6 Mobile Application and Dashboard Development:

A monitoring interface was developed to display weather data in real time.

- The dashboard displays:

  - Temperature.
  - Humidity.
  - Atmospheric pressure.
  - Wind speed and direction.
  - Rain intensity.
  - Battery and connection status.

- It also supports:

  - Historical graphs.
  - Automatic updates.
  - Alerts and notifications.

Figure IV.14: Smart Weather Station Application Interface.

IV.7 Communication Protocol and Data Flow:

- The data passes through the following stages:

  - Reading data from the sensors.
  - Processing data inside the ESP32.
  - Transmitting data through GSM.
  - Storing data in the cloud server.
  - Retrieving data inside the application.
  - Displaying the results to the user.

- This architecture provides:
  - Real-time monitoring.
  - Fast response.
  - Reliable communication.
  - Future scalability.

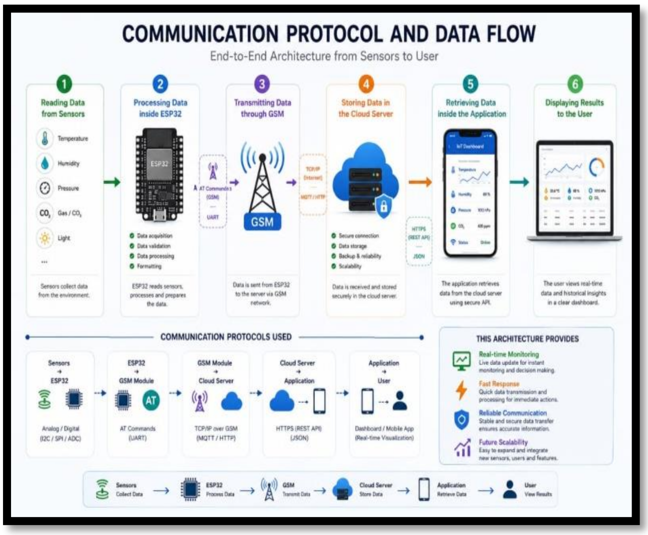

Figure IV.15: Communication Protocol and Data Flow.

IV.8 Calibration and Field Testing:

After completing the design and implementation of the smart weather station, a series of calibration procedures and field tests were conducted at the university level, specifically at El Oued University, to verify measurement accuracy, system stability, and operational efficiency under real-world conditions.

IV.8.1 Temperature and Humidity Validation:

The AM2301 sensor readings were compared against reference laboratory instruments.

- **Experimental Results:**

Parameter	Reference Device	Proposed Station	Error
Temperature	32.8°C	33.1°C	±0.3°C
Humidity	58%	60%	±2%

Table IV.1: Temperature and Humidity Validation.

The results demonstrate acceptable accuracy for agricultural monitoring applications.

IV.8.2 Wind and Rainfall Validation:

Wind speed measurements were validated under different airflow conditions.

- The rainfall sensor successfully detected:
  - Light rain
  - Moderate rain
  - Wet surface conditions

- The system responded correctly to precipitation events with immediate dashboard updates.

IV.8.3 Communication Range Testing:

Communication stability was evaluated under outdoor conditions.

❖ **Results:**

Communication Type	Maximum Stable Distance
Wi-Fi	85–100 m
GSM	Wide-area coverage

Table IV.2: Communication Range Testing.

The system maintained stable operation during continuous transmission tests.

IV.9 Experimental Results and Discussion:

The practical results confirmed the successful implementation of the proposed smart weather station and its effectiveness in environmental and agricultural applications.

IV.9.1 Measurement Accuracy:

The employed sensors achieved good accuracy compared with reference instruments, especially for temperature and atmospheric pressure measurements.

IV.9.2 System Reliability Under Harsh Conditions:

The system demonstrated good operational capability under various operating conditions, including:

- High temperatures.
- High outdoor humidity.
- Dust exposure.
- Variations in solar charging conditions.

IV.9.3 Power Consumption Efficiency:

The use of Deep Sleep mode significantly reduced power consumption.

Operating Mode	Current Consumption
Active Mode	180–240 mA
Sleep Mode	8–15 mA

Table IV.3: Power Consumption Efficiency.

IV.9.4 Real-Time Visualization Performance:

The dashboard demonstrated:

- Smooth data updates.
- Clear and organized visualization.
- Good response speed.
- Stable synchronization with the cloud server.

☒ **Proposed Graphical Visualizations:**

After collecting 24 hours of data from the application, it was displayed as graphs.

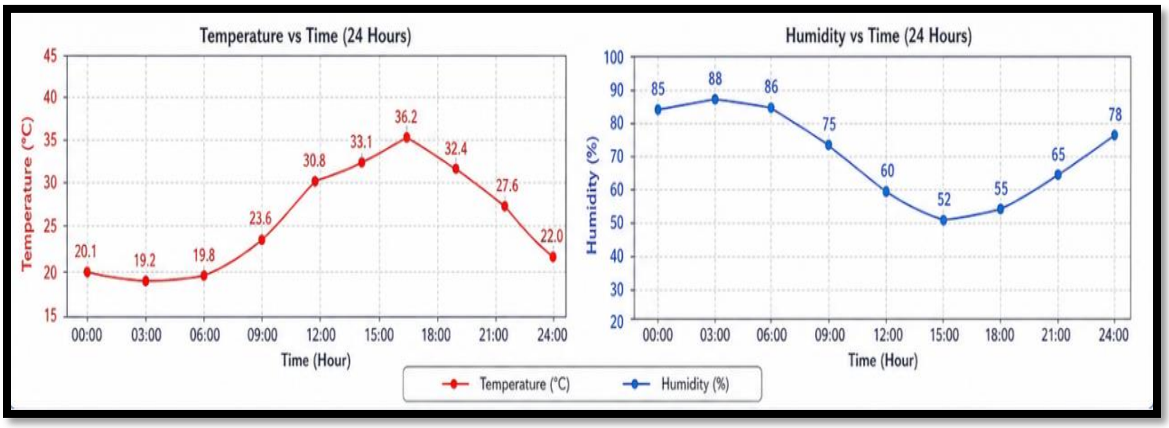

Figure IV.16: Temperature and Humidity Daily Curves.

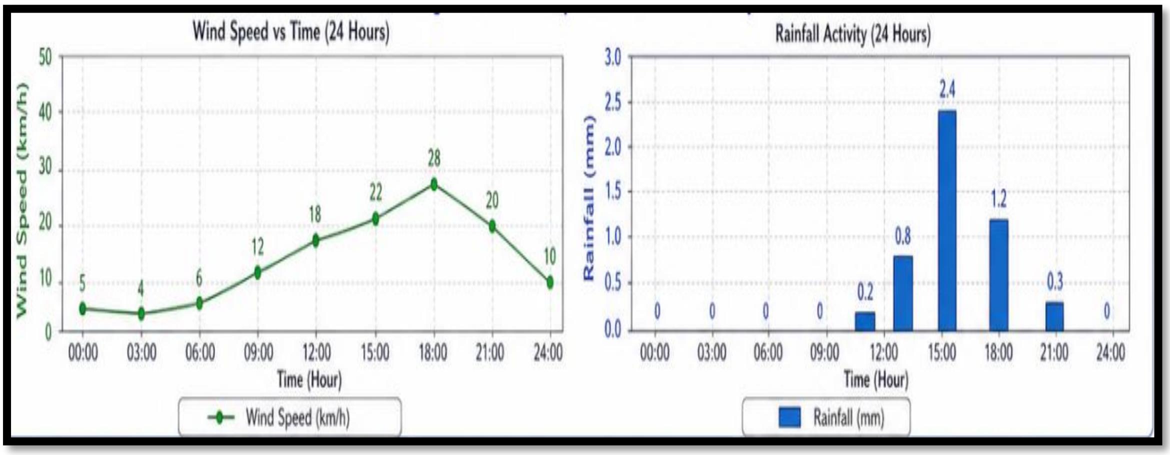

Figure IV.17: Wind Speed and Rainfall Activity.

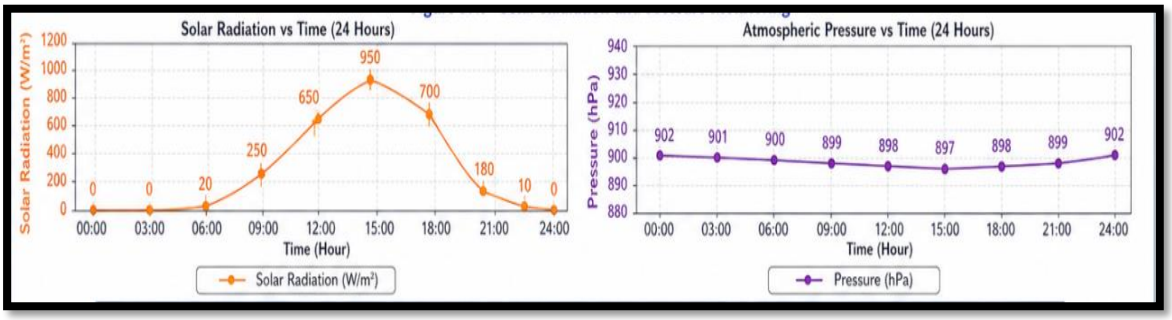

Figure IV.18: Solar Radiation and Pressure Monitoring.

IV.9.5 System Limitations and Future Development:

Despite the success of the system, several technical limitations still exist, including:

- Weak communication coverage in some remote areas.
- The need for periodic sensor recalibration.
- Limited accuracy of the low-cost rain sensor.

The system can be further improved in the future through:

- Adding weather prediction algorithms using artificial intelligence.
- Creating multi-station weather monitoring networks.
- Adopting LoRaWAN technology for long-range communication.
- Developing advanced climatic data analysis tools.

IV.10 Conclusion:

This project aims to design and implement a smart weather station based on the ESP32 microcontroller and Internet of Things (IoT) technologies for real-time and accurate environmental monitoring. A set of sensors was integrated to measure temperature, humidity, atmospheric pressure, wind speed, wind direction, rainfall, and solar radiation, while transmitting the collected data to a cloud server for remote monitoring and visualization.

The work included the development of a software system for periodic data acquisition and processing using filtering and noise reduction techniques to improve measurement accuracy and system stability. A monitoring interface was also designed to allow users to observe environmental measurements in real time.

To ensure autonomous operation in outdoor environments, a solar power system was adopted, consisting of a solar panel, a rechargeable battery, and an MPPT charge controller to provide stable and continuous energy for the station.

Experimental results demonstrated that the system provides good accuracy and high reliability in data acquisition and transmission, with stable performance and low power consumption, making it suitable for agricultural applications, environmental monitoring, and smart monitoring systems.

General Conclusion

General Conclusion

This project has shown that an autonomous IoT-based meteorological station can provide a practical and valuable solution for monitoring climate variables in isolated agricultural areas. The need for such a system is justified by the importance of local meteorological data in irrigation planning, crop protection, environmental supervision and early weather awareness. In remote areas, relying only on distant official stations may not be sufficient, because field conditions can vary significantly over short distances. By placing the station directly in the agricultural environment, the user obtains data that are closer to the real conditions affecting crops and field operations.

The proposed design brings together the main elements required for a smart weather monitoring system: sensors, an ESP32 controller, wireless communication, local processing, cloud storage and a user interface. Each subsystem plays a specific role in the global architecture. The sensors convert environmental phenomena into measurable electrical or digital signals; the ESP32 reads formats and manages the data; the communication module transfers measurements to the cloud; and the dashboard makes the information understandable and useful. This integration demonstrates the importance of combining electronics, renewable energy and software in a single coherent system.

A major contribution of the work is the emphasis on autonomy and suitability for outdoor deployment. The solar panel, battery, charge controller and voltage regulation stage allow the station to operate without a permanent external power source, while the protective enclosure and correct sensor placement improve reliability in harsh conditions. The use of sleep modes and scheduled transmissions reduces energy consumption and increases the time during which the station can continue operating independently. These choices are essential for isolated areas where maintenance visits are difficult and where system failure may lead to missing data during critical agricultural periods.

The collected measurements have direct practical value. Temperature and humidity help evaluate plant stress and evapotranspiration conditions; pressure and wind data support weather interpretation; rainfall measurements help adjust irrigation and estimate water availability; solar radiation data contribute to energy and crop-growth analysis; and air quality monitoring can provide additional information about environmental safety. When these variables are transmitted to a dashboard, they become easier to interpret, archive and compare, allowing more informed decisions over time.

Like any engineering prototype, the system also requires careful calibration, validation and improvement. Sensor accuracy depends on correct installation, protection from radiation and moisture, stable power supply, communication reliability and suitable data processing. Field-testing is therefore necessary to compare station measurements with reference instruments and to evaluate the behavior of the system under real operating conditions. This step is important not only for proving that the prototype works, but also for identifying limitations and for improving future versions.

Future development can extend the station toward a more complete smart-agriculture platform. Soil moisture sensors may be added to connect atmospheric monitoring with soil-water status; AI-based forecasting can be introduced to predict short-term weather risks; several stations can be networked to cover larger agricultural zones; and the dashboard can be expanded with maps, alerts and advanced analytics. These improvements would strengthen the practical impact of the project and make the station more useful for farmers, researchers and local decision makers.

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