"Operating Status and Anomaly Monitoring Techniques for ICT Components in Smart Greenhouse"

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ABSTRACT

Information and Communication Technology (ICT) based smart greenhouses have now evolved methods of controlling climate in horticulture to make the production process more efficient. These include the sensors, actuators, communication protocols and possibly cloud computing to enhance the use of resources and obtain the best crop production. Nonetheless, the key components in the implementation of ICT are prone to a number of risks, such as hardware breakdown, interruption in the communication network, and data corruption. Based on the literature review, the paper aims to identify existing methods of monitoring and detecting abnormalities in smart greenhouses for proper functioning. The types of anomalies identified in the study include hardware failure, communication problems, and data outliers, and therefore, appropriate detection methods need to be implemented. Among the approaches of AI and machine learning to use for characterizing and monitoring abnormal activities or improving the system efficiency are the supervised, unsupervised, and deep learning methods. Moreover, signal processing techniques such as Fourier and Wavelet have been introduced for the analysis of anomalous data patterns. The application of multi-variant methods based on machine learning, statistical data analysis, and brainstorming with domain experts would be more effective for creating highly reliable systems for anomaly detection. It also revealed that temperature, humidity, and dust are some of the environmental factors that may have a negative impact on ICT. There are four published corresponding articles planned for the follow-up work, including improving the hybrid models, scalability, and energy saving of the system for sustainable greenhouse management. This research contributes to the development of ICT in modern agriculture, which leads to the establishment of an efficient and effective form of agriculture.

INTRODUCTION

Overview of Smart Greenhouses

Through Information and Communication Technology (ICT) intervention in farming, smart greenhouses are some of the innovations that have emerged due to precision growth environments for plant growth. They assist in controlling water supply, temperature, humidity, and lighting with little reference to human input. Smart greenhouses are beneficial in the current global world, which is affected by climate change, scarcity, and insecurity of resources and food (Escobar-Teran *et al.*, 2025).

Importance of ICT Components in Smart Greenhouse

An innovative greenhouse requires intelligent systems and sensor technology to collect and provide data, analyse the data, and implement reactions independently. These include the sensors, actuators, and devices central to cloud computing, as well as artificial intelligence-based analytics to determine the plant's health and growth conditions and any inefficiencies that might be experienced. Dependability and avoiding faults are crucial requisites for enhanced performance and output.

Challenges in Monitoring and Anomaly Detection

Challenges of mechanical breakdown, connectivity, and disruptions from environmental factors are experienced in ICT-based greenhouse systems. Possible system failures that can be associated with the current system are a common challenge that results in monitoring disruptions, hence the costs like yield loss and wasted resources, among others.

Objectives and Scope of the Review

This research aims to:

- To assess the general approach to operational monitoring in smart greenhouses.
- To discuss the malfunction detection methods of innovative greenhouse management.
- To identify existing gaps in the ICT-based anomaly detection system.
- To discuss future studies to help improve good strategic system performance and dependability.

ICT components in smart greenhouse management

Core ICT infrastructure

In smart greenhouses, the central part of the ICT substructure is based on the interaction of several interconnected technologies required for monitoring and control. It is made of subcomponents that ensure data acquisition in real-time and transmission and real-time processing, which are fundamental in precision agriculture. The four primary components of this structure are sensor and actuator instruments, transmissions and protocols, entry-level devices and gateways, and cloud environments (Inson Green, 2023).

Sensors and Actuators: Classification, Functionalities, and Deployment Strategies

One of the vital parts of smart greenhouses is sensors that assess the environmental condition by measuring temperature, humidity, light intensity, moisture, and CO_2 level. These sensors can be categorised into:

- Environmental sensors (temperature, humidity, and CO_2 sensors) for climate control.
- Soil sensors (moisture, pH, and nutrient sensors) for plant health monitoring.
- Light sensors, including PAR and UV sensors, are used to regulate artificial and outdoor natural light.

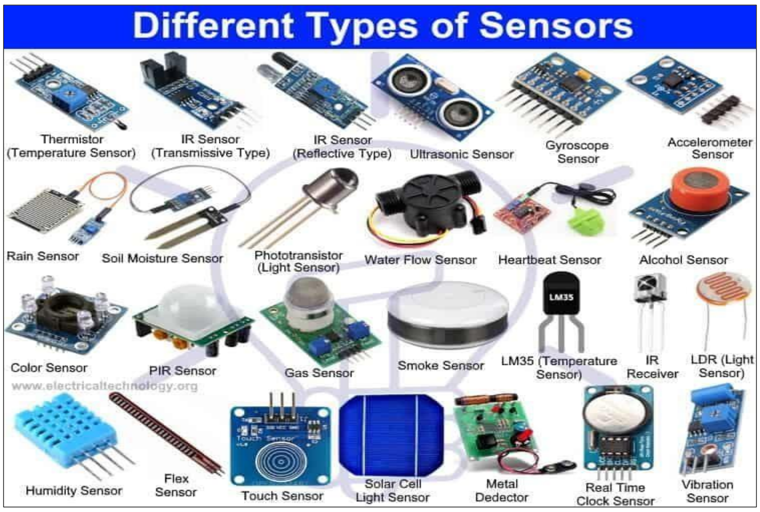

Figure 1: Different Types of Sensors with Applications (Kayadibi, 2025).

Actuators take some inputs from the sensors and perform some operations to control the proper growing environment. These include:

- Irrigation actuators, the electronic computer-controlled mechanisms of automated drip irrigation systems, and the highly effective sprinkling system known as misting.
- Ventilation actuators include exhaust fans and auto-control window openers.
- Lighting actuators (LED grow lights) operate by means of real-time sensing feedback.

The location of sensors and actuators should be good, dividing the entire greenhouse and placing them throughout the area so that they receive the same amount of resources to ensure efficiency. Wireless sensor networks (WSNs) also add to the system's essential advantages by improving elements such as deployment, which can be done wirelessly (Yellampalli, 2021).

Communication Protocols: LoRaWAN, NB-IoT, Zigbee, and Bluetooth

Real-time communication procedures are crucial in forwarding the data sensed to the processing units. The following are the main key protocols which are used in smart greenhouses:

LoRaWAN (Long Range Wide Area Network)

- Optimised for use in long-distance low-power interfaces (Maraveas, 2023).
- It supports distributed sensor networks, each one having low energy utility.
- Ideal for large-scale smart greenhouse deployments.

NB-IoT (Narrowband Internet of Things)

- Operates on licensed cellular networks, hence providing high reliability in its operations.
- The cover provides adequate protection, particularly in capable greenhouse settings.
- It can be used in applications with low data rates as well as high energy consumption.

Zigbee

- It is a protocol that can be used to connect smart greenhouse devices at a low power distance.
- It supports mesh networking that helps work properly and manage data flow, making it self-healing.
- It is frequently employed in wireless sensor-actuator networks.

Bluetooth

- A short-range protocol ideal for local device-to-device communication.
- The following is applied for on-site monitoring and control by using a portable interface through the mobile applications.

All four protocols are selected depending on the size of the greenhouse, the necessary data transfer rate, and energy consumption.

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Gateways and Edge Devices: Role in Real-Time Data Aggregation and Processing

Based on the architecture, edge devices and gateways are very useful in handling data in real time before sending information to the cloud systems (Ali, 2022). Their functions include:

- Information is collected from several sensors and various devices.
- Elimination of the multiple transfers and other elements that may slow down or cause jams in the network.
- Using local models in order to detect anomalies in the machine learning machine quickly.

It has a low latency and minimises data transmission, which speeds up the decision-making process in an automated greenhouse.

Cloud Platforms: Data Storage, Analytics, and System Integration

Cloud solutions are considered to be central points for data storage and analysis as well as for remote control. Their key functions include:

- Big data analysis for predictive modelling and early anomaly detection.
- Remote access to greenhouse conditions via IoT dashboards.
- Seamless integration with AI-driven automation and decision support systems.

Through cloud computing technology, greenhouse operators get real-time information to control them from a distance, thus increasing their efficiency of operation.

Interconnected system architecture

Brilliant greenhouse system architecture facilitates a multi-layer framework for monitoring real-time data, controlling, and decision-making functions. Such layers also help in the proper communication of various nodes, including the sensors, actuators, gateways, cloud platforms, and interfaces that optimise the environment's efficiency (Saiwa, 2023).

Overview of Typical Smart Greenhouse System Architectures

A conventional architecture of an innovative greenhouse encompasses four tiers as follows;

1. Perception Layer (Sensor-Actuator Layer)

- Includes environmental and soil measuring devices (temperature, humidity, light, CO_2, pH, moisture, etc.).
- This category includes components such as irrigation pumps, ventilation fans, and artificial lights, among others.
- It is responsible for collecting data on the surrounding environment and performing specific control actions according to a set threshold.

2. Network Layer (Communication Layer)

- It helps in moving data between sensors, actuators, and processing units.
- Supports Ethernet, Modbus, LoRaWAN, NB-IoT, Zigbee, and Bluetooth connections.

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3. Processing Layer (Edge and Cloud Computing Layer)

- Some of the tasks of edge devices and gateways include filtering, pre-processing, and aggregating information (Resources, 2022).
- Their applications include data mining and analysing the data for predictive analysis as well as identifying abnormalities.
- Cloud service providers provide storage and remote access to greenhouses and producers.

4. Application Layer (User Interface Layer)

- It offers dashboards and mobile applications for remote interfaces for monitoring and controlling.
- It additionally sends notifications to the farmers and advises them by providing them with real-time data.

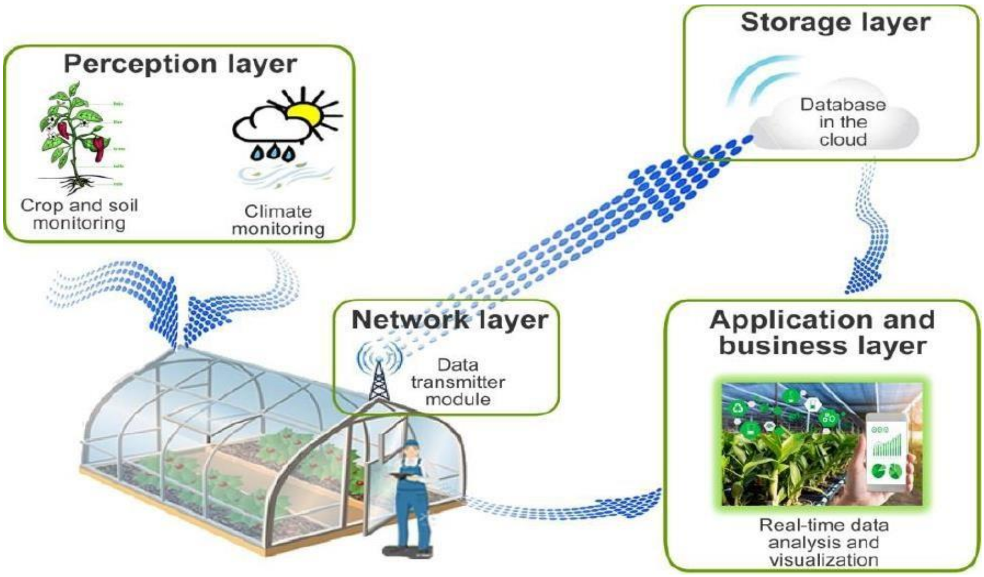

Figure 2: IoT Architecture for Greenhouse Monitoring (Ruiz-Ortega et al., 2022).

For a greenhouse to be innovative, the architecture should consist of multiple layers to allow for effective automation, continuous monitoring of conditions, and sound decisions on what to do next in a greenhouse.

Communication Pathways from Sensors to the Cloud

Communication of data in smart greenhouses is sequential in a top-down manner to warrant the effective organisation of data:

1. Sensors obtain environmental climate data, details on the soil, and information on plant health in real-time.
2. Information using wireless or wired interfaces such as LoRaWAN, NB-IoT, Zigbee or Bluetooth sends data to the edge or gateway devices (Orange, 2024).
3. The idea is that edge devices perform filtering and preprocessing to accentuate latency and bandwidth usage.
4. It flows information to the cloud servers for further storage and analysis after being processed by gates.
5. Machine learning, currently hosted in the cloud, also focuses on data analytics for specific monitoring checks, such as anomaly detection and predictive maintenance.

6. Users quickly acquire the information through its mobile applications, web panels or notification services.

Therefore, both pathways are clear, with low latency and real-time response, thus enhancing resilience and better production in smart greenhouses.

Operational metrics for ICT components

Depending on the type, ICT equipment that is applied in a bright greenhouse must be able to perform its functions effectively and with a high level of reliability. Different key performance indicators are typically used in the evaluation of the system performance with a view to enhancing it. These include latency, throughput, reliability, scalability, and energy efficiency, which help allow real-time operations and prevent wastage of resources (Yang *et al.*, 2021). All these metrics bear great significance to the improvement of the functionality and productivity of an innovative greenhouse system.

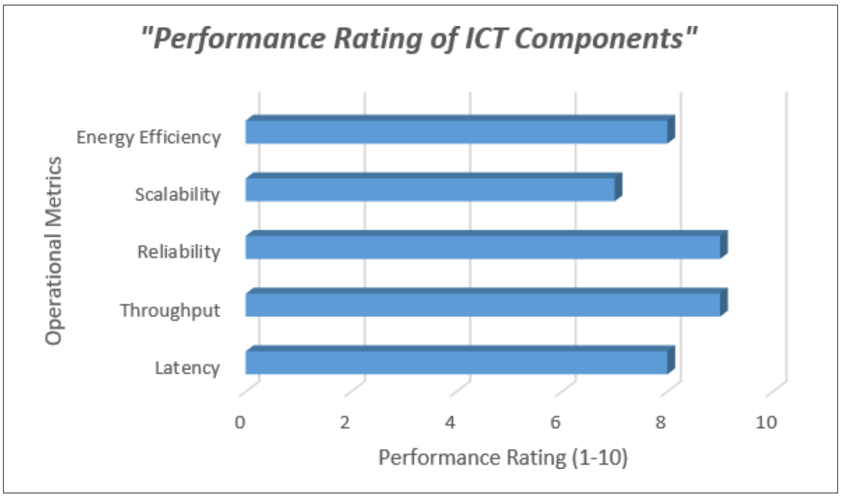

Figure 3: Performance Ratings of ICT Metrics in Smart Greenhouse Systems (self-made).

Latency

Latency relates to the delay time between the time that a sensor measures some form of data and the subsequent action that is carried out by the actuator (Ghosh, 2023). Since smart greenhouses are an integral part of the industrial automation process, the system's latency should be minimal to support the smooth functioning of the process, for example, in irrigation, ventilation, or lighting. High latency results in resource wastage and a disturbance of environmental control, especially when the value chain involves sensitive operations.

- **Goal**

For time-sensitive actions like changing the settings of the irrigation system due to the moisture level in the soil, the response time must be under a sub-second mark.

- **Impact**

Less latency also helps to maintain fast responses without interfering with the conditions necessary for the greenhouse.

Throughput

Throughput is the volume of work that can be accomplished on or through the IT system in a specific period. In an innovative greenhouse, throughput refers to the amount of data that can flow back and forth between the sensors, edge devices, gateway, and cloud platforms involved. This ensures that the system can effectively receive information from several sensors and monitor several sorts of environmental factors.

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- **Goal**

Following throughputs will help to ensure that there are no bottlenecks that would slow the continuous monitoring process.

- **Impact**

High throughput enables technology to receive data from various sensors without data loss, thereby allowing the system to more effectively control and monitor the greenhouse environment.

Reliability

Reliability is a component of the ICT system that enables it to operate correctly without breakdowns (Tuba, Akashe and Joshi, 2022). In an innovative greenhouse, some basic standards for irrigation, lighting, and temperature must be constant. A reliable system will not likely break down often or fail in operations, enhancing the greenhouse's sustainability and productivity.

- **Goal**

Ensure that the system is highly available and eliminate equipment malfunctions.

- **Impact**

This system affirms that operations are continuous and without hitches, thus achieving a considerable reduction in operational cost, mainly if a system failure requires repair.

Scalability

Scalability entails the capability of the innovative greenhouse system to expand the number of incorporated sensors, actuators, or devices due to changes in requirements in the future without a negative impact on the system. If an innovative greenhouse is growing or incorporating new technologies, the system should be able to develop and accommodate a higher amount of data and devices.

- **Goal**

Ensure that a scalable IT design can accommodate new devices and technologies without negatively impacting existing ones.

- **Impact**

Scalability enables the system to adapt to the increasing number of devices connected to a greenhouse if it develops into a large one.

Energy Efficiency

Energy efficiency is an essential factor in controlling smart greenhouses, mainly because most of the ICT equipment (e.g., sensors, actuators, and communication tools) in the greenhouse is primarily run by batteries or electrical energy from the greenhouse system (Aleem, Balci and Rawa, 2024). Efficient energy employs less power, hence reducing the cost of operating the greenhouse, and it is environmentally friendly.

- **Goal**

Energetic efficiency in all components’ use and reducing energy consumed by the communication between the devices.

- **Impact**

Energy consumption optimisation lowers operation costs and minimises environmental impacts and greenhouse gas emissions that contribute to climate change.

Challenges in operational status monitoring and anomaly detection

Technical Challenges

Smart greenhouses are systems that require several technologies in order to control and manage the operating process of agriculture (*K et al.*, 2024). However, several technical issues may influence the effectiveness of smart greenhouses based on their technical aspects. The difficulties that need to be surmounted include hardware problems, data integrity questions, and scalability questions. The following are some of the issues that can only be overcome in the long run for innovative greenhouse systems:

Hardware Issues: Reliability, Wear and Tear, and Environmental Impacts

Another significant technical complexity includes achieving reliability in a bright greenhouse's hardware that comprises sensors, actuators, and communication devices. These are some of the components that are exposed to the unfavourable conditions that are characteristic of the environment within a greenhouse. Therefore, some of them wear out with time. For example, high humidity, temperature and dust affect the performance and life expectancy of sensors and actuators. Also, mechanical failure and shock of different kinds harm the devices, thereby resulting in their malfunctioning.

This is made worse by environmental factors that also affect the population. For example, temperature variations affect electrical parts and cause failures in apparatuses with sensitive components; high humidity leads to corrosion, affecting metal apparatuses. This vulnerability necessitates constant checking and adjustment to effectively capture the correct data promptly and for the system to work efficiently. Also, with time, the various worn-out components during the greenhouse construction require replacement, which can otherwise put an extra cost on the greenhouse operators.

- **Solution**

  Such challenges can be overcome by conducting regular maintenance, using weather-resistant materials, and having self-diagnosing systems in the building.

Data Integrity: Packet Loss, Noise, and Incorrect Readings

The whole process of obtaining data has to be accurate since incorrect information may have negative consequences in terms of resource utilisation and the state of plants in the innovative greenhouse system. However, one of the most tangible and prevalent problems in the transmission of data is the variety of packet loss. This is realised when the data that needs to be transmitted does not get to the intended recipient end as a result of lousy communication channels or traffic jams. This is because when the data packets are lost, it means that the system lacks some of the information that it requires in order to come up with the best decisions; therefore, the system will either make a wrong decision or take too long to come up with a decision due to the missing information (Routray and Mohanty, 2021).

Impairments such as noise can occur, usually due to electromagnetic interference (EMI) or sensor signal degradation. For example, soil moisture readings may have poor results that originate from the impact of electrical devices on the nearby signals from the sensor. This may then pose a difficulty in computation since algorithms can have significant issues identifying what may or may not be relevant information and what may be mere noise.

Another issue necessary to consider is data integrity, one of which is sensor calibration. In the long run, the sensors may be off in various ways and thereby provide wrong results. Such drift might be due to their surrounding environment or could just be typical sensor ageing.

- **Solution**

  Employing multiple sensors to compare their results, operating with error-detecting and correcting codes, and daily sensor calibration are the main actions that can help increase the level of data credibility.

Scalability: Challenges in Large-Scale Systems

Other issues considered in this component include system scalability, which is a challenge in innovative greenhouse systems as the system increases from just a small prototype space to a complete operational environment. As the number of sensors, actuators, and devices increases, so does the probated data and the necessity of real-time analysis of the system. More formalism is needed for scaling up to accommodate an enhanced data acquisition and handling system that would be required to process the amounts of data that the sensors will produce.

It is noteworthy that as the number of interconnected devices rises, the complexity of the management task increases as well. For large networks, there is a need for the optimisation of communication protocols with the goal of interfering with the data minimum in the process. The integration between the devices of different producers also becomes a problem since some of them may not be compatible with others, and there must be protocols that can facilitate the work of the IoT (NiuBoL, 2024).

- **Solution**

  Concerning the issue of expansion, the systems must consider being developed with modularity in mind. It is possible to decrease the load on central servers by employing edge computing to perform computations in the area of the source. Alternatively, using cloud computing platforms with a variable amount of resources to meet growing data needs does not slow down system performance.

Environmental and Agricultural Impacts

Temperature, humidity, and dust are some of the environmental issues that affect the ICT systems in smart greenhouses. All of these aspects may directly influence the dependability and performance quality of devices such as sensors, actuators, and communication gadgets within the system. These factors must then be outlined and assessed so as not to harm the greenhouses' present efficiency and future operations.

Effects of Temperature

Temperature as a parameter of the ICT component can be stated as significant with respect to smart greenhouses (Fong, Dey and Joshi, 2022). High and low temperatures are enemy to most machines and, therefore, electronic devices and their components. For example, temperature and humidity sensors may have changed characteristics concerning their activity when exposed to high temperatures when working. As a result, a system may get the wrong data concerning the temperature or humidity. Lower temperatures can also harm batteries, decrease the operating efficiency of all wireless products, and demand more frequent battery purchases.

High temperatures can also cause expansion, which may damage the sensors or communication circuits and, in turn, lead to equipment malfunction. Furthermore, temperature variation increases the chances of data variation, which in turn distorts the communication signalling process, leading to the development of communication interferences that hinder the flow of data in the system.

Effects of Humidity

Other factors may have an impact on ICT systems, among them being humidity. In addition, high humidity affects durability through the accumulation of moisture on the different components of an item, which forms a substrate for a short circuit and corrosion, whereby metallic parts will be affected. It requires extra precautions regarding environmental considerations if are using sensors to measure air or soil moisture because moisture may affect the optimal functioning and the reading from the sensors.

High humidity also affects the performance of wireless communication devices. Moisture in the environment affects the radio frequency signals, leading to attenuation and a reduction in the range of transmission. This may eventually result in the loss of some data packets and delays in the application's system response time.

Effects of Dust

Such conditions in greenhouses imply that there is dust that affects the sensors and decreases their reliability. It can be due to the dust that tends to accumulate on the surfaces of the sensors, which leads to the sensors' failure to respond or giving improper readings. This is especially true for sensors used to monitor the level of pollutants, light intensity, and temperature. In addition, dusting can hinder the flow of fresh air and the rates of fresh air circulation; the performance of appliances like fans or air conditioning systems can also be affected.

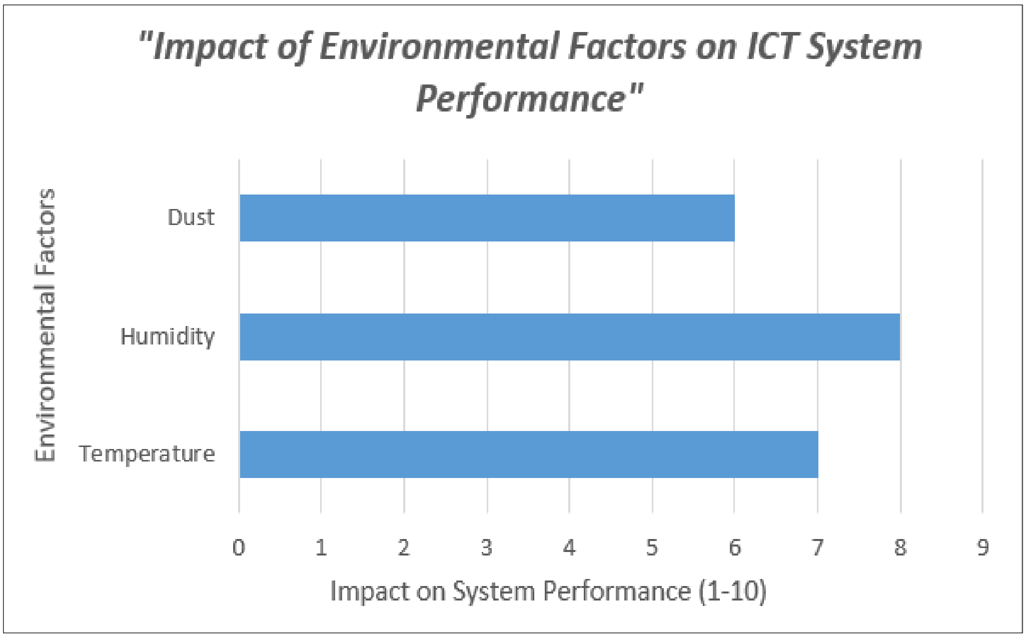

Figure 4: Impact of Environmental Factors (Temperature, Humidity, Dust) on ICT System Performance in Smart Greenhouses (self-made).

Integration and Interoperability

Installing and enabling different devices and integrating various platforms also pose considerable problems in innovative greenhouse systems. These systems may contain different ranges of sensors, actuators, and communication devices from other manufacturers, which include different protocols of communication standards and data formats. This eventually results in compatibility problems that affect the exact linking of the components and, thus, the communication of valid information.

For example, sensors that work with specific protocols, such as LoRaWAN or Zigbee, can face compatibility issues with cloud platforms or gateways that are incompatible with them (Adler, 2023). However, flawed data format or noncompliance with the format can lead to data misunderstandings and strategic organisational and systems management decisions.

To address these problems, commonly agreed protocols and application layer interfaces are needed to interconnect hardware from different vendors. It can also be noted that if one system is designed in a modular way that enables its integration with other systems, it can easily enhance the system's performance.

Anomaly detection in ICT components

Understanding Anomalies in Smart Greenhouses

Malfunctions or irregularities in smart greenhouses are termed anomalies, which are deviations from the normal function of the system. When they arise, such issues can hamper the greenhouse's operation and impact plant growth, resource usage, and efficiency. Therefore, it is necessary to correctly classify and identify these as parameters for monitoring and detection. Primary types of anomalies of smart greenhouses include hardware failures, communication issues, and outliers in data (Simon and Barr, 2023).

Hardware Failures

Among all the above-mentioned anomalies, hardware failures are considered to be one of the most severe issues in smart greenhouses. These failures arise when the sensors, actuators or another part of the system fail to provide the correct data or to execute planned actions such as irrigation or ventilation in this case. Other standard components that cause hardware failure are customisation, which causes wear and tear on components and harm by the environment; climate changes such as humidity or temperatures that are very high or low; and physical damage due to drastic mechanical pressure. For example, a soil moisture sensor may not attain an accurate measure when its internal components are faulty. Likewise, an irrigation actuator may not operate efficiently, and therefore, the crops are watered to a wrong level than what is required.

Communication Issues

In some cases, there will be a problem with communication from a sensor or actuator within the system because the network may fade or the signal may be interrupted. Some of these problems result from connectivity complications, interference, or mismatch of protocol connections of the concerned devices. For example, a LoRaWAN sensor may fail to send packets or may take time to send data to the end node due to several objectives on the channels or communication lines (Di Francia and Di Natale, 2023). This case means that the performance of crucial tasks such as climate control or irrigation may be slowed down due to communication problems.

Data Outliers

These are perturbations of the sensor data which appear abnormally and can be very much higher or lower than the typical expected values. They can be caused by some changes in the parameters of a car’s sensors, its environment, or by interference. For example, an increase in temperature values may point to the sensor's fault instead of an increase in temperature. If there is an influential number of such data, it can cause a wrong decision and lead to further actions (for example, the climate control system may be turned on, although it is not necessary).

By dividing the anomalies into three categories, innovative greenhouse systems can detect the causes of problems and address them appropriately to ensure that greenhouse systems are up and running as they are supposed to be.

AI and Machine Learning-Based Techniques

The incorporation of Artificial Intelligence (AI) and Machine Learning (ML) methods is an inevitable step towards the improvement of smart greenhouses. Through the application of supervised and unsupervised learning, deep learning and the integration of these together, smart greenhouses can, in essence, identify faults, energy and water consumption, and system breakdowns. These techniques facilitate the extraction of advanced data analysis so as to enable efficient decision-making on the operations of greenhouses.

Supervised and Unsupervised Learning Models

Supervised learning train on labelled datasets in which the input data is joined with an outcomes data drain. In the case of smart greenhouses, supervised models can be used to predict system behaviour based on past information. For example, a model could be trained to take temperature, humidity and moisture of the soil as input parameters and estimate the most suitable irrigation levels for specific plants. Among those algorithms that can be used in supervised learning are the Decision Trees, Support Vector Machines (SVMs), and Random Forests (Serrano, 2021). These models can effectively identify the input data for classification or in making decisions such as identifying abnormal values from a sensor and forecasting the extent of environmental conditions after a specific period using the records from the past.

Unsupervised learning comes into play when the data doesn’t have an output to learn from, and the model begins to look for the forms by itself. For example, an unsupervised approach can identify groups of factors that influence plant stress conditions, such as temperature, humidity, etc. For example, the K-means clustering and the Principal Component Analysis (PCA) methods can be employed to identify hidden patterns and outliers that exist in the received data set if the system behaviour is unknown in advance. This might aid in identifying previously unidentified trends within the data, such as an odd activity by a sensor that may be a symptom of the system failure.

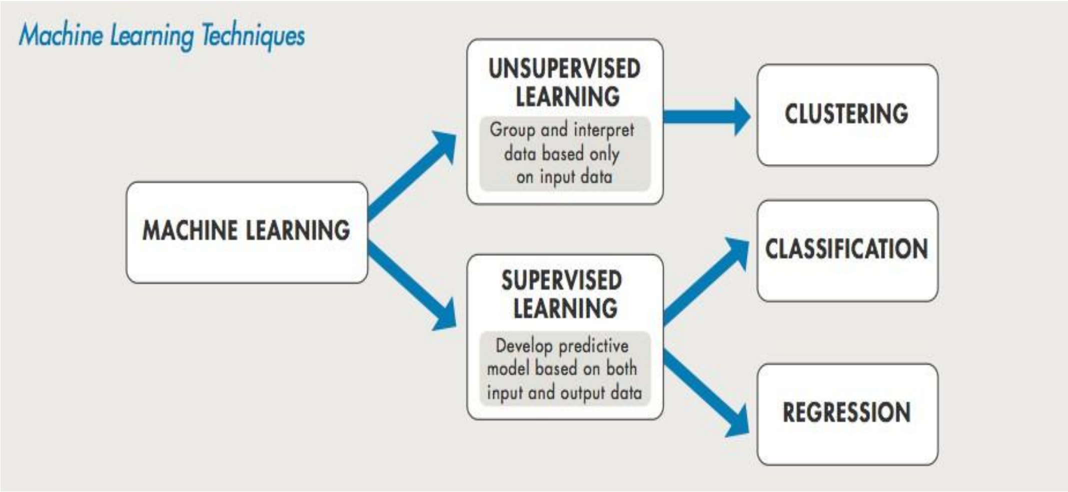

Figure 5: Supervised & Unsupervised Learning Difference (Kumar, 2023).

Deep Learning and Hybrid Approaches for Complex Systems

Deep learning is the use of more than one layer in the neural network, as more layers help capture more data relations. In smart greenhouses, deep learning algorithms are capable of handling a tremendous amount of data and generating multiple predictions. For example, Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) can be used to analyse and forecast the time-series data on temperature, humidity and other weather changes (Swain, Pattnaik and Gupta, 2020). Deep learning is powerful in areas such as high-level image analysis, where it would be used in analysing the output from cameras monitoring the health of plants; the trees or plants may contract diseases or pests that may be seen from the pattern of the leaves.

When the system uses a hybrid of supervised learning, unsupervised learning, and deep learning, it improves the performance of the system on such tasks. For example, in a hybrid model, the first step could be performing clustering to group normal operating conditions and, indeed, identify anomalous ones; the second stage would be classification using further methods such as supervised or deep learning to predict the behaviour of the outliers in the future. This possibility makes it possible for the system to handle a broad spectrum of data and increase the ability to diagnose the variations within the greenhouses.

With such methods of machine learning as supervised and unsupervised learning, deep learning, and their combinations, there is the possibility of enhancing the decision-making process and automating the processes in smart greenhouses. These concepts, in a way, help the system to learn from past values, detect deviation from standard signals, and even predict future circumstances that make greenhouses more optimally efficient, sustainable, and reliable.

Signal Processing for Anomaly Detection

Signal processing methods are crucial in the case of smart greenhouses to detect anomalies where sensor measurements are sometimes corrupted by noise or any form of interference (Doroudi, Lavassani and Shahrouzi, 2024). Some quantitative tools that are applied are the Fourier transforms and wavelet transforms.

Fourier Transforms

Fourier transforms and decomposes a time signal into its components, which are frequencies. This enables the detection of the harmonic structure and other changes in the signal. Fourier transforms help based on the frequency analysis of inputs and outputs, which can reveal irregular frequencies of sensors, such as temperate or humidity sensors, that are considered to be faulty. It is most helpful in detecting cyclical anomalies since it enables one to compare the differences in variations in related variables over time.

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Wavelet Transforms

Wavelet transforms are more flexible because they analyse non-stationary signals in terms of time and frequency. They subdivide such signals into several segments of frequency, which helps detect short-term irregular behaviour or changes in the sensors. Wavelet transforms are useful for detecting short-lived impulses, for example, sharp or higher temperatures and moisture, which point towards a system failure.

Both methods can increase the degree of accuracy detected in identifying anomalies within a greenhouse's dynamic environment.

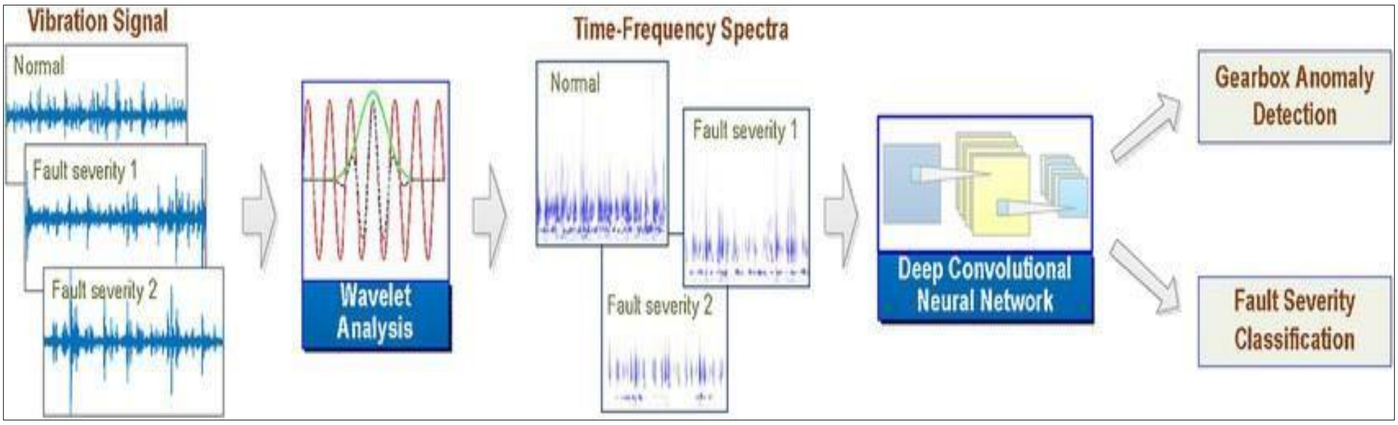

Figure 6: Signal Processing for Anomaly Detection (Wang et al., 2017).

Hybrid Approaches

The integration of statistical and machine algorithms with model knowledge, on the other hand, compiles superior and optimum systems for the analysis of anomalies in smart greenhouses. They then reach the maximum level in order to excel in green house environment. They can also point on any kind of pattern that cannot be spotted when using only one of the techniques.

AI and Statistical Methods

Regression analysis as well as the probabilistic modality can be used alongside machine learning and AI for a better prediction model (Tallón-Ballesteros & Chen, 2020). For instance, while AI models offer an approximate of conditions, on the other hand, statistical models qualify and quantify their ability to do so in order to offer a predicted range to be adopted in decision making.

Incorporating Domain Expertise

Combining knowledge from both agriculture and horticulture would make it easier for a hybrid system to apply rules that concern a specific type of field depending on existing knowledge of anomalous behaviour. For example, integrating outputs that are made by AI solutions into the human experts' knowledge about how plants develop allows for a more effective evaluation of integrative conditions that differ from the normal state, which in turn contributes to greater levels of system optimisation.

It ensures more accurate, reliable and contextual approaches to the identification of required anomalies in dynamic greenhouses.

Practical Applications and Validation

Smart greenhouses and the use of effective and efficient detection systems, such as anomaly detection systems in agriculture, have become vital in the current society. These systems have many application examples, as evidenced by real-world scenarios where they have been implemented to deal with numerous operational issues.

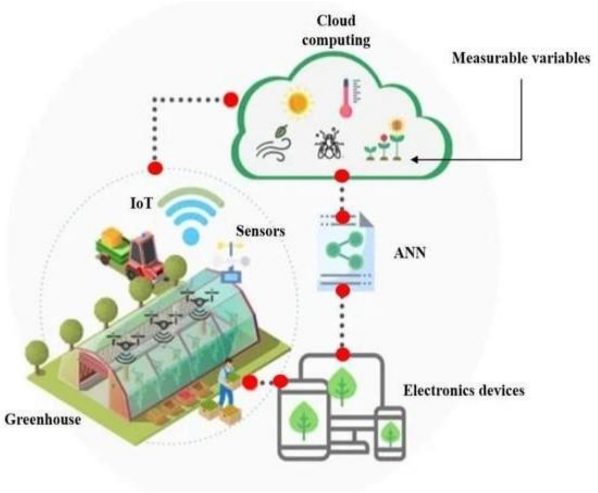

Figure 7: Agriculture applied in a greenhouse (Escamilla-García et al., 2020).

For example, currently, an application in a greenhouse in the Netherlands is using AI-based anomaly detection, where the algorithms detect abnormality in sensing data, such as temperature, humidity, and the CO_2 levels in the greenhouse, in real-time. These systems have been effective in the identification of undesirable or otherwise unanticipated changes like a decrease in temperature or variation in humidity, thus triggering subsequent actions like an increase in ventilation or provision of water, among others.

The following example comes from Japan, where the Fourier and wavelet transforms have been applied to detect sensor faults (Ferracuti, Freddi and Monteriù, 2021). It includes abnormal data pattern recognition, where the system alerts that the sensors are out-of-calibration or require replacement. These examples show that anomaly detection systems when tested on accurate data, improve plant health status assessment, ensure more efficient resource usage, and minimise breakdowns.

CONCLUSION AND FUTURE DIRECTIONS

Conclusion

This research discusses how ICT systems can effectively contribute to the improvement of innovative greenhouse productivity, efficiency, and sustainability. Smart greenhouses empower various activities in horticulture by employing the help of sensors, actuators, communication protocols and data analysis. Nevertheless, the functions and effectiveness of the system are tested with problems in hardware resources, communication, data integrity and accuracy, and temperature, humidity, and dust. Machine learning algorithms, Artificial intelligence-based tools, and signal processing tools like fast and discrete Fourier transforms, wavelet transforms, etc, also help a lot in Anomaly detection and Predictive maintenance. These approaches make it possible for smart greenhouses to immediately notice any inefficiencies that may be there so as to increase efficiency in the use of resources.

Future Directions

It would be helpful for future studies to build on the knowledge and advance the hybrid models which integrate AI and statistics, as well as domain knowledge that would result in more reliable systems. Moreover, the use of edge computing in different devices increases the compatibility of greenhouse systems and the ways to enhance large-scale optimisations for future systems. Further developments in innovative greenhouse technologies should ensue with key considerations on sustainability, improvement of energy efficiency, and flexibility of implementation.

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