CLSU International Journal
of Science and Technology
https://ijst.clsu.edu.ph/
ISSN 2507 -9638 (online)

The CLSU International Journal of Science and Technology was previously published as CLSU Scientific Journal since 1965.

Development of an Automated Water Hyacinth Dryer for Handicraft Production

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Submitted: August 21, 2024. Accepted: December 01, 2024. Published Online: December 15, 2024.

Abstract

An automated water hyacinth stalks dryer was developed as a means of addressing the issues brought on by the widespread distribution of water hyacinth in bodies of water as well as the issues encountered during the drying of the crop using sun drying and the existing DOST-FPRDI dryer. When compared to the current methods of drying water hyacinth stalks, this developed dryer has a significant advantage because it encloses the stalks in the drying chamber, protecting them from insect and pest infestation. Additionally, because the dryer is automatically controlled, it provides the ideal environmental conditions for drying the said stalks, resulting in higher-quality dried products. The main components of the dryer are drying chamber, heating element, blower/fan, and control panel Prior to final testing, the dryer was subjected to a no-load test. Centralized Composite Design experimental design represented the design of experiments that resulted to 13 drying treatments. The blower was tested at fan speeds of 90, 91.46, 95, 98.54 and 100 CFM, while the heater (5.4 kW) was tested to produce 70°C, 72.92°C, 80°C, 87.07°C and 90 °C. Trial run number 5 got the highest drying efficiency of 55.249% with a drying rate of 29.674 g/min and a moisture ratio of 9.702. ANOVA test revealed that drying temperature greatly affects the drying rate, moisture ratio, and drying efficiency , while airflow rate only significantly affects drying rate. Run 13 got the highest drying rate of 29.674 g/min while Run 1 got the lowest drying rate of 19.348 g/min; for moisture ratio, the highest value was 9.70 obtained at run number 13 also while the lowest moisture was 3.03 attained at run number 12; for drying efficiency, highest drying efficiency was 59.23% obtained at run number 5, while lowest drying efficiency 18.28% obtained at run number 12. These findings show that the higher the drying temperature and airflow rate the higher the drying rate, moisture ratio and drying efficiency. In addition, a techno-economic evaluation of the developed system and an economic analysis of the automated dryer were conducted, the results showed that the system is highly viable, feasible, and economical with a break-even point and payback period of 197,777 stalks and 7 months, respectively.

Keywords: Break-even, CCD, Economical, Payback

Introduction

Water hyacinth, popularly known to Filipinos as water lily, is an abundant free-floating water weed that thrives in freshwater (Shoughy et al., 2014) and is characterized by smooth leaves, erect stalks, and blue or violet flowers (Siburian, 2016). Since this aquatic herb has been distributed throughout the world and can survive and grow even in severely polluted bodies of water (So et al., 2003), it is now considered one of the world's worst aquatic weeds (Zhang et al., 2015; Shanab et al., 2010; Tellez et al., 2008).

DOI: https://doi.org/10.22137/ijst.2024.v8n2.02

Few of the severe effects brought by the widespread distribution of this plant are the blocking of waterways, canals and rivers hence become a problem to water transport, also it becomes one of the major reasons why flooding occurs, increase of evapotranspiration has also been recorded, interference with fishing, navigators, recreational activities, sports and eco-tourism management have been experienced by affected areas water (Coetzee et al., 2014; Godana et al., 2022; Onyango & Ondeng, 2015; Pejchar and Mooney, 2009). Fortunately, there are lots of products that can be made out of water hyacinth stalks such as animal feed, biogas, compost, rope, paper pulp, furniture and also used for reducing pollution and a complete raw material for handicraft which serves as a source of income for the communities affected (Casas et al., 2012; Galgali et al., 2023; Gaurav et al., 2020; Guna et al., 2017; Li et al., 2021). However, with the fact that the freshly harvested water hyacinth has 92% moisture content (w.b) and 96 kg/m^3 of bulk density, the processing and transportation of the plant has been limited (Olal, 2003), hence there is a need to reduce the moisture level of water hyacinth stalks for them to be used as a raw material for making handicrafts.

The development of advanced drying techniques is a result of modern technical innovation, particularly for a range of commercial and industrial uses and processes. Energy consumption is always required, whether the process is at room temperature (desiccant drying), low temperature (refrigeration drying), or hot air drying or dielectric heating (Bano et al., 2015). The process of drying simply involves removing enough moisture from crops to prevent decomposition, as moisture in many types of produce makes them more susceptible to deterioration, particularly in tropical climates.

Open sun drying is one of the most common methods of drying water hyacinth stalks (Esper and Muhlbauer, 1998; Casas et al., 2012). Unfortunately, this method has some disadvantages, including that stalks are prone to pest and insect infestation, cannot be dried to the desired level, lacks monitoring of the final product's moisture content, and is especially weather dependent, making it inefficient and unreliable. Hence, this significantly affects the product quality (Shoughy et al., 2014). The Department of Science and Technology - Forest Products Research and Development Institute (DOST-FPRDI) developed a biomass-fed water hyacinth dryer that encloses the stalks in the drying chamber, protecting them from pests and insects. Nonetheless, this dryer is wood-fired and manually operated, meaning it has no controller system, no capability to monitor drying parameters inside the drying chamber, and has no proper monitoring of the dried products' moisture content (Carmelo et al., 2014).

Considering the aforementioned literature, it can be seen that the existing methods and equipment for drying water hyacinth stalks are still manually operated and cannot control the internal condition of the drying chamber; thus, this study intends to develop an automated dryer for water hyacinth stalks, which will be controlled using an Arduino Uno microcontroller.

Materials and Methods

Design of an Automated Dryer Machine for Water Hyacinth Stalks for Handicraft Production

The design and fabrication of an Automated Drying Machine for Water Hyacinth stalks was based on the principle of convective drying, which used a heating element, fan, temperature-humidity sensors, and locally available materials for thermal insulation. It was installed with an Arduino Mega system to automatically control the temperature and airflow inside the drying chamber. The Automated Dryer for Water Hyacinth Stalks consisted of the following main parts, namely the drying chamber, heating element, and fan. The drying chamber is cylindrical to uniformly distribute the airflow around the products to be dried. Mustafa et al. (2017) noted that a cylindrically-shaped drying chamber can shorten drying time and produce a homogenous dried product. Moreover, the system was designed to operate at desired temperatures (70℃, 72.92℃, 80 ℃, 87.07℃, and 90℃) and airflow rate (90 CFM, 91.46 CFM, 95 CFM, 98.54 CFM, and 100 CFM), these are the safe temperature and airflow rate ranges recommended by (Casas et al., 2012; Carmelo et al., 2014).

Moreover, the different components of the developed Automated Drying Machine for Water Hyacinth Stalks, such as fan assembly and heating assembly, were designed to be detachable via bolts and nuts for easy repair and maintenance.

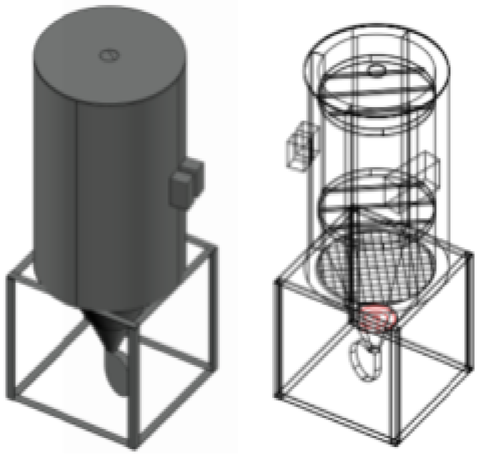

Figure 1. Isometric View of the Drying Machine

Dryer Description

The housing assembly was constructed to ensure that there would be no spaces for heat leak since the main purpose of this system was to maintain the desired temperature inside the drying chamber.

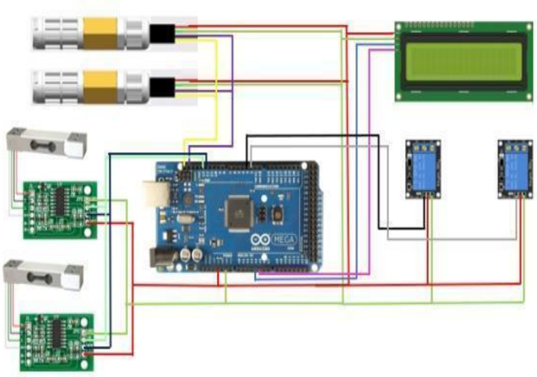

Figure 2. Schematic Diagram of the Controller's Connection

The dryer consisted of a circular drying chamber, a top cover, and a heating system housing as the main components.

Drying Chamber: This was the part of the dryer where the water hyacinth stalks were loaded and dried. The drying chamber was constructed with a capacity of 1000 stalks and has a cylindrical shape. This chamber was cylindrical in shape, made with stainless steel (Stainless Steel 304 Gauge 14). Because of its heat transfer properties, it was also positioned centrally on the dryer frame. The drying chamber has a height of 1.65 meters, an inside diameter of 0.65 meters, and an outside diameter of 0.8 meters. The drying chamber has a perforated screen at the bottom.

Drying Chamber Door: The door of the drying chamber was located on the front side of the drying chamber, which is for ease of loading and unloading of the stalks.

Heating element: This served as the primary heat-generating component of the dryer.

Fan/Blower: The blower pushed the air drying air through an air delivery tube to the drying chamber.

Furthermore, drying takes place through the transfer of heat and mass, and then with the aid of a chimney, the residual/exhaust air exits (Olaniyan et al., 2014); hence, for every dryer, the chimney is an essential part since it allows the moisture of the commodity to be evaporated out from the dryer. The chimney of this dryer was located at the center top portion of the drying chamber.

Principle of Operation of the Automated Dryer for Water Hyacinth Stalks

Process Flow Diagram

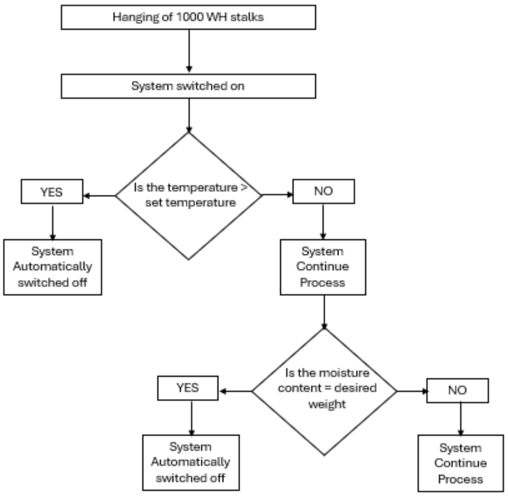

Figure 3. Process Flow Diagram

One thousand stalks of water hyacinth were hung vertically and loaded inside the drying chamber. After the WHS were properly loaded, the chamber was closed then the desired temperature and air flow were set. Heated air with a constant air flow was blown

DOI: https://doi.org/10.22137/ijst.2024.v8n2.02

across the stalks until it reached the set temperature. When the sensor measured that the temperature was already greater than the set temperature, the heater was automatically turned off and was turned on again when the sensed temperature was already lower than the set temperature.

Then, when the load cells have measured that the programmed moisture content is already achieved, the whole system is automatically switched off.

Energy Required for Drying A Unit Amount of Crop

The amount of moisture to be evaporated from the crop can be calculated by subtracting the final mass from the initial mass of the crop or by using the following formulas:

$$M_f = \frac{Mi*(100-IMC)}{(100-FMC)} \qquad \textit{Equation 1}$$

$$M_r = M_i - M_f \qquad \textit{Equation 2}$$

Where Mi is the initial mass, Mf is the final mass, IMC is the initial moisture content, and FMC is the final moisture content.

Also, the amount of useful energy or the amount of theoretical energy needed for drying a unit crop can be calculated by adding the amount of sensible heat and latent heat. Sensible heat is the amount of heat needed to raise the temperature of the liquid substance, while latent heat is the amount of heat needed to vaporize the liquid substance.

$$(Q_s) = Mi * c_p * (Td - Ta) \qquad \textit{Equation 3}$$

$$(Q_l) = MR * \gamma \qquad \textit{Equation 4}$$

Where Q_s is the sensible heat, Q_l is the latent heat, c_p is the specific heat, Td is the drying temperature, Ta is the ambient temperature, MR is the moisture ratio, and γ is the latent heat of vaporization of water at drying temperature.

Insulation of the drying chamber

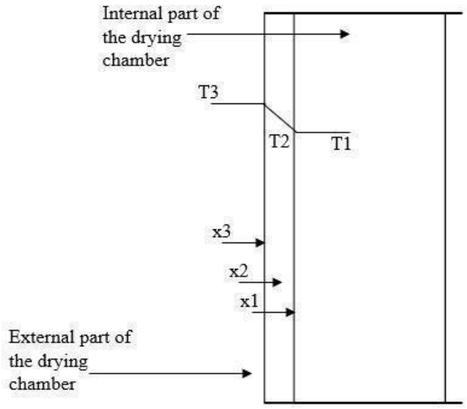

Figure 4. Front View of Insulation Chamber

$$\text{Quantity of heat loss per unit area} = \frac{K1*(T1-T2)}{x1}$$

$$\text{Quantity of heat loss per unit area} = \frac{K2*(T2-T3)}{x2}$$

$$\text{Quantity of heat loss per unit area} = \frac{K3*(T1-T3)}{x3}$$

Quantity of heat loss per unit area = U * (T_1-T_3) *Equation 5*

Where:

K1 and K3 = heat transfer coefficient of stainless steel, 17 W/m.K
K2 = heat transfer coefficient of air, 0.026 W/m.K
X1 and X3 = thickness of stainless steel
X2 = thickness of air

Performance Parameters

a. Drying Rate

Drying rate is the amount of water removed per unit time (Nafate et al., 2019) and will be determined using the equation:

$$D_r = \frac{Mci-MCf}{time} \qquad \textit{Equation 6}$$

Where:

D_r is the drying rate, Mc_i is the initial moisture content, and MC_f is the final moisture content.

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b. Moisture ratio

The equation below will calculate the moisture ratio that represents the proportion of moisture removal at a given time interval (Casas et al., 2010)

MR = $\frac{M-Me}{Mo-Me}$ or simply MR = $\frac{M}{Mo}$ *Equation 7*

Where:

MR is the moisture ratio; *M* is the moisture content at a given time; M_o is the initial moisture content, and M_e is the equilibrium moisture content.

c. Drying Efficiency

Drying efficiency is different from thermal efficiency because it is not only the capacity of the dryer to increase the air temperature assessed, but also the capacity to effectively remove water from the products, providing more relevant information about the device performance (Nafate et al., 2019).

Assuming that heat loss from the dryer medium to the ambient air is negligible and heat is utilized to increase the temperature of the product and to evaporate moisture from the product, hence, the drying efficiency DE (%), at any time period, is expressed as (Ohijeagbon et al., 2016):

DE = $\frac{Mr*L*mf*Cw*\Delta T}{A*t}$ *Equation 8*

Where:

DE = drying efficiency, %
Mr = water evaporated during a time period, kg
L = Latent heat of vaporization, J/kg
This will be determined at the drying air temperature (T_d) ^{0}K, according to ASAE

L = 2,502,535.259 – 2,385.76424 (T_d – 273.16) *Equation 9*
t = desired time period, 3600 sec
A = surface area of the drying space, m^2
mf = mass of sample at a time period, kg
ΔT = temperature difference between the drying air and ambient temperature, ^{0}K

d. Experimental Design

In order to determine the main and interaction effects of the drying air temperature and the drying air flow rate on quality parameters of dried water hyacinth, a two-factor three-level, face-centered central composite design was applied. In the drying process of the water hyacinth stalks samples with this kind of dryer, to investigate the effect of the independent variables on the dependent variables for the experiments, two independent variables of the drying air temperature (70℃, 80℃ and 90℃) and three levels of the drying air flow rate (90 CFM, 95 CFM and 100 CFM) were used on the responses of the drying rate, moisture ratio and drying efficiency. The coded levels will be (−1), (0), and (1) for the two independent variables of the drying temperature and air flow rate, each of which had three different levels, and the dependent variables of the experimental design are listed in Table 2.

A total of 13 experimental runs were done to evaluate the effects of the independent variables on the responses, as shown in Table 2 below.

e. Statistical Analysis

Data obtained was processed using the STAR software statistical package and MiniTab Trial version 15. A 2-factor and 3-level face-centered CCD experimental design was used to investigate the effect of independent variables on the responses. The drying air temperature(X1) and airflow rate (X2) were the independent variables, while the dependent or response variables were drying rate, moisture ratio, and drying efficiency. The two variables (drying temperature and airflow rate), levels, and also the experimental design in terms of actual and coded levels are shown in Table 2. The experiments were carried out in random order to optimize the effect of unexplained variability in the responses caused by extraneous factors. The significance of the results obtained was analysed using analysis of variance (ANOVA) followed by regression analysis.

Table 1. Experimental Layout Of Independent Factors, Related Levels, Criteria And Goals Utilized For Central Composite Design

	Independent Parameters	Coded Symbol	Actual	Response Variables
Input Parameters	*Air Temperature, °C*	-1	70	Drying Rate
		0	80	
		1	90	Moisture Ratio
	Air Flow Rate, CFM	-1	100	
		0	90	Drying Efficiency, %
		1	95	

Table 2. Combination of Drying Temperature and Airflow Rate with Actual and Coded Variable Levels for Experimental Design

Run	Actual Levels	
	Drying Temperature, °C	Airflow Rate, CFM
1	72.92	91.46
2	80.00	90.00
3	80.00	95.00
4	80.00	100.00
5	90.00	95.00
6	80.00	95.00
7	87.07	91.46
8	80.00	95.00
9	72.92	98.54
10	87.07	98.54
11	80.00	95.00
12	70.00	95.00
13	80.00	95.00

Results and Discussion

The study developed an automated dryer machine for water hyacinth stalks for handicraft production. Thirteen (13) drying runs were performed based on the Centralized Composite Design (CCD) of the experiment. The resulting data were analyzed to find whether the independent parameters (Temperature and airflow rate) significantly affect the dependent parameters (drying rate, moisture ratio, and drying efficiency).

Description of the Developed Automated Dryer Machine for Water Hyacinth Stalks For Handicraft Production

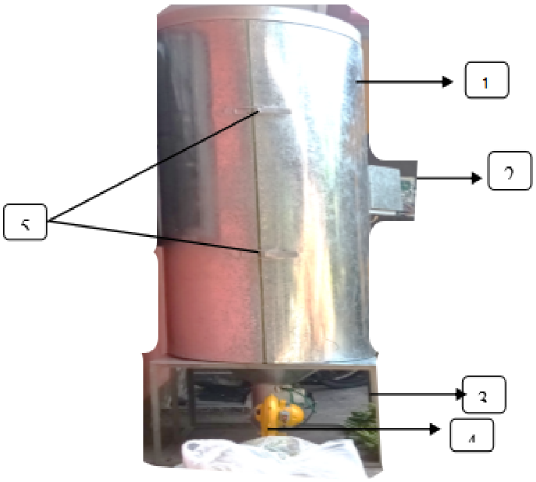

Figure 5. Component Parts of the Automated Dryer Part I (1-Drying Chamber; 2-Control Panel; 3-Drying Machine Stand; 4-Blower; 5-Door Handle)

The developed dryer was automated with the aid of Arduino Mega microcontroller, which was incorporated with temperature sensors, relative humidity sensors, relay switches, and load cells. The drying chamber serves as the loading area where water hyacinth stalks are loaded for drying. All components of the dryer were joined by rivets for ease of repair and maintenance. Also, the drying chamber was given enough thickness in order to minimize the heat loss.

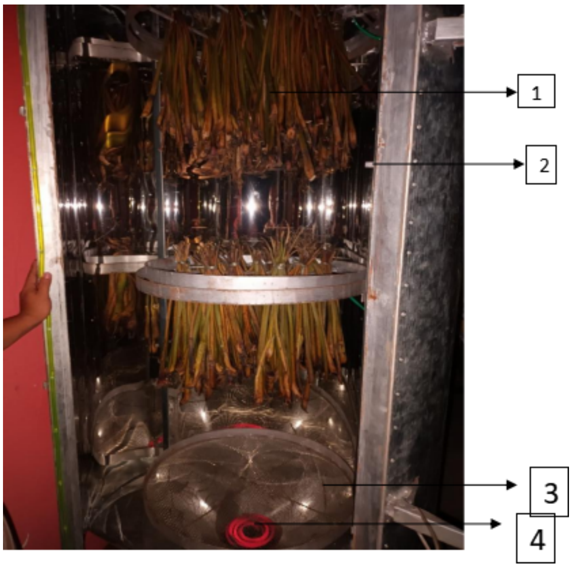

Figure 6. Component Part of the Automated Dryer Part II (1- Water Hyacinth Stalks; 2- SHT20 sensors; 3- Perforated Screen; 4-Heating Element)

Drying

Figure 7. Dried Water Hyacinth Stalk

Figure 8. LCD reading of the Automated Dryer

The samples were dried at 70℃, 72.92℃, 80℃, 87.07℃, and 90℃ drying temperatures and 90 CFM, 91.46 CFM, 95 CFM, 98.54 CFM, and 100 CFM airflow rates. The weight of the samples was monitored through the LCD of the machine every 10 minutes. The drying of the sample continued until the whole system turned off, wherein the load cell sensed that the weight of the samples was already the desired weight. The dried samples were placed inside the resealable plastic bags.

Effects of Independent Parameters on Response Variables

Presented in Table 3 is the summary of the responses at each drying set-up**.** Run 13 got the highest drying rate of 29.674 g/min, while Run 1 got the lowest drying rate of 19.348 g/min. This result was expected since Run 13 has a high drying temperature of 80℃ and an airflow rate of 100 CFM. On the other hand, Run 1 has a low drying temperature of 72.92℃ and an airflow rate of 95 CFM. Therefore, it can be concluded that drying at high temperature decreases the drying time and, in this way, the drying rate increases. This result was also stated by Akoy (2007), wherein they found that as drying temperature increases, the moisture content of the dried products decreases.

Moisture ratio was another response variable investigated. The obtained values of this variable at each drying run are also illustrated in Table 4. The highest value was 9.70 obtained at run number 13, while the lowest moisture was 3.03 attained at run number 12. It was expected that run number 13 would have the highest moisture ratio because it has a high drying temperature. On the other hand, run number 12 has a drying temperature of 70℃. This result implies that drying temperature affects the moisture ratio. This result was in good agreement with the findings of (Mustafa et al., 2023), where they found that the higher temperature significantly affects the moisture content of the dried products.

Drying efficiency was also another response variable investigated. The highest drying efficiency was 59.23% obtained at run number 5, while the lowest drying efficiency was 18.28% obtained at run number 12. Run number 5 got the highest drying efficiency because it has the lowest difference between the drying air temperature and the temperature coming from the heat source. On the other hand, run number 12 got the lowest drying efficiency because it has a high temperature difference between the drying air temperature and the temperature from the heat source. This result agrees with Cheng et al. (2015), who stated that the heat to be supplied should correspond to the rise and fall of the air temperature in the air heater.

ANOVA Test Results

The effects of airflow rate and drying temperature are summarized in Table 5 and were analyzed using STAR (Statistical Tool for Agricultural Research).

The ANOVA test result (Table 4) showed that temperature significantly affected the drying rate, moisture ratio, and drying efficiency at a 95% level of significance. This result was expected since drying temperature and drying rate have a direct relationship; more moisture is expelled as drying temperature increases, and the lower the difference between drying and ambient temperature, the higher the drying efficiency and vice versa.

DOI: https://doi.org/10.22137/ijst.2024.v8n2.02

Airflow rate significantly affected the drying rate at a 95% level of significance, but failed to significantly affect the rest of the independent variables. This result was expected since the medium for heat transfer is through air; different airflow rates significantly affect drying time, which has a direct relationship with drying rate.

Table 3. Summary of Data showing the responses at each drying set-up

Test	Drying Time (min)	Drying Temp.	Airflow Rate	Final mass (g)	Drying rate (g/min)	Moisture Ratio	Drying Eff.
1	160	72.92	95	238.50	**19.348**	5.88234	30.93
2	150	80.00	100	135.29	28.888	5.88235	51.40
3	180	80.00	90	135.29	21.842	3.32669	48.09
4	140	80.00	90	192.45	21.995	5.88235	39.14
5	170	90.00	95	236.74	22.281	5.88235	**59.23**
6	190	80.00	90	242.67	20.435	5.88235	40.94
7	180	87.07	90	328.42	21.431	7.84565	48.78
8	200	80.00	90	241.84	23.850	5.88235	44.20
9	170	72.92	100	256.27	24.119	5.88235	34.41
10	170	87.07	90	284.99	26.823	5.88235	25.33
11	150	80.00	95	237.31	25.313	5.88235	33.95
12	170	70.00	90	260.08	24.478	**3.02761**	**18.28**
13	130	80.00	100	414.47	**29.674**	**9.70194**	32.43

Table 4. Effects of Independent Variables on Responses

		***p*-value**	
PARAMETER	**Drying Rate**	**Moisture Ratio**	**Drying Efficiency**
temperature	0.0138^{s}	0.0208^{s}	0.0284^{s}
airflow rate	0.0340^{s}	0.1469^{ns}	0.4353^{ns}

s – significant
ns – not significant

The figures below show the detailed graph of drying rate, moisture ratio, and drying efficiency versus the drying temperature and air flow rate.

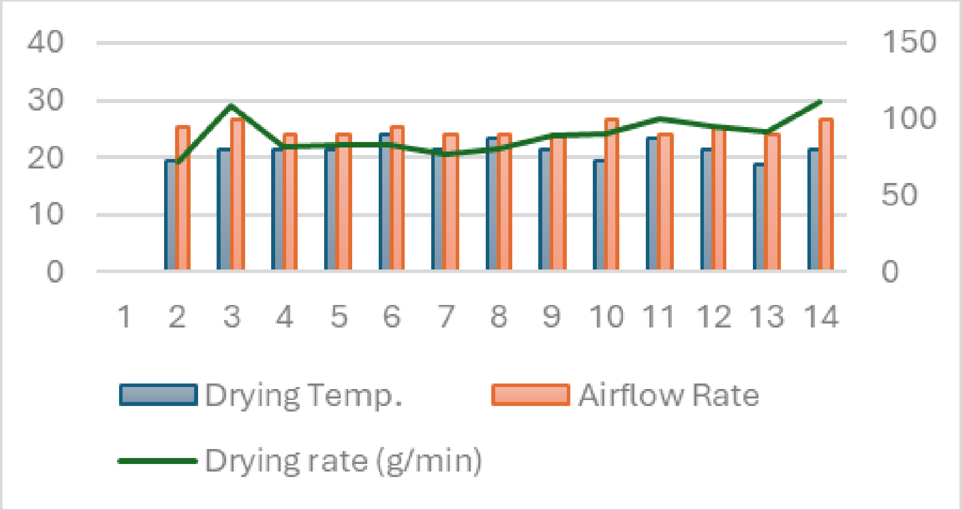

Figure 9. Drying Rate vs Dependent Variables

Figure 9 above shows that the higher the temperature and airflow rate, the higher the drying rate, and this result agrees with Akoy (2013) and Mustafa et al. (2023), wherein the higher the temperature, the faster and higher the removal of moisture content.

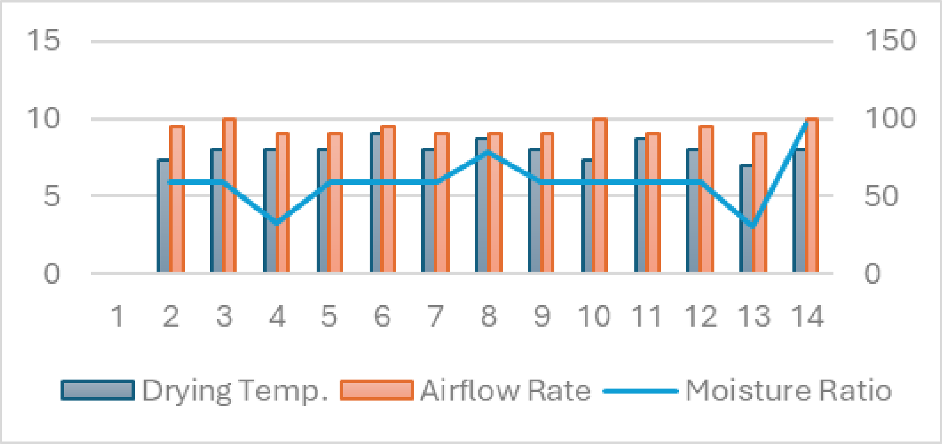

Figure 10. Moisture Ratio vs Dependent Variables

Moreover, Figure 10 above shows that the higher the temperature and airflow rate, the higher the moisture ratio, which means that the removal of moisture is higher. This finding is similar to the study of Mustafa et al. (2023), wherein the moisture content is directly affected when the dried products are exposed to higher temperatures.

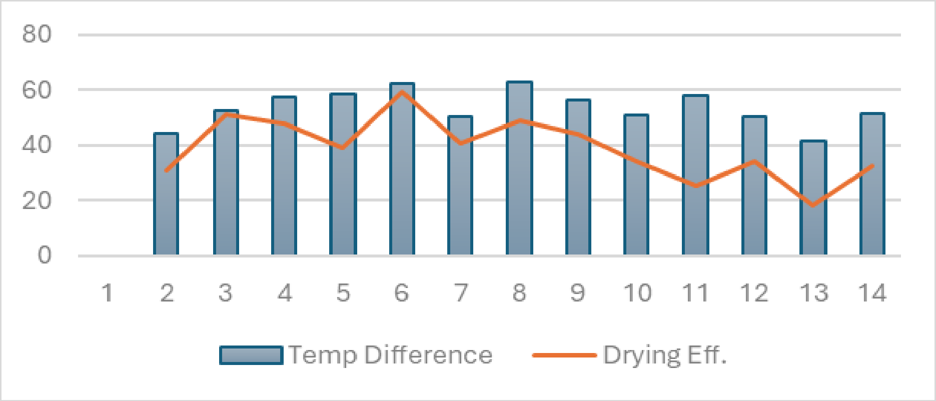

Figure 11. Drying Efficiency vs Ambient Temperature and Drying Temperature

According to Cheng et al. (2015), the drying efficiency is positively affected by drying temperature and air (ambient) temperature; hence, for visual data presentation for this study, the drying efficiency was graphed versus the temperature difference between drying temperature and ambient temperature. Figure 9 above shows that the higher the temperature difference, the higher the drying efficiency.

Cost Analysis

Any system's economic viability can be determined by doing a system economic analysis. It is crucial to understand whether a new technology is economically viable for it to succeed and be commercialized.

Based on the economic circumstances in Oriental Mindoro and the economic analysis of the developed dryer, the relevant characteristics are selected, as indicated in Table 6. The annualized cost technique was used for the cost-benefit analysis of drying water hyacinth stalks.

Table 5. Recurring and Non-Recurring Costs

Item	Value	Unit
Capital Cost of Dryer	81750	Php
Life Span of Dryer	10	years
Operating Time per Day	8	hours
Electrical cost kW-hr	11.63	Php
Rated Capacity of Dryer	5.5	kW
Number of Operating Days per Year	307	Days

Capacity of Dryer	1000	stalks/batch
Salvage Value (10% of Capital)	8175	Php
Repair and Maintenance Cost (10% of Capital)	8175	Php/year
Operational Labor Cost	320	per day
Eletricity Cost	528	per day
Interest Rate	12%	per year
Rate of TIS per year	3%	per year

Table 6. Economic Indicator

Items	Value	Unit
Break even point (BEP)	197777.5	Stalks
Payback Period	0.527786	Years

Conclusion

To address the problems caused by the widespread infestation of water hyacinth and the difficulties in drying the crop using sun drying and the DOST-FPRDI dryer, an automated water hyacinth stalk dryer was designed and fabricated. It consisted of a drying chamber, heating element, blower/fan, and control panel. The developed dryer was subjected to a no-load test before final testing.

Testing and evaluation used two independent variables, which include drying temperature and airflow rate. The study investigated the effects of these independent variables on the following responses: drying rate, moisture ratio, and drying efficiency. The study employed a Centralized Composite Design experimental design that resulted in 13 drying treatments.

Experimental results showed that the drying temperature significantly affects the drying rate, moisture ratio, and drying efficiency. Airflow rate has a significant effect on drying rate only.

From the results, the heater (5.4 kW) was tested to produce drying temperatures of 70, 72.92, 80, 87.07, and 90 °C while the blower was tested at fan speeds of 90, 91.46, 95, 98.54, and 100 CFM. Results revealed that Run number 5 got the highest drying efficiency of 55.249% with a drying rate of 26.823 g/min and a moisture ratio of 7.84.

The computed break-even point and payback period of the developed automated dryer were 197,777 stalks and 0.53 years, demonstrating its viability and feasibility as well. Also, the computed payback period is shorter than the life span of the machine, which makes the system economical.

As this research aims for innovation and promotes livelihood, this corresponds to SDG 9, which is Industry, Innovation, and Infrastructure. For scalability in the future, relative humidity should be considered, as it greatly affects the drying process of any crops.

Acknowledgements

The author gratefully acknowledges the Department of Science and Technology – Engineering Research and Development for Technology for providing financial assistance all throughout the conduct of this research. The author also deeply appreciates the CLSU-ERDT staff for their guidance and support.

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