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A Study on the Application of Wireless Sensor Networks in Perishable Agro-Food Inventory Management

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Abstract

Effective inventory management is crucial in the agro-food industry, particularly for perishable goods. The increasing demand for efficient tracking and monitoring systems has led to the exploration of wireless sensor networks (WSNs) as a potential solution. This study aims to investigate the application of WSNs in perishable agro-food inventory management to enhance product quality, reduce waste, and improve overall supply chain efficiency. The research begins by reviewing the existing literature on inventory management techniques and WSNs in the context of the agro-food industry. The study then proposes a conceptual framework for the implementation of WSNs in perishable agro-food inventory management, considering factors such as sensor deployment, data collection and analysis, communication protocols, and decision-making processes. In order to manage and control the aforementioned issues that occur in agro-food and perishable inventory management systems, a wireless sensor network model is developed in this study. A MATLAB platform with an embedded ANN performs the model simulation. ANN training-testing is used to estimate temperature anomalies. The model is viable and useful for real-world applications, according to evaluation results of the simulator performance used in this work to estimate temperature abnormalities of cold storage/agro-based post-harvest perishable food products.

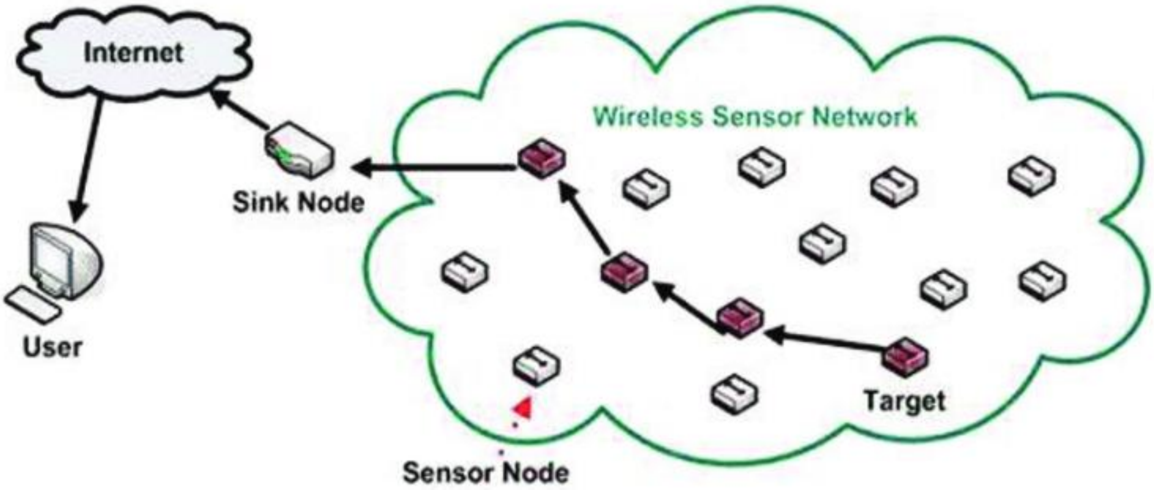
Keywords: Wireless Sensor Networks, WSN, perishable goods, agro-food industry, inventory management, tracking, monitoring systems, product quality, waste reduction, supply chain efficiency, sensor deployment, data collection, data analysis, communication protocols, decision-making processes.

1. Introduction

A developing field called wireless sensor networks unifies communication, computing, and sensing into a single, portable unit. Thanks to sophisticated mesh networking protocols, these devices create a sea of connectivity that extends the virtual and physical worlds. Although each device's capabilities are severely constrained, the use of multiple gadgets together creates entirely new technological possibilities. The capacity to deploy a huge number of micro nodes that self-assemble and construct wireless sensor networks gives them their power. Real-time tracking, environmental condition monitoring, ubiquitous computing environments, in-situ structural or equipment health monitoring, and other uses are all possible with these sensors. They are frequently referred to as wireless sensor networks, but they can also operate actuators that bring cyberspace-based control into the real world. Monitoring remote locations for low-frequency data trends is the simplest application of wireless sensor network technology [1].

Figure 1.1: General Wireless Sensor Network Architecture [2]

Due to the demands of globalisation, industrial segments are developing their infrastructure quickly while paying increased attention to maintaining and monitoring the quality of their output. The agro-based food business stands out among them due to its focused inventory



management and quality control objectives. The importance of this condition is increased by the rising need for food, food items, and health supplements. So, in order to control the inventory of perishable goods and food, advance monitoring systems are being used.

Micro, Small, and Medium-Sized Enterprises (MSMEs) operating in the food retailing sector today face two major challenges with regard to their perishable inventory management system: the investment in warehouse monitoring systems and the product's shelf life.

These problems can be effectively solved with the use of modern technologies like the Internet of Things (IoT), automated inventory control platforms, and automatic storage and retrieval systems [3].

Based on this need, this research was designed and developed in an effort to offer a feasible plan for an economical and sustainable wireless sensor network system that is especially devoted to managing the inventory of agro-based foods. The goal of this project is to create a system that will aid in minimising food wastes and the associated environmental concerns that result from damaging contamination brought on by excessive and unplanned industrial food wastes. The study also foresees the significance of inventory management and quality control in this process, as well as the vigour of demand-supply balance.

As a result, a wireless sensor network model is created in this study that is efficient in managing and regulating the aforementioned problems that exist in agro-food and perishable inventory management systems.

1.1. Background Study:

Effective inventory management in the agro-food industry is crucial to ensure the availability of fresh and safe perishable goods, minimize waste, and optimize supply chain operations. The unique characteristics of perishable agro-food products, such as limited shelf life, temperature sensitivity, and susceptibility to spoilage, present significant challenges for inventory management systems. Traditional inventory management approaches often rely on periodic or manual checks, leading to delays in detecting deviations from optimal storage conditions. This can result in product quality deterioration, increased waste, and financial losses. Moreover, the perishable nature of agro-food products necessitates real-time monitoring to ensure timely decision-making and effective management of inventory. Wireless sensor networks (WSNs) have emerged as a promising technology for addressing these challenges in perishable agro-food inventory management. WSNs consist of a network of interconnected wireless sensors that can monitor various parameters such as temperature, humidity, light, and gas levels in real time. These sensors are strategically placed throughout the supply chain, including storage facilities, transportation vehicles, and retail stores, enabling continuous monitoring of the environmental conditions that impact perishable goods.

By utilizing WSNs, agro-food businesses can obtain accurate and timely data on the storage conditions of perishable goods. This information can be analyzed to detect deviations from optimal parameters, enabling proactive interventions to prevent quality degradation and reduce waste. Furthermore, WSNs facilitate data-driven decision-making by providing insights into inventory levels, demand patterns, and supply chain performance.

The integration of WSNs into perishable agro-food inventory management offers several benefits. It enables improved product quality through enhanced monitoring and control of storage conditions, reducing the risk of spoilage and ensuring that products meet regulatory and quality standards. Additionally, the real-time data provided by WSNs enables better demand forecasting, inventory optimization, and supply chain coordination, leading to improved efficiency and reduced costs.

1.2. Problem statement

The problem addressed in this study is the inadequate management of perishable agro-food inventory using traditional inventory management systems. These systems struggle to effectively monitor and control perishable goods due to their limited shelf life, sensitivity to environmental conditions, and the need for real-time monitoring. As a result, the industry faces challenges such as compromised product quality, increased waste, and inefficient supply chain operations. There is a need for innovative solutions that can enhance perishable agro-food inventory management by addressing these unique challenges and improving overall efficiency and effectiveness.

1.3. Objectives

The study attempts to achieve the following research objectives through its outcome and findings:

1. To develop and assess a Wireless Sensor Network Model for quality control measures applicable in agro-based perishable inventory management system
2. To evaluate the performance of the proposed model ensuring its sustainability and economic advantages as applicable in the chosen commercial segment
3. To justify the suitability and need of the developed model in context of the food security concern and demand-supply management as existing in India's perishable Agro-Product Market.

1.4. Expected Research Outcome and its Significance

The research is conceptualised to technically develop the current inventory management systems of agro-based perishable items of India or any other developing countries where food security is a prime concern. Endeavour of this research is to make effective quality check and reduce pre-harvest food spoilage, timely control of supply chain and meet the consumer demand aspects efficiently. The present research framework is developed to ensure dedicated quality management of the perishable inventories that can be further extended to make the model effective in decision-making and prediction purposes that can upgrade the system to support for better and diverse usages of the items it is used to monitor.

2. Literature Review

2.1. Food Crisis and Need for Advance Inventory Management for Post-Harvest Perishable Crops

The state of the literature on food loss and waste (FLW) in food supply chains (FSC) was examined by **Chauhan et al. in 2021** [4]. In order to investigate and synthesise the findings of the current literature for this study's FLW in FSC main research issues, research gaps, and future research opportunities, the authors employed a systematic literature review (SLR) approach. The authors of the study isolated eight major themes from the body of literature. The topics covered everything from the causes of FLW generation to brand-new, cutting-edge fields of study like digitalization and food surplus redistribution.

The study's authors expected their conclusions to clarify present FSC waste avoidance practises and serve as a foundation for subsequent legislative and strategic efforts in this area. According to the findings, the main causes of FLW include improper management of perishable food items, stakeholder attitudes, buyer-supplier agreements, and supply chain disruptions. Among the study's key recommendations were formal guidelines and policy-level measures to help with the accurate quantification of FLW and a focus on digitization to lessen FLW. With the creation of a research framework, this study came to a successful conclusion. First-in-first-out (FIFO) and last-in-first-out (LIFO) dispatching policies were contrasted by **Murmu et al. (2022)** [5] and used to assess the impact of quality on sales of fresh items while keeping sustainability in mind. The underlying conception of the study was the assumption that the quality of these products got worse with time. Its deterioration rate followed two parameters of the Weibull distribution due to higher adaptability for various things subjected to degradation and fitness for a variety of shape and scale features.

The authors came to the conclusion that in order to preserve the quality of such products, proper preservation measures must be taken, such as controlled atmosphere (CA) storage and modified atmosphere packaging (MAP) techniques. The demand for these goods changes according on customer purchasing patterns and their interest in product quality and selling price. Demand was thought to be influenced by the product's quality and unit selling price. Authoritarian governments' regulations on carbon emission control in taxation were considered crucial for contemporary sustainable inventory strategies. The influence of inflation, namely the time worth of money, was taken into consideration. The unit pricing and lot size for the system's maximum average profit were established using the current models as seen and compared by the authors.

2.2. Prospects of Wireless Sensor Network (WSN) Based Perishable Inventory Management System

A flexible monitoring system with real-time communication was designed by **Torres-Sanchez et al. (2021)** [6] for use in the supply chain of perishable foods. Wi-Fi wireless communication was used as a collaborative network between numerous measurement units. To assess the system's adaptability, certain aspects including consumption, performance, and feasibility were addressed in detail. The study claimed that although temperature was frequently the primary factor influencing quality and shelf life, other factors, such as relative humidity, oxygen, carbon dioxide, ethylene, etc., would also have a significant impact on quality losses. Therefore, real-time knowledge of these metrics' evolution along the whole supply chain would enable suppliers to stop food losses.

A supply chain network (SCN), a model created by **Khumaidi et al. (2020)** [7], was utilised to cut expenses and improve the efficiency of managing perishable goods. Prior studies typically covered the use of genetic algorithms, WSN, and RFID for monitoring and making decisions about products in supply chains and warehouses, but they did not concentrate on managing fresh goods and warehouses using the SCN paradigm.

2.3. Issues and Challenges of WSN based Inventory Management System

A review-based status survey on inventory management of perishable goods was presented by **Bottani et al. in 2022** [8]. Information was gathered from 164 scholarly papers that addressed this problem and were published between 2017 and 2020. To achieve the research's goal, descriptive (such as temporal and geographic distributions and research type) and contents-related (such as keywords analysis) factors were examined. The results revealed a rising trend with a preponderance of analytical inventory management models produced. Sustainability-related issues ended up emerging as hot themes. According to the authors, managing perishable inventory was essential for many businesses, particularly small and medium-sized ones. Since it contributed to determine the match between supply and demand, the researchers believed that an efficient and optimal system surely represented a competitive advantage in today's dynamic market.

The authors said that because they could degrade or go out of date, maintaining perishable goods (including food, drinks, medicines, flowers, etc.) was particularly challenging. This uniqueness led to the development of a specialised area of inventory management research: inventory management for perishable goods, which are characterised by a finite shelf life during which they can be sold or consumed profitably.

2.4. Perishable Inventory Management Requirements In Terms of India's Context

According to **Borah (2022) [9]** , despite the fact that local demand for numerous food goods had increased in recent years, Indian shippers were discovered to be dealing with serious problems, such as a lack of competent labour, a lack of reefer trucks, capacity limitations, and insufficient cold storage facilities. The author anticipated that these factors could elevate the problem of the perishable agro-food inventory management system in India.

3. Methodology

3.1. Conceptualization of model

In this study, the operational features of Wireless network system is utilized to monitor the temperature variations of cold storage and hence detect abnormalities that can reduce the shelf-life of perishable post-harvest agro food items. A MATLAB based simulation is developed to assess the operational efficacy of the WSN model.

The architecture diagram of WSN based temperature monitoring system is given below:

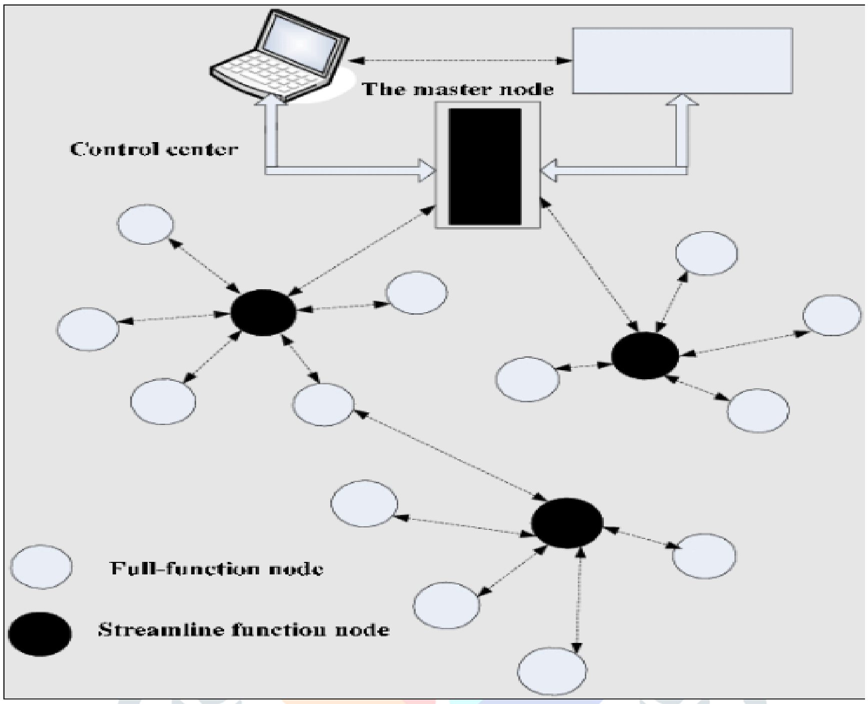


Figure 3.1: Architecture of WSN based environment monitoring system of a cold storage/agro based post harvest perishable item inventory [10]

3.2. Method and Tools

The model details of the temperature monitoring WSN-based cold storage/perishable agro food post-harvest items and its operational efficacy MATLAB simulation procedure is given below.

3.2.1. WSN based Temperature Monitoring Model

For the temperature tracking in this study, a hierarchical network design with sensor terminal nodes at the bottom, followed by an ordered master node and monitoring centre, is constructed. The system is designed in accordance with Haiyan Zhu's (2014) [10] suggestion regarding the operation of WSN networks. The monitoring centre, which is used to display the results of environmental observation and send directives to the network, can in theory be a computer. The WSN is in charge of collecting data on the environment thanks to the terminal node and master node. The network, which consists of master and terminal nodes, is in charge of gathering environmental data. The network coordinator, who is in charge of setting up the network, managing it, and maintaining it, including giving new equipment a network address, managing the nodes, and distributing and updating the network security key, is included to ensure timely and accurate monitoring.

The monitoring centre is in charge of keeping track of the working conditions and states of the sensor nodes, presenting the original address information, data gathered by the sensors, and data variation patterns so that tasks of the nodes can be altered in accordance with them. The states of nodes include powered-down status, sensor functionality, and communication components. By keeping an eye on the health of the sensors, duty periods may be modified in a timely manner, and workloads can be redistributed to prevent nodes from failing too soon and to increase the network's overall lifespan.

The working voltage of the nodes was now the primary factor in determining the residual energy information of the nodes. The node must increase the low voltage node's sleep time and decrease its sampling frequency if the voltage value is too low since it interprets the sensor's data dependability as lowered.

Selected sensor specifications are given below:

Parameter	Sensor	Unit
Voltage Supply	3 – 5.5	V
Resolution	9-12	bits
Measure Range	-55 to 125	°C
Thermometer error −10 ◦C to 85 ◦C	± 0.5	◦C
Thermometer error −30 ◦C to −10 ◦C	± 1	◦C
Stand by current	750	nA
Active current	1	mA
Communication protocol	1 Wire	

Table 3.2: Temperature Monitoring Sensor Specification

3.2.2. MATLAB Simulator Framework

The simulation is implemented in MATLAB, and the code presented in this research provides a detailed description of the process. The key steps involved in the simulation are as follows:

1. **Node Initialization:** The simulation begins by defining the number of sensor nodes and their initial positions within the cold storage facility.
2. **Visualization:** A figure window is created to visualize the sensor node positions using a scatter plot. Each node is represented by a blue filled circle.
3. **Training Data Generation:** Training data for the ANN is generated by simulating temperature and moisture readings for each sensor node. Normal nodes have random temperature and moisture values, while abnormal nodes are specifically manipulated to introduce anomalies.
4. **ANN Model Training:** An ANN model with a specified number of hidden units is defined and trained using the generated training data. The ANN aims to learn the patterns associated with normal and abnormal sensor node behavior.
5. **Main Simulation Loop:** The simulation progresses through a loop that represents the passage of time. Within each iteration, temperature and moisture readings are simulated for each sensor node, incorporating abnormalities for specific nodes. The visualization is updated accordingly to reflect the current state.
6. **Abnormality Detection and Classification:** The trained ANN model is employed to detect and classify abnormalities. The simulated temperature and moisture readings serve as input features for the ANN, which produces predicted labels indicating normal or abnormal node behavior.
7. **Visualization Update:** Abnormal nodes predicted by the ANN are highlighted in red within the visualization. The figure is updated to show the color-coded circles representing temperature readings, with a color bar indicating the temperature range.
8. **Animation and Iteration:** The visualization is animated by adding a title to indicate the current simulation time and pausing for a specified duration. The highlighted abnormal nodes are removed before the next iteration.

4. Data Analysis

4.1 Data Collection and Preprocessing

The temperature fluctuations, moisture content and room warming faults are the principal contributor to affect the shelf life of perishable post harvest agro food items. The other factors, including computer power usage, are insignificant when compared to this one when it comes to changing room temperature. The measured temperature values are clearly periodic and consistent, and they are gradually rising as a result of seasonal warming. In this study, approximately 2000 temperature values for each sensor are used after extracting and analysing the data gathered over the course of a week's time; each of these numbers reflects the average temperature in one minute. In order to build the artificial neural network model and verify its correctness, we used the earlier 75% of the data as the training data and the remaining data as the test data.

4.2. ANN WSN Temperature Monitoring Sensor Analysis

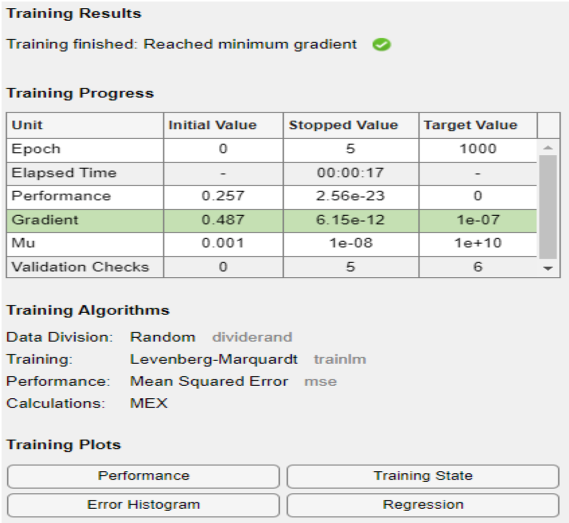


Figure 4.1: ANN Parameters set for Temperature Abnormality Estimation of Cold Storage/Post Harvest Perishable Agro Food

The variable parameters taken into account for the Data Estimation assignment are listed below:

The network's input data can be temperature, moisture, or a combination of the two, depending on the test being run.

The number of inputs: Multiple analyses are run using data from a single sensor or by integrating data from two sensors.

Quantity of output: Two simulations are run to estimate the data, one to estimate the temperature in one sensor and the other to estimate the moisture in that same sensor.

The variable parameters taken into account for the Data Prediction task are listed as follows:

Time horizon: Different tests were performed to predict the abnormalities of temperature when it is detected by a sensor (capacity of range -55 to 85 ^{o}C with 0.5 ^{o}C accuracy) to have exceeding the chosen threshold value considered good for the cold storage: 30, 50 and 100 minutes in advance.

Length of input sequence: The length of the input sequence fed into the ANN was also changed in order to conduct the prediction.

4.3. Simulation Results

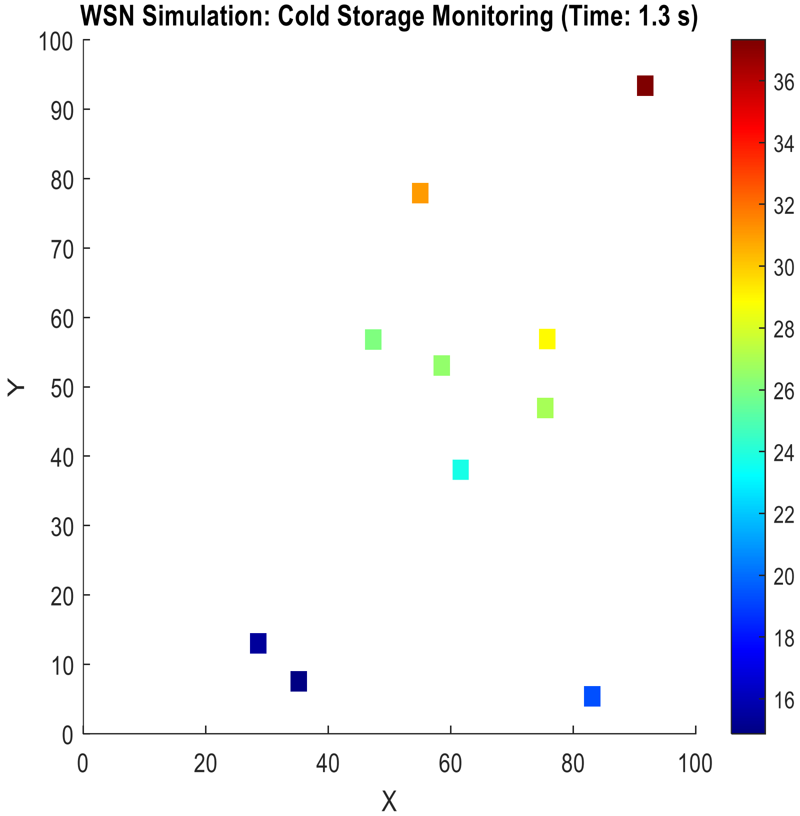


Figure 4.2: Regression Graph showing Temperature Abnormality in Terms of Temperature and Time Lapse

The above simulation graph shows the regression between temperature abnormality detection and the elapsed time. The red dots indicates the ANN detected temperature abnormality as found by the WSN node. The right colour gradient bar is the temperature range chosen.

4.4. ANN Temperature Abnormality Performance Analysis

The ANN abnormality estimation process is evaluated for its performance with the help of confusion matrix as given below:

Confusion Matrix

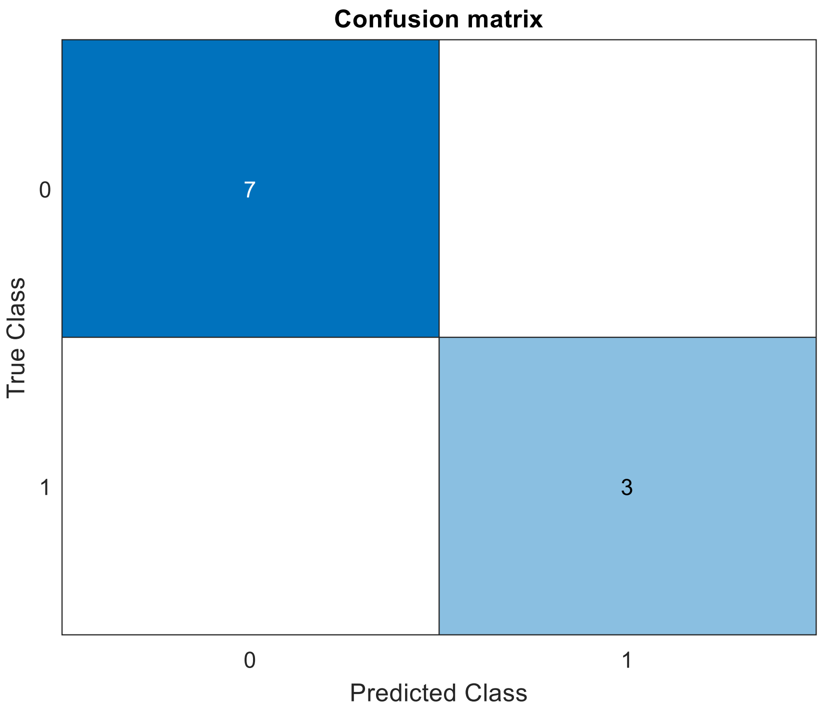


Figure 4.3: Confusion Matrix of ANN Performance Evaluation

The ANN temperature abnormality prediction model is evaluated in terms of Accuracy, Specificity and Sensitivity. From the result, it is established that the proposed model is effective in detecting temperature abnormalities of cold storage/agro based perishable inventory management system as monitored by WSN model.

Performance Metrics:

Accuracy	**Specificity**	**Sensitivity**
100	100	100

Table 4.1: Performance Score of ANN Estimation Model for Temperature Abnormality Estimation

4.5. Findings and Discussion

The simulation provides real-time monitoring of the cold storage facility, visualizing the sensor node positions, temperature readings, and the detection of abnormal nodes. By employing the ANN model, the simulation demonstrates the ability to accurately detect and classify abnormal conditions, aiding in proactive maintenance and preventing potential spoilage or damage to stored products.

This study results present a WSN simulation framework for cold storage/post harvest agro food perishable item monitoring, leveraging ANNs to detect abnormalities in temperature and moisture levels. The simulation showcases the effectiveness of the proposed approach in providing real-time monitoring and timely identification of abnormal node behavior. The results suggest that the combination of WSNs and ANNs hold promise for enhancing cold storage management and reducing product losses. Future work could explore the integration of additional sensor data and advanced anomaly detection techniques to further improve the monitoring capabilities of the proposed framework.

5. Conclusion

With the use of an integrated ANN MATLAB simulator, the WSN cold storage/post harvest perishable agro food inventory management system's capability to monitor temperature is successfully created and tested for a range of temperatures. The model's temperature abnormality assessment for various temperature thresholds is checked and evaluated using the performance evaluation scheme described in the previous chapter.

In reality, the WSN temperature data can be sent back to the inventory monitoring centre via GPRS or PPPoE via AGS to compute the shelf life for the batch of perishable food product it is attached to. To assist cold chain managers in minimising the quality loss of perishable food products as well as the spoiling brought on by the present First In First Out strategy, cold chain managers make a more accurate Least Shelf-life First Out storage and transportation strategy selection based on the shelf-life information.

This research can be expanded by integrating several sensor types into the network model to provide real-time shelf-life prediction and supply chain decision-making, or by integrating GIS technology. The technology is anticipated to offer simple location data for perishable food products.

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