FUOYE Journal of Engineering and Technology, Volume 8, Issue 4, December 2023 ISSN: 2579-0617 (Paper), 2579-0625 (Online)

Modelling of a Greenhouse Climatic Conditions Control System with PID Controller for Plant Growth Optimization

[1]Theddeus T. Akano, and *[2]Olumuyiwa S. Asaolu
[1]Department of Mechanical Engineering, University of Botswana, Botswana
[2]Department of Systems Engineering, University of Lagos, Nigeria.
akanott@ub.ac.bw | asaolu@unilag.edu.ng

Received: 22-NOV-2023; Reviewed: 12-DEC-2023; Accepted: 21-DEC-2023
http://doi.org/10.46792/fuoyejet.v8i4.1144

ORIGINAL RESEARCH

Abstract- In modern agriculture, our focus is on optimizing crop cultivation, particularly in greenhouses, to enhance productivity and resource efficiency. This paper investigates the pivotal role of temperature and humidity control in greenhouses for optimal plant growth. Our study employs a MATLAB/ Simulink-designed system for continuous monitoring, analysis, and real-time adjustments, connecting with various actuators and integrating external data. Results show the system efficiently corrects variations, ensuring temperature and humidity return to set points of 25°C and 60% respectively. This underscores the trans-formative potential of the control system in revolutionizing agriculture for increased efficiency and sustainability.

Keywords- Greenhouse, Humidity, PID Controller, Temperature.

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1 INTRODUCTION

The cultivation of crops in controlled environments, such as greenhouses, has become an essential component of modern agriculture. Greenhouses offer advantages in terms of crop yield, quality, and resource efficiency. However, to maximize the benefits of greenhouse cultivation, it is crucial to maintain optimal growing conditions. Among the many environmental factors influencing plant growth, temperature and humidity stand out as critical parameters that demand precise control and management (Ahamed et al., 2023). Inadequate control of these factors can lead to reduced crop yields, increased susceptibility to diseases, and diminished product quality (Gruda & Tanny, 2014).

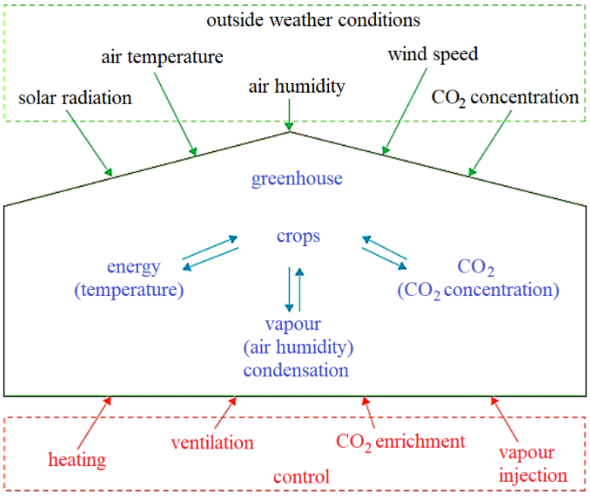

Fig. 1: Schematic diagram of greenhouse climate model (Vanegas-Ayala et al., 2022)

To address these challenges and harness the full potential of greenhouse cultivation, the development of a robust and adaptive control system is imperative. Such system will focus on achieving precise regulation of temperature and humidity within the greenhouse, with the overarching objective of optimizing plant development. This project's significance lies in its potential to contribute to sustainable agriculture and food security, particularly in regions where adverse weather conditions or resource limitations may otherwise hinder crop production (Wheeler, 2015).

The model begins with a fundamental framework of the greenhouse environment, as seen in Fig. 1. This diagram illustrates the external weather conditions and the control systems that influence the interior climate of a greenhouse. The growth of crops within the greenhouse is influenced by factors such as energy balance, CO_2 concentration, and air humidity, all of which are subject to the impact of external variables. By leveraging advanced technologies, data-driven strategies, and innovative control algorithms, this research endeavours to create a control system that can continuously monitor, analyze, and adjust the greenhouse environment in real time.

2 LITERATURE REVIEW

The survey of literature relating to the topic will be subdivided into three sections as presented.

2.1 EFFECTS OF TEMPERATURE AND HUMIDITY ON PLANTS AND GREENHOUSES

Relative humidity greatly affects transpiration. Transpiration transports water for photosynthesis and growth and cools plants. Thus, has become crucial to the plant's health. Similar to humidity swings, sudden changes can kill plants. Short-term 20% relative humidity changes can harm tissue (Jaworski & Hilszczański, 2013). Since plants are used to moderate humidity fluctuations in nature, they cannot quickly adapt to such rapid shifts. The link between greenhouse temperature and relative

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*Corresponding Author

Section C- MECHANICAL/MECHATRONICS ENGINEERING & RELATED SCIENCES
Can be cited as:
Akano T. T. and Asaolu O. S. (2023). Modelling of a Greenhouse Climatic Conditions Control System with PID Controller for Plant Growth Optimization, FUOYE Journal of Engineering and Technology (FUOYEJET), 8(4), 478-482. http://doi.org/10.46792/fuoyejet.v8i4.1144

humidity is important because air temperature impacts moisture retention.

Crops are mostly affected by humidity and temperature. Controlling these edaphoclimatic conditions can boost plant health (Maher et al., 2016: Putti et al., 2017). Effective greenhouse management requires temperature and humidity adjustment, which affects crop growth and production (Putti et al., 2017; Boughamsa&Ramdani, 2018). Exclusively regulating air temperature may result in insufficient greenhouse management since temperature and humidity affect important biological functions like transpiration and photosynthesis (Hadidi et al., 2021). Greenhouse temperature and humidity management is complicated and depends on the expertise of agricultural specialists (Cui & Wang, 2013; Hong, 2014).

The synthesis of findings emphasises the integral relationship between relative humidity, temperature, and plant health. Achieving effective greenhouse management requires a comprehensive approach, considering both temperature and humidity adjustments, and underscores the importance of agricultural specialists in navigating the intricacies of this relationship.

2.2 CONTROL OF GREENHOUSE CLIMATIC VARIABLES

To enhance the efficacy of environmental controls in greenhouses, a foundational comprehension of greenhouse climate models is essential. The quality of these models is crucial for developing high-performance controllers, necessitating connections to external factors like solar radiation, outdoor air temperature, wind speed, and various operational activities such as ventilation, cooling, and heating. Achieving optimal performance requires effective regulation of the internal climate, with decision-making across temporal scales to promptly respond to alternative climatic circumstances (Javadikia et al., 2009; Salgado & Cunha, 2005; Subin et al., 2020; Faouzi et al., 2017; Hadidi et al., 2021, Maher et al., 2016). To address the greenhouse effect, numerous methodologies employing artificial intelligence (AI) methods such as artificial neural networks (ANNs), fuzzy logic (FL), and genetic algorithms (GAs) have been developed for monitoring and regulating climatic conditions in greenhouses. These AI strategies find application in various sectors, including contemporary manufacturing, robotics, automation, and the food industry (Hadidi *et al.*, 2021).

A well-engineered greenhouse control system has the potential to effectively manage temperature and humidity levels amidst varying external circumstances. The literature extensively explores desiccant air-conditioning alternatives for greenhouse air-conditioning, and numerous studies delve into control systems managing temperature and humidity in greenhouses, aiming to improve energy efficiency in both traditional and low-energy setups (Shahzad et al., 2021; Sultan et al., 2014, 2016, 2020; Hamidane et al., 2021, 2023; Outanoute et al., 2016; Pawlowski *et al.*, 2017; Piscia *et al.*, 2015; Wang & Wang, 2020; Zhang et al., 2020). These works employ mathematical modelling, experiments, simulations, parametric sensitivity analysis, and greenhouse performance factors to guide the development of innovative control systems that minimize energy usage and optimize growth conditions. This survey establishes the foundational importance of greenhouse climate models, AI methodologies, and control systems in optimizing environmental conditions for greenhouse cultivation.

The subsequent focus of this work centres on the deployment of the Proportional–Integral–Derivative (PID) controller for greenhouse temperature and humidity regulation. Acknowledged for its simplicity and robustness, the PID controller calculates control signals for actuators based on current and desired temperature and humidity values (DiStefano et al., 2012). Various researchers have applied the PID controller in diverse fields, including DC motor response (Martins et al., 2022; Abba et al., 2022) and temperature control in milk pasteurization (Adegbola et al., 2022).

3 MODELS DESCRIPTION AND SIMULATIONS

The components used included set point blocks, which specified desired temperature and humidity levels, and sensor blocks, which simulated temperature and humidity sensors to provide real-time feedback on the actual environmental conditions. The controller blocks serve as the heart of the system, responsible for implementing control algorithms to adjust heating, cooling, humidification, and dehumidification systems based on the sensor feedback. Additionally, plant model blocks captured the dynamics of the greenhouse, describing how the temperature and humidity change in response to control actions. The greenhouse model and control implementation flowchart is shown in Fig. 2

This holistic model aims to achieve precise and stable control of the greenhouse's internal conditions, ensuring that temperature and humidity consistently remain within the desired ranges for optimal plant growth. The greenhouse's dynamic relative humidity model may be determined using (Fitz-Rodríguez et al., 2010)

$$\frac{dH_i}{dt} = \frac{1}{d_a V}\left(E - V_r(H_i - H_o)\right) \quad (1)$$

H_i and H_o are the relative humidity levels inside and outdoors, respectively. The evapo-transpiration rate, denoted as E, is determined by the combined processes of soil evaporation and crop transpiration. This rate may be computed using Eq. (2).

$$E = C_e W_i (p_o - p_i) \quad (2)$$

where $p_o$and $p_i$represent the outside and interior saturated vapour pressure, respectively, while $C_e$denotes the transfer coefficient of water vapour in the air. The equation that governs the internal air temperature is given by as (Fitz-Rodríguez et al., 2010),

$$\frac{dT_i}{dt} = \frac{1}{d_a C_a V}\left(Q_{c-i}^{C} + Q_{ca-i}^{C} + Q_{s-i}^{C} - Q_{inf}^{C_{ventilation_{heating}}}()\right) \quad (3)$$

$Q_{ventilation}$ is the rate of heat lost from the activating the ventilation expressed as,

$$Q_{ventilation} = V_r C_a d_a (T_o - T_i) \quad (4)$$

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where V_r is the ventilation rate; $Q_{heating}$ is the heat provided by the heating system defined as,

$$Q_{heating} = \frac{N_h R_h}{S_s} \quad (5)$$

where N_h is the number of the heaters with the capacity R_h.

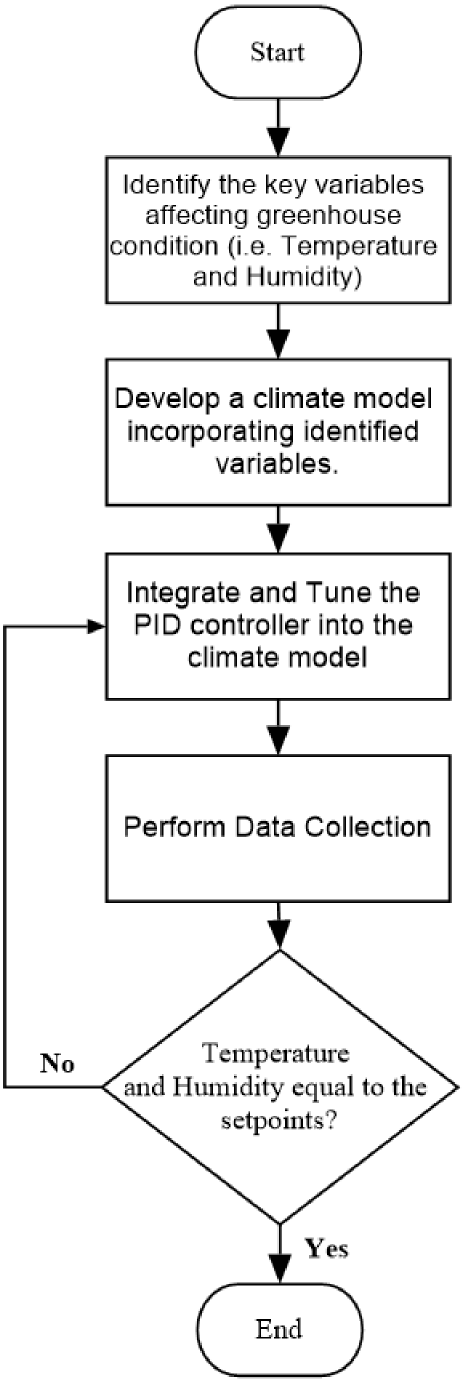

Fig. 2: Greenhouse Control Model Flowchart

The present study employs a PID controller to effectively control both temperature and humidity. The general mathematical description of PID mentioned is given as (Chang, 2007); Arruda et al., 2008),

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right) \quad (6)$$

Where K_p is the proportional gain, T_i is integral time; T_d is the derivative time; $K_i = K_p/T_i$ is the integral gain; $K_d = K_pT_d$ is the derivative gain; $e(t)$ is the current error signal described as $e(t) = x(t) - u(t)$; $x(t)$ are the controlled variables which include the inlet temperature T_{in} and inlet humidity, H_{in}; $u(t)$ are the manipulated variables, which include ventilation rate and water capacity of fog system of greenhouse respectively. The general block diagram of the PID controller for the greenhouse is shown below in Fig. 3.

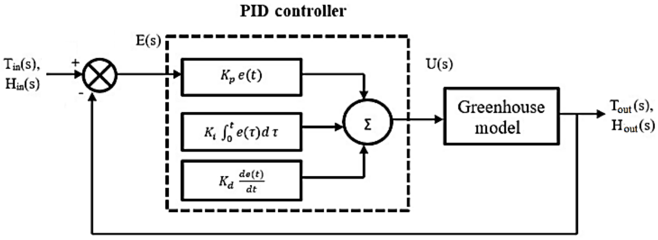

Fig. 3: Closed-Loop Feedback system for Greenhouse using PID Controller

Tuning the PID controller gains enhances the effectiveness of the control system by reducing departures from set-points, minimizing oscillations, and providing stable greenhouse conditions. Visualizations utilizing the scope block enable users to see the system's monitoring of set-points, evaluate overshoot, settling time, and steady-state error, hence easing the assessment of control system performance.

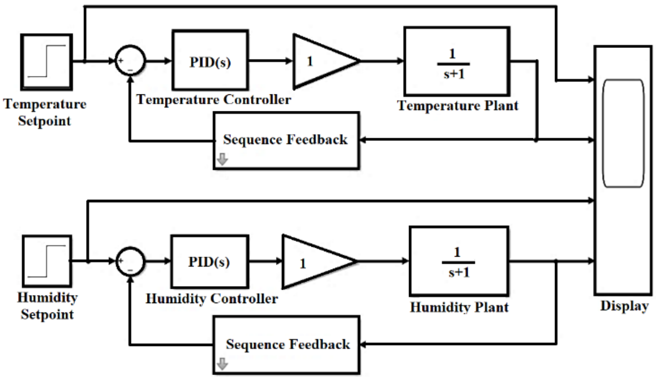

Fig. 4: Simulink model of the greenhouse system

Fig. 4 depicts a Simulink model for a greenhouse control system aimed at effectively regulating temperature and humidity for optimal plant development. The PID controller assesses discrepancies between desired set points and sensor outputs, while a plant model captures greenhouse dynamics. The feedback loop continuously adjusts until stability is achieved, ensuring temperature and humidity align with intended limits. Control strategy selection and controller tuning significantly influence system performance observed overshoot and oscillations during steady-state transition.

4 RESULTS AND DISCUSSION

The findings from the Simulink simulations align well with existing theories and principles in control systems and greenhouse management as reported by Adams et al. (2012) and Hanan et al. (2012). The study yielded positive outcomes, successfully achieving the stated objective of developing a control system capable of restoring the temperature and humidity to a predetermined level of 25°C and 60% (see Fig. 5).

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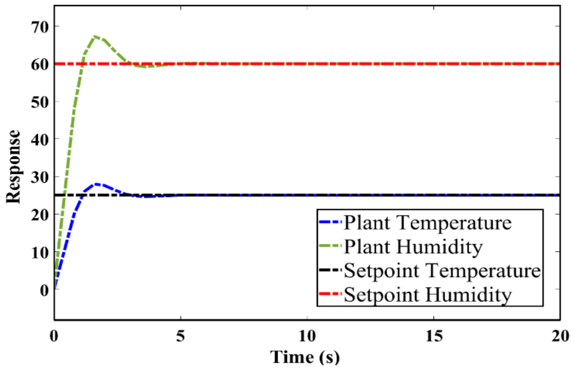

Fig. 5: Temperature and humidity response of the greenhouse

Figure 5 depicts the response of the greenhouse's internal temperature over time. It demonstrates the system's capacity to monitor the temperature set point and emphasises any variations or departures from the intended temperature range. This aligns with the concept of system dynamics (Ogata, 2020). System dynamics theory involves understanding the behaviour of dynamic systems over time. The essential parameters for analysis in the results encompass overshoot, which denotes the extent to which the temperature surpasses the set point prior to achieving stability, settling time, which signifies the duration required to attain a stable condition, and steady-state error, which indicates any enduring discrepancy between the set point and the ultimate temperature value. This discussion is in conforms with control system theory (Dorf, 2016); and these parameters are key metrics in evaluating the performance of control systems. The utilization of a PID controller facilitated the stabilization of the aforementioned variables corresponds with the expected outcomes based on control theory. The inclusion of the integral component in the system's control loop serves to mitigate steady-state error, whilst the derivative term plays a role in attenuating oscillations. This is consistent with classical PID control theory. Collectively, the use of these concepts can effectively mitigate overshoot and enhance the overall responsiveness of the system.

Furthermore, an essential outcome depicted in Fig. 5 is the response of the greenhouse's humidity level over time, in addition to the temperature. The graph has a parallel structure to that of the temperature graph, with the x-axis representing time and the y-axis representing humidity response. The Figure offers valuable information into the efficacy of the control system in maintaining humidity levels within the specified range. Additionally, it elucidates several aspects, including overshoot, settling time, and steady-state error, within the realm of humidity regulation. The humidity PID controller has a similar stabilizing effect on the theses as the temperature PID controller.

The figures show that initially, both temperature and humidity departed from the set point. However, the system efficiently controlled these deviations and brought them back to the target values reflecting the concept of efficient system response (Franklin et al., 2015; Åström and Wittenmark, 2013). In control systems theory, an efficient response implies that the system can quickly and effectively correct deviations from the desired state.

The graphical representations derived from Simulink simulations offer a full perspective on the practical performance of greenhouse control systems. A full comprehension of the fundamental principles and mechanisms in physics is crucial to effectively analyse these graphical representations and make well-informed judgments on the adjustment of control variables and the development of the greenhouse setting. The successful management of greenhouse conditions necessitates a careful equilibrium between the transmission of heat, thermal mass, humidification, dehumidification, and the accurate implementation of control algorithms to sustain the ideal environment for plant cultivation.

The study's success in maintaining temperature and humidity within predetermined levels corresponds with environmental science principles. Achieving and sustaining specific climate conditions is essential for optimal conditions in controlled environments, such as greenhouses or laboratories (Spellman and Stoudt (2013)).

5 CONCLUSION

The simulations showcase the proficiency of the greenhouse control system. The result illustrates its success in monitoring and controlling internal temperature, effectively addressing overshoot, settling time, and steady-state error through PID control. The parallel analysis of humidity further highlights the system's adeptness in maintaining both temperature and humidity within specified ranges. Despite initial deviations, the system efficiently corrects variances, ensuring both parameters return to set points. The graphical representations provide a comprehensive view, emphasizing the importance of a nuanced understanding of physics principles for informed decision-making in greenhouse management. Overall, the control system demonstrates effectiveness in orchestrating environmental variables, fostering an ideal environment for optimal plant cultivation.

REFERENCES

Abba, A. M., Karataev, T., Thomas, S., Ali, A. M., Yau, I., & Mikail, S. A. (2022). Optimal PID controller tuning for DC motor speed control using smell agent optimization algorithm. FUOYE Journal of Engineering and Technology, 7(1), 23-27. https://doi.org/10.46792/fuoyejet.v7i1.740.

Adegbola, Oluwole A., Ebenezer K. Ojo, and Oluwagbemiga D. Aborisade. 2022. 'A Review on Optimal Temperature Control of Milk Pasteurization Using Extremum Seeking Based Proportional Integral Derivative Controller'. FUOYE Journal of Engineering and Technology 7(1). https://doi.org/10.46792/fuoyejet.v7i1.754.

Ahamed, M. S., Sultan, M., Monfet, D., Rahman, M. S., Zhang, Y., Zahid, A., Bilal, M., Ahsan, T. M. A., & Achour, Y. (2023). A critical review on efficient thermal environment controls in indoor vertical farming. Journal of Cleaner Production, 425, Article 138923. https://doi.org/10.1016/j.jclepro.2023.138923.

Arruda, L. V., Swiech, M. C. S., Delgado, M. R. B., & Neves-Jr, F. (2008). PID control of MIMO process based on rank niching genetic algorithm. Applied Intelligence, 29(3), 290-305. https://doi.org/10.1007/s10489-007-0095-6, 2008.

Åström, K. J., & Wittenmark, B. (2013). Adaptive control. Courier Corporation.

Chang, W. D. (2007). A multi-crossover genetic approach to multivariable PID controllers tuning. Expert systems with applications, 33(3), 620-626. https://doi.org/10.1016/j.eswa.2006.06.003.

Cui, W., & Wang, X. D. (2013). Study on the fuzzy expert system of cucumber planting temperature humidity control in greenhouse. Applied Mechanics and Materials, 336, 820–825. 10.4028/www.scientific.net/AMM.336-338.820.

Ding, J.-T., Tu, H.-Y., Zang, Z.-L., Huang, M., & Zhou, S.-J. (2018). Precise control and prediction of the greenhouse growth environment of Dendrobium candidum. Computers and Electronics in Agriculture, 151, 453–459. https://doi.org/10.1016/j.compag.2018.06.037.

DiStefano, J. J., Stubberud, A. R., & Williams, I. J. (2014). Feedback and control systems, Schaum's Outline of Feedback and Control Systems. 2nd ed. New York: McGraw-Hill Education.

Dorf, R. C., & Bishop, R. H. (2022). Modern Control Systems, 14th Pearson. Santa Monica.

Faouzi, D., & Bibi-Triki, N. (2016). Modeling, Simulation and Optimization of agricultural greenhouse microclimate by the application of artificial intelligence and/or fuzzy logic. https://doi.org/10.20944/preprints201607.0064.v1.

Fitz-Rodríguez, E., Kubota, C., Giacomelli, G. A., Tignor, M. E., Wilson, S. B., & McMahon, M. (2010). Dynamic modeling and simulation of greenhouse environments under several scenarios: A web-based application. Computers and Electronics in Agriculture, 70(1), 105–116. https://doi.org/10.1016/j.compag.2009.09.010.

Franklin, G. F., Powell, J. D., & Emami-Naeini, A. (2015). Feedback control of dynamic systems (Vol. 33). London: Pearson.

Gruda, N., & Tanny, J. (2014). Protected crops. Horticulture: Plants for People and Places, Volume 1: Production Horticulture, 327–405. https://doi.org/10.1007/978-94-017-8578-5_10.

Hadidi, A., Saba, D., & Sahli, Y. (2021). The role of artificial neuron networks in intelligent agriculture (case study: greenhouse). Artificial Intelligence for Sustainable Development: Theory, Practice and Future Applications, 45–67. https://doi.org/10.1007/978-3-030-51920-9_4.

Hamidane, H., El Faiz, S., Guerbaoui, M., Ed-Dahhak, A., Lachhab, A., & Bouchikhi, B. (2021). Constrained discrete model predictive control of a greenhouse system temperature. International Journal of Electrical and Computer Engineering, 11(2),1223. http://doi.org/10.11591/ijece.v11i2.pp1223-1234.

Hamidane, H., Faiz, S. E. L., Rkik, I., El Khayat, M., Guerbaoui, M., Ed-Dahhak, A., & Lachhab, A. (2023). Constrained temperature and relative humidity predictive control: Agricultural greenhouse case of study. Information Processing in Agriculture. https://doi.org/10.1016/j.inpa.2023.04.003.

Javadikia, P., Tabatabaeefar, A., Omid, M., Alimardani, R., & Fathi, M. (2009). Evaluation of intelligent greenhouse climate control system, based fuzzy logic in relation to conventional systems. 2009 International Conference on Artificial Intelligence and Computational Intelligence, 4, 146–150. https://doi.org/10.1109/AICI.2009.494.

Jaworski, Tomasz & Hilszczański, Jacek. (2013). The effect of temperature and humidity changes on insects development their impact on forest ecosystems in the expected climate change. Forest Research Papers. 74. https://doi.org/10.2478/frp-2013-0033.

Maher, A., Kamel, E., Enrico, F., Atif, I., & Abdelkader, M. (2016). An intelligent system for the climate control and energy savings in agricultural greenhouses. Energy Efficiency, 9, 1241–1255. https://doi.org/10.1007/s12053-015-9421-8.

Martins, O. O., Adekunle, A. A., Arowolo, M. O., Uguru-Okorie, D. C., & Bolaji, B. O. (2022). The effect of an evolutionary algorithm's rapid convergence on improving DC motor response using a PID controller. Scientific African, 17, e01327. https://doi.org/10.1016/j.sciaf.2022.e01327

Ogata, K. (2020). Modern control engineering, 5th ed. Prentice Hall.

Outanoute, M., Lachhab, A., Ed-Dahhak, A., Guerbaoui, M., Selmani, A., & Bouchikhi, B. (2016). Synthesis of an Optimal Dynamic Regulator Based on Linear Quadratic Gaussian (LQG) for the Control of the Relative Humidity Under Experimental Greenhouse. International Journal of Electrical & Computer Engineering (2088-8708), 6(5). https://doi.org/10.11591/ijece.v6i5.pp2262-2273.

Pawlowski, A., Sánchez-Molina, J. A., Guzmán, J. L., Rodríguez, F., & Dormido, S. (2017). Evaluation of event-based irrigation system control scheme for tomato crops in greenhouses. Agricultural Water Management, 183, 16–25. https://doi.org/10.1016/j.agwat.2016.08.008.

Piscia, D., Muñoz, P., Panadès, C., & Montero, J. I. (2015). A method of coupling CFD and energy balance simulations to study humidity control in unheated greenhouses. Computers and Electronics in Agriculture, 115, 129–141. https://doi.org/10.1016/j.compag.2015.05.005.

Putti, F. F., Gabriel Filho, L. R. A., Gabriel, C. P. C., Neto, A. B., Bonini, C. dos S. B., & Dos Reis, A. R. (2017). A Fuzzy mathematical model to estimate the effects of global warming on the vitality of Laelia purpurata orchids. Mathematical Biosciences, 288, 124–129. https://doi.org/10.1016/j.mbs.2017.03.005.

Salgado, P., & Cunha, J. B. (2005). Greenhouse climate hierarchical fuzzy modelling. Control Engineering Practice, 13(5), 613–628. https://doi.org/10.1016/j.conengprac.2004.05.007.

Shahzad, K., Sultan, M., Bilal, M., Ashraf, H., Farooq, M., Miyazaki, T., Sajjad, U., Ali, I., & Hussain, M. I. (2021). Experiments on energy-efficient evaporative cooling systems for poultry farm application in Multan (Pakistan). Sustainability, 13(5), 2836. https://doi.org/10.3390/su13052836.

Spellman, F. R., & Stoudt, M. L. (2013). Environmental science: Principles and practices. Rowman & Littlefield.

Subin, M. C., Singh, A., Kalaichelvi, V., Karthikeyan, R., & Periasamy, C. (2020). Design and robustness analysis of intelligent controllers for commercial greenhouse. Mechanical Sciences, 11(2), 299–316. https://doi.org/10.5194/ms-11-299-2020.

Sultan, M., Miyazaki, T., Koyama, S., & Saha, B. B. (2014). Utilization of desiccant air-conditioning system for improvement in greenhouse productivity: A neglected area of research in Pakistan. Int J Environ, 4(1), 1–10.

Sultan, M., Miyazaki, T., Saha, B. B., & Koyama, S. (2016). Steady-state investigation of water vapor adsorption for thermally driven adsorption based greenhouse air-conditioning system. Renewable Energy, 86, 785–795. https://doi.org/10.1016/j.renene.2015.09.015.

Sultan, M., Niaz, H., & Miyazaki, T. (2019). Investigation of desiccant and evaporative cooling systems for animal air-conditioning. Low-Temperature Technologies; IntechOpen: London, UK, 21–37. https://doi.org/10.5772/intechopen.88945.

Vanegas-Ayala, S.-C., Barón-Velandia, J., & Leal-Lara, D.-D. (2022). A systematic review of greenhouse humidity prediction and control models using fuzzy inference systems. Advances in Human-Computer Interaction, 2022, 1–16. https://doi.org/10.1155/2022/8483003.

Wang, L., & Wang, B. (2020). Greenhouse microclimate environment adaptive control based on a wireless sensor network. International Journal of Agricultural and Biological Engineering, 13(3), 64–69. https://doi.org/10.25165/j.ijabe.20201303.5027.

Wheeler, T. (2015). Climate change impacts on food systems and implications for climate-compatible food policies. In: Elbehri, A. (ed.) Climate Change and Food Systems: Global assessments and implications for food security and trade. Food and Agriculture Organization of the United Nations, Rome, 315-336.

Zhang, S., Guo, Y., Zhao, H., Wang, Y., Chow, D., & Fang, Y. (2020). Methodologies of control strategies for improving energy efficiency in agricultural greenhouses. Journal of Cleaner Production, 274, 122695. https://doi.org/10.1016/j.jclepro.2020.122695.