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# Automation of an Evaporative Cooling System for Agricultural Produce

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**ABSTRACT**
Fruits and vegetables readily spoil immediately after harvest due to their highly perishable nature. Unfortunately, energy-efficient storage facilities are not available or not within the reach of small holder farmers. Conventional evaporative cooling systems (ECS) have gained popularity as a cost-effective and energy-efficient method for the short-time storage of perishable produce. However, conventional ECS sometimes requires frequent manual intervention and water refilling which might impede their efficiency, reliability and scalability for smallholder farmers. A mixed method was used to identify this gap. An automated evaporative cooling system was designed, developed and tested to evaluate its performance for the storage of agricultural produce. The ECS consists of the storage chamber and a micro-controller-based instrumentation unit for measurement and data collection. The Microcontroller (ESP 32) was interfaced with digital temperature and humidity sensors (DHT 22), Load cells HX711, RTC, 12C LCD. The entire system was powered by a 2.0 kVA inverter, a 165 W solar panel and a deep-cycle battery. The micro-controller-based instrumentation unit measured temperature, relative humidity and weight of produce stored both in the ECS and under ambient conditions at predetermined intervals. The results indicated that the temperature within the ECS was consistently lower than the ambient temperature, while the relative humidity inside the ECS was higher. Furthermore, produce stored under ambient conditions exhibited greater weight loss compared to those stored in the ECS. The high cooling efficiency and reduced weight loss observed in the ECS shows that the automated system performed effectively in extending shelf life and minimizing post-harvest losses of the stored produce.

(**Keywords:** Automation, Evaporative Cooling System (ECS), Ambient, Storage, Micro-controller, Post-harvest loss)

## I. INTRODUCTION

The integration of automation into ECS has introduced a new paradigm in postharvest storage technology. Automation enables real-time monitoring and control of environmental parameters such as temperature, humidity, and airflow, thereby enhancing the consistency and reliability of storage conditions. Recent advancements in microcontroller technology, sensor networks, and wireless communication have enabled the development of smart ECS that can operate autonomously with minimal human intervention (Choudhary et al., 2021; Singh et al., 2023).

Singh et al. (2023) developed an IoT-enabled smart evaporative cooling system for storing perishable commodities, which showed significant improvements in temperature and humidity control. Their system utilized microcontroller-based sensors and wireless communication to monitor and adjust environmental conditions in real time. These findings underscore the potential of automated ECS in extending the marketability of perishable produce and improving farmers' livelihoods. Similarly, Olanrewaju et al. (2022) designed an IoT-based monitoring system for evaporative cooling structures, enabling remote data access and alerts. This innovation not only improved system reliability but also allowed for timely maintenance interventions, reducing the risk of postharvest losses. Ahmed et al. (2021) developed a solar-powered IoT-based ECS that used cloud computing to store and analyze environmental data, enabling real-time decision-making and predictive maintenance. Mekonnen et al. (2022) reported a significant reduction in physiological weight loss (up to 7%) in tomatoes stored in an automated ECS compared to ambient conditions.

Recent breakthroughs in sensor technologies, microcontroller-based systems (for example, Arduino and Raspberry Pi), and the Internet of Things (IoT) have made it possible to automate these systems in a cost-effective and efficient manner (Singh et al., 2023; Olanrewaju et al., 2022). Automated evaporative cooling systems (AECS) offer enhanced consistent storage conditions, reduce labour input, and prolong the shelf life of perishable produce such as tomatoes, leafy greens, and bananas. Moreover, the integration of wireless data transmission and remote monitoring help farmers to make timely, informed decisions, hence improving total postharvest management (Ahmed et al., 2021). As climate variability continue to threaten food security, especially in Sub-Saharan Africa, the automation of ECS is a timely innovation that aligns with worldwide goals for sustainable and smart agriculture (World Bank, 2023).

Postharvest losses remain a significant problem to agricultural production, particularly in developing nations, where up to 40–50% of fruits and vegetables may deteriorate prior to consumer access due to insufficient storage and preservation technology (FAO, 2019). Conventional evaporative cooling systems (ECS) have gained popularity as a cost-effective and energy-efficient method for the short-time storage of perishable produce. These systems' function based on the principle of latent heat of vaporization and are especially efficient in hot and arid areas, where they can significantly reduce storage temperatures while maintaining high relative humidity levels (Mekonnen et al., 2022). Conventional ECS sometimes requires frequent manual intervention and water refilling which might impede their efficiency, reliability, and scalability for smallholder farmers. The integration of automation into ECS offers the potential to improve performance through real-time monitoring of environmental variables, including temperature, humidity, and water flow. This study focuses on the design, development, and implementation of an automated evaporative cooling system for agricultural produce storage, with emphasizes on improving its functionality and energy efficiency.

## II. MATERIALS AND METHODS

### Description of the Evaporative Cooling System

The Evaporative cooling system (Figure 1) consists of two major functional units: the main cooling chamber and a micro-controller-based instrumentation unit for measurement and data collection. The Evaporative cooling system is rectangular in shape so as to create a wider surface for circulation of air and consists of the storage chamber which was made of stainless-steel sheet with dimensions (0.56 m ×0.56 m ×1.27 m). The inner and outer wall of the storage chamber was lagged with Polystyrene of thickness 0.02 m to prevent exchange of heat between both walls. Four trays made of stainless mesh with the dimensions (0.50 m x 0.50 m x 0.002 m thickness) at 0.30 m intervals were placed in the storage chamber. Two water tanks, one below the storage chamber which is the water collector, was made of plastic with dimensions (0.51 m ×0.37 m ×0.34 m) and the other above the storage chamber which is the water reservoir, was also made of plastic with dimensions (0.51 m ×0.37 m ×0.34 m). Jute bag of thickness of 0.001m with dimensions (1.27 m ×0.56 m) was used as the wetted pad material. The pad material was held in place at one side of the Storage chamber with galvanized mesh with dimensions (1.27 m ×0.56 m). Two suction fans of 0.15 hp were used to drive the ambient warm and dry air through the wetted pad into the storage chamber and expel the humidified air out. A 0.5 hp water pump was used to lift water from the water collector tank through a 0.5-inch diameter Polyvinyl chloride (PVC) pipe to the water reservoir tank as water passing through the pad drains back to the water collector tank. A horizontal PVC pipe of 0.75-inch diameter with 0.42 m length was drilled having twenty holes of diameter 0.001 m at 0.02 m intervals runs over the jute bag pad area so water flows over the jute bag pad by sprinkling when the control valve is opened.

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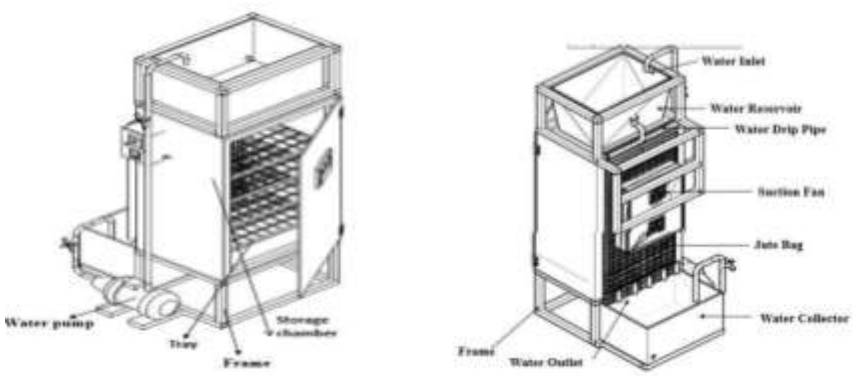


Figure 1: Conceptual View of the Evaporative Cooling System

**Design of the Instrumentation System**

The instruments and sensors used in this work's instrumentation system are interfaced with the microcontroller board, removing the need for human efforts. By doing so, users would be able to automatically measure and control the parameters of the Evaporative cooling system such as the air temperature, relative humidity and weight of produce stored. These instruments and sensors are as follows:

i. A digital humidity and temperature sensors (Aosong electronic, Model DHT22), it measures the temperature and relative humidity of the environment and the Evaporative cooling system using a thermistor and a capacitive humidity sensor.
ii. A load cell (Model Z1635-1kg) with HX711 of precision 24-bit analogue-to digital converter was used to measure the weight of produce.
iii. A liquid crystal display (I2C 2004 LCD module) was used to display the measured parameters inside the evaporative cooling system.
iv. An SD RAM card was used for storing the data.
v. A Real-Time Clock (RTC) (Model DS3231) was used for recording the time and dates of parameter measurements during cooling in the Evaporative cooling system.
vi. A microcontroller (ESP32) which functions as the central processing unit for data acquisition, data display, data storage and for operating the relevant actuators. A computer program written in C programming language controlled the microcontroller in performing its numerous tasks.

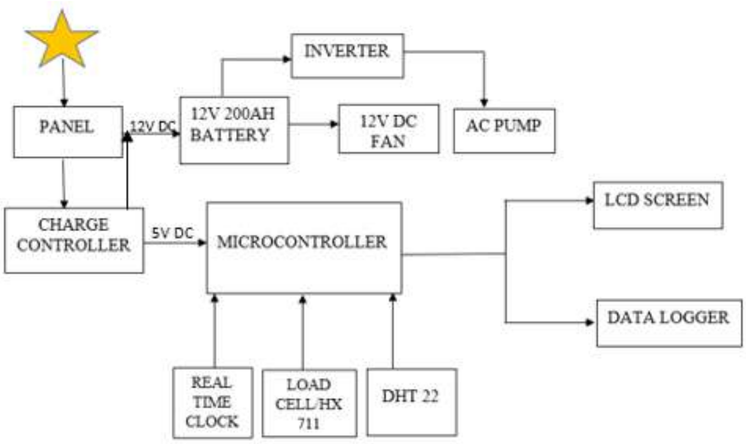


Fig 2: Block Diagram of the Instrumentation System

The microcontroller in this work performed three functions namely: measurements of air temperature, relative humidity, and the weights of stored produce; displayed and data logged the parameters at five minutes intervals.

**Design of Processing Unit**

An Esp32 microcontroller was employed to execute numerous tasks such as collection of data from sensors, processing the data, displaying the results on the I2C LCD screen, and data logged

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values in the SD. Esp32 was chosen in this study because it has the following excellent features. It is a 12-bit microcontroller which works with the Arduino IDE. The board can be programmed using writing/processing language. It has more memory space and more input/output pins. It can be power either through micro-USB cable or Vin pin or regulated 3.3V. The technical specifications of all instrumentations/sensors are presented in Table 1.

**Table 1: Technical Specifications of Instruments/sensors**

| S/N | Instruments/Sensors | Technical Specifications |
|---|---|---|
| 1 | ESP32 | (Model: ESP32-DOWDQ6) Operating Voltage 2.2-3.6V, Power supply 5V - 12V, Digital I/O Pins39, Digital I/O Pins with PWM 16, Analog Input Pins 12-bit 18 channel, DC Current per I/O Pin40 mA, DC Current for 3.3V Pin 50 mA, Flash Memory 520 KB, SRAM 16 KB, EEPROM 4096 bytes, Clock Speed 240MHz, USB. |
| 2 | DHT22 | (Model: 2302), power supply: 3.3V-5.5V, output signal: digital Signal via 1-wire bus, sensing element: polymer humidity capacitor, operating rang: (humidity 0-100% and temperature -40 -80℃), accuracy: (+-2% to +-5%RH; temperature +- 0.5℃), repeatability: (+-1% RH; temperature +-0.2℃). |
| 3 | I2C LCD | Supply voltage: 5V, Interface: I2C, I2C address: 0x27 or0x3F, Contrast adjust: potentiometer, low-power consumption character LCD module with a built-in controller, easily interfaced with a MCU, Display format: 20 Characters x 4 lines. |
| 4 | Load cell HX711 | (Mode (CZL635-1kg), Force variation output: Voltage signal, operating voltage: 2.6 to 5.5V, Operating temperature range: -20 to + 85℃, Typical operating current: <1.7mA, Output data rate: 10Hz or 80Hz, the module uses 24-bit A / D converter chip hx711, For high-precision electronic scale and design, two analog channel inputs, programmable gain of 128 integrated amplifier. |
| 5 | SD RAM card | Working Voltage: 3.3 & 5V (DC Both required), Requires SPI Capable Microprocessor Size limitations are library dependent, Package Contents: 1*SD Card Reader/Writer. |
| 6 | RTC | (Model: DS3231) Programmable square wave output signal, automatic power-fail detect and switch circuitry, consumes less than 500nA in battery backup mode with oscillator running, available in 8-pin DIP or SOIC, Underwriters Laboratory (UL) recognized, counts in seconds, minutes, hours, date of the month, month, day of the week, and year, 56-byte non-volatile RAM for data storage. |

**Architecture Design of the Instrumentation System**

Figure 3 shows the architecture design of instruments/sensors used, while the interface of the instrumentations/sensors pin(s) with the ESP32 microcontroller pins are presented in Table 2

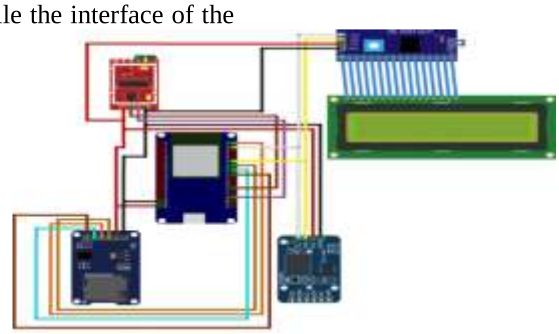

Fig 3: Architectural Design of the Instrumentation System (Microcontroller)

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Table 2: Instruments/sensors Mapping-out pins Interfaced with the ESP32 pins

| S/N | Instruments/sensors | Pins | ESP 32 Pins |
|---|---|---|---|
| 1 | DHT22 | VCC | 5v |
| | | Data | Digital pin 4 |
| | | NC | not connected |
| | | GND | Ground |
| 2 | I2C LCD | VCC | 5v |
| | | SDA | SDA pin 20 |
| | | SCL | SCL pin 21 |
| | | GND | Ground |
| 3 | SD RAM card | VCC | 3.3v |
| | | MISO | SPI MISO 50 |
| | | MOSI | SPI MOSI 51 |
| | | SCL | SPI SCL pin52 |
| | | SS | SPI SS pin 53 |
| | | GND | Ground |
| 4 | RTC | VCC | 5V |
| | | SDA | SDA(I2CInterface) |
| | | SCL | SCL(I2CInterface) |
| | | GND | Ground |
| 5 | Load cell HX711 | Red E+ to GND | Ground |
| | | Black E- to SDA | Digital pin 3 |
| | | White A- to SCL | Digital pin 2 |
| | | Green A+ to VCC | 5v |

**Design of the Software System**

The software system consists of two components which include: (i) Software Programming Setup; and (ii) Source Code Uploading. The programming language used in coordinating the entire activities of this designed system was written in C programming language in the Arduino IDE. Program Development: Figure 3.10 shows the flow chat of the algorithm of the software program. The Arduino project development environment, often known as integrated development environment (IDE), was used to develop the program, which was then translated to machine code and uploaded to the onboard ESP32 microcontroller. On the computer, the IDE was first downloaded and installed. A blank sketch was opened after the installation was completed and the writing of program was kick-started. The Arduino board was then connected to the computer serial port via a USB cable, resulting in the installation of the requisite USB driver for the ESP32 board on the computer serial communication port, in which COM9 was assigned by the system to the board. The following steps were engaged in the process: (i). making a new file; (ii) opening a sketch; (iii) compiling the sketch code; (iv) using the sketch code in conjunction with the Arduino libraries and (v) uploading the sketch code to the ESP32 microcontroller.

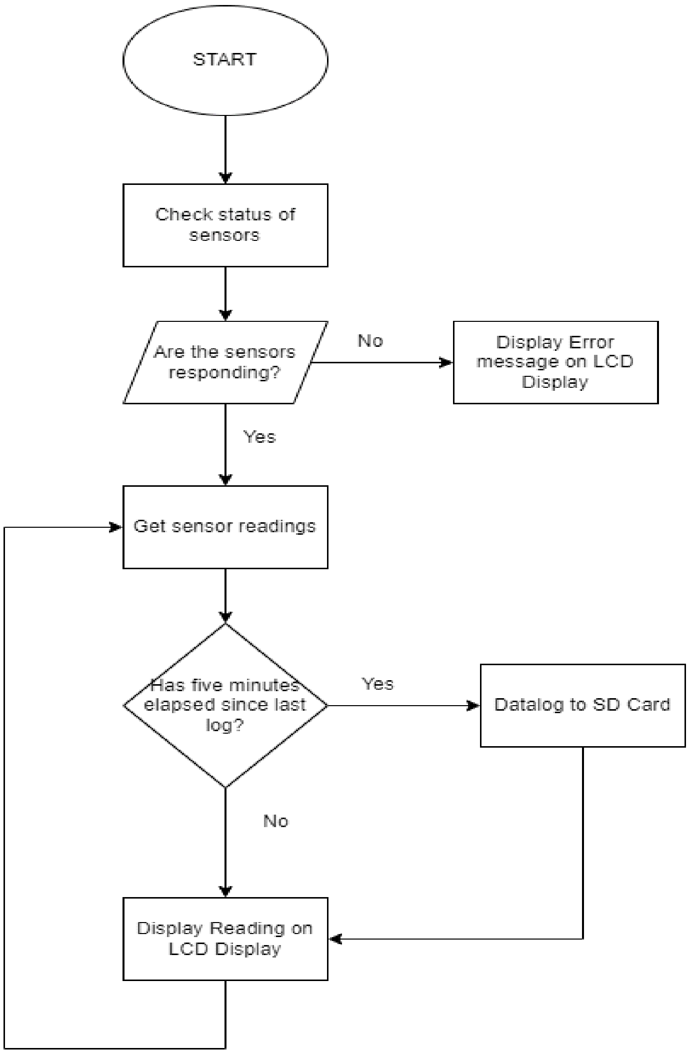


Fig. 4: Flow Chart of the Programming Algorithm

**Building and Installation of the Instrumentation System**

Plate 1 shows how all the instruments/sensors output pins with the ESP32 microcontroller pins were assembled together according to the detail's specifications designed in Table 1. The zip libraries files of all instruments/sensors were installed from the Arduino library. This was done by first downloading each zip libraries files on the computer, an Arduino integrated development environment (IDE) was then opened, a menu appeared and sketch was clicked followed by include library, add zip library was shown so each instruments/sensor zip files were selected and installed. The developed program for monitor and control of the microcontroller was copied and open with Arduino (IDE) to ascertain their functionalities. After confirmation of proper working of each program, these program where integrated to form a comprehensive program that operate the whole system. The comprehensive program was simulated on the Arduino serial monitor before uploaded to the ESP32 microcontroller to ensure proper functionality. The LCD displayed temperature, relative humidity, weight of product, time and data. The embedded software to the ESP32 was done by first housing the chip to the Arduino board to configure the board and port then uploaded the program to the ESP32 microcontroller. The microcontroller was disengaged from the computer and plugged into solar charge controller USB port to operate the system.

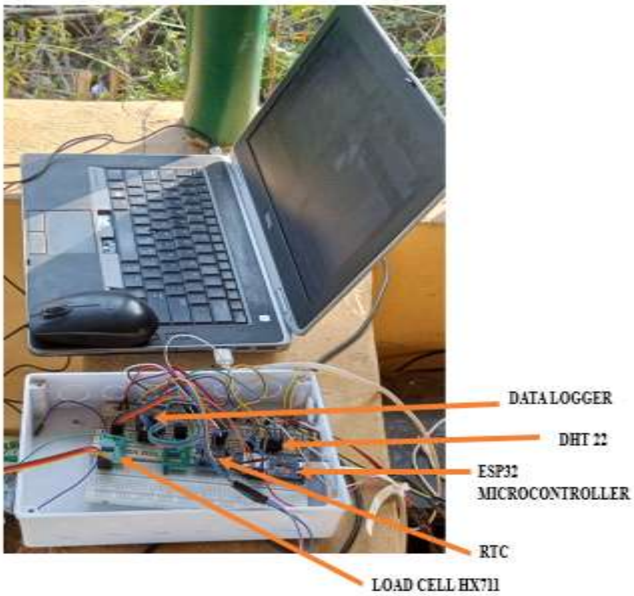


Plate 1: Building and Installation of the Instrumentation System (Microcontroller)

## III. RESULTS

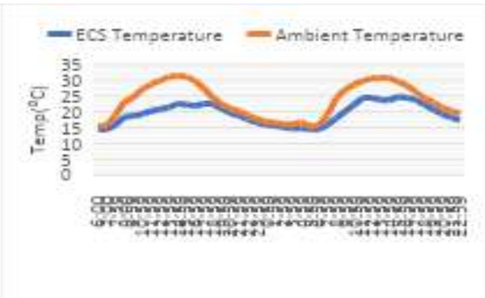


Fig 1: Hourly Variations of Temperature

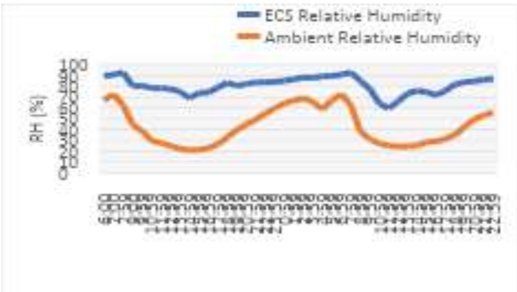


Fig 2: Hourly Variations of Relative humidity

Figures 1 and 2 shows the hourly temperature and relative humidity inside and outside the Evaporative cooling system. The temperature and relative humidity were measured with the use of DHT 22 sensor. This digital sensor is known for its reasonable accuracy (±0.5°C for temperature and ±2–5% for humidity) and stability over time. The smooth trends and expected fluctuations observed in Figures 1 and 2 showed that the DHT22 provided consistent readings, adequate for monitoring the microclimatic conditions within the cooling chamber. In the Morning hours, as the solar insolation gradually increased, the ambient temperature also increased while the relative humidity decreased which led to a higher rate of evaporation and cooling, resulting to a more significant temperature difference between the evaporative cooling system and the ambient temperature. With the Microcontroller system, the maximum temperature difference observed was between 12:00 -14:00. However, as the solar insolation began to decline, there was also a gradual reduction in the ambient temperature and an increase in the relative humidity leading to a lower rate of evaporation and cooling.

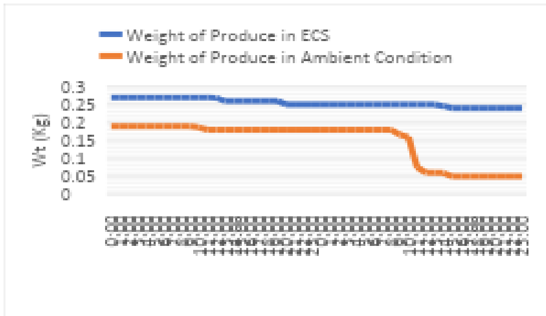


Fig 3: Hourly Variations for the Weight of Produce

Figure 3 shows the hourly weight of produce inside and outside the Evaporative cooling system. The weight of produce was measured with the use of load cell HX sensor. This sensor is capable of detecting small changes in weight with high sensitivity, especially when calibrated properly. The gradual and logical pattern of weight reduction in Figure 3 indicates that the Load Cell responded effectively to the subtle mass losses associated with moisture evaporation. Its digital interface and ability to produce stable outputs over time make it suitable for continuous monitoring in an automated setup. An initial slight difference in the loss of weight for produce in both the evaporative cooling system and under ambient conditions was observed. However, as the storage period increased, the difference became more significant. The variations in the differences in weight loss between the produce stored in the evaporative cooling system and those under ambient conditions could be explained by the field heat and respiratory heat generated. At the beginning of the storage, the produce was washed with cool water, as the produce contains both field heat and respiratory heat. The field heat is almost removed from the produce by the cool water before storage (This means that at the initial stage, there was less or no field heat in the produce stored in both the evaporative cooling and under ambient conditions. However, as the storage period increased, the produce stored in the evaporative cooling system could not pick up heat (field heat) from the evaporative cooling system and the heat generated by the respiration was low due to the reduction in the respiratory activities of the produce as a result of low temperature. Under ambient conditions, the produce reabsorbed heat from the surroundings due to the ambient high temperature, and at the same time the high temperature accelerates the heat of the respiration produced. These two aspects account for the high differences in weight loss between the produce as the storage period increased. Furthermore, due to the high relative humidity in the evaporative cooling system as compared to the ambient conditions, the produce in the evaporative cooling system lost less water, while the low relative humidity under the ambient conditions accelerated the loss of water from the produce.

**Table 1: One-Way ANOVA Value of Parameters Inside and Outside of the Evaporative Cooling System during the storage of produce**

| Parameters | ECS | Ambient | F | P-value |
|---|---|---|---|---|
| Temperature ($^0$C) | 20.94$^a$ | 24.04$^b$ | 69.10 | <0.001* |
| Relative humidity (%) | 87.56$^a$ | 63.65$^b$ | 328.10 | <0.001* |
| Physiological weight loss (%) | 0.07$^a$ | 0.30$^b$ | 12.60 | <0.001$^*$ |

Table 1 shows the comparison of mean temperature and mean relative humidity inside and outside the Evaporative Cooling System (ECS) for the produce. The mean inside temperature of the ECS 20.94℃ was significantly ($P< 0.05$) lower than mean outside temperature 24.04℃. The mean inside relative humidity of the ECS 87.56% was significantly ($P< 0.05$) higher than 63.65% obtained outside, also the value for physiological weight loss inside the ECS 7% was significantly ($P<0.05$) lower than the value of 30% outside. The result of the average temperature value observed was similar to the value, 20.77°C reported by (Ogbuagu et al., 2017). However, Babaremu et al., (2018) reported a higher value of 23.70°C. The relative humidity obtained was within the range of 85.6%- 96.8% reported by (Ndukwu et al., 2013).

## IV. CONCLUSIONS

An evaporative cooling system for the storage of agricultural produce was successfully automated. The automated system effectively monitored key environmental parameters both within the cooling chamber and in the ambient environment, with readings taken at predetermined intervals. Results demonstrated that the evaporative cooling system showed better cooling efficiency and with significantly reduced weight loss in stored produce compared to ambient storage. This led to an extended shelf life and a notable reduction in postharvest losses, highlighting the system's potential as a sustainable and cost-effective storage solution for perishable produce.

## V. RECOMMENDATIONS

Based on the findings from this study on the automation of an evaporative cooling system for the storage of agricultural produce, the following recommendations are proposed: Further designs of automated evaporative cooling system should integrate wireless modules (wi-fi, IotT based platforms) to allow real time data access and alerts on control storage conditions. Also, further research should be conducted to evaluate the performance of the automated ecs for a broader range of agricultural produce with varying storage requirements.

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