Smart and Sustainable IoT-Driven Vertical Farming Solution for Agricultural Challenges in Pakistan

Solución de agricultura vertical inteligente y sostenible basada en IoT para los desafíos agrícolas en Pakistán

Solução de agricultura vertical inteligente e sustentável baseada em IoT para desafios agrícolas no Paquistão

Sadiq Ur Rehman [1(*)], Muhammad Adeel Mannan [2], Muhammad Ahsan Shaikh [3], Muhammad Uzair [4]

Recibido: 15/05/2025 Aceptado: 23/07/2025

Summary. - Agriculture in Pakistan faces critical challenges such as water scarcity, inefficient resource use, and climate change impacts, particularly in urban and peri-urban areas. This study presents a smart, solar-powered vertical farming system designed to address these issues by integrating capacitive soil moisture sensors, temperature and humidity sensors (DHT22), and light sensors (BH1750), controlled via Raspberry Pi 4. The off-grid system, powered by a 100-watt solar panel and battery, features intelligent irrigation driven by a Random Forest algorithm to optimize water use. Over a six-week trial cultivating cherry tomatoes, the system achieved a 60–65% yield increase, 40% energy savings, and a 28.57% reduction in water consumption compared to traditional methods. While promising, limitations include the small trial size and lack of long-term environmental impact data. Scalability challenges such as cost, maintenance, and local constraints must be addressed for wider adoption. Future work will focus on expanding crop varieties, enhancing AI integration, and improving accessibility for small-scale farmers to support sustainable urban agriculture and food security in Pakistan.

Keywords: Agriculture, Vertical Farming, Sustainable Agriculture, Water Efficiency, Solar Energy.

[1] Ph.D., Associate Professor, Faculty of Engineering Science and Technology, IQRA University (Pakistan), sadiq.rehman@iqra.edu.pk, ORCID iD: https://orcid.org/0000-0002-6308-450X
[2] Ph.D., Associate Professor, Bahria School of Engineering and Applied Sciences, Bahria University (Pakistan), madeelmannan.bukc@bahria.edu.pk, ORCID iD: https://orcid.org/0000-0002-0811-4753
[3] Ph.D., Assistant Professor, Faculty of Engineering Science and Technology, Hamdard University (Pakistan) muhammad.ahsan@hamdard.edu.pk, ORCID iD: https://orcid.org/0000-0003-2408-5689
[4] Ph.D., Associate professor, Electrical Engineering Department, Faculty of Engineering, Islamic University of Madinah (Saudi Arabia) muzair@iu.edu.sa, ORCID iD: https://orcid.org/0000-0003-1063-9476

Memoria Investigaciones en Ingeniería, núm. 29 (2025). pp. 95-108
https://doi.org/10.36561/ING.29.7
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

Resumen. - *La agricultura en Pakistán enfrenta desafíos críticos como la escasez de agua, el uso ineficiente de los recursos y los impactos del cambio climático, particularmente en áreas urbanas y periurbanas. Este estudio presenta un sistema de cultivo vertical inteligente alimentado con energía solar, diseñado para abordar estos problemas mediante la integración de sensores capacitivos de humedad del suelo, sensores de temperatura y humedad (DHT22) y sensores de luz (BH1750), controlados mediante Raspberry Pi 4. El sistema autónomo, alimentado por un panel solar de 100 vatios y una batería, cuenta con riego inteligente impulsado por un algoritmo de Bosque Aleatorio para optimizar el uso del agua. Durante un ensayo de seis semanas cultivando tomates cherry, el sistema logró un aumento del 60-65% en el rendimiento, un ahorro de energía del 40% y una reducción del 28,57% en el consumo de agua en comparación con los métodos tradicionales. Si bien es prometedor, las limitaciones incluyen el pequeño tamaño del ensayo y la falta de datos de impacto ambiental a largo plazo. Es necesario abordar los desafíos de escalabilidad, como el costo, el mantenimiento y las restricciones locales, para una adopción más amplia. El trabajo futuro se centrará en ampliar las variedades de cultivos, mejorar la integración de la IA y mejorar la accesibilidad para los pequeños agricultores para apoyar la agricultura urbana sostenible y la seguridad alimentaria en Pakistán.*

Palabras clave: *Agricultura impulsada por el IoT, agricultura vertical, agricultura sostenible, eficiencia hídrica, energía solar*

Resumo. - *A agricultura no Paquistão enfrenta desafios críticos, como a escassez de água, a utilização ineficiente dos recursos e os impactos das alterações climáticas, particularmente nas áreas urbanas e periurbanas. Este estudo apresenta um sistema de agricultura vertical inteligente, alimentado a energia solar, concebido para lidar com estas questões, integrando sensores capacitivos de humidade do solo, sensores de temperatura e humidade (DHT22) e sensores de luz (BH1750), controlados através do Raspberry Pi 4. O sistema off-grid, alimentado por um painel solar de 100 watts e bateria, possui uma irrigação inteligente acionada por um algoritmo Random Forest para otimizar a utilização da água. Ao longo de um teste de seis semanas de cultivo de tomate-cereja, o sistema obteve um aumento de 60–65% na produtividade, 40% de poupança de energia e uma redução de 28,57% no consumo de água em comparação com os métodos tradicionais. Embora promissor, as limitações incluem o pequeno tamanho do teste e a falta de dados de impacto ambiental a longo prazo. Os desafios de escalabilidade, como o custo, a manutenção e as restrições locais, devem ser abordados para uma adoção mais ampla. O trabalho futuro irá focar-se na expansão das variedades de culturas, na melhoria da integração da IA e na melhoria da acessibilidade para os pequenos agricultores para apoiar a agricultura urbana sustentável e a segurança alimentar no Paquistão.*

Palavras-chave: *Agricultura orientada por IoT, agricultura vertical, agricultura sustentável, eficiência hídrica, energia solar.*

1. Introduction. - The global population has been growing at an increasingly rapid pace, which has led to several challenges, such as the strain on land available for agriculture and the growing need for fresh water to meet both drinking and agricultural demands [1]. Experts predict that by 2050, the world's population could reach 9 billion, further intensifying the pressure on land resources needed for living spaces [2]. With only 10% of the land being suitable for farming, it is becoming increasingly difficult to grow enough crops to meet the needs of a growing population. Furthermore, an enormous number of crops are wasted due to natural disasters such as earthquakes, droughts, heavy rainfall, and flooding [3]. Moreover, the crops that make it to the market are often not fresh, as the farming and agricultural lands are located far from cities and residential areas. Pakistan is one of the developing countries whose economy heavily depends on agriculture [4]. However, rapid urbanization has made it difficult for this sector to grow enough food to meet demand. Traditional farming [5] in Pakistan is still widely practiced but faces many challenges, including high water use and vulnerability to environmental degradation (see Table I).

Challenge	Description
Water Scarcity	Low rainfall and over-extraction of groundwater
Energy Shortage	Frequent power outages, especially in rural áreas
Land Constraints	Urban sprawl reduces arable land availability
Climate Variability	Increasing droughts, floods, and heatwaves
Inefficient Irrigation	High water loss due to outdated techniques
Crop Loss & Decay	Delays from rural farms to markets reduce freshness

Table I. Challenges in Traditional Agriculture in Pakistan

Vertical farming [6] offers a promising solution to these challenges by maximizing agricultural space through stacked beds that grow crops vertically in controlled environments. This method optimizes the use of arable land and allows for more efficient water and energy use. By carefully monitoring and controlling factors like light, temperature, humidity, and soil moisture, vertical farming can create ideal growing conditions with fewer resources. Importantly, vertical farming isn't just about saving space, it also addresses critical sustainability issues around water and energy. Using smart sensors to water plants only when needed helps cut down on wasted water, while integrating solar power reduces dependence on unreliable grid electricity. This combination makes the system not only smarter but also much more environmentally friendly and sustainable, something particularly vital for resource-limited countries like Pakistan.

In this study, we propose a practical and fully autonomous vertical farming system that integrates IoT [7-8] sensors, machine learning algorithms [9], and solar power. This combination not only allows precise control of environmental conditions but also reduces reliance on conventional electricity grids by harnessing renewable energy, making it a realistic and sustainable solution for the challenges faced by agriculture in Pakistan and similar regions. Table II presents a comparison between vertical farming and traditional farming methods, showing measurable improvements in space efficiency, water savings, and environmental impact. While traditional farming requires large land areas and often wastes water through inefficient irrigation, vertical farming can reduce water use by up to 90% and increase yield per square foot. Our approach builds on these advantages by incorporating IoT and machine learning to optimize irrigation and lighting further, backed by solar energy to ensure sustainable power supply.

Aspect	Vertical Farming	Traditional Farming
Space Efficiency	High crops grow in stacked layers, maximizing space.	Low; requires large land areas for planting.
Water Usage	Reduced by up to 90% due to efficient irrigation methods (e.g., hydroponics).	High, especially in water-scarce regions with inefficient irrigation systems.
Energy Usage	High, but can be offset with renewable energy (e.g., solar power).	Generally low but dependent on external power sources.
Yield	Significantly higher per square foot compared to traditional methods.	Relatively low per unit area, especially in urban or degraded soils.

Environmental Impact	Lower carbon footprint due to local production and reduced transportation.	Higher due to transportation and potential soil degradation.

Table II. Comparison Between Vertical Farming and Traditional Farming Systems

The rest of the paper is organized as follows: Section II provides a literature review, Section III details the methodology of the proposed system, Section IV presents the results and discussion, and finally, Section V concludes with a summary of key findings and possible future directions.

2. Literature Review. - The world's economic stability is increasingly threatened by challenges such as infectious diseases and rapid population growth, which directly impact agricultural land availability and food security [10]. In countries like Pakistan, where agriculture is a major economic driver, these pressures are intensified by urbanization and climate change, leading to decreased arable land and freshwater scarcity. This calls for innovative farming solutions that maximize productivity within limited resources.

The proposed system seeks to address these challenges by combining vertical farming with modern technologies such as IoT, machine learning (ML), and solar power. The focus is on creating an easy-to-use internal farming platform with shelving units to grow crops efficiently indoors. Before detailing the system design, it is essential to critically review relevant technologies and their current limitations.

2.1 IoT in Agriculture. - IoT technologies have transformed agricultural monitoring by enabling real-time data collection on environmental factors like soil moisture, temperature, and humidity [11-12]. These systems improve water efficiency through automated irrigation and enable precise crop management [13-14]. However, many existing IoT applications focus primarily on data gathering rather than integrating predictive analytics or full automation, limiting their optimization potential.
Furthermore, IoT integration in vertical farming remains nascent. Vertical farms require more sophisticated control over multiple environmental variables simultaneously, which complicates IoT deployment and data processing. Studies rarely address system scalability or robustness in challenging field conditions, especially in developing countries where infrastructure may be unreliable.

2.2 Vertical Farming vs. Traditional Farming. - Vertical farming, characterized by stacking plants in multi-layered structures, offers substantial benefits over traditional farming, including higher space utilization and significant water savings (up to 90% reduction) due to methods like hydroponics and aeroponics [15-16]. While vertical farming promises efficiency gains, it is important to highlight its main challenges. Energy consumption is notably high due to artificial lighting and climate control requirements, which can limit its practicality in energy-constrained regions [15]. Additionally, the upfront costs and technical complexity can be prohibitive, especially for small-scale farmers in developing countries. Hence, integrating renewable energy sources such as solar power becomes critical but is still underdeveloped in current literature.

2.3 Solar Energy in Agriculture. - Solar energy presents a promising solution to reduce reliance on unreliable electrical grids in agriculture, particularly in countries like Pakistan with high solar insolation [17]. Solar-powered irrigation and greenhouse systems have demonstrated reduced operational costs and lower environmental impact [18]. Despite this, solar integration into vertical farming remains limited. Vertical farming's high continuous energy demands require efficient energy storage and management solutions that are often overlooked.
Additionally, the intermittent nature of solar power poses challenges for maintaining the consistent environmental conditions vertical farms need. Most studies do not address how to mitigate this intermittency or evaluate the economic feasibility of incorporating solar power at scale.

2.4 Machine Learning in Agriculture. - Machine learning has shown significant promise in enhancing agricultural decision-making by analyzing sensor data to predict irrigation needs, crop health, and yield [19-20]. For example, Random Forest algorithms have effectively optimized irrigation schedules, reducing water waste [21]. However, many ML models are trained on limited datasets and have not been extensively validated across diverse crops or environments.

Moreover, there is a lack of studies integrating ML with IoT in real-time vertical farming environments to create closed-loop systems for dynamic resource management. Bridging this gap is critical to developing intelligent farms that can autonomously optimize water and energy use.

Study	Technology/Method	Key Findings	Limitations
[13]	IoT-based agriculture	Improved water use and crop yield via soil monitoring.	Focused on monitoring, limited automation and predictive control.
[14]	IoT smart irrigation	Demonstrated water-saving potential with soil moisture sensors.	Prototype scale, lack of scalability analysis.
[15]	Hydroponics/Aeroponics	Efficient space use and water savings demonstrated.	High setup costs and energy needs.
[17],[18]	Solar energy in agriculture	Reduced energy costs and grid dependency shown.	Limited focus on integration with high-demand vertical farming.
[21]	ML for irrigation and yield prediction	Improved irrigation scheduling and yield forecasting.	Limited real-world validation and integration with IoT.

Table III. Comparative Analysis of Technological Interventions in Smart and Sustainable Agriculture Systems

The literature indicates clear potential in combining vertical farming, IoT, solar power, and ML. However, a holistic system that integrates these components efficiently, addresses energy constraints, and is tailored to developing country contexts remains elusive. Our research addresses these gaps by proposing a smart vertical farming system that leverages IoT and ML for automated irrigation, powered sustainably by solar energy.

3. Methodology. - The system was implemented on a practical small scale inside a 12x12-foot room, featuring a two-tiered iron frame structure approximately 45 inches tall, enclosed by transparent acrylic sheets (see Figure. I). This setup created a mini-greenhouse effect, optimizing vertical space by stacking growing beds, which is ideal for urban or space-constrained environments. While cherry tomatoes were the primary crop cultivated during this trial, the system is designed to support a diverse range of crops such as leafy greens, herbs, and peppers, which will be explored in future extended studies to validate broader applicability.

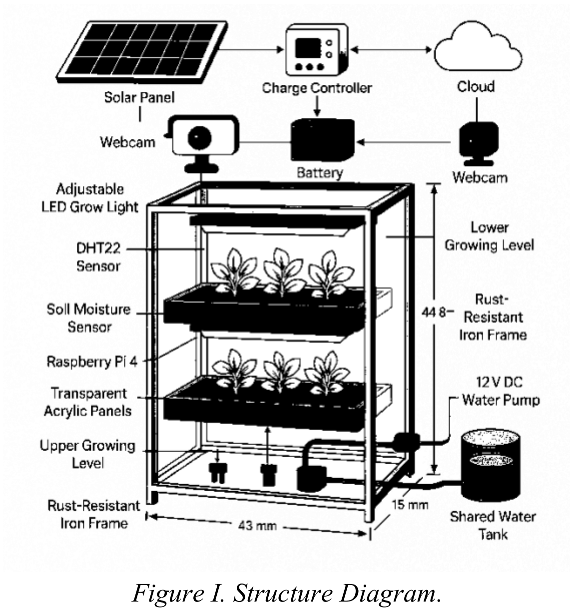

Figure I. Structure Diagram.

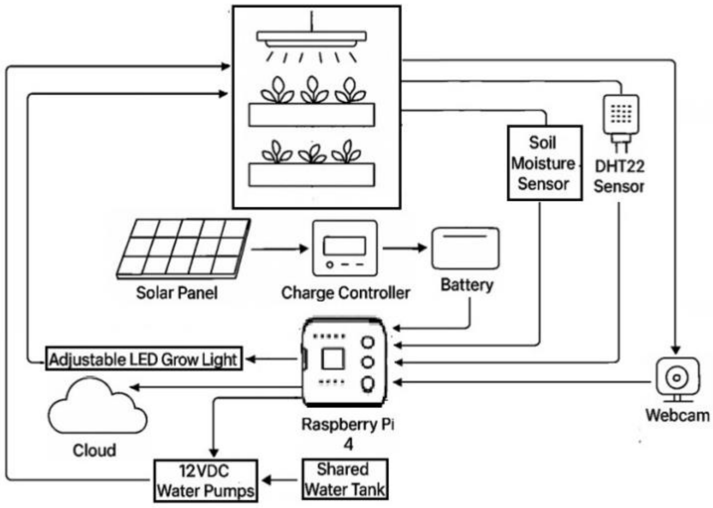

Figure II. System Block Diagram.

Each growing bed was equipped with sensors to continuously monitor environmental and soil conditions, enabling precise control to optimize crop growth. Capacitive soil moisture sensors measured water content, triggering irrigation only when moisture levels fell below 30% to conserve water efficiently. Temperature and humidity were monitored using DHT22 sensors, maintaining the target ranges of 29°C to 34°C and 58% to 68% humidity, respectively. The BH1750 light sensor ensured that plants received adequate light by activating energy-efficient LED grow lights whenever ambient light dropped below 3000 lux. The system architecture is illustrated in Figure II.

The core processing was handled by a Raspberry Pi 4, which collected sensor data every 5 minutes to maintain real-time control of irrigation, lighting, and environmental conditions. The system was powered by a 100-watt solar panel connected to a battery bank via a charge controller, ensuring energy autonomy even during night hours or cloudy conditions. A 12V DC water pump delivered irrigation for approximately 30 seconds per activation, based on sensor readings.

Remote monitoring and manual control were enabled through the Red-Note software dashboard, which presented real-time environmental data and system status to users, facilitating easy intervention if necessary.

To enhance irrigation precision and reduce water waste, a Random Forest regression model was implemented to predict optimal irrigation durations. The model was trained using a dataset comprising 3,200 records collected from preliminary trials. Features included temperature, humidity, soil moisture, and light intensity, while the target variable was irrigation time in seconds. The dataset was split into 80% training and 20% testing partitions. The model achieved an R^2 score of 0.91, indicating strong predictive capability. Predictions were generated every 15 minutes and cross-checked against real-time conditions. When the forecasted irrigation time deviated significantly from the baseline, the machine learning output overrode the rule-based logic, ensuring that water delivery was adapted to actual environmental needs.

Parameter	**Value**
Dataset Size	3,200 points
Training/Test Split	80% / 20%
Features	Temp, Humidity, Moisture, Light
Target	Irrigation Time (sec)
Evaluation Metric	RMSE, MAE, R^2
Model Accuracy	$R^2 = 0.91$

Table IV. Random Forest Model Configuration

To manage energy efficiently, the charge controller prevented battery overcharging, and the system reduced power consumption by limiting non-essential functions during periods of low sunlight, prioritizing critical operations like data logging and irrigation. This adaptive energy management strategy ensured uninterrupted operation while maximizing the use of solar power.

Component	Description	Essential Parameters
Soil Moisture Sensor (FC-28)	Measures the moisture content of the soil to optimize irrigation.	Moisture Range: 0% - 100%
		Threshold: 30% for irrigation trigger
		Accuracy: ±3% to ±10%
Temperature and Humidity Sensor (DHT22)	Monitors the ambient temperature and humidity in the growing environment.	Temperature Range: -40°C to 80°C
		Humidity Range: 0% - 100%
		Accuracy: ±0.5°C for temp
		Accuracy: ±2% for humidity
Light Intensity Sensor (BH1750)	Measures the ambient light intensity to control LED grow lights.	Light Intensity Range: 0 to 65535 lux
		Threshold: 3000 lux for LED activation
Raspberry Pi 4 (Central Controller)	Acts as the main controller for the system, processing sensor data and making decisions.	Processor: Quad-core ARM Cortex-A72
		RAM: 2GB/4GB/8GB
		Connectivity: Wi-Fi, Ethernet
Solar Panel (100W)	Powers the entire system through solar energy, reducing grid dependence.	Power Output: 100W
		Efficiency: Variable based on sunlight intensity
		Voltage: 12V DC
Battery and Charge Controller	Stores energy for night-time use and manages charging of the battery.	Battery Capacity: 12V, 12Ah
		Charge Controller: Protects from overcharging, efficient energy management
DC Water Pump (12V)	Delivers water to the plants based on the moisture level.	Voltage: 12V DC
		Flow Rate: 4-6 liters/min
		Power Consumption: 3- 5W
LED Grow Lights	Provides artificial light to support plant photosynthesis when natural light is insufficient.	Power: 20W-30W per panel
		Color Temperature: 6000-6500K (Daylight)
Cloud-based Dashboard	A web-based interface for remote monitoring and management of the system.	Real-time Monitoring: Temperature, humidity, light, and moisture levels
		User Control: Manual override available

Table V. Components used in the system along with their essential parameters

4. Results and Discussion. - This section discusses the results obtained from the IoT-powered vertical farming system, tested with cherry tomato crops over a 6-week trial period. The key parameters analyzed include water usage efficiency, energy consumption, crop yield, temperature and humidity control, and light intensity. While the system shows promising improvements compared to traditional farming, the scope of the experiment is limited, and statistical analysis has been added to strengthen validity.

Figure III. Assembled hardware of the proposed system model.

4.1 Water Usage Efficiency. - Water efficiency is critical for sustainable farming, especially for crops like cherry tomatoes that require precise irrigation. Using soil moisture sensors integrated with a Random Forest model, the system automated irrigation to maintain soil moisture between 40%-45%, compared to 33%-38% in traditional farming (see Figure V). This resulted in average water savings of 28.6% (±2.3% standard deviation), as shown in Table VI.

Parameter	Traditional Farming	Vertical Farming with IoT	Improvement (%)
Average Soil Moisture (%)	35.5 ± 2.1	42.5 ± 1.8	-
Water Usage (liters)	10.5 ± 0.7	7.5 ± 0.5	28.6 ± 2.3

Table VI. Water Usage Efficiency and Soil Moisture Comparison

Figure IV. Reading of FC-28 on the user interface

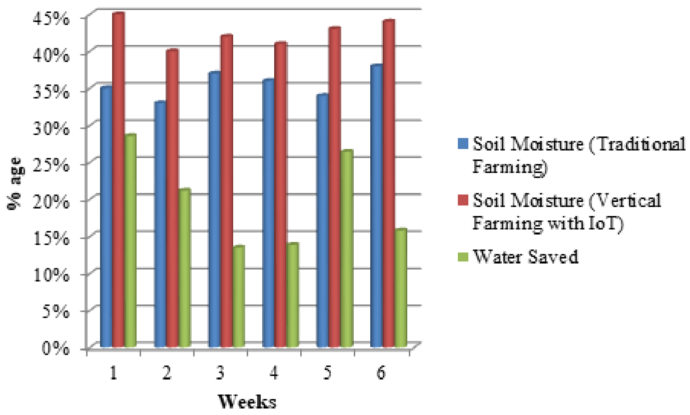

Figure V. Soil Moisture Readings.

4.2 Energy Consumption. - Energy consumption was monitored weekly, comparing the solar-powered vertical farming system with traditional farming relying on grid electricity. Vertical farming consumed between 2.9 to 3.3 kWh per week, significantly less than traditional methods (4.8 to 5.2 kWh). Solar panel efficiency ranged from 35.3% to 40% (see Table VII). Energy savings averaged 39.1% (±1.5%). Figure 6 includes error bars showing weekly consumption variance.

Week	Traditional Energy (kWh)	Vertical Farming Energy (kWh)	Energy Efficiency (%)	Std. Dev (Efficiency)
1	5.0 ± 0.1	3.0 ± 0.1	40	±1.2
2	4.8 ± 0.2	2.9 ± 0.1	39.6	±1.3
3	5.2 ± 0.1	3.1 ± 0.2	40.4	±1.5
4	5.0 ± 0.1	3.2 ± 0.1	36	±1.1
5	4.9 ± 0.2	3.0 ± 0.1	38	±1.4
6	5.1 ± 0.1	3.3 ± 0.2	35.3	±1.6

Table VII. Weekly Energy Consumption and Solar Panel Efficiency

4.3 Crop Yield. - The vertical farming system yielded 60-65% more cherry tomatoes per plant compared to traditional farming (Table VIII). Specifically, plants produced an average of 9 (±1.2) fruits versus 5.5 (±1.0) in the traditional setup. While promising, the limited crop variety and short 6-week trial restrict broader applicability.

Parameter	Traditional Farming (4 Plants)	Vertical Farming (4 Plants)	Yield Increase (%)
Average Fruits per Plant	5.5 ± 1.0	9.0 ± 1.2	63.6 ± 5.4
Total Fruits (6 Weeks)	22 ± 4	36 ± 5	-

Table VIII. Comparison of Crop Yield between Traditional and IoT-Driven Vertical Farming

4.4 Temperature and Humidity Control. - Stable environmental conditions are vital for crop health. The vertical farming system-maintained temperatures between 29°C and 34°C (±1.2°C) and humidity between 58% and 68% (±3%) as can be seen in Figure VI, whereas traditional farming saw wider fluctuations (31°C-36°C, ±2°C; 52%-60%, ±4%). This controlled environment improved plant health and fruit quality.

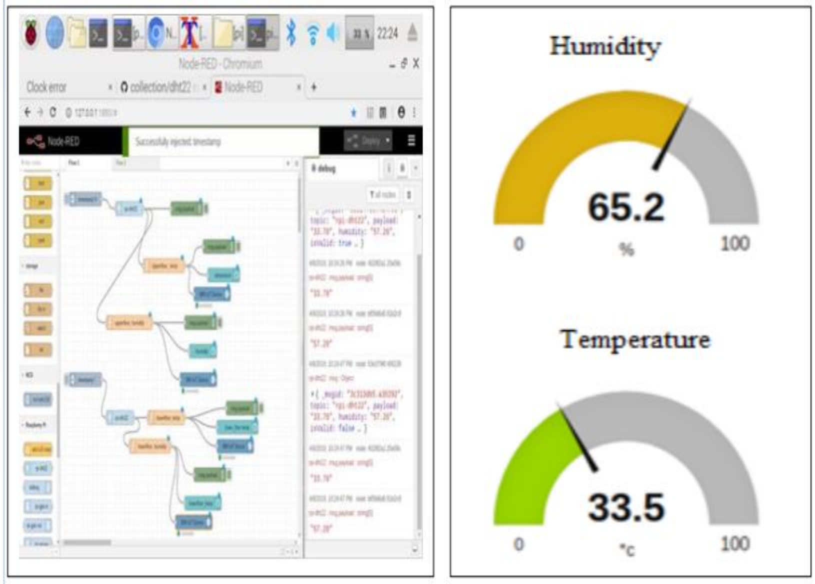

Figure VI. Temperature and Humidity level of a system

Week	Temp Traditional (°C)	Temp Vertical (°C)	Humidity Traditional (%)	Humidity Vertical (%)
Avg ± SD	33.0 ± 1.5	31.5 ± 1.2	57 ± 4	63 ± 3

Table IX. Average Temperature and Humidity Comparison with Variability

4.5 Light Intensity and Growth Conditions. - Light intensity was consistently higher and more stable in the vertical system, ranging from 1150 to 1300 lux, compared to 950 to 1050 lux outdoors. This represents a 22.5% ± 2.1% increase in light availability, promoting better photosynthesis and growth (Table X).

Week	Light Intensity Traditional (lux)	Light Intensity Vertical (lux)	Increase (%)
Avg ± SD	1005 ± 40	1225 ± 55	22.5 ± 2.1

Table X. Light Intensity Comparison

4.6 Baseline Comparison with Other Smart Farming Systems. - To provide broader context for our system's performance, Table XI compares key metrics such as water savings, yield improvement, and energy use against other smart farming solutions reported in the literature. While some field-based IoT irrigation systems demonstrate higher water savings due to starting from less efficient traditional methods, our vertical farming system achieves competitive water efficiency alongside a notably higher yield increase, thanks to its controlled environment. Additionally, the integration of solar power enhances sustainability by reducing reliance on grid electricity an aspect often unreported in other studies. This comparison highlights the practical benefits and unique strengths of our approach within the landscape of smart agriculture technologies.

System Type	Water Savings vs Traditional	Yield Increase	Energy Use Notes
Our Vertical Farm (IoT + Solar)	28.6 ± 2.3 %	63.6 ± 5.4 %	~3.0 kWh/week (solar powered)
[22]	~50 %	~35 %	Not reported
[23]	47.8 %	~34.9 %	Not reported
[24]	~35 %	~24–30 %	—

Table XI. Benchmark Comparison with Other Smart Farming Systems

5. Conclusion and Future Work. - This study successfully developed a smart, solar-powered vertical farming system tailored to the unique agricultural challenges of Pakistan. By integrating real-time environmental monitoring, automated irrigation, and machine learning (Random Forest), the system significantly improved resource efficiency and crop productivity compared to traditional farming. Over a six-week trial, it reduced water use by 28.57%, cut energy consumption by 40%, and increased cherry tomato yield by 60–65%. Its off-grid, solar-powered design ensured reliable operation while maintaining ideal growing conditions, something hard to achieve in open-field farming.

However, this study has some limitations. The experimental scope was limited to a single crop and a short trial period, which restricts the generalizability of the findings. Additionally, long-term environmental impacts and system durability were not assessed, indicating the need for extended studies. Scalability challenges also remain, such as the initial cost of setup, ongoing maintenance requirements, and adapting the system to diverse local conditions and crop types. Addressing these issues will be critical to ensuring wider adoption.

Looking forward, future work should focus on scaling the system for commercial use, expanding to a broader variety of crops, and integrating more advanced AI models for further optimization. Efforts to reduce costs and simplify maintenance will enhance accessibility for small-scale farmers. Moreover, long-term field studies evaluating environmental and economic impacts are essential. With supportive policies and investments, this innovation could play a vital role in driving sustainable agriculture and improving food security in Pakistan.

References

[1] Al Meselmani, Moaed Ali. "Hydroponics: The Future of Sustainable Farming." In Hydroponics: The Future of Sustainable Farming, pp. 101-122. New York, NY: Springer US, 2024. https://doi.org/10.1007/978-1-0716-3993-1_6

[2] Angel, S., Parent, J., Civco, D. L., Blei, A., & Potere, D. (2011). The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. Progress in Planning, 75(2), 53–107. https://doi.org/10.1016/j.progress.2011.04.001

[3] Sivakumar, M. V. K. (2005). Impacts of natural disasters in agriculture, rangeland and forestry: An overview. In Natural disasters and extreme events in agriculture: Impacts and mitigation (pp. 1–22). https://doi.org/10.1007/3-540-28307-2_1

[4] Mahmood, G. G., Liberatori, S., & Mazzetto, F. (2025). Agricultural mechanization perspective in Pakistan: Present challenges and digital future. Journal of Agricultural Engineering. https://doi.org/10.4081/jae.2025.1636

[5] Hamadani, H., Rashid, S. M., Parrah, J. D., Khan, A. A., Dar, K. A., Ganie, A. A., Gazal, A., Dar, R. A., & Ali, A. (2021). Traditional farming practices and its consequences. In Microbiota and biofertilizers, Vol. 2: Ecofriendly tools for reclamation of degraded soil environs (pp. 119–128). https://doi.org/10.1007/978-3-030-61010-4_6

[6] Shi, X., Shi, C., Tablada, A., Guan, X., Cui, M., Rong, Y., Zhang, Q., & Xie, X. (2025). A review of research progress in vertical farming on façades: Design, technology, and benefits. Sustainability, 17(3), 921. https://doi.org/10.3390/su17030921

[7] Rehman, S. U., Khan, I. U., Moiz, M., & Hasan, S. (2016). Security and privacy issues in IoT. International Journal of Communication Networks and Information Security, 8(3), 147.

[8] Rehman, S. U., Mustafa, H., & Larik, A. R. (2021). IoT based substation monitoring & control system using Arduino with data logging. In 2021 4th International Conference on Computing & Information Sciences (ICCIS) (pp. 1–6). IEEE. https://doi.org/10.1109/ICCIS54243.2021.9676384

[9] Botero-Valencia, J., García-Pineda, V., Valencia-Arias, A., Valencia, J., Reyes-Vera, E., Mejia-Herrera, M., & Hernández-García, R. (2025). Machine learning in sustainable agriculture: Systematic review and research perspectives. Agriculture, 15(4), 377. https://doi.org/10.3390/agriculture15040377

[10] Saravanan, S., Akay, Y. M., Chen, T., & Akay, M. (2025). Impacts of climate change on global health: A review of preparedness, infectious disease, and excessive heat. Health and Technology, 15(1), 7–14. https://doi.org/10.1007/s12553-024-00927-7

[11] Rehman, S. U., Khan, I., Rehman, N. U., & Hussain, A. (2022). Low-cost smart home automation system with advanced features. Quaid-E-Awam University Research Journal of Engineering Science and Technology Nawabshah, 20(01), 74–82. https://doi.org/10.52584/QRJ.2001.10

[12] Rehman, S. U., & Khan, A. (2023). Integrating IoT technology for improved distribution transformer monitoring and protection. Electrical, Control and Communication Engineering, 19(1), 22–28. https://doi.org/10.2478/ecce-2023-0004

[13] Chew, K.-M., Tan, S. C.-W., Loh, G. C.-W., Bundan, N., & Yiiong, S.-P. (2020). IoT soil moisture monitoring and irrigation system development. In Proceedings of the 2020 9th International Conference on Software and Computer Applications (pp. 247–252). https://doi.org/10.1145/3384544.3384595

[14] Obaideen, K., Yousef, B. A. A., AlMallahi, M. N., Tan, Y. C., Mahmoud, M., Jaber, H., & Ramadan, M. (2022). An overview of smart irrigation systems using IoT. Energy Nexus, 7, 100124. https://doi.org/10.1016/j.nexus.2022.100124

[15] Verma, S., Kumar, A., Kumari, M., Kumar, N., Hansda, S., Saurabh, A., Poonia, S., & Rathore, S. D. (2024). A review on hydroponics and vertical farming for vegetable cultivation: Innovations and challenges. Journal of Experimental Agriculture International, 46(12), 801–821. https://doi.org/10.9734/jeai/2024/v46i123190

[16] Banerjee, C., & Adenaeuer, L. (2014). Up, up and away! The economics of vertical farming. Journal of Agricultural Studies, 2(1), 40–60. http://dx.doi.org/10.5296/jas.v2i1.4416

[17] Hassanien, R. H. E., Li, M., & Lin, W. D. (2016). Advanced applications of solar energy in agricultural greenhouses. Renewable and Sustainable Energy Reviews, 54, 989–1001. https://doi.org/10.1016/j.rser.2015.10.095

[18] Abdelhamid, M. A., Abdelkader, T. K., Sayed, H. A. A., Zhang, Z., Zhao, X., & Atia, M. F. (2025). Design and evaluation of a solar powered smart irrigation system for sustainable urban agriculture. Scientific Reports, 15(1), 11761. https://doi.org/10.1038/s41598-025-94251-3

[19] Haider, W., & Rehman, A. (2019). Knowledge based soil classification towards relevant crop production. International Journal of Advanced Computer Science and Applications, 10(12), 488–501. https://doi.org/10.14569/IJACSA.2019.0101266

[20] Haider, W., Rehman, A., Durrani, N. M., & Rehman, S. U. (2021). A generic approach for wheat disease classification and verification using expert opinion for knowledge-based decisions. IEEE Access, 9, 31104–31129. https://doi.org/10.1109/ACCESS.2021.3058582

[21] Jegan, D., Surendran, R., & Madhusundar, N. (2024). Hydroponic using deep water culture for lettuce farming using random forest compared with decision tree algorithm. In 2024 8th International Conference on Electronics, Communication and Aerospace Technology (ICECA) (pp. 907–914). IEEE. https://doi.org/10.1109/ICECA63461.2024.10800972

[22] Zia, H., Rehman, A., Harris, N. R., Fatima, S., & Khurram, M. (2021). An experimental comparison of IoT-based and traditional irrigation scheduling on a flood-irrigated subtropical lemon farm. Sensors, 21(12), 4175. https://doi.org/10.3390/s21124175

[23] Ragab, M. A., Badreldeen, M. M. M., Sedhom, A., & Mamdouh, W. M. (2022). IOT based smart irrigation system. International Journal of Industry and Sustainable Development, 3(1), 76-86. https://doi.org/10.21608/ijisd.2022.148007.1021

[24] Zafar, U., Arshad, M., Masud Cheema, M. J., & Ahmad, R. (2020). Sensor based drip irrigation to enhance crop yield and water productivity in semi-arid climatic region of Pakistan. Pakistan Journal of Agricultural Sciences, 57(5). https://doi.org/10.21162/PAKJAS/20.83

Author contribution:

1. Conception and design of the study
2. Data acquisition
3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
6. Approval of the last version of the manuscript

SUR has contributed to: 1, 2, 3 and 4.

MAM has contributed to: 4, 5 and 6.

MAS has contributed to: 6.

MU has contributed to: 6.

Acceptance Note: This article was approved by the journal editors Dr. Rafael Sotelo and Mag. Ing. Fernando A. Hernández Gobertti.