Optimized drying parameters of water hyacinths *(Eichhornia crassipes. L)*

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ABSTRACT

The study investigated the optimum drying conditions of water hyacinth to contribute in the improvement of present drying processes. The effects of independent parameters (drying temperature, airflow rate, and number of passes) on the responses were determined using the Response Surface Methodology. The response parameters were composed of (1) final moisture content, (2) moisture ratio, (3) drying rate, (4) tensile strength, and (5) browning index. Box and Behnken experimental design represented the design of experiments that resulted in 15 drying runs. Statistical analysis evaluated the treatment effects. Drying temperature significantly affected the drying rate, moisture ratio, and browning index. Airflow rate had a significant effect only on the drying rate, while the number of passes significantly affected both the drying rate and browning index. The optimized conditions for drying the water hyacinth were at drying temperature of 90ˆC, airflow rate of 0.044m^3/s, and number of passes equivalent to five. The best model that characterizes the drying of water hyacinth is a rational function expressed as:

$$MR = \frac{1.00 \pm 3.07e^{-3}x}{1 + 9.87e^{-2}x + (3.84e^{-4}x)^2}$$

Keywords: Box-Behnken design, desirability function approach, drying, multiple response optimizations, response surface methodology, water hyacinth

INTRODUCTION

Background of the study

The water hyacinth (*Eichhornia crassipes*), popularly known to Filipinos as the water lily, is a free-floating plant growing in freshwater. This invasive species, native to South America, has fibrous tissue, high energy and protein content, and a moisture content of 95%. It is also primarily used as an ornament in garden ponds. However, due to its large population in water bodies, it has become undesirable and harmful to other aquatic species as well as aquatic ecosystems. It also causes the clogging of waterways, which effectively reduces the flow of water. Moreover, it is also decreasing the dissolved oxygen level in the water, which is needed by many aquatic species like fish.

Nowadays, there are different practical applications to utilize the abundance of the water hyacinths so that they become more useful. For example, paper and rope productions use water hyacinth fibers. In many parts of Asia, it is used as an animal feed for pigs, ducks, and fish. In addition, water hyacinths are also used as fertilizers and aids in water purification either for drinking or for liquid effluent from sewage systems. In the Philippines, the most common use for the plant is for handicrafts like baskets, matting, and furniture. According to Abella (2010), the water hyacinth handicraft industry in Laguna is now in its growth stage since it is in the period of rapid market acceptance and shows substantial profit improvement. Moreover, these handicraft products are exported to other countries in Europe and Asia, like Japan and Korea.

In order to use the water hyacinth as a raw material for handicraft making, its water content must be lowered through a drying process. Currently, sun drying is the most common practice for drying. After gathering the plants from water bodies, their stems are subjected to sun drying for one week. However, this present drying system has many drawbacks. Sun drying does not properly dry the stalks (to desired moisture levels) and it is time-consuming. (2007) stated that sun drying is not a good method for drying because it is prone to losses primarily due to insect infestation and microbial attacks. He also reported that sun-drying method lacks control in the quality of the product. Another problem with sun drying is that it is highly dependent on weather, making it very inefficient and unreliable.

Significance of the study

In any handicraft industry, the major factors that impact on the success of this business are high quality of product and labor productivity. With the growing demand of water hyacinth handicraft products in the international market, production of these products must possess a good quality. One way to achieve this is by improving the present process of drying. Proper drying will prevent rotting and mold growth because it lessens the moisture content of the product. Determining the right combination of drying parameters will be helpful in achieving the satisfactory quality of the product, as well as making the drying operation more economical.

This study determined the optimum heated-air drying condition for water hyacinths. Results of this study will be helpful in the development of more effective drying procedures for water hyacinths.

Objectives of the study

The main objective of this study was to determine the optimum drying parameters for water hyacinth. Specifically, this study aimed to:

(a) determine the effects of air temperature, air flow rate, and dewatering on the responses such as drying rate, moisture ratio, browning index, tensile strength, and final moisture content;
(b) find the optimum drying condition for the heated-air drying of water hyacinths; and
(c) develop a drying model equation for water hyacinths.

This study investigated the heated-air drying process that considered air temperature, airflow rate, and the number of passes in the roller (for dewatering) as independent parameters. A metal roller, normally used for forming metal sheets into smooth cylinders, dewatered the samples. The clearance between the rollers was maintained constant at 3.5mm, though pressures exerted by the roller would be more telling in influencing the water removal during drying.

This study was conducted from March 2011 to March 2012 at the Agricultural Bio-Processing Division, Institute of Agricultural Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños.

Water hyacinth

The water hyacinth (*Eichhornia crassipes*) is an aquatic weed belonging to the floating-type category.

Water hyacinths are normally found in freshwater areas of temperate and tropical regions of the world. They grow in water environments having a pH of 7 with a high abundance of nitrogen, phosphorus, and potassium. The optimum temperature for the growth of this plant is between 28^{o}C to 30^{o}C. The composition of water hyacinths is dominated by a high percentage of water. According to the National Academy of Science (1977), a water hyacinth usually has 5% dry matter. In addition to that, it has a high nitrogen content with at least 80% of it in the form of protein. Based on data from the Bureau of Animal Industry of the Republic of the Philippines, the leaves and roots of the water hyacinth have protein contents of 18.7% and 11.8%, respectively. The fiber contents of leaves and roots of the water hyacinth are 17.1% and 7.9%, respectively (Patent storm 2011).

Water hyacinth in handicraft making

As a material for handicraft making, the water hyacinth generates livelihood programs for many Filipinos. Agribusiness Week writes that members of the Buhi Ecumenical Development Association, Inc. (BEDAI) of Buhi, Camarines Sur use this plant in many handicraft items. Among the products made out of this plant are table runners, placemats, canisters, bags, slippers, and wall décor. In Laguna, one of the livelihood projects of the government is the Comprehensive livelihood and Emergency Program. One of its sub-programs is the Water Hyacinth Development Program that aims to provide employment through water hyacinth gathering and semi-processing. Moreover, this program also intends to develop a barangay-based livelihood enterprise that utilizes and transforms water hyacinths into useful products. Since this program's implementation, 15 towns of Laguna have participated. Nine of them were engaged and trained in water hyacinth handicraft making, while the rest focused on green fertilizer and charcoal making (Abella 2010). Another livelihood project has been developed in Taguig City. Morelos (2008) reports that each *barangay* in Taguig process water hyacinths into different products. Christmas decors, lanterns, and novelty items are some of the examples. Furthermore, the Las Piñas City government is also active in utilizing the water hyacinth as source of livelihood (Echeminacla 2011).

Abella (2010) has written about the status, problems, and prospects of the water hyacinth handicraft produced in Laguna. She notes that there is a great opportunity for water hyacinth handicrafts due to their high demand in the world market and the increase in the preference for environment-friendly products. However, she reports that the climatic condition in the Philippines is one of the problems that hinder the development of the water hyacinth handicraft industry. Another problem, as cited by Ararat (2009), is improper drying and preservation of water hyacinth: a businessperson from Laguna named Cesar Pasco exported several container vans of water hyacinth handicrafts but after just a week, all those products were sent back to him because they had molds. Improper drying and preservation of water hyacinth stems is considered as the main reason for the mold formation. As such, the drying process is vital in attaining good quality water hyacinth products. However, no data are currently available regarding the standard quality attributes of a dried water hyacinth fibers used for handicraft making.

Drying

Henderson and Perry (1987) define drying as the process of removing moisture from the material until it reaches a desired level and it achieves equilibrium with the storage environment. This process is commonly used in food preservation since the shelf-life of a material is highly dependent on its moisture content. A high moisture content increases microbial activity hence deteriorating the quality of a material.

Theory of Drying. Heat transfer and mass transfer are the two fundamental mechanisms that occur in the drying process of solid materials. Heat, in the form of latent heat of vaporization, is brought to the material mainly via convection with a little fraction of radiation and conduction. Air is used as a means for the heat to flow from its surroundings to the actual material. The mass transfer is in liquid or vapor form from the interior of the material and as vapor from the surface (Henderson and Perry 1987).

Factors affecting drying

There are several factors that affect the rate of heat and mass transfer influencing the rate of drying. These include drying air temperature, relative humidity, airflow rate, and thickness.

Temperature. Drying air temperature has the most significant effect on the rate of drying. The drying rate has a directly proportional relationship with temperature. A higher temperature results in faster drying rate. This is due to the temperature dependence of the material properties related to drying.

Relative Humidity. Relative humidity is a significant factor in the determination of the final or equilibrium moisture content of the material. Moreover, it also has a great influence on total drying time. Since the evaporation rate of water is dependent on the partial pressure of water vapor in the air surrounding the product and the pressure on the product's surface, at constant air speed, a lower relative humidity can be used for faster evaporation (Fernandez 2007).

Airflow. Airflow rate is only important during the first stages of drying. Many researchers do not consider this parameter in the determination of drying characteristics of a product due to the negligible effect of surface moisture movement resistance compared to the internal resistance. However, there are studies showing that airflow rate has a considerable effect on the product. Jose (2000) concludes that airflow rate has a great effect on the drying of *carabao* mangoes, since it is needed to transfer energy to the product, to evaporate the water, and to carry the water vapor away.

Thickness. According to Candelaria (1991 cited by Jose 2000), one of the reasons that hasten the drying is that thinner layers reduce the distance travelled by heat in the center of the material. Solpico (2007) found that thickness has no significant effect on drying of cocoa *trinitario* variety.

Drying curve

The amount of residual moisture of a material at any time during drying operation is illustrated by a drying curve. Typically, there are four stages of drying. The first stage is the initial induction stage, which corresponds to the initial unsteady state heating period. After this, the drying process continues to the second stage, which is the constant rate period. In the constant rate period, the drying occurs at the surface. Drying is similar to the evaporation of water from a free surface. In addition to that, there is a linear relationship between moisture content and time during this stage. The surface temperature of the material is constant since heat gained by the material is lost through evaporation. Furthermore, the drying rate is greatly influenced by the drying environment, which includes drying air temperature, relative humidity, and air velocity. The mode of heat transfer is mainly via convection. At the end of this period, critical moisture content is reached; this can be defined as the moisture content at which surface saturation cannot be maintained and the drying rate begins to fall. Falling rate period constitutes the last two stages of drying. It is divided into two zones: the first falling rate, where evaporation occurs from a saturated surface of decreasing area, and the second falling rate period or the sub-surface drying. In this stage, the property of the material has a great influence on the drying rate or moisture movement.

Tensile strength

According to Joseph (1986), tensile strength is obtained by determining the required force to break a fiber cross-sectional mass equivalent to one unit of the measure used. The term designated to the individual strength of fibers is called tenacity. This defines how strong a material is.

Dewatering and crushing

Crushing is a type of size reduction that deals with the application of force to a unit being reduced in excess of its strength. Failure results in the rupturing of the material in many directions. A new surface and particle characteristic depends upon the material property and the force application method, a form of size reduction commonly applied in sugarcane juice extraction, as well as in breaking the forage crops structure to hasten up drying. One of the most common crushing equipment is a rigid roll or bed, which can be seen in sorghum mill. In addition, a double roller, with or without serrated surfaces, produces uniform products (Henderson and Perry 1987).

Browning

Browning is considered acceptable if it boosts the appearance and flavor of foods. The browning reaction rate is dependent on several factors such as drying temperature, pH, moisture content of the product, heat treatment period, and the nature and concentration of the reactants. This reaction affects the color of the product and causes textural change (Unido 2011). For water hyacinths as handicraft materials, browning is desirable since it is an indicator that the product is already dried (sun drying).

MATERIALS AND METHODS

The materials and equipment used in the study comprise of the following:

1. Water hyacinth
2. Dryer
3. Electronic balance
4. Carbolite™ oven
5. Knife
6. Drying tray
7. Ruler
8. Feeler gauge
9. Steel tape
10. Manometer
11. Konica Minolta™ CR-10 color reader
12. Instron Universal Testing Machine
13. Roller
14. Resealable plastic bags
15. Sling psychrometer

Sample preparation

Water hyacinth samples were collected from Laguna de Bay. The leaves and roots of the plant were cut off. Only the stem of the plant was acquired. Then, the stems were cut into a length of 40 cm each.

Dewatering

The prepared samples underwent dewatering using a sheet metal roller. The roller, as shown in Figure 2, was prepared with a clearance of 3.5 mm. Before passing through the roller, the weight of the prepared samples was determined. Each sample was passed through the roller at a specified number of passes (4, 6, and 8). After passing, the samples were weighed again and placed in the pre-weighed drying tray.

The following equation computed the percentage of water removed by dewatering:

$$\%\text{water removed} = \frac{Wi - Wf}{Wi} * 100\% \quad (1)$$

Where:

W_i is the weight of the sample before passing through the roller

W_f is the weight of the sample after passing through the roller

Initial moisture content determination

The air oven method determined the initial moisture content of the sample. Three replicates of fresh dewatered samples, each weighing 25 grams, were prepared. The Carbolite oven dried the prepared samples for 72hours as shown in Figure 3.

Equation (2) below computed the initial moisture content:

$$\%\text{MCi} = \frac{Wi - Wf}{Wi} * 100\% \quad (2)$$

where:

MC_i is the initial moisture content
W_i is the initial weight of the sample
W_f is the final weight of the sample

Airflow rate determination

The orifice flow calculation was used to measure the airflow rate. Using Equation (3), the airflow rate at different blower opening setting was determined (Gasho.org 2010).

$$Q = A * (CK\sqrt{P}) \qquad (3)$$

where:

C is the orifice coefficient = 0.65 (as cited in Palunday 2007)

K = Constant = 4,005 when P is expressed in In. of Water

P is the Pressure differential across the orifice

Q is the Flow rate in cubic feet per minute (CFM)

A is the Total orifice area expressed in square feet (orifice diameter = 8.5cm)

A fluid passing through an orifice constriction (Figure 1) will experience a drop in pressure across the orifice. This change can be used to measure the flow rate of the fluid. The default calculation involves air passing through a medium sized orifice 4" pipe.

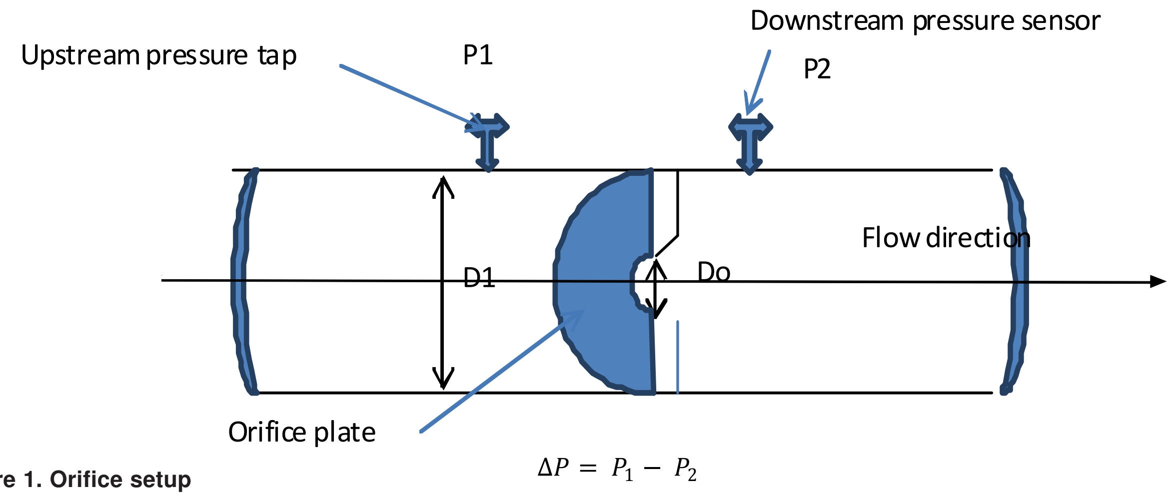

Figure 1. Orifice setup

Drying

The samples were dried using a laboratory dryer that operated at desired drying conditions. The drying temperatures used were 70°C, 80°C, and 90°C. On the other hand, the airflow rates were 0.041m^3/s, 0.047m^3/s, and 0.053m^3/s.

The dryer was first conditioned with a dummy sample for 30 minutes to 1 hour until the specified drying set-up stabilized. Then, the prepared samples were placed inside the dryer. The weight of the samples were measured at 30-minute intervals. The drying of the samples continued until no change in weight had occurred for two successive readings. The moisture content, at which the product had stopped losing water and no change in weight had occurred, is the dynamic equilibrium moisture content. The dried samples were placed inside the resealable plastic bags as shown in Figure 2.

Figure 2. The dried water hyacinth inside the resealable plastic bag

Experimental design

The Box and Behnken (1960) design of experiment matrix was used in this study (Montgomery 2001). A three-level fractional factorial three-parameter experiment design resulting in 15 drying runs was used. Table 1 lists the parameters used for this experiment that resulted in the 15 runs shown in Table 2. Response surface methodology (RSM) is a collection of mathematical techniques that has been successfully used for developing, improving and optimizing processes (Myers and others 2009). RSM enables the reduction in the number of experimental trials needed to evaluate multiple parameters and their interactions thus requiring less time and labor. RSM has been widely applied for optimizing processes in the food industry (Kumar and others 2009, Wang and others 2010).

Optimization procedure

Numerical optimization was carried out using Statistica 7.0 software. Multiple responses were optimized simultaneously using a desirability function that combines all the responses into one measurement maximizing most of the responses except final moisture contents that was minimized.

Table 1. The independent and dependent parameters explored in the experiment

Independent Parameter	Symbol Used	Coded Parameter -1	0	1	Dependent Parameter
Temperature, °C	X_1	70	80	90	Final Moisture Content(Y_1)
Air flow, m^3/s	X_2	0.041	0.047	0.053	Moisture Ratio (Y_2)
					Drying rate (Y_3)
Number of passes through the roller	X_3	4	6	8	Tensile Strength (Y_4)
					Browning Index (Y_5)

Table 2. Combination of the three independent parameters for the 15 drying runs

Run	Temperature °C	Airflow m^3/s	No. of Passes
1	80	0.053	8
2	90	0.047	4
3	80	0.041	8
4	80	0.047	6
5	90	0.047	8
6	80	0.041	4
7	80	0.047	6
8	70	0.047	8
9	90	0.053	6
10	80	0.047	6
11	80	0.053	4
12	70	0.053	6
13	90	0.041	6
14	70	0.041	6
15	70	0.047	4

Response parameters

Drying Rate. Equation (4) calculated the drying rate for the complete drying period represented as:

$$drying\ rate = \frac{MCi - MCf}{time} \qquad (4)$$

where:

MC_i is the initial moisture content
MC_f is the final moisture content

Moisture Ratio. Equation (5) estimated the moisture ratio that represents the proportion of moisture removal at a given time interval (Casas 2010):

$$moisture\ ratio(MR) = \frac{(M - M_e)}{(M_o - M_e)} \qquad (5)$$

where:

MC is the moisture content at time t
MC_0 is the initial moisture content (dry basis)
MC_e is the dynamic equilibrium moisture content

Analysis of the drying data collected

A number of theoretical, semi theoretical, and empirical drying models were reported in the literature. The most frequently used model for thin layer drying is the lumped parameter type, such as the Newton equation (Liu and Bakker-Arkema 1997, Kingsly and others 2007). The moisture ratio during drying is determined by Equation (5).

For the mathematical analysis, it is assumed that the moisture gradient driving force during drying is a liquid concentration gradient. The effect of heat transfer is neglected as a simplifying assumption. For all experimental conditions, the value of (M-Me)/(Mi-Me) expressing dimensionless moisture content obtained are similarly expressed by Akintunde and Afon (2009).

Drying curve and model equations

The subsequent list presents some of the drying model equations used by some authors to describe the drying characteristics of materials.

Equations describing drying characteristics

Model No.	Model Name	Model Equation	Reference
1	Lewis	$M_R = \exp(-kt)$	O'Callaghan 1971 Liu and others 1997
2	Page	$M_R = \exp(-kt^n)$	Zang 1991 Agrawal and Singh 1997
3	Modified Page	$M_{R=\exp}[(-kt)^n]$	Overhults 1973 White and others 1981
4	Henderson and Pabis	$M_R = a\exp(-kt)$	Westerman and White 1973 Chinnan 1984
5	Yagcioglu and others	$M_R = a\exp(-kt) + c$	Yagcioglu and others 2001
6	Two-term	$M_R = a\exp(-kgt) + b\exp(-k_1 t$	Henderson 1974 Rahman and others 1998
7	Two-term exponential	$M_R = a\exp(-kt) + (1-a)\exp(-kat)$	Sharaf-Elden and others 1980
8	Wang and Singh	$M_R = 1 + at + bt^2$	Wang and Singh 1978
9	Thomson	$t = a\ln(M_R) + b\ln(M_R)]^2$	Thomson and others 1968 Paulsen and Thomson 1973
10	Diffusion approach	$M_R = a\exp(-kt) + (1-a)\exp(-gt)$	Kassem 1998
11	Verma and others	$M_R = a\exp(-kt) + (1-a)\exp(-gt)$	Verma and others 1985
12	Modified Henderson and Pabis	$M_R = a\exp(-kt) + b\exp(-gt) + c\exp(-kt)$	Karathamos 1999
13	Simplified Fick's diffusion (SFFD) equation	$M_R \exp(-k\left(\frac{t}{L^2}\right)^n]$	Diamante and Munro 1991
14	Modified Page equation II	$M_R = a\exp(-c\left(\frac{t}{L^2}\right)]$	Diamante and Munro 1993
15	Midilli and Kucuk	$M_R = a\exp(-kt^n + bt$	Midilli and others 2002

Browning Index. Konica Minolta™ CR-10 color reader measured the L, a, b values of the samples after drying. Three measurements taken at random locations for each sample represented the values that calculated Browning index (BI) using equation (6) (De Vela 2011).

$$BI = \frac{100(x - 0.31)}{0.17} \qquad (6)$$

where:

$$x = \frac{a + 1.75L}{5.645L + a - 3.012b} \qquad (7)$$

Tensile Strength. The Instron Universal Testing Machine, as illustrated in Figure 3, was used to determine the tensile strength of the dried samples. Cutting the dried samples in a dumbbell-shaped form prepared the samples for testing. No standard has been established on the tensile specimen shape for water hyacinth.

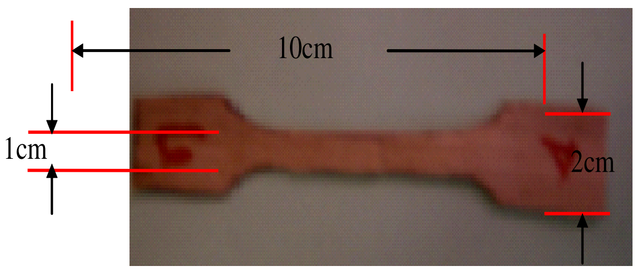

Figure 3. The tensile specimen

The samples, properly aligned and placed between the two grips in the machine, were subjected to tensile tests at a preset crosshead speed of 10mm/min (as cited in Opiña 2008) until they broke. Equation (8), as Opiña (2008) used, computed the tensile strength or tenacity of the dried samples represented by samples represented by:

$$\text{tenacity} = \frac{\text{maximum load}}{\text{linear density}} \qquad (8)$$

where:

Maximum load is in Newton
Linear density is in g/km or mg/m

Equation (9) determined the linear density presented as:

$$\text{linear density} = \frac{\text{weight of the sample}}{\text{length of the sample}} \qquad (9)$$

where:

Length of the sample is in meters
Weight of the sample is in milligram

The test is valid if the break occurred at the middle section of the sample (Figure 4a), otherwise the test is invalid (Figure 4b). The length and weight of the sample was also measured using the electronic balance. This data was used for strength computation.

(a)

(b)

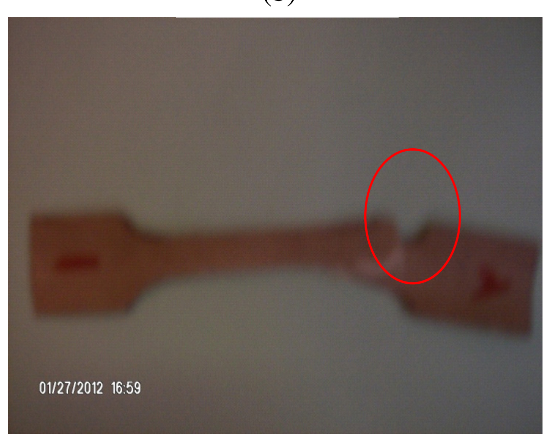

Figure 4. (a) Valid test sample and (b) Invalid test sample

Final Moisture Content Determination. (Equation 10) estimated the final moisture content (Casimina 2010):

$$\mathrm{MCf} = \frac{\mathrm{MCt} * \mathrm{Wf}}{\mathrm{Wt}} \qquad (10)$$

where:

MC_f = final moisture content
MC_t = moisture content at time t
W_f = final weight, g
W_t = weight at time t, g

Statistical analysis

Response surface analysis of the experimental data was carried out using a commercial statistical package, SAS 8 Response Surface Regression program, that did a regression analysis as well as an analysis of variance (ANOVA). The response surface analysis of the experimental data, shown in Table 4, was also done by fitting equation (11) to the experimental data to determine the regression coefficients and statistical significance of the model terms. Significance of the model term was assessed by F-ratio at probability (p) of 0.05. Model adequacies were determined by model analysis, lack of fit test, coefficient of determination (R^2), predicted error of sum of squares (PRESS), and coefficient of variation (CV).

The analysis fit the data to the second order quadratic model for all the responses using RSREG program of illustrated as:

$$Y = \beta_o + \sum_{1}^{k} \beta_{iX_i} + \sum_{1}^{k} \beta_{ij}\ X_i^{\,2} + \sum_{1}^{k}\ \sum_{1}^{k} \beta_{ij}\ X_I X_J \qquad (11)$$

The Response Surface Regression of SAS v8 software performed the ANOVA, regression analysis, and regression coefficient calculations. In determining the optimum values for temperature, airflow, and number of passes, the Response Surface Regression of STATISTICA v7 was used. Additionally, Curve Expert 1.4 was used to generate the model drying equations from the calculated Moisture Ratio (MR).

RESULTS AND DISCUSSION

The study determined the optimum heated-air drying condition of water hyacinth. Fifteen (15) drying runs were performed based on the Box and Behnken design of experiment. The resulting data were analyzed to find whether the independent parameters (drying air temperature, airflow rate, and number of passes in the roller) affect the response considered.

Dewatering and initial moisture content

Dewatering as a pre-drying treatment is primarily done to decrease the water content of the water hyacinth samples so as to speed up the drying process. In this study, the crushing method using a roller was done. The number of passes through the roller is considered as an independent parameter. The amount of water reduced and initial moisture content at each of the 15 runs is summarized in Table 4.

The percentage of water removal due to crushing ranged from 2.42% to 9.49%. The highest reduction of water was attained at Run no. 14 while the lowest was attained at Run no. 11. However, there is no direct relationship established between the number of passes and the percent of water removed.

Aside from reducing the water content, the physical properties of the sample are also affected by this process. The thickness of the sample was reduced in size and the surface area was flatteened. In addition, the clearance between the rollers remained constant (3.5mm) resulting in the lessening of the variability of thickness among the samples. From this, the effect of thickness in the drying process was diminished. However, the presence of damage or breakage in the samples after passing in the roller existed.

Table 3. The percentage of water removed and initial moisture content at each drying run

RUN	$MC_{initial}$ ($\%_{wb}$)	%Water Removed
1	93.45	5.49
2	92.60	7.32
3	93.20	4.46
4	92.81	9.38
5	92.87	3.66
6	93.40	3.05
7	94.32	2.42
8	94.22	3.07
9	94.16	4.88
10	94.43	2.42
11	93.57	2.40
12	92.21	8.64
13	93.35	3.13
14	93.84	9.49
15	92.80	4.40

Determining the initial moisture content of the samples at each set-up, Run no. 10 obtained the highest initial moisture content of 94.43% while Run no. 12 attained the lowest initial moisture content of 92.21%. This result may be attributed to the crushing method.

Effects of the independent variables on response variables

The summary of data on the responses at each drying set-up is presented in Table 4. As shown in Figure 8, Run no. 9 achieved the highest drying rate of 0.322 %MC/min while Run no. 12 obtained the lowest drying rate of 0.216 %MC/min. This was expected since Run no. 9 possessed the highest drying air temperature of 90ˆ C as well as highest airflow rate of $0.053 m^3/s$. On the other hand, Run no. 12 has the lowest drying air temperature of 70°C but highest airflow rate of $0.053 m^3/s$. Drying at high temperature decreases the drying time; in this way, the drying rate increases. This only shows that temperature affects the drying rate.

Moisture ratio (MR) was another response investigated. The obtained values of this response at each drying run are illustrated in Figure 9. The highest value was 0.132 attained by Run no. 13, while the lowest value is 0.096, attained by Run no. 8. It could be noted that

Table 4. Summary of data showing the responses at each drying set-up

	Independent Parameters			Responses				
Run	Tempera-ture	Airflow	No. of Passes	MC Final (%wb)	Moisture Ratio	Drying Rate (%wb/min)	Tensile Strength (N/Tex)	Browning Index
1	80	0.037	8	8.44	0.12312	0.28336	0.00980	77.4191
2	90	0.03	4	6.61	0.13118	0.31826	0.01237	73.3673
3	80	0.023	8	6.21	0.12240	0.28996	0.00978	75.3889
4	80	0.03	6	8.96	0.12475	0.27950	0.01340	49.9864
5	90	0.003	8	7.64	0.12900	0.31566	0.01060	43.388
6	80	0.023	4	5.29	0.11178	0.24476	0.00992	77.9319
7	80	0.03	6	7.62	0.12319	0.28901	0.00702	56.5011
8	70	0.003	8	5.96	0.00619	0.22630	0.00925	64.9468
9	90	0.037	6	7.24	0.1215	0.32191	0.01055	55.8929
10	80	0.03	6.	8.80	0.12092	0.28544	0.01105	53.0061
11	80	0.037	4	8.61	0.12370	0.28320	0.00811	59.4689
12	70	0.037	6	7.83	0.11874	0.21635	0.01378	45.547
13	90	0.023	6	7.93	0.13240	0.28473	0.01038	53.8275
14	70	0.023	6	7.87	0.11377	0.22042	0.01028	53.1614
15	70	0.03	4	7.33	0.10965	0.21916	0.01265	50.5459

Run no. 13 has the highest drying temperature of 90°C set-up. On the other hand, Run no. 8 possessed the lowest drying temperature of 70°C set-up. This implies that drying air temperature influences the moisture ratio. Table 4 summarizes the data on the response variables investigated in drying water hyacinth and discussed in the following sections

Final Moisture Contents. The final moisture contents (Figures 5 and 10) attained by each drying run ranged from 6.21%$_{wb}$ in Run no. 3, due probably to the highest number of passes in the roller that squeezed out most of the initial water prior to drying the samples, to Run no. 4, which obtained the highest final moisture content of 8.96%$_{wb}$ at the end of drying probably due to the high initial moisture content at the initial stage or prior to passing to the roller for squeezing the water from the samples (Table 4 and Figures 9-17).

Average Drying Rates. The average drying rate (Figure 9) measured the speed of moisture removal that ranged from 0.22 % min^{-1} to 0.32 %min^{-1} exhibited by Runs 15 and 2, respectively.

Moisture Ratio (MR). Figure 9 illustrates the average moisture ratio calculated from the 15 drying runs. Run 8 exhibited the lowest MR while Run 13 showed the highest value of MR.

Tensile Strengths. As shown in Figure 15, Run no. 12, subjected to 70°C drying temperature, an airflow rate of 0.053m3/s and number of passes equivalent to 6, exhibited the highest tensile strength of 0.0137N/Tex. On the other hand, Run no. 7, having temperature of 80°C, airflow rate of 0.047m^3/s, and 8 passes through the drying set-up, attained the lowest tensile strength of 0.007N/Tex.

Figure 10 shows the final moisture content of 15 drying treatments. The highest value of final moisture content that the dried sample exhibited was 8.96%, which occurred at Run no. 4, while the lowest value was 5.29%, which was obtained by Run no. 6.

Browning Index. Browning index, which evaluates the browning color of the sample, was also considered in this study. The value for 15 drying treatments is illustrated in Figure 12. Run no. 6, conducted at 80°C, 0.041m^3/s airflow rate, and 5 passes, obtained the highest browning index among the entire drying runs. The lowest value is obtained at Run no. 5 in spite of conducted at temperature of 9°C, airflow rate of 0.047m^3/s, and number of passes equivalent to 8. This may be due to other factors contributing to browning such as oxidation and residual enzyme activity (Unido 2011).

Run 5 showed the lowest browning index while Run 6 had the highest browning index among experimental runs conducted in optimizing the drying parameters of water hyacinths (Figure 11). This shows that samples dried at higher temperatures (above 80°) will have higher probability of having brownish color than those dried at lower temperatures due to the effects of temperatures on color.

Additionally, browning index is significant at 95% level while drying rate is significant at 90% level in cross-product model. The lack of fit test measured the failure of the model to represent the data obtained from the experiment. It was found that the lack of fit was not significant for all of the response variables except in moisture ratio. The non-significant lack of fit is good since it indicates that the data in the experiment fit the generated models.

Effects of the independent parameters on the responses

The effects of airflow rates, air temperatures, and number of passes on the roller are summarized in Table 5. In each experimental run, drying air temperatures significantly affected the average drying rates, moisture ratio, and browning index of the dried samples of water hyacinths but had no pronounced effects on their final moisture contents and tensile strengths. The airflow rates were only significant in the average drying rates of the dried samples. On the other hand, the number of passes on the roller prior to drying the samples had significant contributions in the average drying rates and browning index.

Table 5. ANOVA test results for the significance of the independent parameters

	SUM OF SQUARES				
PARAMETER	**Drying Rate**	**Final MC**	**Moisture Ratio**	**Tensile Strength**	**Browning Index**
temperature	0.01729**	2.482607^{ns}	8.510E-04*	1.008E-05^{ns}	757.78750**
airflow	0.00177**	3.528331^{ns}	9.792E-05^{ns}	5.084E-05^{ns}	355.3798^{ns}
passes	0.000842*	6.04483^{ns}	1.290E-03^{ns}	4.292E-04^{ns}	1190.233**

** significant at 95%
* significant at 90%
ns not significant

The ANOVA results (see Table 5), show that temperature significantly affected drying rate and browning index at the 95% level. Moreover, moisture ratio was also significantly affected by this parameter at 90%. The result for the effect of temperature in drying rate is expected. This is because drying temperature and drying rate have a directly proportional relationship. In addition, more moisture is absorbed when the temperature is high. In terms of the effect in browning, this may be due to temperature on the pigment production of plants. According to Unido (2011), higher temperatures can reduce the amount of pigment resulting in browning phenomena. On the other hand, browning's effect is not established with regard to the final moisture content and tensile strength. This result is confirmed by the data in this investigation. As Opiña (2010) concluded, temperature had no significant effect in the final moisture content and tensile strength of the product.

Airflow rate significantly affected the drying rate at 95% level of significance but failed to influence the rest of the responses. Since air is the medium of heat transfer, different rates of airflow might affect the time of drying. The number of passes also significantly affects drying rate and browning index. The dewatering process might also result in the opening of the porous spaces that have an effect on the process of drying. Meanwhile, the effect of the number of passes in browning may be attributed to the physical damage acquired during the dewatering process (passing through the roller). According to Unido (2011), the color of the plant changed when the tissue is bruised, cut, or exposed to any number of abnormal conditions. This injured tissue darkens on exposure to air.

Figures 5 to 9b depict the surface plots for each response as affected by temperature, airflow rate, and number of passes.

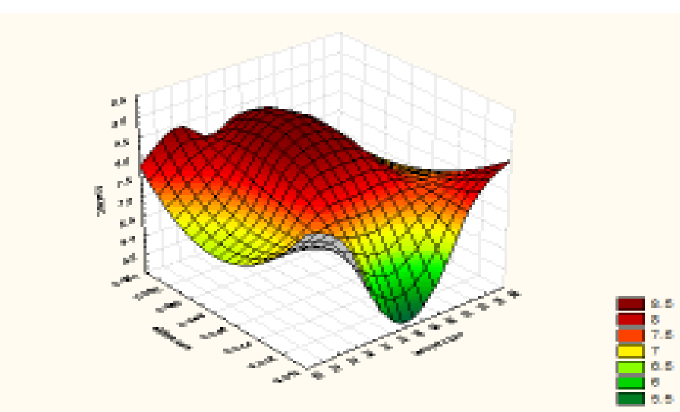

Figure 5. Surface plot for final moisture content vs. airflow rate and drying air temperature

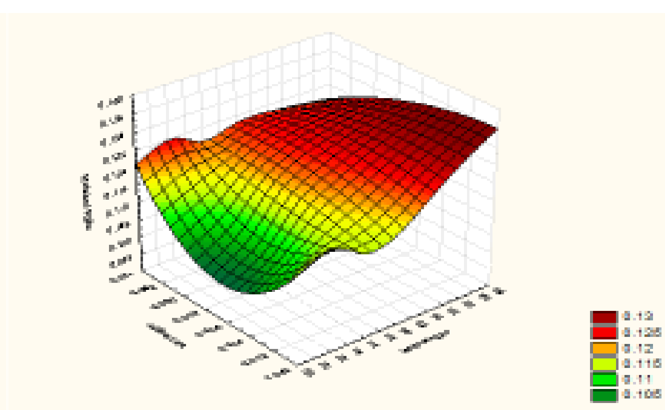

Figure 6. Surface plot for moisture ratio vs. airflow rate and drying air temperature

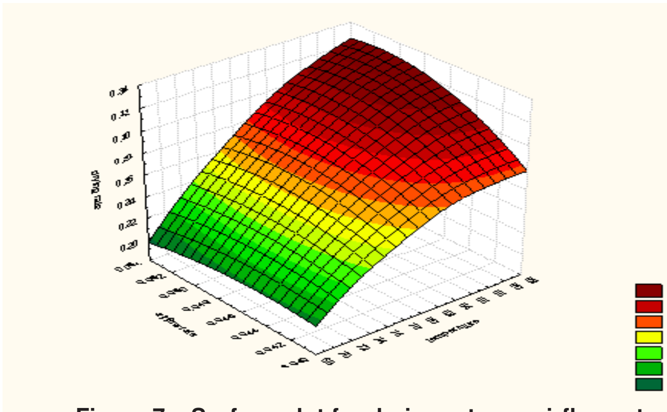

Figure 7a. Surface plot for drying rate vs. airflow rate and drying air temperature

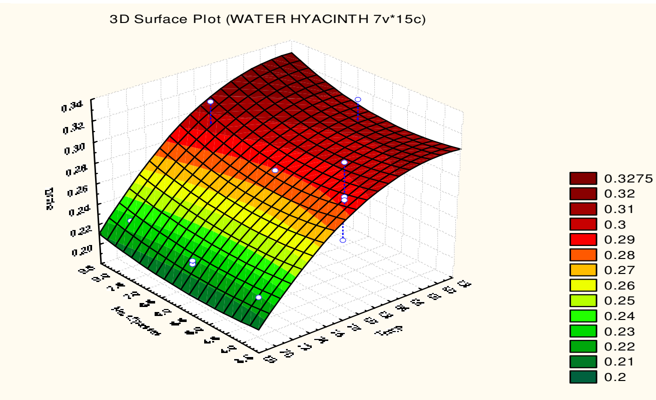

Figure 7b. Surface plot of drying rates as affected by drying air temperature and no. of passes through the roller

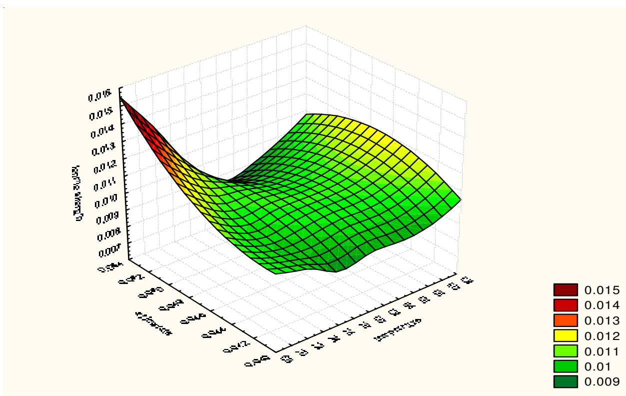

Figure 8a. Surface plot for tensile strength vs. airflow rate and drying air temperature

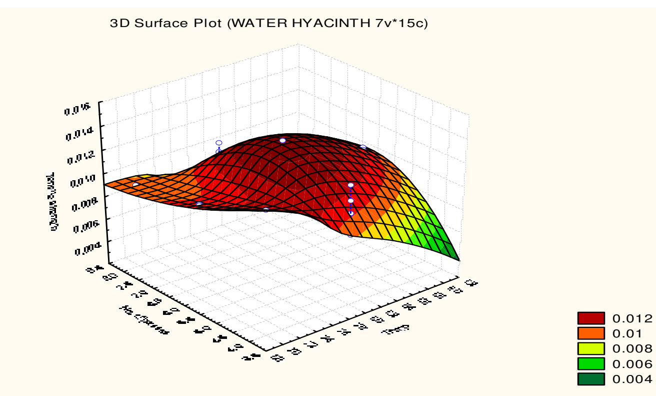

Figure 8b. Surface plot of tensile strength as affected by drying air temperature and no. of passes through the roller

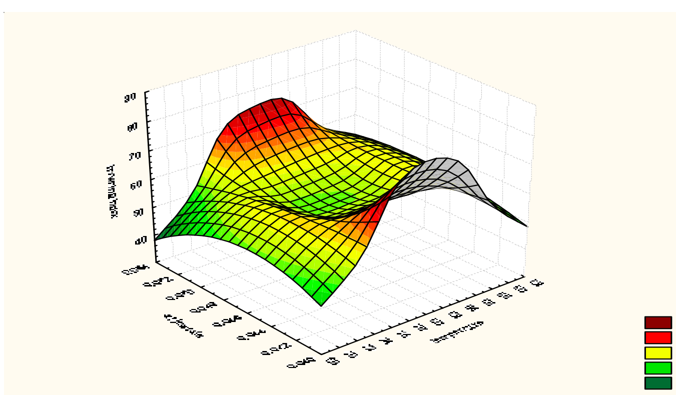

Figure 9a. Surface plot for browning index vs. airflow rate and drying air temperature

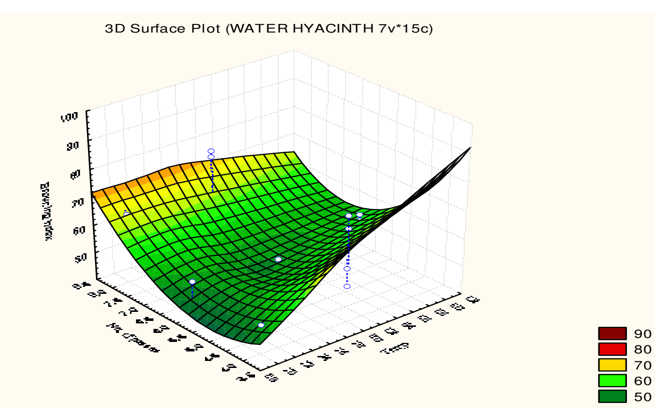

Figure 9b. Surface plot of browning index as affected by drying air temperature and no. of passes the roller

Table 6 presents the ANOVA results of the regression analysis as analyzed by SAS 8. Results showed that drying rate is significant at the 95% level in terms of linear model. Furthermore, drying rate and browning index are significant in both quadratic and total model. Additionally, browning index is significant at the 95% level while drying rate is significant at the 90% level in cross-product model. The lack of fit test measured the failure of the model to represent the data obtained from the experiment. It was found that the lack of fit was not significant for all of the response variables except in moisture ratio. The non-significant lack of fit is good since it indicates that the data in the experiment fit the generated models.

Coefficient of Variation (CV) determines the data variability relative to the mean. A low value of CV is desirable since it signifies more consistency of data values. If the value is more consistent then the variation is less. The ANOVA test showed that drying rate obtained the lowest CV value of 2.84%, indicating some degree of accuracy of the data gathered (especially weights of samples at particular designated time intervals). On the other hand, tensile strength has more variation among the responses since it obtained the highest CV value of 24.02% possibly due to the high sensitivity of the Instron machine during tensile force measurements.

Table 6. ANOVA test results for the significance of response surface regression model

		SUM OF SQUARES				
SOURCE	**df**	**Final MC**	**Moisture Ratio**	**Drying Rate**	**Tensile Strength**	**Browing Index**
linear	3	2.948175[ns]	0.000761*	0.016889**	0.00000261[ns]	79.237108[ns]
quadratic	3	4.990845[ns]	0.00009483[ns]	0.00104**	0.000008974[ns]	1028.441736**
cross product	3	1.84265[ns]	0.000114[ns]	0.000956**	0.000004274[ns]	620.815352**
total model	9	9.781668[ns]	0.00965[ns]	0.018884**	0.000015858[ns]	1728.494196**
lack of fit	3	5.355825[ns]	0.000241**	0.000252[ns]	0.000011576[ns]	146.701531[ns]
pure error	2	1.07126	0.000007418	4.62E-05	0.000020823	21.258213
total error	5	6.427025	0.000248	2.98E-04	0.00003299	167.959745
coefficient of variation, CV	15.13	5.8573	2.83389	24.0236	9.7641	
r^2	0.6035	0.7955	0.9845	0.3286	0.9114	

Coefficient of determination (r^2) is another parameter used to analyze the regression model. It measures how well the model represents the data. Among the responses, drying rate generates the highest value with 0.9845. This means that 98% of variation in the drying rate can be explained by the model generated (Gomez and Gomez 1984). In contrast, tensile strength attained the lowest value with 0.3286. It could be noted that tensile strength is not significantly affected by the independent parameters, whereas, the drying rate is greatly affected by the independent parameters.

Table 7 presents the values of regression coefficients of the second order polynomials model for each of the responses. The generated model is based on the coded data in of the form of:

$$Y = ß_{k0} + ß_{k1}X_1 + ß_{k2}X_2 + ß_{k3}X_3 + ß_{k11}X_1^2 + ß_{k21}X_2^2 + ß_{k22}X_3^2 + ß_{k31}X_1X_2 + ß_{k32}X_1X_3 + ß_{k33}X_2X_3 \quad (9)$$

where:

$ß_{k}$ = coefficient

Y = response parameter

X_1(drying temperature), X_2(airflow rate), X_3(passes) = independent variables

Table 7. Regression coefficients of the second order polynomials

COEFFICIENT	Response parameter				
	Final MC (Y1)	MR (Y2)	Drying Rate (Y3)	Tensile Strength (Y4)	Browning Index (Y5)
$ß_{k0}$	-55.601	-0.2821	-1.3332	0.02527	-324.83
$ß_{k1}$	0.74867	0.00665	0.02055	-0.0016	14.8829
$ß_{k2}$	1093.06	2.64991	17.1542	2.30104	-13578
$ß_{k3}$	1.92542	0.01166	0.05747	-0.002	-4.6229
$ß_{k11}$	-0.005	-2E-05	-0.0015	1.3E-05	-0.0777
$ß_{k21}$	-2.7083	-0.0593	0.17188	-0.0139	34.5707
$ß_{k21}$	-6805.6	38.9815	-254.48	-14.688	137070
$ß_{k31}$	0.03	0.00014	-0.0001	2E-05	-0.5548
$ß_{k32}$	-22.708	-0.2333	-0.9383	0.38125	365.95
$ß_{k33}$	-0.2694	-0.001	-4E-05	-0.0001	3.16781

The regression equation for each response, based on Table 7 and following equation (9), is presented below:

$$Y1= -55.601+ 0.74867X_1 + 1093.06X_2 + 1.92542X_3 -0.005X_1^2 -2.7083X_2^2 - 6805.6X_3^2+ 0.03X_1 X_2 -22.708X_1X_3 -0.2694X_2X_3 \quad (10)$$

$$Y2= -0.2821+ 0.00665X_1 + 2.64991X_2 + 1.92542X_3 -0.005X_1^2 -2.7083X_2^2 -6805.6X_3^2 + 0.03X_1X_2 -22.708X_1 X_3 -0.2694X_2X_3 \quad (11)$$

$$Y3= -1.3332+ 0.02055X_1+ 17.1542X_2 + 0.05747X_3 -0.0015X_1^2 +0.17188X_2^2 - 254.48X_3^2 -0.0001X_1X_2 —0.9383X_1 X_3 -4E-05X_2X_3 \quad (12)$$

$$Y4= 0.02527-0.0016X_1+ 2.30104X_2 -0.002X_3 +1.3E-05X_1^2 -0.0139X_2^2 -14.688X_3^2 +2E-05X_1X_2 +0.38125X_1 X_3 -0.0001X_2X_3 \quad (13)$$

$$Y5= -324.83+14.8829X_1-13578X_2 -4.6229X_3 - 0.077X_1^2 +34.5707X_2^2 +137070X_3^2 -0.5548X_1X_2 +365.95X_1 X_3 +3.16781X_2X_3 \quad (14)$$

Optimum drying conditions

The optimum combination of the three independent parameters was determined and analyzed by STATISTICA v7.0, which employed 100 iterations to arrive at the optimum condition for drying. Based on the result, the optimum drying condition for water hyacinths is at a temperature of 90^{o}C, an airflow rate of 0.044m^3/s, and a number of passes equivalent to 5. With 68.89% desirability, the following predicted values for each response could be attained as shown in Table 8. Highlighted values show the predicted values at optimum conditions. Figure 10 presents the plot of responses at optimum conditions of the independent parameters tested with desirability profile.

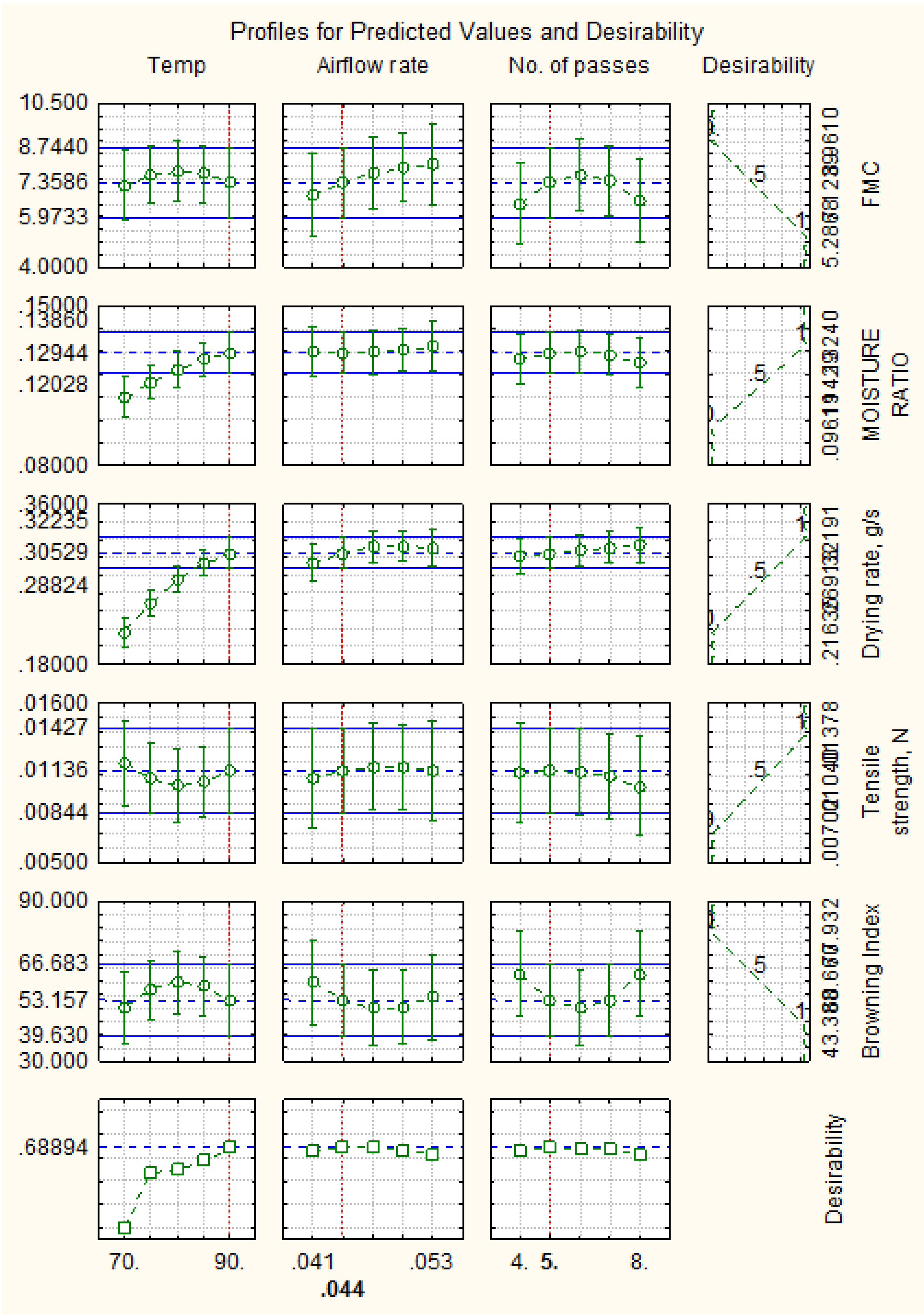

Figure 10. Predicted responses at optimum conditions with desirability

Table 8. Predicted responses at optimum conditions of independent parameters

Factor*	Factor Level	Predicted FMC	Predicted MR	Predicted Drying Rate	Predicted Tensile Strength	Predicted Browning Index	Desirability Value
Temp	70	7.2519	0.1100	0.2157	0.011873	50.0879	0.00000
Temp	75	7.6497	0.1166	0.2490	0.010781	56.6854	0.46367
Temp	80	7.8001	0.1221	0.2751	0.01033	59.396	0.50572
Temp	85	7.7031	0.1263	0.2938	0.010522	58.21972	0.57325
Temp	**90**	**7.3586**	**0.1294**	**0.3052**	**0.011355**	**53.15656**	**0.68893**
Airflow rate	0.041	6.8755	0.1299	0.2943	0.01084	59.56775	0.65168
Airflow rate	**0.044**	**7.3586**	**0.1294**	**0.3052**	**0.011355**	**53.15656**	**0.68893**
Airflow rate	0.047	7.7206	0.1296	0.3116	0.011605	50.10358	0.68760
Airflow rate	0.05	7.9614	0.1304	0.3134	0.011589	50.40883	0.66245
Airflow rate	0.053	8.0812	0.1320	0.3106	0.011307	54.07229	0.62155
No. of passes	4	6.5234	0.1267	0.3020	0.011162	62.67069	0.65749
No. of passes	**5**	**7.3586**	**0.1294**	**0.3052**	**0.011355**	**53.15656**	**0.68893**
No. of passes	6	7.6546	0.1301	0.3084	0.011269	49.97804	0.68226
No. of passes	7	7.4116	0.1287	0.3115	0.010902	53.13515	0.67572
No. of passes	8	6.6296	0.1253	0.3145	0.010256	62.62789	0.63171

*highlighted values represented the optimum conditions for drying water hyacinth

Verification of the optimum drying conditions

After determining the optimum values, three validation runs were performed to compare and verify the validated response against the predicted response. Table 9 shows the average responses obtained by the three verification runs at optimum conditions.

As Table 9 depicts, the verification run obtained an average final moisture content of 7.34%wb, a moisture ratio of 0.122, a drying rate of 0.281%wb/min, a tensile strength of 0.011N/Tex, and a browning index of 54.25. The Table also shows that final moisture content attained the lowest percent error of 0.32%. In contrast, the highest percent error value was obtained by drying rate with 8.11%. These verification results validated the established optimum conditions within the range of independent parameter values tested.

Table 9. Comparison between the predicted and verified values at each response

Response	Predicted	Verified	Error (%)
Final Moisture Content	7.3586	7.335005	0.320
Moisture Ratio	0.129437	0.121972	5.767
Drying Rate	0.305295	0.280532	8.111
Tensile Strength	0.011355	0.010899	4.017
Browning Index	53.15656	54.25077	2.058

Thin layer drying modeling for water hyacinth

Curve Expert 1.4 analyzed the drying data and generated the model equation that best represents the data for 15 drying runs. Table 10 presents the best regression model describing the MR over time. It also includes the standard error(s) and correlation coefficient(r), which depict the goodness of fit of the model. Low s value, in particular approximating zero, is desirable. On the other hand, high R-value approaching 1 is desired. Based on these criteria, Run no. 6 obtained the best model described by rational function model shown below.

$$MR = \frac{1.00 - 3.07e^{-3}x}{1 + 9.87e^{-2}x + (3.84e^{-4}x)^2} \qquad (15)$$

where:

MR = moisture ratio (dimensionless) and
x = drying time, minutes

This shows that not all drying models of agricultural materials fall in the exponential, logarithmic, and page models. In addition, Figure 11 illustrates the generated Rational model.

The selection of a suitable drying model entails analyzing the MR data and drying time using Curve Expert 1.4. to find the best expression to represent the data. The coefficient of determination R^2 and standard deviation were the main criteria for selecting the best equation. In addition to the coefficient of determination, the goodness of fit was determined by various statistical parameters such as reduced mean square of the deviation and root mean square error RMSE. For quality fit, R^2 value should be higher, and mean deviation, and RMSE values should be lower (Togrul and Pehlivan 2002), (Goyal and others 2008).

SUMMARY AND CONCLUSION

The study determined the optimum drying condition of water hyacinths. Investigations and analyses used three independent parameters that include drying temperature, airflow rate, and number of passes through a roller. The study investigated and analyzed their effects on the following responses: (1) final moisture content (2) moisture ratio, (3) drying rate, (4) tensile strength, and (5) browning index. The study employed Box and Behnken design of experiment that resulted in 15 experimental drying treatments.

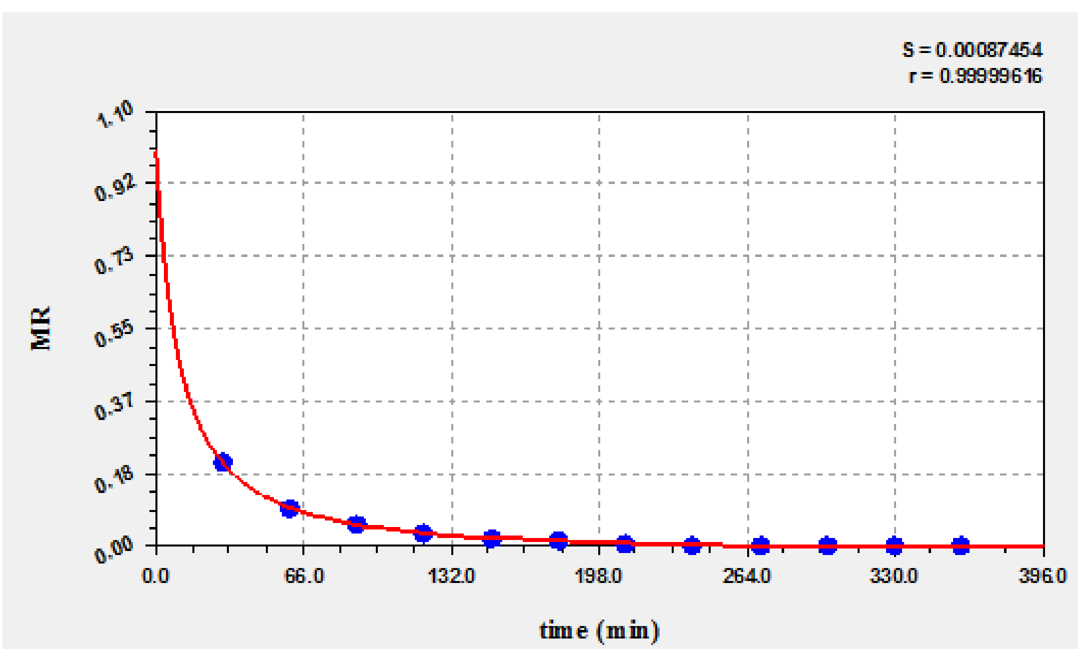

Figure 11. Moisture ratio vs. time of Run no. 6

Experimental results revealed that drying temperature significantly affected drying rate, moisture ratio, and browning index. Airflow rate has a significant effect on the drying rate only, while the number of passes significantly affected both the drying rate and browning index.

The optimum drying condition for water hyacinth is at a temperature of $90^{o}C$, an airflow rate of $0.044m^3/s$, and a number of passes equivalent to 5, with a desirability of 68.69%. The predicted responses are 7.36%wb for final moisture content, 0.129 for moisture ratio, 0.305%MCwb/min for drying rate, 0.0113N/Tex for tensile strength, and 53.16 for browning index.

Table 10. The best-fit model for 15 drying runs

Run	Model	Coefficient	r	s
1	Harris Modely=1/(a+bx^c)	a =1.00005523042E+0		
		b =3.30183500112E-002	0.999775	0.00702
		c =1.46668439402E+0		
2	Harris Modely=1/(a+bx^c)	a =1.00004473005E+000		
		b =1.30928391619E-002	0.999842	0.00625
		c =1.72426998311E+000		
3	Harris Modely=1/(a+bx^c)	a =1.00005215880E+000		
		b =2.39857648115E-002	0.999811	0.00642
		c =1.54992776612E+000		
4	Harris Modely=1/(a+bx^c)	a =1.00005652566E+000		
		b =2.26207802164E-002	0.999822	0.00623
		c =1.54628769281E+000		
5	Harris Modely=1/(a+bx^c)	a =9.99974113763E-001		
		b =4.11336454945E-002	0.999597	0.00997
		c =1.42897052299E+000		
6	Rational Function	a =1.00000413749E+000		
	y=(a+bx)/(1+cx+dx^2)	b =-3.07074708753E-003	**0.999996***	**0.00088**
		c =9.87235806713E-002		
		d =3.84339630684E-004		
7	Harris Modely=1/(a+bx^c)	a =1.00005859539E+000		
		b =3.57582990477E-002	0.999739	0.00753
		c =1.44622888295E+000		
8	Rational Function	a =9.99973074346E-001		
	y=(a+bx)/(1+cx+dx^2)	b =-2.96250878191E-003	0.999969	0.00236
		c =1.78121101892E-001		
		d =-5.00855559474E-005		
9	Harris Modely=1/(a+bx^c)	a =1.00002252503E+000		
		b =3.55091977548E-002	0.999835	0.00639
		c =1.55481149148E+000		
10	Harris Modely=1/(a+bx^c)	a =1.00005195841E+000		
		b =2.88889379873E-002		
		c =1.51673974815E+000	0.999788	0.00681
11	Harris Modely=1/(a+bx^c)	a =1.00006073191E+000		
		b =2.30702158390E-002	0.999784	0.00687
		c =1.54812594422E+000		
12	Harris Modely=1/(a+bx^c)	a =1.00040497838E+000		
		b =3.55494618261E-002	0.998872	0.01358
		c =1.29290400827E+000		
13	Harris Modely=1/(a+bx^c)	a =1.00011096476E+000		
		b =1.26392023222E-002	0.999759	0.00726
		c =1.63096327027E+000		
14	Rational Function	a =9.99924438129E-001		
	y=(a+bx)/(1+cx+dx^2)	b =-2.89792856124E-003	0.999972	0.00225
		c =9.11988779985E-002		
		d =4.98218837768E-005		
15	Harris Modely=1/(a+bx^c)	a =1.00015477627E+000		
		b =3.60377446995E-002	0.999542	0.00865
		c =1.34811348987E+000		

*Evolved as the best-fit model for MR

Verification runs showed that the percent error for all of the responses ranged from 0.32% to 8.11% with final moisture content having the lowest and drying rate obtaining the highest. Regression analysis resulted in model equations that sufficiently illustrated moisture ratio with time. Rational function is the best model that characterizes the drying of water hyacinth with an equation expressed as:

$$MR = \frac{1.00 - 3.07e^{-3}x}{1 + 9.87e^{-2}x + (3.84e^{-4}x)^2} \quad (16)$$

where:

MR is the moisture ratio; and
x is the time in minutes

The model was very much different from most models developed for agricultural products that normally come in the form of exponential or exponential association.

RECOMMENDATIONS

Future studies should consider the following:

1. Relative humidity should be considered as an independent parameter if the dryer has the capability to control this parameter since it is one of the factors affecting drying.

2. The clearance between the rollers can also be used as an independent parameter by adjusting it into different ranges. Also, the force applied by the rollers during pressing should be included in future studies.

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