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Design, Fabrication, and Performance Evaluation of a Varying Temperature Dehydrator for Food Preservation

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Abstract: This study focuses on creating and evaluating a dehydrator that can operate at different temperatures for preserving food. The dehydrator includes a drying chamber, an axial fan, a heating element, trays, vents, and a thermostat. Various experiments were carried out on the food dehydrator for performance evaluation. The first experiment was carried out on plantain, and it was observed that the drying time decreased as the drying temperature increased. The shortest drying time for plantain drying was obtained at 75℃, which is 210 minutes, followed by 70℃, with a total drying time of 240 minutes, and 65℃, with a total drying time of 270 minutes. Equilibrium moisture content was reached when no more change in weight was observed. These results explained that temperature significantly affected the selected product during dehydration. For the second experiment, it was observed that the higher the proximity of trays to the heating element, the faster the drying time. The shortest drying time for tomato was obtained at the tray closest to the heat source, with a total drying time of 90 minutes. The second tray in the middle had a total drying time of 120 minutes, whereas the third tray at the top took 150 minutes for the tomatoes to completely dry. This boldly explains that the dehydrator's efficiency depends on the tray position. The food dehydrator increases its utility for drying a wide range of foodstuffs, including fruits, vegetables, meats, and fish, which have different moisture content and drying requirements.

Keywords: Dehydration and Drying; Performance Evaluation; Drying Curves; Drying Kinetics; Drying Efficiency; Varying Temperature; Electrical and Control System Design; Connection wires and Thermostat.

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1. Introduction

Food preservation encompasses a range of processes employed in treating and handling food to mitigate or halt spoilage and prevent foodborne illnesses. Food preservation is essential to extend its shelf life, ensure its safety, and reduce waste [1]. In the

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hot, dry climate of the Middle East, for example, people learned that exposing sliced fruits and vegetables to the sun could significantly extend their shelf life [2]. Similarly, in the high Andes Mountains of South America, the Inca people learned that freezing potatoes at high altitudes and then drying them in the sun preserved [3]. In the 17th century, the French military began freezing the food and using a vacuum pump to remove the ice crystals, resulting in a much lighter product and easier transport than fresh food [4]. French Inventors Mason and Chollet created the first automated food-drying machine in 1795. Since then, many different food dehydration techniques have been developed [5].

A food dehydrator is a device that removes moisture from food items to help preserve it by circulating hot air over the food, which causes the water to evaporate [6]. Food dehydrators typically have the following key components: a heating element, fan, trays, and vents. The advantages of compactness largely drove modern dehydration techniques, as dehydrated foods are about 1/15th the bulk of the original or reconstituted product [7]. Dehydration is a process that involves both heat and mass transfer. It is a complex process involving chemical and biochemical reactions that modify the item’s quality [8].

Food dehydration’s objectives include preservation due to water activity depression, reduction in weight and volume, food transformation, and food modification [9]. Various drying methods are utilized to remove moisture from foods for preservation and storage, including solar dehydration, an affordable method of dehydrating food products using sun energy [10]. Solar dehydrators are eco-friendly and use renewable energy to preserve food. Temperature and airflow management are critical for optimal drying, with temperatures needing to be high enough to evaporate moisture but not so high as to cook the food [11]. Tray drying is also commonly used for food dehydration, and a tray dryer is employed to eliminate moisture from food products. The proper functioning of the tray dryer depends on ensuring uniform airflow distribution across the trays for consistent drying [12].

Spray drying is a popular method for dehydrating food, which involves converting liquid or semi-liquid food items into dry powder form. Spray drying is an effective preservation method for food, ensuring uniform quality and usability of food products over long distances [13]. Osmotic dehydration is a technique frequently utilized as a pre-treatment before the actual drying process to enhance the quality of the end product. Osmotic dehydration helps preserve the food’s color and flavor [14]. Freeze drying is a process of low-temperature dehydration that involves freezing the product and reducing pressure to remove ice by sublimation, as opposed to conventional drying methods that use heat to evaporate water [15].

Edith [16] conducted a performance test and evaluation on a cabinet dryer using okra, pepper, and plantain as the test materials. The study showed that the moisture content of the materials decreased with an increase in drying time and airflow rate. Tortoe et al. [17] assessed the performance of a wooden cabinet dryer used to dry mango, pineapple, and papaya. This performance evaluation aimed to determine the effect of the dryer on the weight of fruits, yield, and drying temperature over six to eight hours.

Ticar and Celda [18] evaluated the performance of a Programmable Dehydrator Machine for Herbal Tea Materials. The machine combined electric heaters with solar heat catchers for drying herbal tea materials. The study showed lower relative humidity resulted in faster drying times. Obaseki et al. [19] designed and evaluated the performance of a thermostat-controlled electric dehydrating machine. The machine consisted of a heating coil and a thermostat set. The study showed that a thermostat controller would help retain food quality and protect equipment against overheating. Jibia [20] experimented with 1kg of fresh tomatoes at different temperatures on an automated fruit drying system, which employed a PIC controller. The results indicated a significant reduction in the drying time compared to conventional methods with better quality preservation.

New drying technologies such as photovoltaic, thermal imaging, and microwave-assisted drying have been developed to reduce drying time and improve energy efficiency, making the processing more sustainable [21]. Meanwhile, researchers have focused on the energy consumption of food dehydrators. This has led to the development of more energy-efficient drying technologies and the implementing of waste heat recovery systems [22]. A smart multi-farm produce dehydrator has also been designed, which uses a low-cost programmable logic controller and Raspberry Pi. It is easy to operate with automated electronic controls, and it is novel, inexpensive, and facilitates a continuous and permanent automated process [23]. Various innovative drying technologies, such as refractance window drying, corona air or electrohydrodynamic drying, super-critical CO2 drying, and bio-film drying, are being explored for their potential to offer new solutions to traditional drying challenges [24]. A study developed a low-cost, energy-efficient food dehydrator using an infrared heating lamp, cooling fan, and voltage regulator dimmer. These advancements have contributed to developing more efficient, sustainable, and cost-effective food dehydration processes [25].

The existing literature on dryers and dehydrators covers various aspects, including emerging dehydration technologies, uniform drying, and the conceptual design of smart multi-farm produce dehydrators. However, there is limited research on developing electric dehydrators compared to the abundance of resources based on solar drying systems. Hence, our study will focus on developing a cost-friendly electric food dehydrator with varying temperatures that will help reduce environmental impact.

2. Methodology

2.1. Moisture Content

The moisture content can be determined by calculating the water weight in food. This can be obtained by obtaining the difference between the weight of the food product before and after food dehydration. On a wet basis, moisture content can be expressed as a ratio of the weight of water available in a product to the unit weight of the initial product before drying.

$$M_{wb} = \frac{W_o - W_d}{W_o} \tag{1a}$$

Where M_{wb} is the wet bulb moisture content, W_o is the initial weight of the product/unit weight of the initial product, and W_d is a unit weight of the dried matter. On the other hand, for the dry basis, the moisture content can be expressed as the ratio of the weight of moisture in the product to a unit weight of the dried matter in the substance.

$$M_{db} = \frac{W_o - W_d}{W_d} \tag{1b}$$

Where M_{db} is the dry bulb moisture content. Moisture can also be expressed in terms of percentage,

$$M_{wb}\% = \frac{W_o - W_d}{W_o} \times 100\% \tag{1c}$$

$$M_{db}\% = \frac{W_o - W_d}{W_d} \times 100\% \tag{1d}$$

The moisture content based on wet basis and dry basis can be related, resulting in the following equations:

$$M_{wb} = \frac{M_{db}}{M_{db} + 1} = 1 - \frac{1}{M_{db} + 1} \tag{1e}$$

$$M_{db} = \frac{M_{wb}}{1 - M_{db}} = \frac{1}{1 - M_{db}} - 1 \tag{1f}$$

2.2. Drying Rate

The drying rate in food dehydration refers to how moisture is removed from the food during the drying process. Several factors influence the drying rate, including temperature, humidity, airflow, and the food's surface area. The formula for calculating the drying rate in a dehydrator is given by:

$$R_d = \frac{M_i - M_f}{t} \tag{2}$$

Where R_d is the drying rate, M_i is the initial moisture content, M_f is the final moisture content or moisture content of a unit weight of dried matter and t_c is the total drying time.

2.3. Efficiency

The efficiency of a food dehydrator can be determined using the drying rate, and we need to determine the amount of water removed from the food during- the drying process and the amount of energy used to remove the water. The efficiency can be calculated using the formula:

$$\eta = \frac{M_w \times L_{vap}}{P_{in} \times t} \tag{3}$$

Where η is the efficiency of the food dehydrator, M_w is the quantity of moisture removed, L_{vap} is the latent heat of vaporization, P_{in} is the power input, and t = total drying time.

2.4. Mechanical Design

2.4.1. Design of the Drying Chamber

The dehydrator's specified volume must be greater than the volume of the food products to be dehydrated and the volume required for air circulation inside the drying chamber. If this is done, the dehydrator's dimensions are deemed adequate for drying/dehydrating operations. For various products, any food with a high moisture content can be used for design analysis. Assuming the dehydrator's maximum capacity is 4kg of Plantains. This calculates the volume of food to be dried and the amount of circulation necessary. The finely cut plantain slices will be distributed uniformly across the wire mesh. The true density of ripe plantain is estimated to be 0.46 g/cm^3. Therefore, the density of ripe plantain is

$$\rho_y = 460kg/m^3$$

From the above density, the volume of 4kg of plantain is:

$$V_d = \frac{4kg}{460kg/m^3} = 0.0087m^3$$

Therefore, 1kg of plantains will occupy $0.0087m^3$

The dehydrator is expected to contain more than six times the volume. This calculation provided the unoccupied necessary capacity for unobstructed air movement. Therefore, the unoccupied volume is

$$V_u = 6 \times\ 0.0087 = 0.0522m^3$$

Therefore, the drying chamber's total volume is

$$V_t\ =\ 0.0522m^3 +\ 0.0087m^3 = 0.0609m^3$$

Taking into account the provided dehydrator volume, specified volume = cuboid volume

$$V_s = V_c \qquad (4a)$$

$$V_s = L \times B \times H \qquad (4b)$$

$$V_s = 0.390m \times 0.385m \times 0.425m = 0.0638m^3$$

The specified dehydrator volume of $0.0638m^3$ exceeds the design volume of $0.0609m^3$. Consequently, the maximum dehydrator capacity is around 4kg.

2.4.2. Heat and Power Requirements

Assumptions: The specified assumptions are as follows:

- The highest acceptable temperature is 110°C.
- According to the literature, the initial moisture content of plantain is 60%. We are assuming a final moisture content of 15% for our analysis.
- Consequently, based on the above, the percentage of moisture to be eliminated is 45%.
- The dehydrator has been designed with a mass capacity of 4kg.

Hence, for a 45% moisture removal, $0.45 \times 4kg = 1.8kg$

Since the latent heat of vaporization, L_{vap} is the amount of energy a substance must absorb for moisture to vaporize, the quantity of heat required to evaporate the moisture, Q_w is given by:

$$Q_w = M_w \times C_{pw} \times \Delta T + M_w \times L_{vap} \qquad (5a)$$

$$Q_w = 1.8 \times 4182 \times (110 - 27) + 1.8 \times 2260 \times 1000$$

$$Q_w = 4692790.8J$$

Where C_{pw} is the specific heat capacity of water given as 4182J/Kg°C, ΔT is the temperature difference between the ambient, the designed maximum temperature, which is $110°C$, L_{vap} = 2260KJ/Kg and the ambient temperature is 27°C.

The power required is calculated by dividing the quantity of heat transferred by the drying time.

$$P = \frac{Q_w}{t} \tag{5b}$$

$$P = \frac{4692790.8}{2700} = 1738.1W$$

Hence, an 1800W heating element was used to construct the dehydrator.

2.5. Electrical and Control System Design

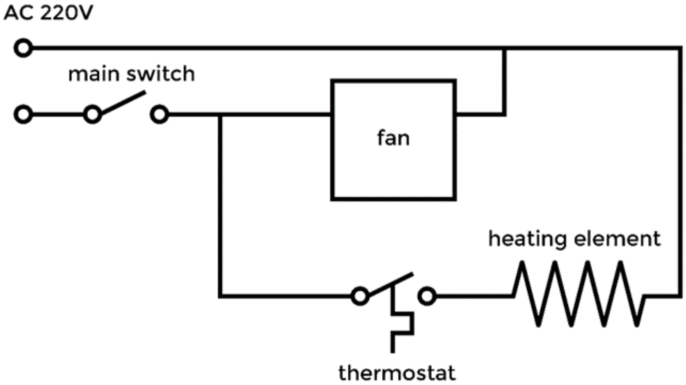

Figure 1: Circuit diagram of the dehydrator

The dehydrator is powered by a standard 220V AC mains supply, which is stepped down and rectified to provide the required DC voltage for the control circuitry and heating element (Figure 1). The power is supplied to a switch, which transfers electric current to the fan and the thermostat. The thermostat's temperature sensor continuously monitors the air temperature. It compares the sensor signal with the user-selected setting. If the temperature is below the setting, the thermostat activates the relay, allowing current to flow to the heating element, generating heat.

As the heating element operates, the air temperature inside the dehydrator increases. Once the desired temperature is reached, the sensor signal tells the thermostat to instruct the relay to cut power to the heating element. The heating element turns off, and the temperature stabilizes. The temperature sensor continues monitoring, and the cycle repeats (turning the heating element on and off) to maintain a consistent temperature for dehydration.

The electrical components include a capillary thermostat (with temperature control ranging from 30-110C, rating of 250V & 16A), electric stainless steel hot plate heater coil (with a rating of 220V, 1800W), electric fan and motor (with a rating of 220-240V, 50/60Hz, 5-6W & 0.2A), power switch (with a rating of 30A, a 4 pin 2 position ON/OFF power switch with a red indicator light) and electrical wires (1.5 mm by 3 cores flex wires of about 3 yards) (Table 1).

For the temperature sensing and feedback process to function, an underlying control system mechanism is associated with the thermostat, which initiates as a formidable ally for the dehydrator and dehydration process. The drying process is initiated by turning on the switch. The user adjusts the temperature using the thermostat, and the controls monitor the dehydrator's temperature as it rises. If the temperature surpasses the setpoint temperature, the heating element turns off, and the heating element and chamber cool down until the chamber temperature matches the desired setpoint temperature. The user can set the desired temperature at various levels. Still, it is important to consider the suitability as different products require different temperature ranges for optimal drying. The diagram below illustrates the feedback closed-loop control system, which ensures an equilibrium between the set point temperature and the temperature of the drying chamber (Figure 2).

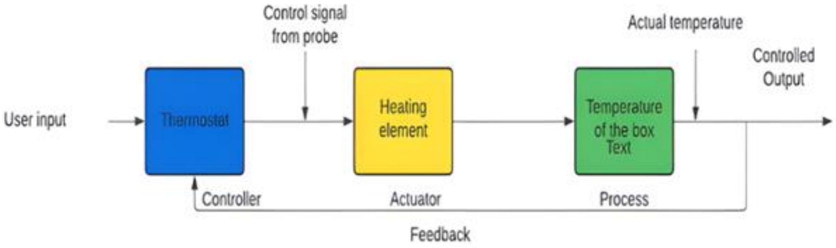

Figure 2: Corresponding control diagram for the designed system

2.6. Material Selection

Table 1: Material selection and specification for dehydrator fabrication

Material	Specification	Quantity
Heating element	1800W	1 pc
Electric fan	5-6W	1 pc
Thermostat	250V, 16A	1 pc
Wire mesh	Aluminium	1 yard
Plywood (3/4-inch board)	1.22m x 1.22m	1 pc
Plywood (1/2-inch board)	1.22m x 0.61m	1 pc
Sealant	Silicone	1 pc
Fasteners (nails and screws)	1/2”	100 pcs
Wood strip	1 ply	6 pcs
Aluminium tape	40cm x 6cm	1 pc
Staple	Steel	1 pc
Hinges	Steel	2 pcs
Door handle	Aluminium	1 pc
Glass	0.29m x 0.25m	1 pc
Wire	Copper	1 yard
Electric plug	3-pin	1 pc
Connection wires	Copper	1/4 yard
Switch	250V, 30A	1 pc

2.7. Conceptual Design

The food dehydrator model was created using Autodesk Fusion 360. It is an electric dehydrator made of plywood for its durability and cost-effectiveness. The inside walls of the dehydrator are lined with aluminum to avoid heat loss in the drying chamber. The fan, heating element, and electricals are in a separate enclosure from the drying chamber. The final model, an illustration of the drying process, and the orthographic view with dimensions can be found below, with the picture of the fabricated dehydrator.

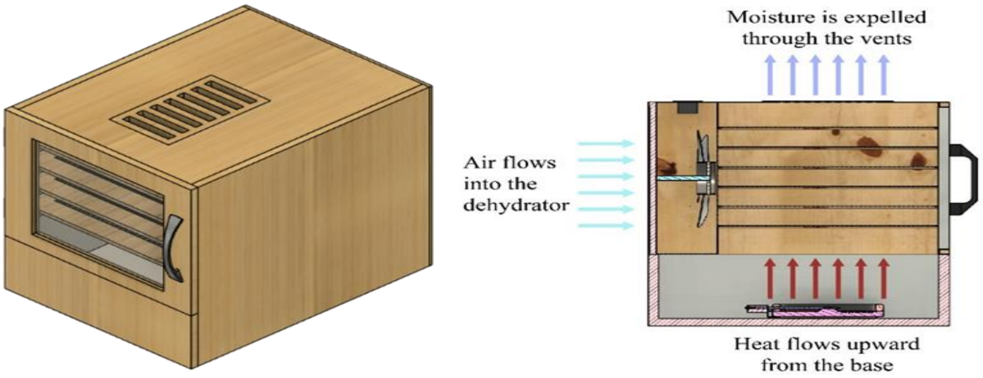

Figure 3: Final model & illustration of the drying process

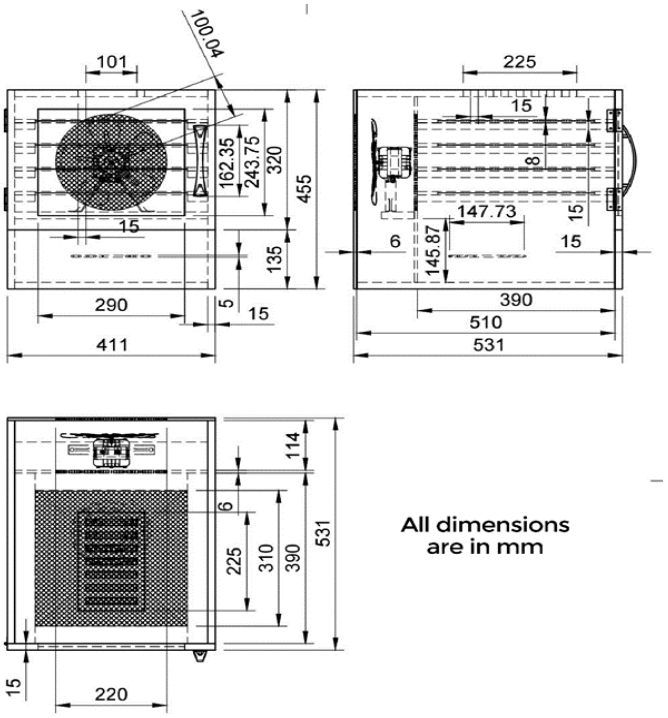

Figure 4: Orthographic views of the model with dimensions

Figure 5: Fabricated dehydrator

3. Results and Discussions

From Figures 3 and 4, plantain drying reached its shortest time at 75°C, taking 210 minutes, followed by 240 minutes at 70°C and 270 minutes at 65°C. The point of equilibrium moisture content was reached when no further weight change was detected while maintaining constant relative humidity and airflow rate. These findings indicate that temperature significantly influences the dehydration process of the chosen product. This is likely because higher temperatures result in a greater partial pressure difference between the plantain and its surroundings. This increases moisture migration from the internal region and evaporation at the product surface. This equilibrium is attained at a weight of 0.041 kg. This shows that the drying time decreased as the drying temperature increased.

From the results of the research shown in Figures 5 and 6, plantain slices were found to dry significantly faster when the temperature was raised because higher thermal energy is associated with a faster rate of heat transfer, which heightens the ability to permit the flow of moisture from the material's interior to its exterior. In order to analyze the results at each temperature and determine the best dehydrating temperature for plantains among the range of temperatures included in the experiment, the effectiveness of the dehydrator was evaluated by taking into account the stated temperatures. The performance evaluation results in 'Table 2' indicate that the dehydrator's efficiency is contingent on temperature. Consequently, higher temperatures lead to improved drying times.

Table 2: Calculated table of values for dehydrator efficiencies at different temperatures

No.	Temperature (℃)	Drying time (secs)	Mw (kg)	Lvap (kJ/kg)	Pin	Efficiency (%)
1	65	16200	0.076	2260	1800	5.89026063
2	70	14400	0.076	2260	1800	6.62654321
3	75	12600	0.076	2260	1800	7.57319224

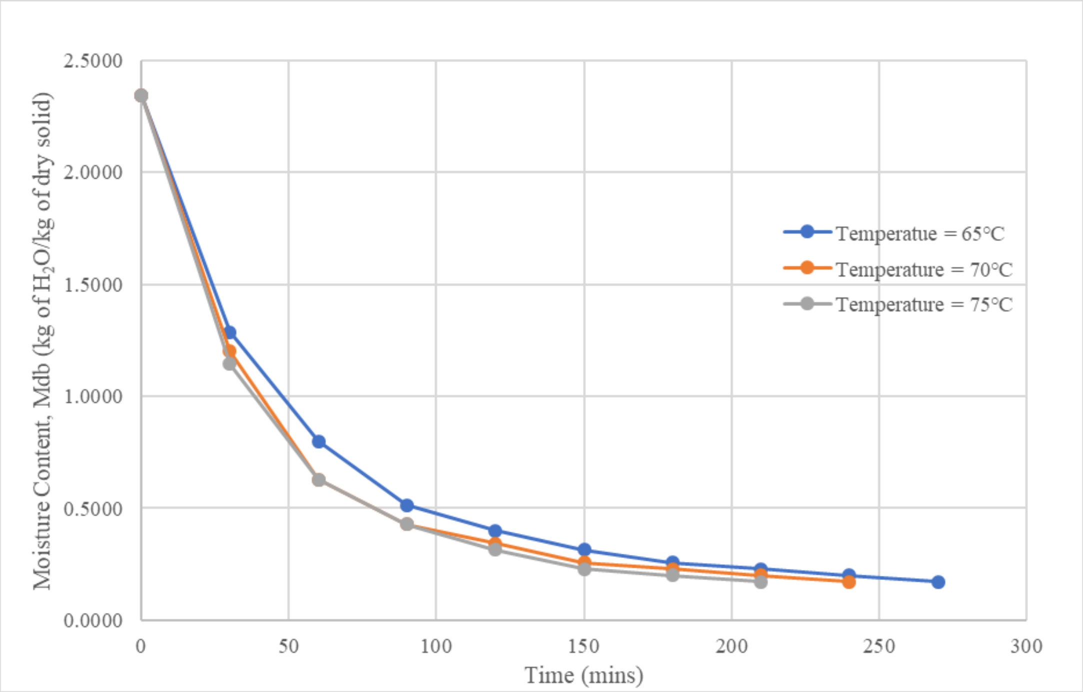

Figure 6: Drying curves for plantain at 65℃, 70℃ and 75℃

From Figure 6, the shortest drying time for tomato drying was on Tray C at 150 minutes, followed by Tray B at 120 minutes, and Tray A at 90 minutes. The performance evaluation results in Table 3 indicate that the dehydrator's efficiency depends on the tray position, with Tray C being the closest to the heating element. This shows that the farther the tray is from the heating element, the longer the drying time will be, leading to reduced efficiency in drying. Figure 7 shows that Tray C reaches the desired moisture content at 90 minutes, Tray B at 120 minutes, and Tray A at 150 minutes. It was observed that the closer the trays were to the heating element, the faster the drying time.

Table 3: Calculated table of values for dehydrator efficiencies at different tray positions

No.	Tray Position	Drying time (secs)	Mw (kg)	Lvap (kJ/kg)	Pin	Efficiency (%)
1	A	9000	0.117	2260	1800	16.32222222
2	B	7200	0.117	2260	1800	20.40277778
3	C	5400	0.117	2260	1800	27.20370370

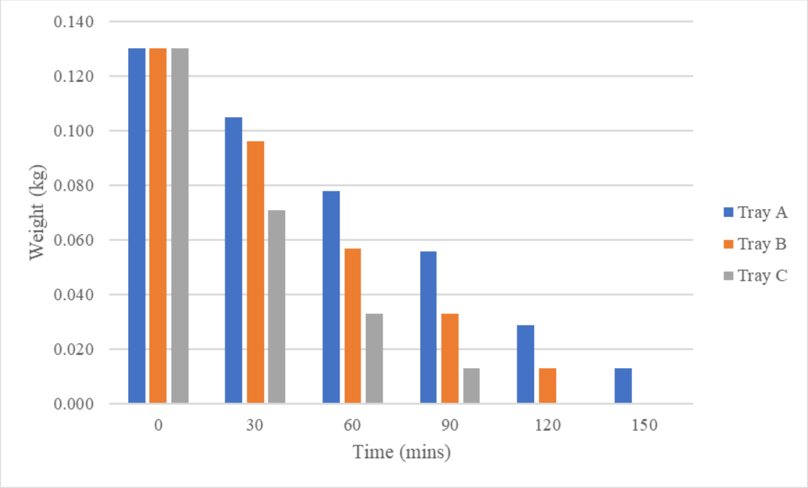

Figure 7: Impact of Tray Position on Drying Time

Using the experimental data from the test on carrots, linear and exponential curves were generated. A perfect fit of the data to the predicted curve would have been 1.0000. From Figure 8, the linear curve had an R^2 value of 0.4202, quantifying how poor this fit is. This shows an extreme deviation from the experimental data, rendering that kinetic model unusable. However, the exponential curve had an R^2 value of 0.9503. The deviation of the predicted data from the experimental data is minimal. It can practically be used to closely predict the moisture content of carrots at any point within 11 hours of operation, provided the drying parameters remain the same.

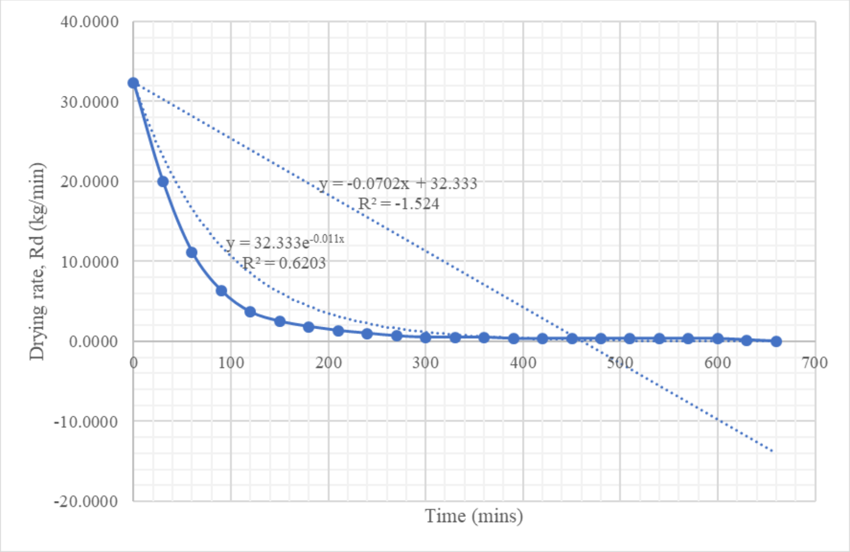

Figure 8: Linear and exponential curve fitting for drying of carrots

4. Conclusion

The fabrication and performance evaluation of a varying temperature dehydrator for food preservation has been successfully achieved. The performance of the dehydrator has been examined by dehydrating plantains at different temperatures, tomatoes at different tray positions based on the distance to the heating element, and carrots at an extended drying time to create a drying kinetic model. The first experiment was carried out at 65℃, 70℃, and 75℃ using plantains as the test sample showed that the drying time is a function of the dehydrator's operating temperature. The second experiment was carried out at 70℃ using tomatoes, which showed that the efficiency of the dehydrator was the highest on the tray closest to the heating element. With the third experiment, which employed carrots as test samples dehydrated at 60℃, the experimental data was used to create a predictive that would enable us to predict the moisture content within 11 hours closely. The dehydrator's efficiency was also computed, and the results showed that the efficiencies are a function of drying time, temperature, and tray position.

The varying temperature dehydrator is designed to dry various foods with precise temperature control, minimizing degradation of quality and nutrients. Features such as the thermostat-based feedback control system contribute to its reliability. This dehydrator can help reduce food waste, extend shelf life, and improve food security, especially in regions with limited access to advanced preservation methods, by enabling effective food preservation. The project's focus on environmental friendliness and suitability for small-scale applications further enhance its potential to impact communities and support sustainable food systems positively. The insights gained from the fabrication and performance evaluation of this varying temperature dehydrator can pave the way for further advancements in dehydration technology, leading to more efficient, versatile, and user-friendly food preservation solutions.

4.1. Recommendations

- Investigate the feasibility of incorporating additional features that allow for greater customization of drying parameters, such as programmable temperature profiles or the ability to handle a wider range of food types with varying moisture content.
- Explore using renewable energy sources, such as solar or wind power, to power the dehydrator, reducing the environmental impact and expanding the accessibility of the technology, especially in off-grid or resource-constrained regions.
- Continuously refine the mechanical and electrical design of the dehydrator further to improve reliability, ease of use, and cost-effectiveness, making it more accessible to a wider range of users.
- Conduct more extensive performance evaluations, including testing with a broader range of food products, to validate the dehydrator's versatility and optimize its performance across different applications.

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Ethics and Consent Statement: This research adheres to ethical guidelines, obtaining informed consent from all participants.

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