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PHOTOSYNTHESIS INSIGHTS FROM MICROCLIMATE MONITORING USING AN IOT-BASED AIR IRRIGATION SYSTEM IN CHILI CULTIVATION

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Abstract

An IoT-enabled air-irrigation system was put in place to keep the humidity levels in the canopy zone of Capsicum annuum (chilli) plants stable and to see how this microenvironment affects how plants act. During the investigation, the system kept track of important climatic and soil factors, such as temperature, relative humidity, CO_2 concentration, incident light, wind velocity, and soil wetness. The control logic only changed the humidity directly, but the intervention also changed a number of other things. It is important to note that the levels of CO_2 and temperature changed in ways that were consistent with greater photosynthesis. When the relative humidity fell below a certain level, the controller started a short air-irrigation cycle to put the microclimate back into a range that was good for the crop. After weeks of taking observations, it was evident that humidity and CO_2 concentration shifted in different directions. For example, during the regulated periods, CO_2 levels at the canopy dropped from approximately 504 ppm to about 469 ppm, while RH levels rose from about 78% to about 89%. Correlation tests confirmed this observation by regularly yielding a robust negative Pearson coefficient (about - 0.88) during high humidity conditions.

This behaviour is consistent with established physiological reactions in crops. As the humidity in the air rises, the vapour pressure deficit falls, which makes stomata stay open for longer. Wider or longer stomatal openings help plants take in more CO_2, which in turn helps photosynthesis continue. The temperature changed only a little throughout these occurrences, yet even these small changes helped keep the microenvironment steady. Among all the factors that were tracked, RH and CO_2 showed the strongest connection to stomatal changes.

In general, the results show that a relatively basic humidity-control method, when combined with real-time IoT sensors, may provide microclimatic conditions that are good for gas exchange and plant comfort. The study emphasises airborne humidity modulation as a viable approach for climate-resilient agricultural management, especially in scenarios with heightened vapour pressure deficit.

Keywords:

IoT-based air-irrigation system; Relative Humidity (RH); Vapour Pressure Deficit (VPD); CO_2 concentration; Stomatal conductance; Microclimate regulation

1. Introduction

To attain maximum yields in agriculture crops, it is crucial to create and sustain a stable microclimate that fosters physiological equilibrium and photosynthetic efficacy. This requirement is especially crucial for crops like chilli peppers (Capsicum spp.), which demonstrate swift physiological reactions to changes in their environment. The moisture content of the air is a crucial environmental element, as it directly affects transpiration, stomatal function, and gas exchange processes inside the plant canopy. Traditional irrigation techniques concentrate on supplying water to the root zone, whereas innovative methods like "air irrigation" seek to adjust the aerial microenvironment around the canopy to sustain ideal relative humidity and alleviate stress caused by vapour pressure deficit.

Recent research indicates that controlling ambient humidity can increase stomatal conductance, enhance photosynthetic efficiency, and promote greater biomass accumulation in horticultural species [1][2].
Air-irrigation systems produce a fine mist or aerosolised water to increase relative humidity under the canopy, thus establishing a microenvironment favourable for photosynthesis and development while enhancing water efficiency [3].

Figure 1: Master and slave node with installed sensor and control unit

The overall system configuration is illustrated in Figure 1. Fluctuations in environmental parameters such as temperature and relative humidity exert a marked influence on plant physiological processes, including transpiration, stomatal regulation, and carbon assimilation in *Capsicum annuum* (chili) plants. Under open-field conditions, these parameters exhibit considerable variability, often causing increases in vapor pressure deficit (VPD) that can disrupt stomatal function, induce physiological stress, and ultimately constrain photosynthetic efficiency and crop performance.In order to retain water, plants block their stomata when the VPD is high. However, in order to protect plants, this mechanism slows down photosynthesis and keeps CO_2 out [4][5].

Assuming no additional stressors are present, stomata often remain open for longer when the humidity is higher and the VPD is lower. This improves photosynthesis by allowing more CO_2 to enter the leaf's interior.VPD is a great way to blend temperature and humidity, so changing the RH is a good approach to get this balance just right. Peppers do well in a VPD window of 0.5 to 1.0 kPa, which is usually associated to relative humidity values of 65 to 85 percent. This lets in enough CO_2 without letting too much water out. If plants leave this area, they might not work as well. Too much humidity can slow down transpiration and nutrient transport, while too little humidity can stress the plants and close the stomata. Recent experimental studies have confirmed these theories; for example, lettuce grown under stable, moderate vapour pressure deficit (VPD) conditions demonstrated increased stomatal conductance and improved photosynthetic efficiency relative to plants subjected to fluctuating high-VPD conditions [6][7]. Other studies have demonstrated that increasing air humidity generally keeps stomatal openings larger and enhances net photosynthesis, but only up to a threshold when concerns regarding disease and nutrient imbalances emerge [8].

These investigations jointly underscore that humidity modulation is not solely an aspect of ambient comfort, but a strategic method for regulating stomatal dynamics and enhancing photosynthetic efficiency.

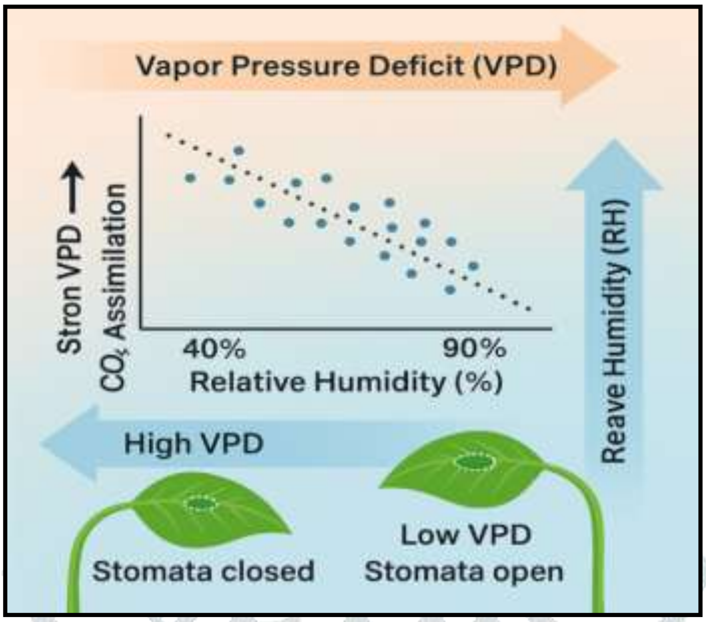

Figure 2: Conceptual diagram of VPD-RH-CO_2-stomatal behavior

In the past, it was mostly only possible to manipulate humidity levels in places like greenhouses and growth chambers. Chilli plants planted in these controlled settings always do better than those grown in open fields, with better gas exchange and faster growth. Previous research indicates that when temperature and relative humidity are kept within ideal ranges, chilli cultivars demonstrate increased stomatal conductance and enhanced CO_2 assimilation relative to plants subjected to variable outside climates [9]. These advantages come from being able to stop low-humidity stress, which usually makes the stomata close up and restricts photosynthesis. Even though these are good things, it is still hard to reproduce greenhouse-like control in open fields. This is mostly because farmers don't have the physical and technological infrastructure needed to manage the environment in this way.

Recent advancements in Internet of Things (IoT) technology are starting to close this gap. With distributed sensors and automatic actuators, smart farming systems make it feasible to keep an eye on microclimatic conditions all the time and change them as needed. Research on chilli farming has demonstrated that real-time environmental monitoring facilitates prompt decision-making and mitigates stress-induced losses [10]. Other experiments show that IoT-enabled air-irrigation systems can keep the humidity levels around crops at the right amount while using less water, which will help plants grow better and produce more [11]. Inspired by these innovations, the current study employs an active humidity-regulation strategy via a sensor–actuator network situated around chilli plants in the field.

The primary objective of this study is to examine the effects of regulated increases in relative humidity on the CO_2 dynamics within the crop's immediate microenvironment, and to investigate the correlation between these changes and the plant's physiological responses. We use continuous data streams from the installed IoT system to see how the rise in RH caused by air irrigation changes the patterns of CO_2 concentration near the canopy. In theory, a wider stomatal opening in high-humidity conditions should lead to more CO_2 uptake. This could show up as a drop in ambient CO_2 or as swings that are linked to humidity. On the other hand, if the humidity is below the ideal values, photosynthesis may be limited, which could show up as stable or rising CO_2 levels since less CO_2 is being absorbed. We want to separate these behaviours and measure how much humidity alone can affect plant gas-exchange mechanisms through a series of rigorous trials. This investigation aims to empirically validate that targeted humidity control, facilitated by IoT technology, can function as an effective mechanism for enhancing crop performance. The findings from this study elucidate the interplay between relative humidity and carbon dioxide in chilli microclimates and enhance the overarching design principles for forthcoming smart agriculture climate management systems.

Despite significant advancements in automated irrigation and precision agriculture, the majority of existing research has predominantly focused on soil-based irrigation management. They have not examined how altering air humidity can assist plants in maintaining stability within their microenvironment. Limited study exists about the interaction of vapour pressure deficit (VPD), relative humidity, and CO_2 assimilation in open-field chilli cultivation. Moreover, there is an absence of IoT-based frameworks that integrate real-time monitoring and automated control for managing humidity at the canopy level. This research tackles the existing gap by developing and accessing an IoT-based air irrigation system that directly modulates aerial humidity, quantifies its physiological impacts, and verifies its correlation with photosynthetic activity and CO_2 concentrations in Capsicum spp. under real-world conditions.

2. Materials and Methods

This section discusses the design, configuration, and operating technique of the IoT-based air-irrigation system implemented in open-field chilli farming. The experimental configuration aimed to assess the impact of regulated fluctuations in relative humidity on microclimate dynamics and CO_2 assimilation adjacent to the plant canopy. This section elaborates on the hardware components, control logic, data gathering architecture, and analytical methods utilised for quantitative evaluation.

2.1 Components and System Architecture

For the study, an air irrigation system was set up in an open field where chilli plants were planted. There were two IoT nodes in the setup: a Master node and a Slave node. Both were built to watch the area around them and regulate the humidity levels around the plant canopy at a good level. Each unit has its own humidifier actuator and was built on a low-power microcontroller platform. The two nodes could sense their environment and turn on their misting units independently when the relative humidity fell below a set level.
The Master node was in charge of the whole process. It contained an SD card module for storing data on-site and Wi-Fi for connecting to the cloud. The Master and Slave nodes were connected via a LoRa link, which was good for open-field circumstances since it allowed for long-range, low-energy communication. The Master node collected its own data and that of the Slave node every three to four minutes, sent the values to a cloud server, and saved them on the SD card at the same time for backup.
Both nodes monitored the following environmental factors:

● Temperature, ● Relative humidity, ● Carbon dioxide (CO2), ● Intensity of light, ● Moistness of soil

The Master node also has sensors for wind speed and rain. Even though they weren't used to control humidity, these numbers were noted to give a better picture of the environment. To provide an accurate picture of the microclimate around the leaves, the Slave node was placed inside the crop canopy and the Master node was placed just outside of it.

Each node controlled its own misting machine based on the humidity in the area. When the relative humidity dropped below the optimum level, which is usually around 80%, the node turned on its humidifier to make a fine mist. This raised the humidity levels near the detecting area without wetting the leaves directly. The targeted response strategy kept the microclimate fairly stable all day, which was good for both the canopy and the ambient zones.

Figure 3: Node installation in the open field

The system was made to be able to grow. Future installations can add slave nodes to cover more land for growing. The new nodes would link to the Master node using LoRa using the same way for measuring temperature and humidity. This modular design helps the gadget keep microclimates for specific plants in bigger open-field plots in a way that works well.

Modern smart agriculture combines closed-loop environmental control and real-time sensor feedback to make changes right away [12] [13]. Modular and distributed IoT technologies provide scalable microclimate management across diverse field conditions [14].

2.2 Humidity Control Logic

The air irrigation system-maintained humidity within the desired comfort range for chili plants through a threshold-based closed-loop strategy. Relative humidity was the only factor that influenced control decisions, while other parameters such as CO2 concentration, temperature, and light intensity were simply recorded for later analysis. Both the Master and Slave nodes executed the same logic independently, which allowed each device to operate its humidifier according to the conditions measured in its immediate surroundings.

The humidifier stayed active only until the local humidity rose above the target range for the crop. This avoided the inefficiency of fixed-interval timing and instead created a dynamic response based on real-time measurements. To prevent the actuator from switching repeatedly between on and off states, a small deadband was included in the control logic. This hysteresis window ensured smoother functioning and helped extend the lifespan of the humidification unit.

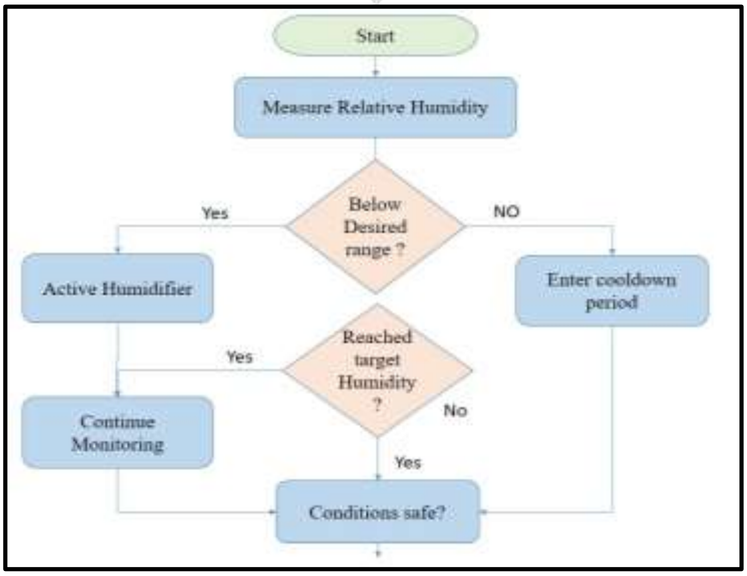

Figure 4: Humidity logic flowchart

This method of control kept the relative humidity at a level that was good for stomatal conductance and made sure that the vapour pressure deficit (VPD) was balanced. Both conditions are essential for the efficient entry of CO2 through the stomata [15]. When the vapour pressure deficit (VPD) goes down, the plant has less evaporative stress and may keep its stomata open for longer periods of time.

To avoid inadvertent stress, the control logic included a number of safety factors.

• Humidification was automatically turned off when the humidity in the air reached a certain level. This reduced the chance of the leaves being too wet, which could make them more likely to get sick.

• The system prevented humidification when the temperature dropped below a set threshold to avoid cold-related stress on the plants.

• Soil moisture constraints can be added in future versions so that root-zone irrigation is prioritized when the soil becomes excessively dry.

Through this local feedback method, each node could maintain a stable microclimate even during hot or dry weather when humidity tends to fall sharply.

Table 1: Example misting logic behavior under different microclimate conditions

Condition	System Response
RH drops below the desired threshold	Humidifier ON (until target humidity is reached)
RH returns to comfort range	Humidifier OFF (enters cooldown)
RH stays within acceptable range	No humidification triggered
Temperature drops below critical level	Humidification blocked (safety override)
RH high and CO_2 stable	No action needed — conditions favorable

The field observations showed this pattern over and over again. The relative humidity often dropped below the ideal level about noon, which started the humidification cycle. When the humidity in the air was restored, the amount of CO2 near the canopy kept going down. People thought that this drop meant that the stomata were opening more and the plants were taking in more CO2 [16].

The adaptive control system followed the rules for climate-responsive irrigation that are widely established. Instead of running the misting system all the time or waiting for the user to turn it on, the system made microclimate changes at exactly the right times based on feedback from sensors. This helped the plants use water in the best way possible and made their bodies respond better [17][18].

2.3 Steps for Collecting and Analysing Data

The IoT-based system ran for almost three and a half months without stopping to see how regulated aerial humidification affected the microenvironment of chilli plants. The Master and Slave nodes both gathered high-resolution data on temperature, relative humidity, CO2 concentration, light intensity, and soil wetness throughout this time. The Master node also kept track of the speed of the wind and the amount of rain. Every node saved data to its SD card and sent measurements to a cloud platform every three to four minutes. The time of each entry, the full set of sensor readings, and the name of the node that collected the data were all included.

The schematic flow diagram (figure 5) below represents the overall methodology integrating IoT architecture and control logic. It combines sensor data acquisition, communication between master and slave nodes, and automated actuation based on humidity and VPD thresholds.

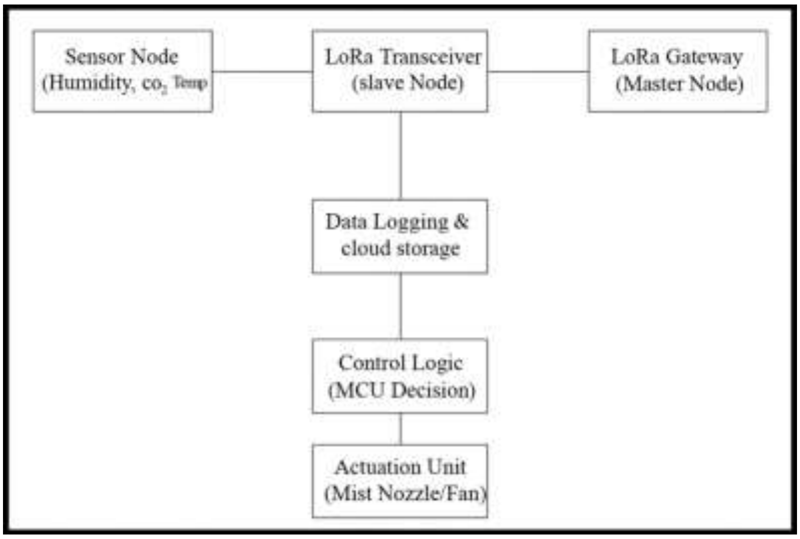

Figure 5: Schematic flow of the proposed IoT-based Air-irrigation system

2.3.1 Cleaning and preparing the data

The raw data showed random problems that were caused by sensor drift, power changes, or temporary communication failures. The preprocessing phase had a number of steps: To filter outliers, CO2 values that were higher than 2000 ppm or lower than 50 ppm were removed. A limited quantity of anomalous data resulting from transient sensor malfunctions, such as measurements approaching 43000 ppm, were excluded.

• Time alignment: The timestamps from the Master node (recorded in UTC) and the Slave node (recorded in IST) were converted to a single reference time, which was IST (UTC+5:30).

• Resampling and smoothing: To make the data easier to see, the relative humidity readings were rounded to the nearest 0.1 percent and the CO2 readings were rounded to the nearest 1 ppm. Linear interpolation fixed small gaps that happened when data was lost temporarily.

2.3.2 Event Identification and Segment Partitioning

To study how plants react to humidification, individual misting events were identified. An event was defined as a period during which the humidifier was operational and the local humidity experienced a substantial elevation above its baseline level.

Time-series graphs were employed to categorise each event into two intervals:

• Pre-event: The 10 to 15 minutes prior to misting, indicating low humidity levels.

• During the event: The prolonged duration of elevated humidity following the initiation of misting. The subsequent metrics were calculated for both intervals:

• Mean relative humidity and carbon dioxide concentrations

• Variation in Relative Humidity (RH) and Carbon Dioxide (CO2) • Pearson correlation coefficient (r) between RH and CO2

These computations enabled us to determine the inverse correlation between humidity and CO2 concentration during active air humidification cycles.

Table 2: Summary of RH and CO_2 Changes during Sample Air Irrigation Event

Date	Phase	RH (%)	CO_2 (ppm)	Δ RH	Δ CO_2	r (RH–CO_2)
22 Aug 2025	Before	78.4	503.8	–	–	–
	During	88.9	469.3	+10.5	−34.5	–0.88
05 Sep 2025	Before	75.2	514.1	–	–	–
	During	86.1	478.9	+10.9	−35.2	–0.85

2.3.3 Analytical Techniques

A combination of visual and statistical methods was utilised to interpret the sensor data obtained during the investigation. The primary techniques included:

• Dual-axis time-series plots: Relative humidity and CO2 concentration were displayed jointly on synchronized graphs. These overlays clearly highlighted the opposing behavior of the two variables during misting periods and helped link the timing of air irrigation to ensuing microclimate changes.

• Scatter plots: CO2 measurements were plotted against relative humidity for each incident, and simple regression lines were fitted. These visualizations corroborated the presence of a negative link between the two variables during humidification.

• Correlation analysis: Pearson correlation coefficients (r) were determined for every recorded event to evaluate the strength of the RH and CO2 relationship. Strong negative correlations, mainly between r = minus 0.85 and r = minus 0.89, were seen throughout the dataset.

• Comparative tables: Summary tables were generated to display the before and after results for each occurrence, highlighting the size of the humidity rise and the accompanying fall in CO2 concentration.
• Literature comparison: The observed alterations, such as CO2 reductions of around 30 to 40 ppm and relative humidity increases of about 10 percent, were analysed alongside findings given in plant physiology literature to validate that the responses matched expected stomatal behavior.

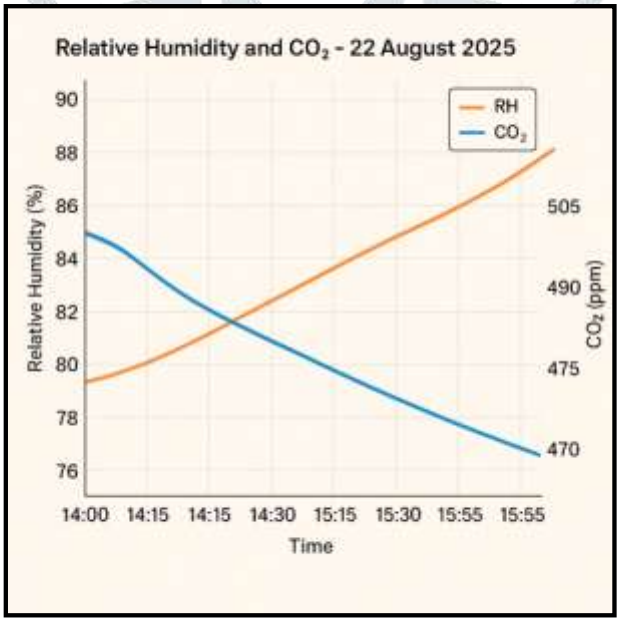

Figure 6: Time-series overlay showing RH increase and corresponding CO_2 decrease during air irrigation

3. Results and Discussion

The implementation of the air irrigation system in actual field settings enabled us to meticulously monitor the evolution of the microclimate surrounding the chilli plants and its correlation with plant physiology. The ongoing measurements obtained from the Master and Slave nodes recorded the variations in humidity, CO2 levels, and temperature prior to, during, and subsequent to each misting cycle. The subsequent subsections elucidate these observations comprehensively and contextualise them within the overarching framework of plant environmental reactions, emphasising stomatal function, photosynthesis, and ramifications for crop management.

3.1 Alterations in Microclimate during Air Irrigation Events

Field measurements indicated a distinct and consistent pattern upon activation of the humidification system. An important event transpired on 22 August 2025 in the late afternoon. Upon the initiation of misting, the relative humidity next to the canopy rose consistently, whereas the CO2 concentration in that area diminished. The identical phenomena manifested in many occasions, indicating that the trend was a biological reaction rather than random fluctuation.

Figure 6 depicts an exemplary occurrence. Relative humidity increased from roughly 78.2 percent to almost 89.0 percent within a span of about 20 to 25 minutes. During this increase, the CO2 content decreased from approximately 504 ppm to around 469 ppm. A robust negative Pearson correlation of about -0.88 corroborated this inverse association, suggesting that increased humidity promoted stomatal openness and enhanced CO2 absorption for photosynthesis [19].

A basic simplified summary of the changes shows below:

Table3: Canopy microclimate before and during air humidification on 22 August 2025

Condition	RH near canopy (%)	CO2 near canopy (ppm)
Before air humidification	~78.2	~504
During humidification	~89.0	~469

These measurements align with established plant physiology findings. As relative humidity increases, vapor pressure deficit decreases, allowing stomata to remain open. This supports CO2 diffusion into the leaf and strengthens the photosynthetic process [20]. When humidity is low, plants conserve water by partially closing their stomata, which limits gas exchange and results in higher CO2 concentrations near the foliage. Because our sensors were positioned close to the leaves, they captured this drawdown effect clearly, making CO2 reduction a practical indicator of stomatal response.

Overall, the observed shift in microclimate demonstrates the potential of targeted humidity control to encourage beneficial gas exchange in open-field crops through a non-invasive approach [21].

3.2 Stomatal Function and Photosynthetic Implications

The consistent negative relationship between relative humidity and CO2 concentration in the recorded data provides important insight into stomatal behavior. Stomata, which are microscopic openings on the leaf surface, regulate both gas exchange and water vapor release. The opening and closing of stomata are influenced by the turgor pressure of guard cells, which respond to environmental factors such as humidity and vapour pressure deficit (VPD). Increased humidity reduces VPD, enabling guard cells to swell and maintain wider stomatal openings, thereby enhancing CO2 availability for photosynthesis. Conversely, dry air elevates VPD, leading to a decrease in guard cell pressure and subsequent stomatal closure, which restricts CO2 entry. This mechanism is evident.

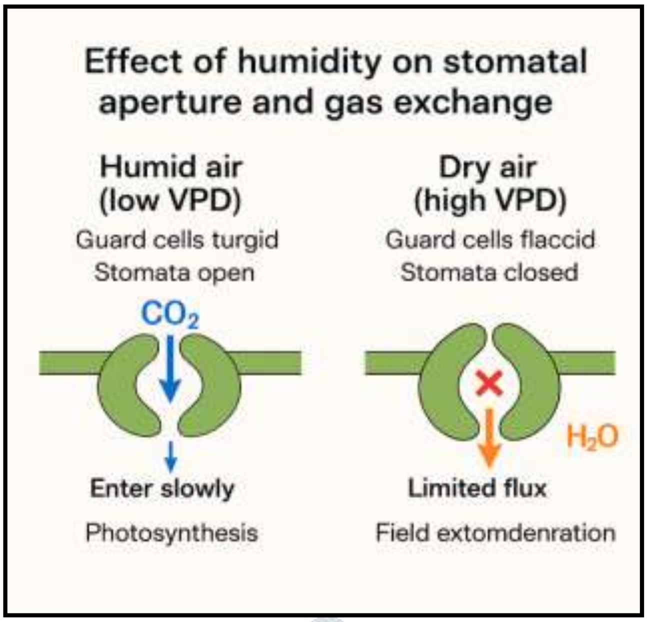

Figure 7: Conceptual diagram showing the effect of RH/VPD on stomatal aperture and CO_2 diffusion

The field observations are in good agreement with accepted theories of plant physiology. As long as the plant receives enough light and CO2 for photosynthesis, a number of studies show that stomatal conductance increases with increased relative humidity [22][23]. In our deployment, the largest decreases in CO2 levels occurred during mid-day and afternoon humidification episodes, when photosynthetically active sunlight was at its peak. Early in the morning, when the light is less bright and the need for CO2 is naturally lower, there were a few drops. This pattern demonstrates that while humidity has a significant impact on stomata opening, other factors that interact, such as available light and atmospheric CO2, also affect photosynthetic efficiency.

The system primarily addressed a significant environmental issue. By lowering the vapour pressure deficit, the technique preserved the conditions that were optimal for stomatal opening. On the other hand, research on CO2 fertilisation shows that excessive CO2 levels can sometimes hinder stomatal conductance if they are not accompanied by sufficient humidity [24]. In order to determine whether air irrigation and carefully managed CO2 enrichment work together to enhance absorption without triggering stomatal closure from oversaturation, future controlled-environment studies may investigate this combination.

Together, the physiological model and our real-time sensor data demonstrate that maintaining the proper humidity level in the canopy zone facilitates continuous gas exchange in the crop. On a field scale, air irrigation successfully increased the amount of time that plants could engage in active photosynthesis each day.

3.3 Temperature and Vapor Pressure Deficit Considerations

Although humidity control was the main driver of improved gas exchange, the air irrigation system also produced modest temperature buffering through evaporative cooling. In one documented misting event, the local canopy temperature decreased from 25.9 degrees Celsius to roughly 25.2 degrees Celsius. This change of about 0.7 degrees Celsius, while not large, is consistent with the physics of evaporation. As fine water droplets turn into vapour, they absorb heat from the surrounding air, which can assist control leaf temperature and lessen physiological stress caused by heat [25].

However, the lowering of the vapour pressure deficit was the most significant consequence of misting. VPD is a crucial modulator of stomatal behaviour and characterises the atmospheric demand for water. Midday VPD values under the chilli canopy usually ranged between 1.2 and 1.5 kilopascals prior to misting. Many crop species experience partial or whole stomatal closure as a result of these levels [26]. When misting began, the relative humidity rose sharply and VPD declined to a range between 0.5 and 0.6 kilopascals. This shift created a microclimate that favored stomatal opening and facilitated greater gas exchange [27].

Keeping VPD within this moderate range is widely recognized as supportive of both photosynthesis and nutrient movement within the plant [28]. At the same time, excessively high humidity can restrict transpiration or promote disease. To avoid such issues, the system included time-based deadbands and safety conditions that prevented prolonged misting. Evening and night conditions naturally allowed humidity to rise, causing VPD to increase again, which helped maintain a healthy daily rhythm of physiological processes.

Overall, the results emphasize that VPD is more critical to stomatal regulation than temperature alone. Because the system responded to humidity in real time, it could intervene precisely when plants were under the most stress. This produced not only physiological comfort for the plants but also efficient use of the limited water required for misting, ultimately improving gas exchange during key daylight periods [29].

3.4 Natural and Air-Irrigated Conditions: A Comparative View

The chilli plants frequently showed signs of physiological stress when exposed to natural daylight conditions without misting. In contrast, leaf temperatures rose and sometimes exceeded ambient air temperatures because of low transpiration, while relative humidity often dropped to 60–70 percent, while leaf temperatures increased and occasionally surpassed ambient air temperatures due to limited transpiration. Observable stress markers, including slight wilting and premature stomatal closure, consistently manifested by early afternoon. Throughout these intervals, CO2 concentrations near the canopy remained at or marginally above ambient values, generally ranging from 420 to 450 parts per million. The deficiency in CO2 reduction indicated restricted assimilation activity. These data align with the established pattern of midday stomatal closure induced by increased VPD, despite the availability of enough sunshine for the plants [30].

During misting, the microclimate transitioned to circumstances akin to those of a regulated greenhouse. Relative humidity consistently ranged from 80 to 90 percent. The air temperature near the canopy either corresponded with or significantly fell below ambient levels, and importantly, VPD spikes were averted. Under these conditions, the plants did not exhibit usual indicators of midday fatigue. Stomata remained open over extended periods, while CO2 concentrations near the canopy consistently decreased, signifying continuous assimilation. Leaves exhibited a cooler temperature during misting, occasionally corroborated by infrared thermometry. This cooling indicated active transpiration, signifying that the plant is operating efficiently. The results correspond with earlier research, including that of Zhang et al. (2017), which indicated that fog cooling facilitated the preservation of stomatal function under elevated VPD stress in tomato crops [31].

Nocturnal observations indicated little disparities between misted and non-misted environments. As a C3 species, chilli plants exhibit stomatal closure in the absence of light, which was reflected in the consistent nighttime CO2 measurements across all treatments. The findings indicate that air irrigation is most advantageous during daylight, especially when elevated VPD may restrict photosynthesis [32].

The results suggest that microclimate humidification can prolong the effective duration of daily photosynthesis from an agronomic perspective. Extended stomatal openness not only improves CO2 absorption but also facilitates nutrient transfer inside the plant. The mobility of calcium is significantly associated with transpiration. Decreased transpiration at elevated vapour pressure deficit (VPD) is recognised to induce localised calcium shortages. Studies, including ReduSystems (2019), have associated elevated humidity with enhanced calcium distribution resulting from the preservation of stomatal conductance [33]. This study did not directly assess nutrient uptake and yield; however, previous literature indicates that maintaining an optimal vapour pressure deficit (VPD) may enhance production. Greenhouse fogging systems have demonstrated an increase in tomato yields of approximately 13 to 15 percent throughout summer when employed to alleviate high vapour pressure deficit (VPD) [34].

Comparing natural and humidity-regulated circumstances reveals the significant physiological benefits of intelligent aerial microclimate management. By regulating relative humidity during critical stress periods, air irrigation mitigates midday stomatal closure and fosters continuous photosynthetic activity.

3.5 Integration with Smart Farming Systems

This case study shows how combining IoT technologies with real-time microclimate control can make plants work better. The Master node sent local data to the misting system, which used continuing relative humidity measurements to figure out when to start misting. The prototype is based on simple threshold logic, but its system design works with more advanced controllers like PID or fuzzy logic approaches, which might give VPD very precise control. The cloud connectivity feature made it possible for farmers to watch their crops from a distance and change setpoints based on short-term weather forecasts. For example, if it was expected to be very hot and dry, the target humidity could be raised ahead of time.

Using predictive algorithms can lead to better results. A machine learning system that uses past microclimate and CO2 data could anticipate when stomata are likely to close. This would let the device start misting a little early to keep the best gas exchange possible. Modern greenhouse automation technologies have shown that these strategies work. Systems that combine sensor networks with predictive control have shown that they can keep light, temperature, and humidity at the same level, which leads to higher crop yields [35].

Using water is an important practical issue. Air irrigation uses water in a way that is different from soil irrigation. Instead of giving water directly to the root zone, it sends tiny amounts of mist into the air around the canopy. In our tests, each plot only used a few litres of water each day, which is much less than what is usually used in drip irrigation. The main goal is to change the microclimate, since most of the mist evaporates before it can reach the soil and not to give water to the roots. This trade-off was planned. A small amount of water loss from evaporation is acceptable in exchange for improved physiological performance, especially longer periods of stomatal openness.

The results point to a broader idea. Controlling the air around plants can have big benefits for farming. This method shows that these benefits may be achieved in real wide areas using cheap technology and solar-powered nodes. Traditional irrigation focusses on managing the soil, but our experiment shows that changing the air over the canopy can improve plant microclimate control, boost photosynthesis, and reduce stress. This complementing method, which uses water for the roots and controlled humidity for the canopy, is a good way to do climate-smart farming, especially as water is becoming more-scarce and the environment is becoming less stable.

4. Conclusion

This study provided a detailed assessment of an IoT based aerial microclimate conditioning system and its influence on the physiological behavior of chili plants under real field conditions. The central concept was to apply targeted misting around the canopy to regulate humidity and to examine how this regulation shapes gas exchange, particularly the uptake of CO2 which is fundamental to photosynthesis.

Across the entire experimental period, the field data showed a consistent inverse relationship between relative humidity and CO2 concentration near the canopy. This relationship has a clear physiological basis. When humidity rises, the vapor pressure deficit falls, allowing stomata to remain open and permitting more CO2 to enter the leaves. As stomatal opening increases, the surrounding CO2 concentration decreases, creating a measurable signal of enhanced photosynthetic activity.

Quantitative analysis supported this mechanism. During misting, canopy humidity increased by about ten percent, while CO2 concentrations fell by thirty to fifty parts per million. A strong negative correlation coefficient of approximately r equals minus 0.88, recorded during one representative event, further confirmed the connection between higher humidity and greater CO2 drawdown. Before misting, when vapor pressure deficit ranged between 1.2 and 1.5 kilopascals, the plants showed limited CO2 consumption. Once humidity increased and vapor pressure deficit declined to roughly 0.5 kilopascals, the rate of CO2 drawdown rose noticeably.

These observations reflect a clear sequence rooted in plant physiology: an increase in humidity lowers vapor pressure deficit, which promotes stomatal opening, enhances CO2 uptake, and reduces ambient CO2 concentrations near the foliage. Continuous monitoring validated this sequence and showed that active humidity control can strengthen gas exchange in an open field environment. The system therefore offers a way to bring certain advantages of controlled environment agriculture into more traditional cultivation settings using accessible IoT hardware.

In real life, the misting system worked as an aerial supplement to watering the earth. It didn't just focus on getting water to the roots; it also looked at the weather variables that can damage plants. The system made short microclimatic windows during bright, dry hours, when vapour pressure deficit usually rises. This let photosynthesis continue before stomatal closure would ordinarily happen.

Misting does require some water, but the health benefits suggest that it could make water use more efficient, which means that more carbon is fixed for every unit of water lost. Studies in greenhouses have already shown that under low vapour pressure deficit situations, water consumption efficiency can go up by 20 to 40 percent. Although this study did not explicitly measure transpiration, the observed behaviour indicates that managed misting may provide comparable efficiency improvements by prolonging stomatal opening.

In the future, plant-centered sensors like leaf temperature or stomatal conductance probes could be used more often, combined with predictive control methods based on fuzzy logic or machine learning. With these improvements, the algorithm might be able to predict when stress will happen and mist even more accurately. Adding more crops or combining this method with soil-based irrigation methods may also make crops grow better and use resources more efficiently.

The study showed that IoT-enabled aerial microclimate regulation can significantly improve gas exchange by controlling the canopy's relative humidity and vapour pressure deficit. It changes the way we think about irrigation from being only about the soil to being a way to regulate the ecosystem. The findings indicate that precision misting systems may extend stomatal openness, enhance CO2 absorption, and promote healthier plant growth, especially in locations where heat and aridity jeopardise productivity.

This study has some limitations; however, the proposed IoT-based air irrigation system demonstrated effective microclimate control and a robust correlation between relative humidity and CO_2 levels. The experiment lasted approximately four and a half months, which may be insufficient to see all the environmental changes and plant physiological responses that occur across the seasons. The study primarily examined microclimate regulating parameters without directly evaluating yield, fruit quality, or long-term production consequences. Future research should extend the monitoring period and incorporate yield-based metrics to comprehensively evaluate the agronomic benefits and water-use efficiency of the system.

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