Volume 4 (Issue 2) 2024, pp. 198 -210 Science Mundi ISSN: 2788-5844 http://sciencemundi.net

Optimization of Drying Parameters for Minimization of Moisture Content in Black Tea Production

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ABSTRACT

Study focuses on black tea drying process on fluidized bed dryer in tea factories. Tea drying variables considered in the study were air temperature, air velocity and time. The response variable in the experiment was the black tea moisture content. Air velocity was varied between 0.21 m/s and 0.55 m/s. Whereas air temperature was varied between 70 ^{0}C and 130 ^{0}C. Drying time ranged between 0 minute and 20 minutes. Black tea drying experiment was conducted in the macerated tea laboratory at Sotik Tea Company using the miniature FBD Sherwood Tornado model 501. It took 20 minutes experimental time to lower the dhool moisture from 72% to 3.5%. Experimental data was used to develop black tea drying curve and drying rate. The Box Behnken design under response surface design methodology in Minitab software was used to analyze and optimize the black tea drying variables. The optimum variables were found to be at hot air temperature of 100 ^{0}C, hot air velocity of 0.38 m/s and drying time of 12.9 minutes. These drying parameters resulted in a more acceptable black tea moisture content of 3.5% db which falls between the acceptable black tea moisture content of 3% db to 4% db.

Keywords: Dhool, Drying, Fluidized, Moisture, Optimum, Tea

I. INTRODUCTION

Tea is a common aromatic and nonalcoholic beverage consumed globally (Lang'at, Thoruwa *et al.*, 2016). Tea originated from China, and it is the second most popular beverage in the world after water (Pou, Paul *et al.*, 2019). Total world tea production stands at 6012 tons. Major producers are Kenya, China, India, Sri Lanka, Indonesia and Vietnam. Kenya is the leading exporter of tea globally (Hajra, 2021) (Hicks, 2009)**.** Tea is rich of antioxidant owing to Polyphenols, or flavonoids composition and medicinal applications such as cancer prevention (Panda and Datta, 2016) (da Silva Pinto, 2013).

All tea is produced from two leaves and one bud with botanical description of Camellia Sinensis Tea is classified depending on the processing method. Tea is mainly produced in four major types, Cut Tear and Curl (CTC), Orthodox, green and Oolong. Black CTC tea goes through plucking, withering, rotor vane, maceration, fermentation, drying and packaging process. Orthodox tea is processed through, plucking, withering, rolling, fermentation, drying and packaging. Green tea goes through the Plucking withering maceration drying and packaging. Oolong tea is processed through withering, rotor vane, CTC, Oxidation, drying and packaging. Black tea constitutes of 78% of the total tea produced globally, hence the leading produced tea. (Stodt, Blauth *et al.*, 2014)**.** Tea drying is a very vital process. Drying ceases the progression of enzymatic oxidation, inhibits growth of bacteria, gives the final product colour, reduces moisture content from 70% db to 4% db and prolongs products shelf life (Temple and Van Boxtel, 1999). Fluidized bed dryer is considered as the most efficient dryer in tea industries (Özahi and Demir, 2013). The ideal drying temperature for black lays between 70 ^{0}C to 130 ^{0}C. In tea industries, tea drying process is the major consumer of energy about 10% to 15%. Thermal energy constitutes above 75% of the total energy consumption (Chaudhari, Kostha *et al.*, 2018). The thermal energy is directly consumed during green leaves withering and during dhool drying for moisture removal from the leaves (Akhtaruzzaman, Ali *et al.*, 2013). Studies on drying processes has shown that about 30% exergy utilization in fluidized bed dryers (Handayani, Atmanto *et al.*, 2020). Hence, 60% to 70% of total production cost (Das, Mahanta *et al.*, 2021)**.** For sustainable development achievements, energy efficiency is a key factor in industries (bahu RE Energy consumption). In this regard, maximum energy utilization through process optimization and thermal analysis is foremost (Akbulut and Durmuş, 2010) (Sarker, Ibrahim *et al.*, 2015)

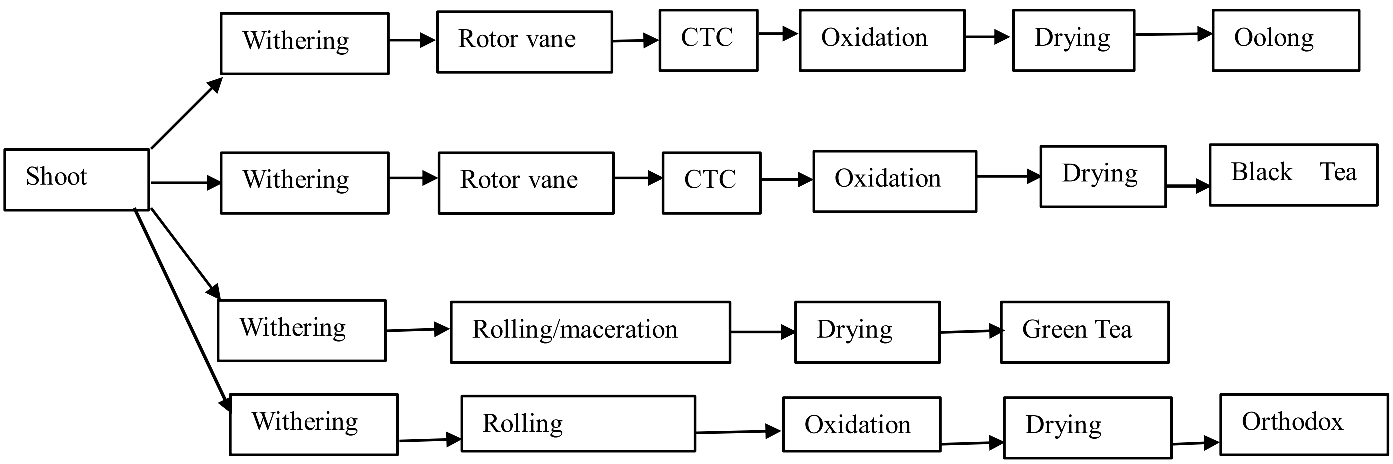

Figure 1
Tea processing flow chart (Pou *et al.*, 2019)

Various techniques are used in tea drying process, this includes Fluidized bed dryer, endless chain pressure dryer, spray dryer, super-heated tea dryer, solar energy assisted dryer and microwave. Fluidized bed dryer is used in tea drying process since dhool is of nonuniform particle and drying air can be modelled to allow for bigger particle fluidization and at the same time the smaller particles are fluidized and maintained the drying chamber (Handayani, Yohana *et al.*, 2023). Hot air inlet in FBDs also provides pneumatic transport of tea particles, increases tea agitation on the drying bed that enhances energy utilization (Temple *et al.*, 1999).

Four distinct process take place at the same time during black tea drying phase.

a. Heat transfer: Hot air transfers heat to the surface of the wet dhool through convection. The rate of heat transfer is function on dhool property and temperature gradient. Transferred heat from the hot air to the room temperature dhool, will be the latent heat of vaporization. Dhool convectional heating will increase the temperature gradient on the surface of the dhool consequently the heat will tend to flow towards the center of the dhool particle through conduction (Chukwunonye, Nnaemeka *et al.*, 2016)
b. Mass transfer: As the hot air blows through the dhool, vaporized moisture will be carried with air resulting in moisture reduction in dhool and increase in air humidity. Transfer of moisture from dhool goes on until when the vapour pressure in the dhool will be equal to the partial pressure of water vapour in the air. This state is known as equilibrium moisture content, and this varies depending with the surrounding ambient (Chukwunonye *et al.*, 2016).
c. Heat transfer: Heat is transferred from the dhool surface to the center on the dhool particle through conduction
d. Mass transfer: Moisture transfer from the center dhool particle to the dhool surface.

Study of moist air is known as psychometry (Singh and Heldman, 2009)**.** The psychometry chart was useful to study black tea convective drying processes. Psychometric chart is defined for a pressure of 101.3 kPa which is the case of black tea drying process. On the psychometric chart, specific humidity is displayed on the Y axis while the X axis displays dry bulb temperature. The curves depict constant wet bulb temperature, constant enthalpy, constant relative humidity and constant specific volume.

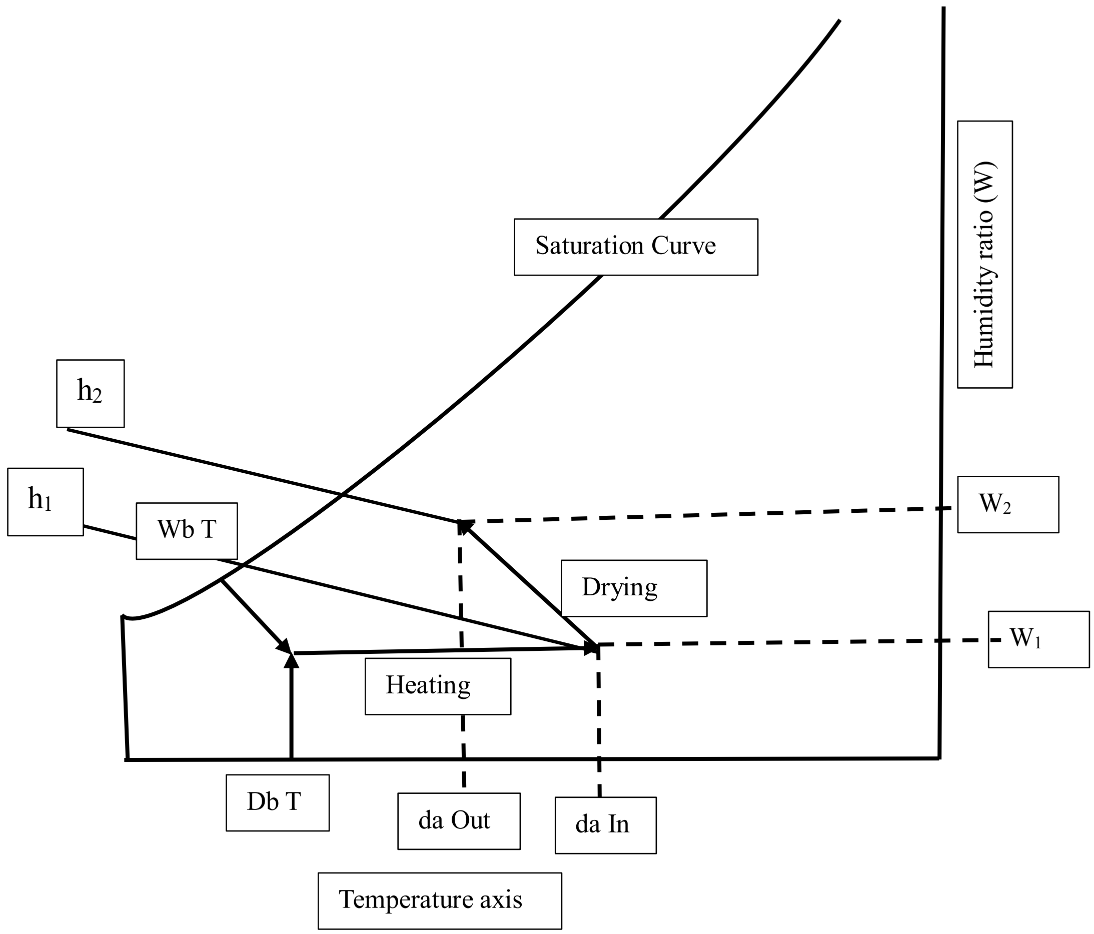

Figure 2
Drying process presentation on Ashae psychometric chart

A number of research works has been done on drying process optimization but, they have all considered only one drying parameter holding other parameters constant. Therefore, this study focused on linear, square and 2-way interaction models for process optimization. Thus, this justifies the objective of this study, to present optimal black tea drying process parameters, determine the black tea drying rate and develop black tea drying curve.

II. MATERIALS AND METHODS

2.1 Materials

Green leaves from the field were plucked (two leaves and a bud). The leaves were withered and then macerated on the CTC to wet macerated leaves referred to as dhool. The dhool from the CTC was fermented at the continuous fermenter's units with conditioned air at 27 ^{0}C. Fermented dhool was taken from the tea processing line for drying at the laboratory using a lab scale fluidizes bed dryer Sherwood 501 model. Figure 3 shows the exploded Sherwood 501 dryer.

2.2 Experiment set up

The fluidized bed dryer used to study tea drying consists of the following components.

1. Blower
2. Electric heater
3. Drying chamber with perforated bed
4. Control panel (Air temperature, air velocity and drying time)

Figure 3. Shows the schematic flow diagram of the laboratory fluidized bed dryer. Fluidized bed dryer experimental study was conducted at the Sotik Tea Company limited using a miniature laboratory quick fluidized bed dryer Sherwood Tornado model 501. Dhool weighing 300 grams was used in conducting the drying experiment. The initial moisture content of the fermented dhool was determined (W_w). Fluidized bed dryer was switched on pre-run for 5 minutes in order to achieve the initial experimental start conditions of FBD. This phase reduced the heat loss through the FBD wall which was at room temperature. After the FBD pre heating was complete, dhool was put into the FBD to start the drying experiment. After time (t), dry dhool was weighed and weight recorded as ($W_{d.}$). Tea moisture content X, was then calculated in dry base db using equation 1. Referenced to experimental researches by (Tasirin, Kamarudin *et al.*, 2007) and (Akpinar, Bicer *et al.*, 2003).

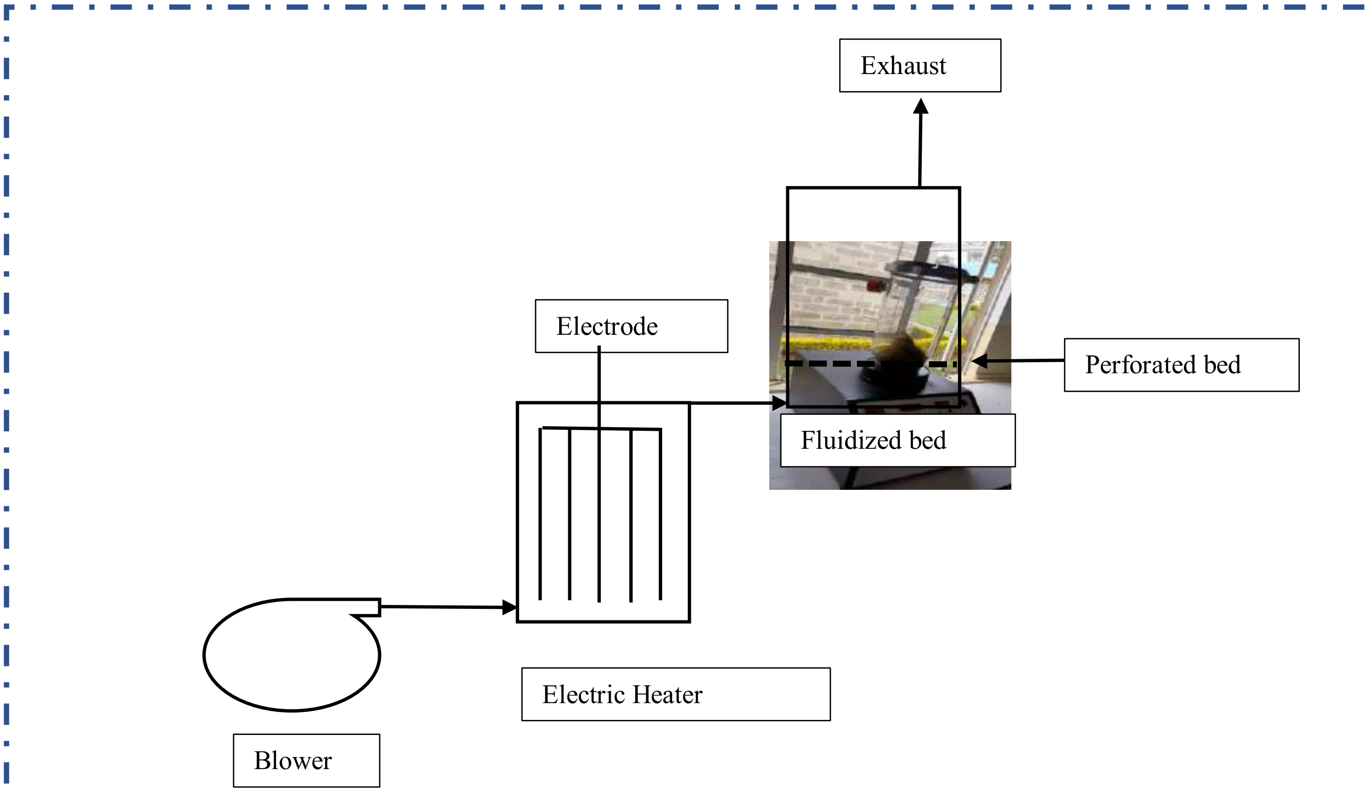

Figure 3
Schematic illustration of fluidized bed dryer

The moisture content in this study was calculated on dry base using the equation 1.

$$\boldsymbol{X} = \frac{(\boldsymbol{W_w} - \boldsymbol{W_d}).\boldsymbol{W_d}}{\mathbf{100}} \tag{1}$$

Figure 4
Laboratory KERN 1000-2 weighing scale

2.3 Design of experiment

Minitab software was used for design of experiment and analysis of experimental data. Box Behnken design of the response surface methodology with 3 factors and two levels was used to design experimental models, analyze and optimize the drying process. Table 1. Shows levels and factors that were used in the experiment.

Table 1
Experimental Levels and Factors

Symbol	Intermediate variables	Actual levels uncoded factors	
		Low	High
da_T	Air temperature (^{0}C)	70	130
da_V	Air Velocity (m/s)	0.21	0.55
t_d	Drying Time (min)	3	20
D	Dhool	300 (g) and 4 cm height	

2.4 Experimental models

Table 2. Illustrates the experimental models that were developed from the Box Behnken methodology.

Table 2

Statistical summary of models

Std Order	Run Order	Blocks	Temperature	Velocity	Time
1	1	1	70	0.21	11.5
2	2	1	130	0.21	11.5
3	3	1	70	0.55	11.5
4	4	1	130	0.55	11.5
5	5	1	70	0.38	3
6	6	1	130	0.38	3
7	7	1	70	0.38	20
8	8	1	130	0.38	20
9	9	1	100	0.21	3
10	10	1	100	0.55	3
11	11	1	100	0.21	20
12	12	1	100	0.55	20
13	13	1	100	0.38	11.5
14	14	1	100	0.38	11.5
15	15	1	100	0.38	11.5

III. RESULTS & DISCUSSION

3.1 Experimental results

Table 3 below, shows the moisture content experimental data obtained during dhool drying process using laboratory scale Sherwood 501 fluidized bed dryer. Tea samples were taken manually intermittently from the dryer, tea weight measured using KERN 1000-2 laboratory weigh scale and tea moisture content determined in dry basis.

Table 3

Moisture content at different drying time

Moisture Content (kg H_2O / kg DM)	72	32	21	15	11	9	7	5	3.5
Time (min)	0	3	5	8	10	13	15	17	20

3.2 Drying curve

Figure 5 shows the moisture content profile of black tea drying process verses drying time. The initial moisture content of the fermented macerated tea was 72% db. The moisture content of fermented tea decreases with time in the fluidized bed dryer as hot air was blown through the bed. The final black tea moisture content of 3.5% db was attained after 20 minutes.

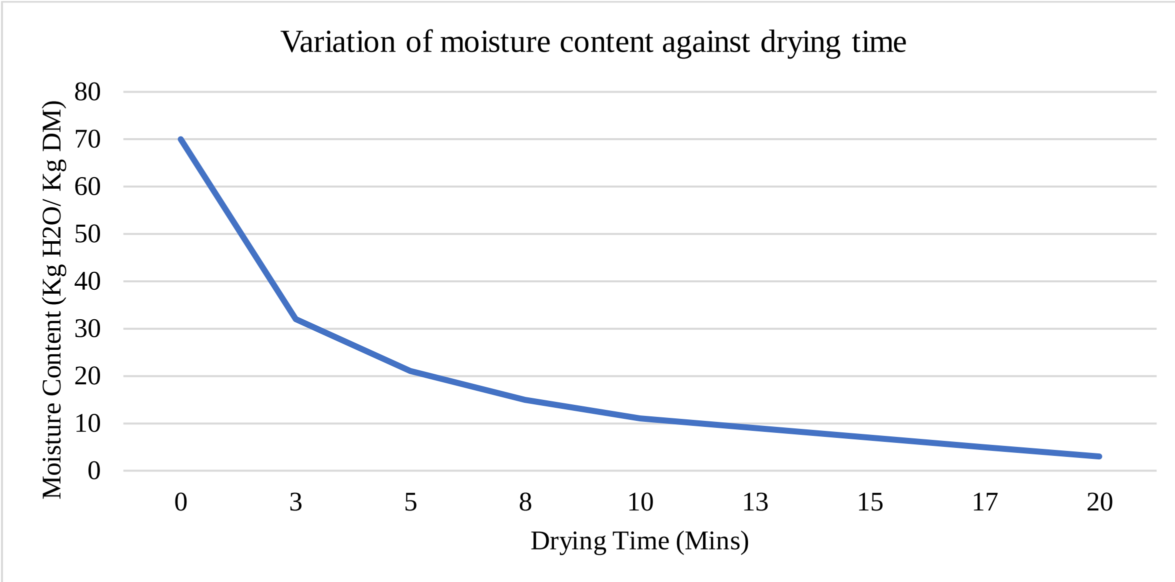

Figure 5
Black tea drying curve

3.3 Drying rate curve

Figure 6 exhibits four regions during the black tea drying process. The first phase is the initial drying phase (A’ - A) also referred to as the preheating phase. During this phase, dhool surface was heated to ambient air temperature. Region A to B on the curve is the constant rate period. At the beginning of the constant rate point A, the dhool was wet and fully covered with superficial water. During drying period at constant rate, the unbound water around the wet dhool was evaporated whereas the temperature of dhool remained unchanged. At point B, all superficial water is observed to have been removed and the dhool is at critical moisture content. The critical moisture content of the dhool transitioned to falling rate point B to C. At this point, the dhool drying rate started to decrease. Region C to D is the second falling rate. At this stage of drying, the amount of water removed from the dhool was relatively small compared to other regions. Dhool attained a dynamic equilibrium moisture content of 3.5 kg H_2O/ kg DM at point D.

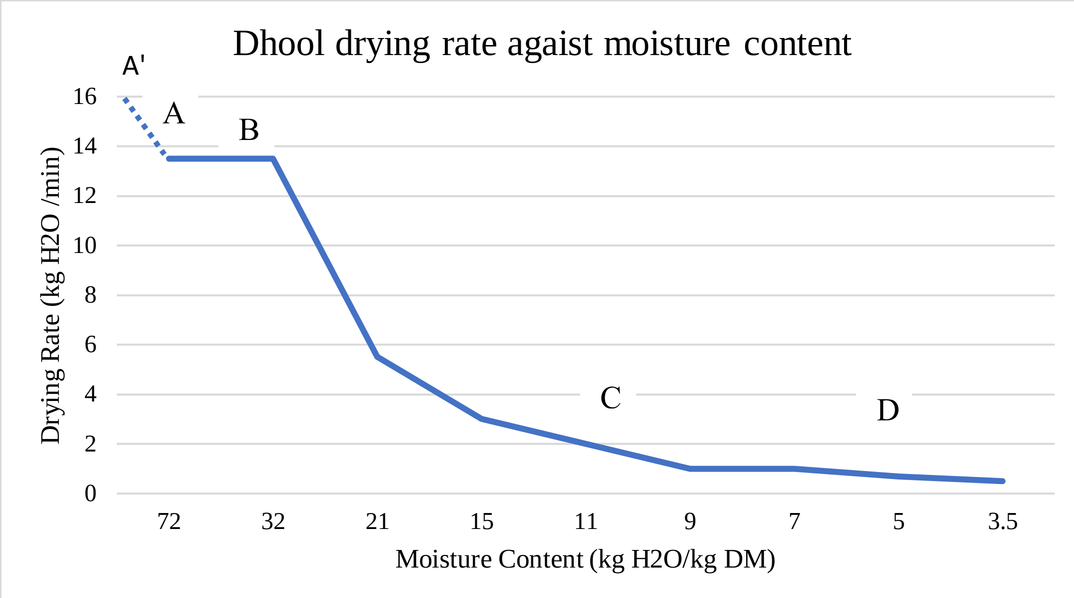

Figure 6
Black tea drying rate curve

3.4 Statistical Data

Table 4. Shows the response parameter (moisture content) at various input variable combinations for each of 15 experimental runs. The data obtained from the experiment were analyzed using Box Behnken under surface response method. Drying air temperature, drying air velocity and drying time were the experiment factors while moisture content was the response variable for the experiment.

Table 4
Experimental and response moisture content at different drying conditions

Std Order	Run Order	Blocks	Temperature (^{0}C)	Velocity (m/s)	Time (mins)	Moisture (%)
1	1	1	70	0.21	11.5	55
2	2	1	130	0.21	11.5	32
3	3	1	70	0.55	11.5	25
4	4	1	130	0.55	11.5	15
5	5	1	70	0.38	3	68
6	6	1	130	0.38	3	21
7	7	1	70	0.38	20	10
8	8	1	130	0.38	20	4
9	9	1	100	0.21	3	50
10	10	1	100	0.55	3	32
11	11	1	100	0.21	20	11
12	12	1	100	0.55	20	9
13	13	1	100	0.38	11.5	7
14	14	1	100	0.38	11.5	3.5
15	15	1	100	0.38	11.5	8

3.5 Model Summary

Model at the confidence level of 95% and 5% significant, resulted to coefficient of determinants R^2 and adjusted R^2 of 96.98% and 91.54% respectively. This shows that the model is significant and adequate. The R-sq value of 96.98%, means that the model's response which is the dhool moisture content can explains tea drying variables of study.

Table 5

R – Squared summary

Co-efficient of determinant	Value
S	5.88926
R-square	96.98%
Adjusted R- squared	91.54%
Predicted R- Squared	54.35%

3.6 Analysis of variance

Analyze response surface design tool under response surface methodology was used to analyse the experimental data shown in Table 4. Table 6, illustrates analysis of variance of the model at 95% confidence level and 5% significant level. Analysis yieded a F-value and a P-value of 17.87 and 0.003 respectively. This depicts that the model was significant. It is also evident from the ANOVA table that all variable of study are significants as because they are all less than the significant value of 0.05.

Table 6

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	5567.82	618.65	17.84	0.003
Linear	3	3831.75	1277.25	36.83	0.001
Air Temperature	1	924.50	924.50	26.66	0.004
Air velocity	1	561.13	561.13	16.18	0.010
Drying Time	1	2346.12	2346.12	67.64	0.000
Square	3	1209.57	403.19	11.62	0.011
Air Temperature*Air Temperature	1	616.03	616.03	17.76	0.008
Air velocity*Air velocity	1	592.41	592.41	17.08	0.009
Drying Time*Drying Time	1	164.10	164.10	4.73	0.082
2-Way Interaction	3	526.50	175.50	5.06	0.056
Air Temperature*Air velocity	1	42.25	42.25	1.22	0.320
Air Temperature*Drying Time	1	420.25	420.25	12.12	0.018
Air velocity*Drying Time	1	64.00	64.00	1.85	0.232
Error	5	173.42	34.68		
Lack-of-Fit	3	162.25	54.08	9.69	0.095
Pure Error	2	11.17	5.58		
Total	14	5741.23			

3.7 Regression Equation in Uncoded Units

Equation 2 shows the overal regression equation which relates the moisture content and the three factors of study.

Moisture Content = 385.4- 3.933 Air Temperature- 478 Air velocity- 9.21 Drying Time
+ 0.01435 Air Temperature*Air Temperature+ 438 Air velocity*Air velocity
+ 0.0923 Drying Time*Drying Time+ 0.637 Air Temperature*Air velocity
+ 0.0402 Air Temperature*Drying Time + 2.77 Air velocity*Drying Time **(2)**

3.8 Modified Regression Equation in Uncoded Units

The significant variables were evaluated as shown in the ANOVA Table 5. The model was therefore improved with elimination of non-significant variables. The regression equation 3, consequently shows the improved regression equation with only significant terms in the study.

Moisture Content = 385.4- 3.933 Air Temperature- 478 Air velocity- 9.21 Drying Time
+ 0.01435 Air Temperature*Air Temperature+ 438 Air velocity*Air velocity
+ 0.0402 Air Temperature*Drying Time **(3)**

3.9 Optimization of drying variables

Response optimizer tool of surface response design methodology was used to optimize the black tea drying process parameters. The response optimizer gave the optimal process variables values of 100 ^{0}C drying air temperature, 0.38 m/s drying air velocity/s and 12.9 minutes dhool retention drying time. The resultant moisture content of black tea was 3.5 kg of water/ kg DM.

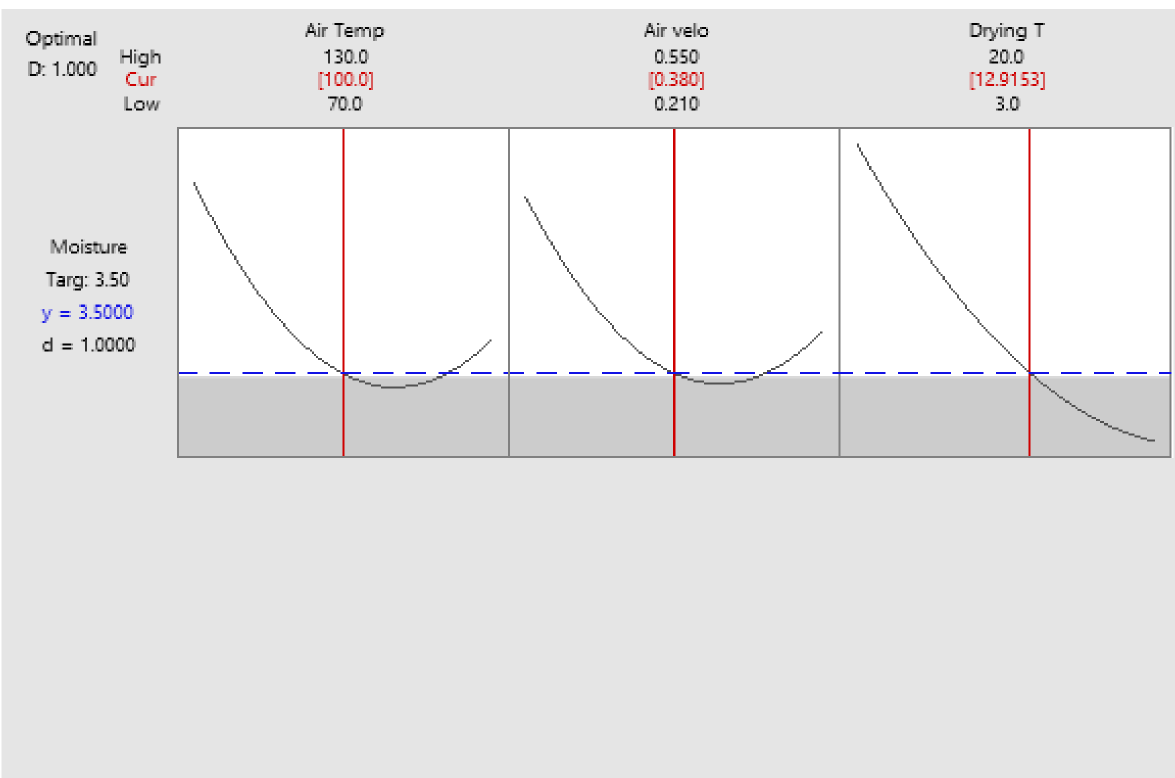

Figure 7
Optimal drying process variable

3.10 Surface and contour plots

Figure 7, show the surface plot of moisture content vs drying air temperature and drying air velocity. From the surface plot, it is observed that the dhool moisture content reduces with increase of both drying air velocity and drying air temperature.

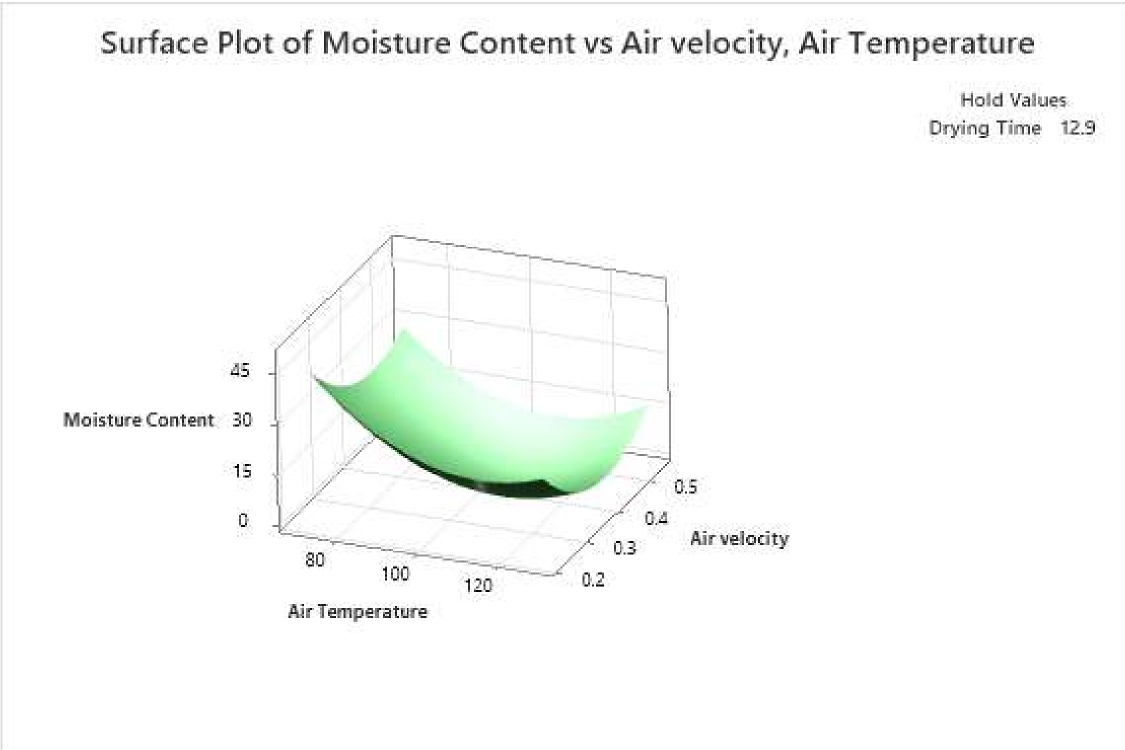

Figure 8
Surface Plot of moisture vs velocity, temperature

Figure 8 shows contour plot of dhool moisture content visa vee drying air velocity and drying air temperature. Drying air temperature between 88 ^{0}C to 130 ^{0}C and air velocity between 0.3 m/s to 0.55 m/s yielded moisture content of below 10 kg of water / kg MD. The most acceptable moisture falls within this region. This is validates the Minitab response optimizer results of, 100^{0}C drying air temperature and 0.38 m/s drying air velocity.

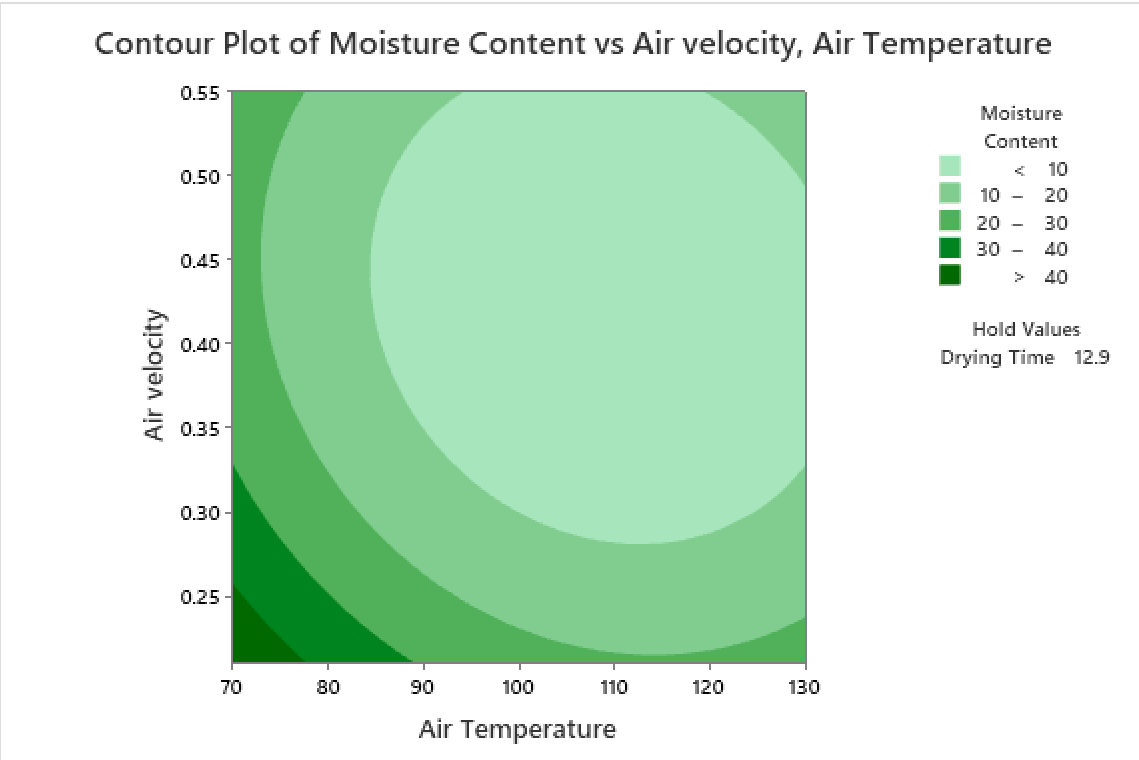

Figure
Variables contour plot of moisture Vs velocity, Temperature

IV. CONCLUSION

The drying process of black tea is key since it ceases enzymatic reactions and growth of bacteria in tea. Drying also enhances tea leaves color and sensory. Drying also reduces tea leaves moisture content to fall between 3 - 4 kg of water / kg of DM, with intention of increasing shelf-life. In fluidized bed dryer, most dhool drying process happened in the falling rate period. The experimental analysis of tea drying resulted to a dynamic equilibrium moisture content of the black tea of 3.5 kg of water / kg DM was attained after 12.9 minutes of drying time. Drying process optimization gave optimal drying parameters of, drying air velocity of 0.38 m/s, drying air temperature of 100 ^{0}C and drying time of 12.9 minutes. Experimental results in this study is projected to be helpful in optimizing tea industry fluidized bed dryers and for future design and production of dryers.

Recommendation

Since dryers are energy intensive and they consume much of the energy produced in the tea factories. Study ought to be explored on dhool pre-treatment prior to drying process with the intention of reducing dryer's energy consumption and tea leaves quality.

Acknowledgement

Much of acknowledgement to the Sotik Tea Company for their support towards the success of this research work.

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