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RESEARCH ARTICLE

Design of a 25 Metric Tons Capacity Automated Yam Tubers Storage Warehouse

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ABSTRACT

Insufficient storage facilities pose a significant challenge in food production, standing as one of the primary contributors to food insecurity worldwide. The study was initiated with the goal of creating an automated warehouse capable of storing up to 25 tons of yam tubers. The storage structure incorporates an advance automation technology to streamline its operations and maximized efficiency. From the design calculations, the structure will contains 8,500 yam tubers with total heat of respiration of 6,621,500 kJ/kg, and total ventilation capacity of 15.625 tons. The design further depicted that the warehouse will necessitate six units of air conditioning machines, each with a capacity of 10 tons, to ensure sufficient cooling for the yam tubers. Additionally, the design incorporates DHT11 sensors, Arduino Uno, relay module, and control device (duct fans and air conditioning systems) to continuously monitor the temperature and relative humidity within the structure. This intelligent system, tailored to the unique climatic conditions of southern Nigeria, showcases a commendable effort in preserving yam tubers within the country.

Keywords: *Air-Conditioning Machines; Food Security; Yam Tubers Storage Warehouse; Refrigeration Capacity*

Introduction

Automation in agricultural production is the incorporation of advanced technologies to streamline and improve the various unit operations involved in the food production. Automation allows better traceability and monitoring of production processes, leading to greater transparency and compliance with regulatory standards. Successful yam tubers storage required both sound internal and external factors. The main internal factor is the state of the yam tubers; while external factors include post-harvest treatment given to the yam tubers, storage condition, etc. Adequate ventilation systems in yam tubers storage structures is essential requirement (Nwakonobi *et al*., 2012), since it helped to expel heat generated by the yam tubers, and the materials used for the structure construction. Yam tubers store best a low temperature, dry and well ventilated environment (relative humidity of approximately 80%), to reducing spouting and decaying rate during the storage operation (Umogbai, 2013).

Yam tubers generate applicable amount of heat during storage - which is be linked to the heat respiration, and this heat has to be evacuated from the storage system constantly to maintain the integrity of the yam tubers inside the storage structure (Nwakonobi *et al*., 2012; Obetta *et al.,* 2017). Yam tubers spouting rate, weight loss and nutritional deterioration rates are dependent on the prevailing environmental conditions (temperature and relative humidity) of the storage system. Apart from the structure system, other factors that contribute to the weight loss and decay rate of yam tubers during storage are pre-harvest treatments pattern, maturity stage, post-harvest treatments, pests' infestation and agro climatology (Ijabo *et al*., 2019). To enhance the storage of yam tubers, it has been advised to maintain a temperature range of 15-16°C and relative humidity between 70-80%. It is expected that under these conditions, yam tubers can be stored for 6-7 months irrespective of the cultivars (Osunde, 2008). Air conditioning at a temperature ranging from 12^0C to 16^0C and RH of approximately 75%, have proven to inhibit yam tubers spoilage through metabolic activities during storage, hence improving the shelf life and nutritional value of the yam tubers (Ray and Swain, 2013; Adamu *et al.,* 2015). Adamu *et al.* (2015) reported that for large quantity of yam tubers air-conditioning is better option than natural ventilation or force conventional ventilation through the use of fans. This is because the conditioned air helps to remove heat and other toxic gases at a faster rate, when compared to fans or natural ventilation.

Utilizing modern technological solutions in food management enhances the efficiency of the food product supply chain. Numerous designs incorporating airflow facilities, including heat exchangers, have been developed to maintain consistent internal temperatures within storage structures. These designs aim to establish an optimal environment for stored items, where temperature, humidity, and airflow are meticulously monitored to uphold the quality and freshness of perishable produce (Nasser Eddine *et al.,* 2022; Idama and Ekruyota, 2023). Although, several storage systems have been designed, literature review indicated that there is paramount need to design an automated storage structure for yam tubers, taking into account the region's prevailing climatic conditions. Therefore, the aim of this study is to develop a smart warehouse that is capable of accommodating 25,000 kg of yam tubers.

Design Methodology

Warehouse Plan

The warehouse was designed to accommodate 25 tons of yam tubers, and was outfitted with sufficient ventilation and lighting systems. The warehouse has external dimensions of 25 m × 10 m × 3 m was, which is subdivided into a control room and a storage room. Figures 1 shows the plan of the warehouse.

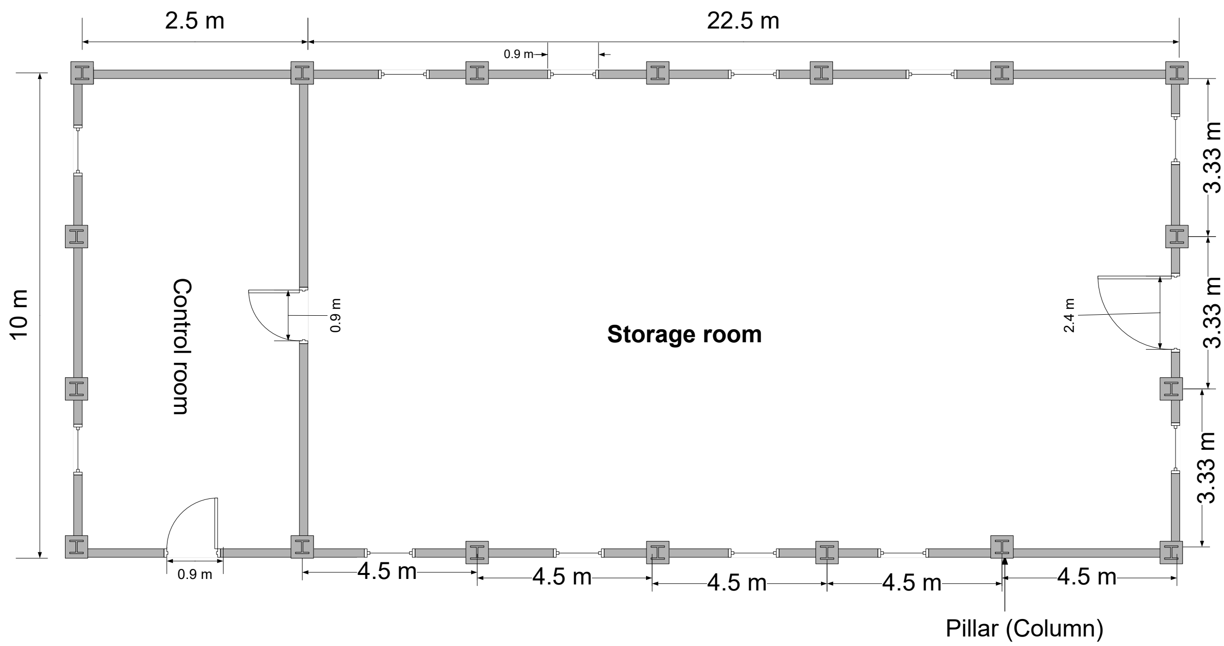

Figure 1: Floor plan of the warehouse

Construction Materials Selection

The warehouse walls will be erected using 9-inch hollow sandcrete blocks, providing sturdy construction. To reinforce the beams, columns, and foundation, 12 mm and 8 mm mild steel rods will be utilized. Riverbed sand and 20 mm crushed granite were selected as the fine and coarse aggregates, respectively. For the roofing and shelves construction, lightweight wood resistant to pests was chosen due to its durability and minimal additional dead load on the warehouse. Temperature control and ventilation within the warehouse will be facilitated by the installation of microcontrollers, sensors, relay modules, duct fans and air conditioners.

Design Parameters

The following parameters were considered in the design of the automated warehouse. Interior temperature ~ 20-25^{o}C, interior relative humidity ~ 85% RH, external temperature ~28 – 32°C (Reference to localize weather condition, obtained from the University metrological station), mean external relative humidity ~ 69% RH, and Air exchange rate ~ 3 – 6 [ACH] (Fan, 2004)

ACH (Air changes per hour) is the volume of fresh air that is required to be introduced into warehouse. The temperature within the warehouse is primarily influenced by the heat of respiration emitted by the yam tubers and the total quantity of yam tubers stored therein.

Yam Tuber Dimension

It was assumed that white yam variety will be stored in the warehouse.

Yam tuber length (L) = 50 cm (0.5 m), and yam tuber width (W) = 10 cm (0.15 m).

Design for the Warehouse Size

The warehouse will be designed to provide ample space for storing yam tubers while also allowing for easy movement of people and equipment, particularly during the loading and offloading operations. An average human height of 1.5 meters was taken into consideration for the design of the structure. To achieve reasonable storage volume, the following dimensions were designated:

Length = 22.5 m

Width = 10 m

Height = 3 m.

Therefore: warehouse volume = 22.5 x 10 x 3 = 675 m^3.

Warehouse floor area = 22.5 x 10 = 225 m^2

Design for the Shelves for the Yam Tubers Storage

Dimension of each shelf = 0.8 (L) x 0.6 (W) x 0.4 (H)

Mass of each shelf (made from pests resistance wood) = 5 kg

Design Calculations

Total number of yam tubers to be accommodated

The average mass of white yam tuber at harvest was estimated to be 3.0 kg. Since the warehouse will be designed for 25 metric tons of yam tubers, then the total number of yam tuber to be stored in the warehouse at maximum capacity was calculated using Equation 1

$$Number = \frac{total\ mass\ of\ yam\ tubers}{mass\ of\ each\ yam\ tuber} \qquad 1$$

$$number\ of\ yam\ tubers = \frac{25{,}000}{3}$$

= 8,300 yam tubers

A safety factor of 200 yam tubers was added to the design consideration

Therefore, this design calculation is based on 8,500 yam tubers

Total volume of the yam tubers to be accommodated

The average volume of the yam tuber was determined by adopting the liquid displacement method.

Volume per yam tuber = 2.01×10^{-3} m^3.

Therefore at the full warehouse capacity (8,500 yam tubers)

8,500 x 2.01×10^{-3} m^3 = **17.09 m^3**

This revealed that the yam tubers will occupy 17.09 m^3 of the total volume of the warehouse.

Sensible Heat Calculation

Since the temperature and weight of the yam tubers are known, Equation 2 is adopted to calculate the cumulative sensible heat of the yam tubers:

$$Q = MS(t_1 - t_2) \qquad 2$$

Where:

Q = Total heat exchange

M = Weight of yam tubers (25,000 kg)

S = Coefficient of thermal capacity (0.89 W/m·K)

t_1 = Outdoor temperature (32°C)

t_2 = Indoor temperature (25°C)

Q = 25,000 x 0.89 (32-25)

= **155,750 KW**

Therefore; the total exchange in the warehouse at maximum capacity = 155,750 KW

Respiration Rate

The respiration rate of yam tubers is influenced by both the environmental temperature and the duration of storage. Therefore, it is assessed based on the temperature prevailing in the storage facility (Wills *et al*., 1989; Osunde and Orhevba, 2009). During respiration, yam tubers consume oxygen within the warehouse, producing water, carbon dioxide (CO_2), and heat as byproducts, which are then released into the environment (Equation 3).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 677cal\ (heat) \qquad 3$$

The energy (heat) produced by yam tuber due to respiration is referred to as respiration heat or heat evolution rate. Heat of respiration (R_{ht}) is calculated by multiplying respiration rate (R_{rt}) by a conversion factor of 10.676 J/mg CO_2, as shown in equation 4.

$$R_{ht} = 10.676R_{rt} \qquad 4$$

Where:

R_{rt} = mg CO_2/kg h,

R_{ht} = respiration heat in J/kg.h.

The R_{ht} values reported by ASHRAE (1993), heat of respiration heat of yam tuber at 15-16°C is 310 kJ/kg h; and as the temperature increases to 25 - 27°C, the heat of respiration heat ranges between 577 and 779 kJ/kg h.

For the purpose of this warehouse design, the indoor environment will be kept at 25°C and 85 RH; then, a higher (779 kJ/kg h) heat of respiration was adopted.

If 1 yam tuber produces 779 kJ/kg of heat;

Then 8,500 yam tubers heat of respiration will be:

779 x 8,500

= 6,621,500 kJ/kg.

Design for Ventilation

It's crucial to expel excess moisture and heat from the warehouse. The airflow rate within the warehouse is determined by the quantity of heat generated by the yam tubers. Moisture exchange between the warehouse and the surrounding can be calculated with Equation 5.

$$M = \frac{W_e}{\mu_2 W_{s2} - \mu_1 W_{s2}} \quad 5$$

Where:

M = air flow per hour,

W_e = total heat produced by the yam tubers,

μ_2 and μ_1 = relative humidity of the outdoor and indoor air,

W_{s2} and W_{s1} = Saturated of air-vapour mixture of the outdoor and indoor air.

According to the thermodynamic properties of air-vapour mixture:

At 25°C, the weight of vapor per kg dry air = 59.5 kg;

At 32°C, the weight of vapor per kg dry air = 98.4 kg.

Then total heat produced by the yam tubers = 6,621,500 kJ/kg

Incorporating this into equation 5

$$M = \frac{6{,}621{,}500}{69(98.4) - 85(59.5)}$$

$$M = \frac{6{,}621{,}500}{1732.1}$$

M = **3822.82 kg/hr**

Therefore, the rate of air flow = 3822.82 kg/hr

The HVAC system, which stands for heating, ventilating, and air conditioning system, is commonly referred to as the air conditioning system. A block diagram illustrating the components and operation of the air conditioning system for the warehouse is provided in Figure 2.

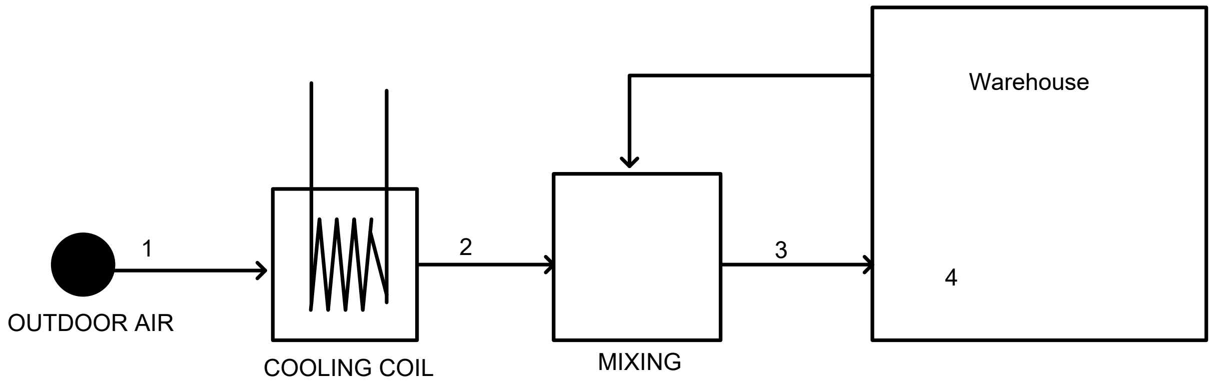

Figure 2: The block diagram description of the air conditioning system of the warehouse

Heating load due to transmission is calculated using Equation 6.

$$Q = U \times A \times (Ti - To) \quad (6)$$

Where: Q = heat loss by transmission,

U = heat transfer coefficient

A = area of the surface (wall, window, roof, etc.),

Ti = inside design temperature, and

To = outside design temperature.

Design for Force Ventilation System

A duct fan was used to supply adequate airflow in the warehouse. This means that the supply airflow rate should be approximately equal to the exhaust rate and that the supply devices should be placed in such a way that the incoming air does not disturb the exhaust flow fields. Airflow is the volume of air moved by a fan per unit of time, and it is usually expressed in m^3/s or m^3/h. Since the warehouse area is constant, an adequate airflow requirement in m^3/h will be provided to monitor the temperature and gasses buildup within the warehouse.

The **occupancy ventilation method** was used to determine numbers and capacity of duct fans to be installed in the warehouse.

Fan ventilation requirement was assumed as 5.3 m^3/h of fresh air per yam tuber in the warehouse design.

The number of yam tubers = 8,500

Therefore, airflow (Q) = 5.3 x 8500

= 45,050 m^3/h

If a duct fan (extractor fans) with a capacity of 5580 m^3/h was selected

Total numbers of fans required

$$= \frac{45050}{5580}$$

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= 8 Activair extractor fans of capacity 5580 m^3/h, will be installed in the warehouse

Air Conditioning System

Area of the Warehouse = 225 m^2

Refer to ASHRAE Standard 62 for ventilation requirements

Ventilation requirement of the ware house space (floor area "Fa")

45 m^2 required 1 ton capacity AC

Therefore, floor area of 225 m^2 will require 5 ton capacity AC

Yam Tubers Cooling

Refer to ASHRAE Standard 62 for ventilation requirements

Ventilation requirement of 1 yam tuber (Yc) = 0.5 cfm

But 400 cfm = 1 ton unit of ventilation

Therefore 0.5 cfm = $\frac{1 \times 0.5}{400}$ = 0.00125 ton

Therefore 8,500 yam tubers will required this ventilation rate

Yc = 0.00125 x 8500

= 10.625 ton capacity of AC

Total ventilation requirement (AC)

AC = Yc + Fa

= 10.625 + 5

= 15.625 ton capacity AC

But 1 ton capacity AC (refrigeration) = 3.52 kW of cooling

15.625 ton is equivalent to 55 kW capacity AC.

Total numbers of AC required

= six (6) units of 10 tons capacity AC

Warehouse Automation Design

Hardware

The following hardware will be used for the design of the automation unit of the warehouse

Microprocessor (Arduino UNO)

The smart unit was designed using the Arduino Uno microcontroller, specifically the ATmega328P model. This microcontroller operates with a voltage rating ranging from 7V to 12V DC and has a clock speed of 16 MHz. Additionally, it has a current consumption of approximately 50mA.

DHT11 (Temperature) Sensor

The DHT11 sensor was used to design for the temperature regulation of the warehouse.

Relay Module

This device is utilized to control the activation and deactivation of ventilation units - air conditioners and duct fans.

Software Requirements

The program was written using the C++ programming language, and the instructions were crafted using the Arduino Compiler (IDE). C++ language is a versatile and powerful language, which permits an effective programming of various functionalities (Plauska *et al*., 2022).

Automation Methodology

The design was dome to fully automate the warehouse ventilation system. The temperature sensor will be used to detect the ambient temperature and sends the data to a microprocessor (Arduino board), for interpretation and processing. After interpreting the temperature data, the microcontroller will instruct a relay module on the necessary action to be taken regarding the ventilation hardware. The system was designed to operate using a 12-volt DC power source.

Figures 3 and 4 depict the flowcharts outlining temperature management protocols aimed at maintaining the warehouse temperature between 22°C and 27°C. In Figure 3, when the temperature exceeds 27°C, the cooling systems, including the air conditioning and duct fans, are triggered for activation. Conversely, Figure 4 illustrates that if the internal ambient temperature drops below 16°C, measures may be taken to deactivate the cooling and ventilation systems. These flowcharts incorporate iterative loops to continuously monitor and regulate the temperature until it aligns within the designated range.

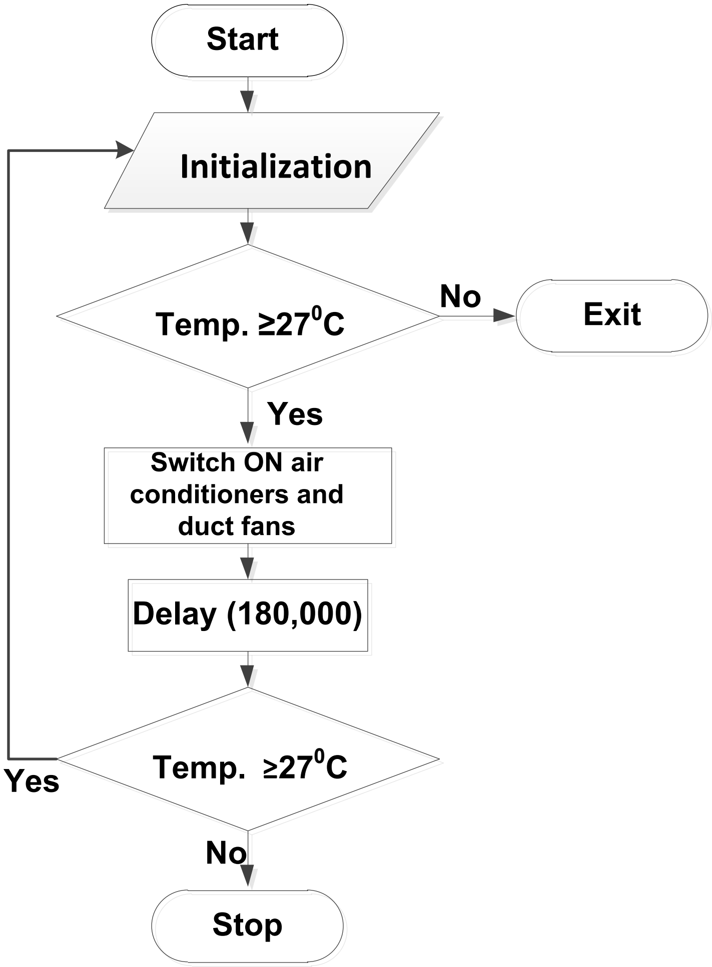

Figure 3: Temperature control at the maximum point

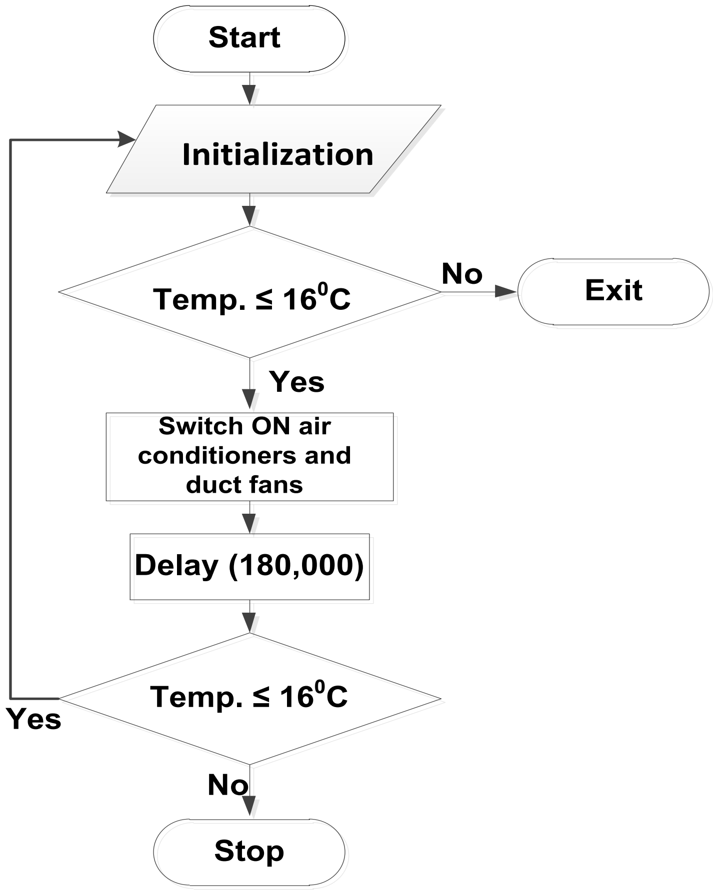

Figure 4: Temperature control at the minimum level

Conclusion

Inadequate storage facilities are major problem in food production, which is one of the leading causes of food insecurity globally. The study was embarked upon to design an automated warehouse with storage capacity of 25 tons of yam tubers. The storage facility integrates advanced automation technology to optimize its operations and maximize efficiency. Based on design calculations, the structure will accommodate 8,500 yam tubers with a total heat of respiration of 6,621,500 kJ/kg and a total ventilation capacity of 15.625 tons. According to the design, the warehouse will require six units of air conditioning machines, each capable of handling 10 tons, which will be controlled by a smart system. The implementation of this designed will holds significant promise for the food industry.

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