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Optimum Air Velocity, Air Temperature and Maize Layer Thickness for Highest Moisture Removal Rate and Drying Efficiency in a Forced Convection Grain Dryer

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Abstract The performance of a forced convection grain dryer may be evaluated based on different criteria, such as drying rate, moisture removal rate and efficiency. This performance is dependent upon various drying parameters, such drying air velocity and temperature as well as grain layer thickness. It is necessary to apply an optimal combination of levels of the various parameters in order to achieve improved performance of such a dryer. This study developed an experimental grain dryer and investigated its performance under different drying conditions. The Taguchi approach was used to determine the optimal combination of drying air velocity, temperature and grain layer thickness that could be used to ensure greatest drying efficiency and moisture removal rate (MRR). ANOVA and LSD tests were used to determine whether change of air velocity and grain layer thicknesses significantly affected drying efficiency as well as MRR.The experimental grain dryer developed was of dimensions 0.5 m x 0.5 m x 1.0 m and was equipped with a 0.7 kW centrifugal fan. It was found that the optimal combination of grain layer thickness and air velocity were 0.04 m and 0.34 m/s respectively for solar drying, if drying efficiency was the determining criterion. When drying was done under laboratory conditions, a combination of 0.41 m/s air velocity, 45°C air temperature and 0.02m layer thickness resulted in greatest MRR and drying efficiency. These findings are useful because use of combination enable the design and use of such a dryer in a manner that ensures minimal energy wastage. Appropriate time management is also facilitated as drying can be undertaken at the shortest possible time.

Keywords: *forced convection grain dryer, moisture removal rate, drying efficiency, taguchi approach of optimisation*

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1. Introduction

Postharvest food loss in developing countries is estimated to be of the order of 40%, but can rise to be as high as 80% under very adverse conditions. A significant percentage of these losses is related to improper and, or untimely drying of foodstuffs [1]. Postharvest loss of maize in Kenya in 2007 was 21.1% [2]. Drying of the grain is necessary to avoid loss between harvesting and consumption. Moist and partly moist crop is prone to fungus infection, which renders it unusable. High moisture content also encourages loss due to attacks by insects, pests and increased respiration [3,4]. According to [5], drying of crop helps to achieve better product quality, longer safe storage and reduction of post-harvest loss hence ensuring more food is available for the growing world population.

Grain drying may be carried out using different sources of energy. However, solar energy is preferred to other alternative sources of energy such as wind and shale since it is abundant, inexhaustible and non-polluting [6]. Natural convection solar dryers are limited due to inadequate air flow, leading to low drying rates and sometimes rotting of the crop. The grain layer thickness is also limited for similar reasons. In Forced convection solar drying, a fan is used to force the air through the grain in order to enhance the circulation of the heated air. Such dryers produce greater drying rates and it is easier to control the drying process [7,8]. The performance of a dryer may also be evaluated based on other criteria such as drying and dryer efficiency, uniformity of drying and quality of final product (extent of cracking and discoloration of grain) as well as total drying time [8,9].

Some performance characteristics of a dryer, such as efficiency and drying rate, are desirable and should be maximized. Others, such as total drying time as well as cracking and discoloration of grain, should be minimized since they are undesirable. It is always necessary to design a dryer that maximizes desirable performance characteristics, while at the same time minimizing undesirable ones. This may be done using the process of optimisation, during which a combination of parameter levels that result in minimum or maximum performance measures, whichever is desired is determined. [11] define optimisation as the process of determining the best design based on certain criteria. The process of optimization enables finding of the best possible solution under given circumstances [12]. Its objective is often some form of maximization or minimization, of a certain performance characteristic [12, 13].

Structural optimisation, genetic algorithm, artificial neural networks, simulated annealing and Taguchi approach, to mention a few, are examples of the many optimisation techniques that are available for application.

For example, the purpose of Structural Optimisation is to find an optimal material distribution according to the demands of a given structure. Optimisation is done manually and follows three iterative – intuitive steps. First, a design is suggested, after which the design is evaluated by Finite Element Analysis. Finally, the process is finished unless the requirements are not met, in which case modifications are made and the cycle repeated. Because intuition, and sometimes trial and error is used, this optimisation technique is time consuming and at times results in sub-optimal designs [12]. In topology optimisation, a form of structural optimisation, the optimal distribution of material is sought without prior knowledge of the optimal topology, Optimisation soft wares such as Solver Optistract may be used [12,14]. Structural optimisation was not applied in this research, since performance was to be optimized, rather structure.

Genetic Algorithms (GAs) are optimisation techniques inspired from evolution, and which are therefore based on the ‘survival for the fittest strategy’. GAs use search operators (selection, mutation and cross over) to determine the optimal solution [13]. A GA search begins with a random set of solutions, coded in binary string structures, every solution being assigned a fitness related to the optimisation problem. The population of solutions is then modified into a new one by application of the search operators, through an iterative process that ends when a termination criteria is satisfied [15]. In a project aimed at determining optimal design for a hydraulic brake model [13] applied GAs to determine the combination of inputs (supply pressure and area curves) that resulted in an efficient (largest possible velocity change due to deceleration) and comfortable (predetermined maximum jerk) brake system. This technique was not used in this research because of its computer based approach, as opposed to the experimental method used in this research.

Another optimisation technique is the Neural Networks (NN), also called Artificial Neural Networks (ANN). [16] describes ANN as a computational model consisting of a number of elements (neurons). A neuron is a processing unit that receives input from outside the network and/ or from other neurons, applying a local transformation to the input, thereafter providing a single output, which is then passed on to other neurons or to the outside of the network. The main elements of an ANN are the computing element (artificial neuron), the connection pattern (structure or architecture) and the process used to train the ANN (learning algorithm). Training of the ANN, according to [17], utilises available useful information from several optimum designs. The trained ANN, as an expert designer, can then be used to predict an optimum design from a new situation. [18] applied ANN for optimising the design of a multilayer patch antenna to minimise patch sizes and maximise resonance band width. This was also not used in this research because of its computer based approach.

In this study, the Taguchi approach was adopted for use, since it is based on experimental data. The other optimisation techniques apply a computer based approach, which would not have been appropriate in the current research. Taguchi Approach allows collection of necessary data to determine which factors affect a product quality most. By studying the effect of individual factors on the results, this approach may be used to enable determination of the best combination of factors. It does this with a minimum amount of experimentation, thus resulting in savings on time and resources [19,20].

The first step in the Taguchi method is to define a target value of the performance measure such as flow rate or temperature. Alternatively, the aim may be to maximize or minimize the performance measure. Secondly, the design parameters that affect the performance measure are determined. These may include temperature, pressure among other variables. The number of levels at which each parameter is to be varied is also specified. The third step is to create orthogonal arrays for the parameter design, indicating the number, and conditions for each experiment. These Taguchi arrays, which may be derived or found online, depend on the number of parameters and number of levels. Next is to conduct the experiments as indicated in the arrays to collect data on the effect on the performance measure. Finally, data analysis is done to determine the effect of the different parameters on the performance measure. A confirmation experiment is then carried out to verify the optimal process parameters obtained, unless the optimal combination coincidentally matches with one the experiments in the orthogonal array [19,20].

The analysis of data to determine the effect of each variable on the output involves calculation of the signal to noise ratio, called the SN number, using eqs. (1) - (3). The term ‘signal’ refers to the product quality i.e. the desirable effect, while ‘noise’ entails the uncontrollable factors i.e. the undesirable effect. Usually, there are three categories of quality of characteristics in the analysis of SN ratio: the-lower-the-better, the-higher-the-better and the-nominal-the-better. Regardless of the category, greater SN ratio corresponds to better quality characteristics, hence the optimal level of the parameter is the level with greatest SN ratio.

$$SN_i = 10log\frac{\bar{y}_i^2}{s_i^2} \tag{1}$$

Where: $\bar{y}_i = \frac{1}{N_i}\sum_{u=1}^{N_i} y_{i,u}$

and $s_i^2 = \frac{1}{N_i-1}\sum_{u=1}^{N_i}(y_{i,u} - \bar{y}_i)$

Also, i is experiment number, u the trial number, N_i the number of trials for experiment, y_i the mean value and s_i the variance.

For minimizing the performance characteristic, the SN number is determined using eq. (2).

$$SN_i = -10\log\left(\sum_{u=1}^{N_i} \frac{y_u^2}{N_i}\right) \qquad (2)$$

For maximizing the performance characteristic, eq. (3) yields the SN number.

$$SN_i = -10\log\left[\frac{1}{N_i}\sum_{u=1}^{N_i} \frac{1}{y_u^2}\right] \qquad (3)$$

After calculating the SN number for each experiment, the average SN value is found for each parameter and level, and the larger the range of SN value for the parameter, the larger its effect on the performance characteristic. Analysis of Variance (ANOVA) on the collected data from Taguchi design experiments may be used to select new parameter values to optimize the performance characteristic. The data from the arrays may also be analysed by plotting and performing visual analysis, and Chi-square test [19,20].

The Taguchi approach has been applied by different researchers in the optimisation process. For example, [20] used the optimisation technique and found that a combination of 240℃ melting temperature, 110 bar injection pressure, 96 bar holding pressure, 5 second holding and 10 second cooling time resulted in optimum minimum shrinkage of 0.1645 cm. [21] applied the technique to optimize machining parameters that influence the machinability of AI2124SiCp (45 % wt) metal matrix composite. They found that the optimal combination of parameters for lowest specific power were 40 m/min cutting speed, 0.15 mm/rev feed rate, 0.20 mm depth of cut and polychrystalline diamond (PCD) tool. After similar experiments, [22] determined the optimum combination of cutting speed, feed rate and depth of cut for minimum tool vibration to be 215 m/min, 0.07 mm/rev and 0.5 mm, respectively. It is evident that the Taguchi technique has, in most cases, been applied in manufacturing sector. Studies conducted on solar drying systems using Taguchi method are few in literature, according to [23]. They suggest that researchers can apply the method for modeling drying systems because it reduces number of trial experiments. The method was adopted in this research due to its suitability for optimisation that relies on experimental data.

This research focused on two performance characteristics, all of which require maximization in a dryer. namely drying efficiency (ratio of energy used in removing moisture to sum of energy lost by drying air and that used for running fan and moisture removal rate (ratio of mass of moisture removed to mass of wet grain per unit time).This is a measure of drying rate, and was adopted since drying rate changes every instant, and would thus not be a useful measure for estimating drying capacity. Also, it gives an indication of how long it would take to dry a given amount of product. Moisture removal rate is, however, be affected by factors influencing drying rate. According to [24] factors affecting drying rate include air temperature and velocity, product type, layer thickness and moisture content of product, method of drying, moisture diffusivity and drying kiln structure.Others are crop porosity and humidity of the surrounding air. The surface area of the crop exposed is yet another factor that affects drying rate [1,4]. Efficiency of a dryer, however, is affected by air flow rate and drying air temperature [25,26]. This research determined the best combination of air velocity and grain layer thickness to maximize the selected performance characteritics.

2. Materials and Methods

In order to find the optimum combination of air velocity and grain layer thickness resulting in greatest drying efficiency and moisture removal rate, three approaches namely the Taguchi approach, Analysis of Variance (ANOVA) and Least Square Differences (LSD) and were used.

2.1. Dryer in Open Sun

The Taguchi approach was used to select the combination of air velocity and grain layer thickness resulting in greatest drying efficiency as well moisture removal rate. The two parameters and their levels are shown in Table 1.

The L’16 orthogonal array involving 16 experiments was used as indicated in the experimental plan in Table 2. In each experiment, with the dryer in the open sun, a specific layer thickness of wet grain was dried in the experimental solar dryer using solar heated air at a specified velocity. The grain was weighed at the beginning, and again at the end of the drying session 3 ½ hours later. Taguchi optimisation was also done using Minitab 17 statistical software and the results obtained were the same.

Table 1. Parameters affecting Dryer Performance and their Levels

Factor	Parameter	Units	Level 1	Level 2	Level 3	Level 4
A	Air velocity	m/s	0.21	0.27	0.34	0.41
B	Grainlayer thickness	m	0.02	0.04	0.06	0.08

Table 2. Experimental Plan (L’16 Orthogonal Array)

Experiment	Parameter/Levels		Actual Values of Parameter/Levels	
	Air Velocity	Grain Layer Thickness	Air Velocity (m/s)	Grain Layer Thickness (m)
1	**1**	**1**	**0.21**	**0.02**
2	1	**2**	0.21	**0.04**
3	1	**3**	0.21	**0.06**
4	1	**4**	0.21	**0.08**
5	**2**	**1**	**0.27**	**0.02**
6	2	**2**	0.27	**0.04**
7	2	**3**	0.27	**0.06**
8	2	**4**	0.27	**0.08**
9	**3**	**1**	**0.34**	**0.02**
10	3	**2**	0.34	**0.04**
11	3	**3**	0.34	**0.06**
12	3	**4**	0.34	**0.08**
13	**4**	**1**	**0.41**	**0.02**
14	4	**2**	0.41	**0.04**
15	4	**3**	0.41	**0.06**
16	4	**4**	0.41	**0.08**

a) Drying efficiency

In order to determine the drying efficiency, the energy E_w required to remove the moisture from the grain was determined using eq. (4), in which m_w and H_v represented mass of water vapour evaporated and latent heat of vapourisation respectively.

$$E_w = m_w H_v \tag{4}$$

The energy E_a supplied by the hot air to the grain was given by eq. (5). In this equation, mass flow rate of air used for drying for a duration of time t_s, and specific heat capacity of air are represented by $\dot{m}_a$ and c_{pa} . ΔT_i represents the temperature drop as the hot air passes through the grain.

$$E_a = \dot{m}_a c_{pa} t_s \Delta T_i \tag{5}$$

The energy E_f consumed by the fan was given by eq. (6), in which t represents the total drying time and P_f the power consumed by the fan.

$$E_f = P_f t \tag{6}$$

P_f was determined from eq. (7), with V and I being the voltage and current consumed by the suction fan.

$$P_f = VI \tag{7}$$

Drying efficiency η_{dr} was then determined for the different experimental sessions using eq. (8), ΔT_m being the mean temperature drop as air passes through the grain.

$$\eta_{dr} = \frac{m_w H_v}{\dot{m}_a c_{pa} t \Delta T_m + P_f t} \tag{8}$$

To find the mass of moisture lost m_w, the grain was weighed at the beginning and at the end of the drying session using a digital balance. Air velocity, v, measured at the dryer exit, using a thermo-anemometer, was used to calculate volume flow rate Q for the exit radius of 0.05 m, by applying eq. (9).

$$Q = Av \tag{9}$$

$$\dot{m} = Q\rho_a \tag{10}$$

(Q = flow rate in m^3/s, A= cross sectional area in m^2, v = air velocity in m/s, $\dot{m}$ = mass flow rate in kg/s and ρ_a= density of air in kg/m^3)

It was then possible to calculate air velocity through different sections of the dryer using the same equation. Mass flow rate $\dot{m}_a$ was subsequently obtained from eq. (10). Latent heat of vapourisation of water at air exit temperature (H_v) and specific heat capacity of air (c_{pa}) were obtained from Engineering Thermodynamics Properties tables. As suggested by [27], $H_v$was be increased by 15% since bound water was to be removed. Fan power, P_f was obtained from eq. (7), the current I being measured using a multimeter, and taking the voltage V to be 240 V. ΔT_i was determined from temperature readings every 30 minutes.

b) Moisture Removal Rate (MRR)

To determine moisture removal rate (R_{mr}), moisture loss in each drying session was calculated from the difference between the mass of grain before and after drying, weighed using a digital balance. MRR was determined using eq. (11), and was defined as the mass of moisture m_m, lost during a drying session of time t for every unit mass of wet grain m_w.

$$MRR = \frac{m_m}{m_{wg} t} \tag{11}$$

Drying efficiency and MRR determined for each experiment were then used for determining SN ratio through application of eq. (2).

The mean S/N values for each parameter level were also calculated and used to determine the optimal combination of air velocity and grain layer thickness for maximising the performance indicators. The larger the mean SN value for the parameter level, the better it was for maximizing the performance characteristic in question. The results were in agreement with the main effect plots obtained from Minitab 17.

Although the Taguchi approach enabled determination of the optimum combination of air velocity and grain layer thickness for maximizing the dryer performance,it did not show whether the two parameters had a significant effect on the dryer performance characteristics. Two-way Analysis of Variance (ANOVA) was used to test the existence, or otherwise, of significant effects of different air velocities and grain layer thicknesses on dryer performance. When ANOVA gives a significant result, it only indicates that at least one group differs from the other groups. It was thus necessary to do LSD tests to compare pairs of groups for any significant difference between them. This was done to determine whether the varying air velocity and grain layer thickness levelshad any significant effects on dryer performance. Statistical Analysis Systems (SAS) software wasused for the analysis.

2.2. Dryer in Laboratory Conditions

In this section, experiments were carried out in laboratory conditions where in addition to application of different air velocities and grain layer thickness, it was also possible to control drying air temperature. The aim was to determine the combination of these drying parameters resulting in optimal MRR and drying efficiency. The three parameters and their levels are shown in Table 3.

Table 3. Parameters Affecting Dryer Performance and their Levels

Factor	Parameter	Units	Level 1	Level 2	Level 3
A	Air velocity	m/s	0.24	0.33	0.41
B	Drying Air Temperature	℃	45	50	55
C	Grainlayer thickness	m	0.02	0.04	0.06

Experiments were carried out as in section 2.2 following the experimental plan in Table 4 and values of MRR and drying efficiency determined in a similar manner.

Table 4. Experimental Plan (L'9 Orthogonal Array)

Experiment	**Parameter/Levels**			**Actual Values of Parameter/Levels**		
	Air Velocity	**Drying Air Temperature**	**Grain Layer Thickness**	**Air Velocity (m/s)**	**Drying Air Temperature (°C)**	**Grain Layer Thickness (m)**
1	1	1	1	0.24	**45**	**0.02**
2	1	2	2	0.24	**50**	**0.04**
3	1	3	3	0.24	**55**	**0.06**
4	2	1	2	0.33	**45**	**0.04**
5	2	2	3	0.33	**50**	**0.06**
6	2	3	1	0.33	**55**	**0.02**
7	3	1	3	0.41	**45**	**0.06**
8	3	2	1	0.41	**50**	**0.02**
9	3	3	2	0.41	**55**	**0.04**

3. Results

3.1. Optimisation of Dryer in Open Sun

3.1.1. Taguchi Approach for Dryer in Open Sun

Experiments were carried out as shown in the L'16 orthogonal array (Table 2) and Table 5 shows the results, as well as the SN ratios for each test run.

Table 6 shows the mean SN ratio for each of the levels of air velocity and grain layer thickness. The mean SN ratio values give an indication of the effect of each parameter at the various levels, the larger the mean SN ratio, the greater the effect. The means are computed after isolating the SN ratios for each level of a given parameter. For example, to find the mean SN ratio for air velocity at 0.21 m/s (air velocity level 1), the SN ratio values for experiments 1-4 were averaged. Similarly, to determine the mean SN ratio for 0.02 m grain layer thickness (grain layer thickness level 1), SN ratio values for experiments 1,5,9 and 13 were averaged.

It is evident from Table 6 that the greatest mean SN value for air velocity (A) is at level 4, while that for grain layer thickness (B) is at level 1.This is confirmed by the Main Effects Plot shown in Figure 1, which displays the mean values of SN ratios for the various levels of Factor A and B. Thus the optimum combination for greatest moisture removal rate is 0.41 m/s air velocity and 0.02 mm grain layer thickness. ANOVA was used to establish whether varying the parameter levels had any significant effect on moisture removal rate.

Table 5. Moisture Removal Rates & SN Ratios

Test run	Air Velocity (m/s) / Layer Thickness(m)	MRR (kg Moisture kg^{-1}Wet Grain. Hr^{-1})	SN Ratio (MRR)	Drying Efficiency (%)	SN Ratio (Drying Efficiency)
1	0.21/0.02	0.048	-26.38	8.9	18.99
2	0.21/0.04	0.027	-31.17	8.2	18.28
3	0.21/0.06	0.014	-37.08	6.2	15.85
4	0.21/0.08	0.008	-41.94	5.4	14.60
5	0.27/0.02	0.050	-26.02	9.3	19.37
6	0.27/0.04	0.024	-32.4	10.1	20.09
7	0.27/0.06	0.012	-38.42	8.3	18.38
8	0.27/0.08	0.007	-43.10	4.7	13.44
9	0.34/0.02	0.061	-24.29	10.1	20.09
10	0.34/0.04	0.053	-25.51	13.5	22.61
11	0.34/0.06	0.029	-30.75	10.5	20.42
12	0.34/0.08	0.021	-33.56	11.2	20.98
13	0.41/0.02	0.061	-24.29	12.7	22.08
14	0.41/0.04	0.048	-26.38	13.9	22.86
15	0.41/0.06	0.030	-30.46	11.0	20.83
16	0.41/0.08	0.022	-33.15	11.4	21.14

Table 6. Mean SN Ratios for Moisture Removal Rate

Symbol	Parameter/Factors	Mean SN Ratio			
		Level 1	Level 2	Level 3	Level 4
A	Air Velocity	-34.14	-34.99	-28.75	-28.57
B	Grain Layer Thickness	-25.25	-28.87	-34.18	-37.94

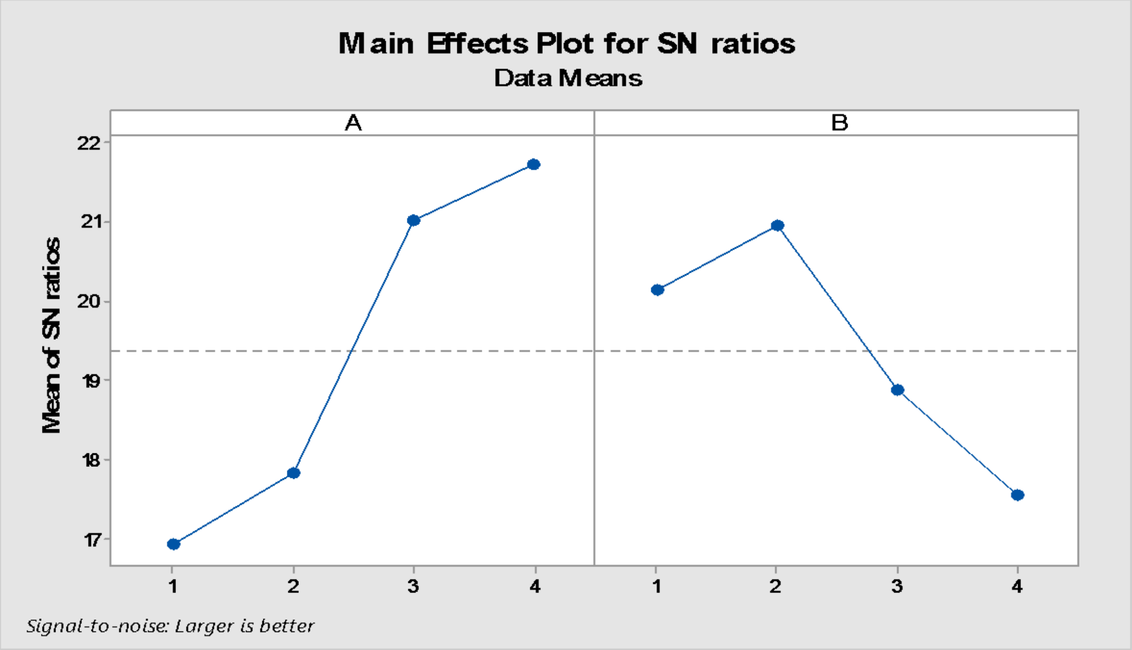

Figure 1. Main effects Plot for MRR during Solar Frying

The mean SN ratios for drying efficiency are shown in Table 7 and its main effects plot in Figure 3. It is evident that the mean SN value for air velocity is highest at level 4. This implies that air velocity of 0.41 m/s gives the best performance in terms of drying efficiency. In the case of grain layer thickness, the highest mean SN ratio is at level 2, suggesting that a grain layer thickness of 0.04 m provides greatest drying efficiency. This is in spite of the fact that a layer thickness of 0.02 m was expected to yield highest drying efficiency. The discrepancy may be attributable to higher mean plenum temperatures during the drying of the former. Thus, the optimum combination for greatest drying efficiency was air velocity of 0.41 m/s and grain layer thickness of 0.04 m. This is confirmed by the Main Effects Plot (Figure 2).

Table 7. Mean SN Ratios for Drying Efficiency

Symbol	Parameter/Factors	Mean SN Ratio			
		Level 1	Level 2	Level 3	Level 4
A	Air Velocity	16.93	17.82	21.03	21.73
B	Grain Layer Thickness	20.13	20.96	18.87	17.54

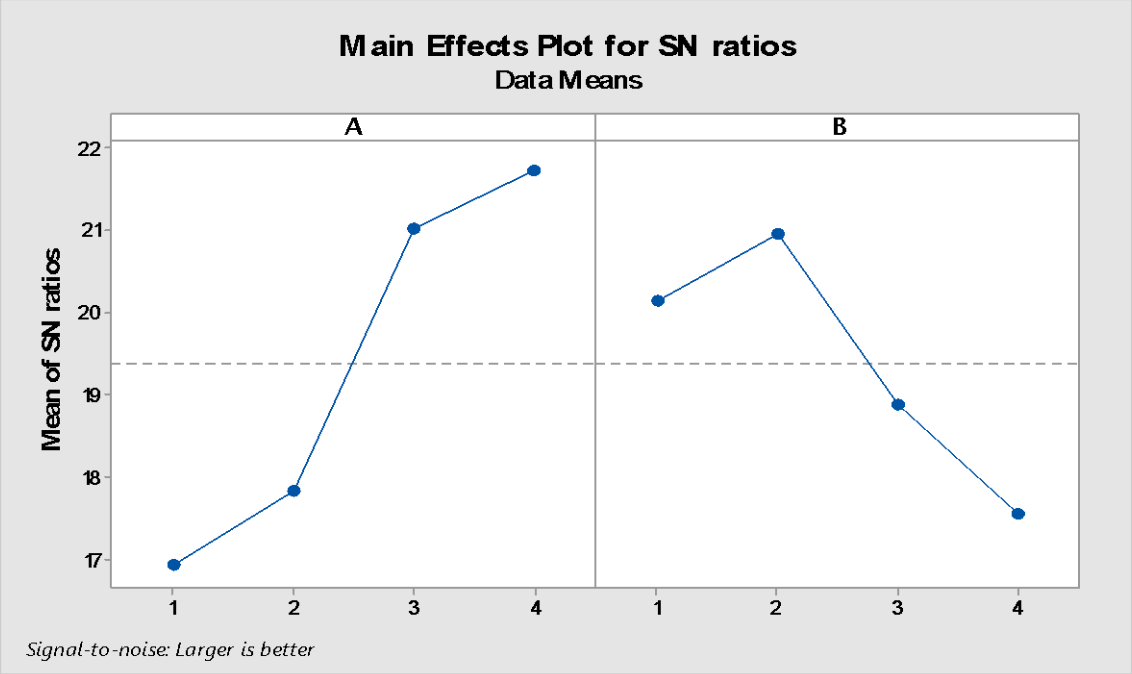

Figure 2. Main Effects Plot for Drying Efficiency during Solar Drying

3.1.2. ANOVA and LSD Results

ANOVA results computed using SAS showed the existence of a significant difference ($P<0.05$; F_{comp} = 5.654; $F_{Crit.\ 5\%}$= 3.863) for the effect of grain layer thickness on drying efficiency. Similarly, air velocity had a significant effect on drying efficiency ($P<0.05$; F_{comp} = 16.775; $F_{Crit.\ 5\%}$= 3.863). Also, there existed a significant difference ($P<0.05$; F_{comp} = 103.639; $F_{crit.\ 5\%}$= 3.863) for the effect of grain layer thickness on moisture removal rate and a significant difference ($P<0.05$; F_{comp} = 30.202; $F_{Crit.\ 5\%}$= 3.863) for the effect of air velocity on moisture removal rate.These results showed that changing between at least one pair of grain layer thickness levels, and at least one pair of air velocity levels, had a significant effect on moisture removal rate. However, it was not possible to tell the specific pair of levels that would significantly affect moisture removal rate. It was therefore necessary to perform least significant difference (LSD) tests, the results of which are shown Table 8 and Table 9.

Table 8. Effects of Air Velocity on MRR and Drying Efficiency

Velocity (m/s)	Moisture Removal Rate (kg Moisture.kg^{-1} wet grain. Hr^{-1})	Drying Efficiency (%)
0.21	0.024^{b}	7.175^{b}
0.27	0.023^{b}	8.100^{b}
0.34	0.041^{a}	11.325^{a}
0.41	0.040^{a}	12.250^{a}
$LSD_{\alpha=0.05}$	0.006	1.918

(Means with same letter are not significant).

Table 9. Effect of Grain Layer Thickness on MRR and Drying Efficiency

Grain Layer Thickness (m)	Moisture removal Rate (kg Moisture.kg^{-1} wet grain. Hr^{-1})	Drying Efficiency (%)
0.02	0.055^{a}	10.250^{a}
0.04	0.038^{b}	11.425^{a}
0.06	0.021^{c}	9.000^{b}
0.08	0.014^{d}	8.175^{b}
$LSD_{\alpha=0.05}$	0.006	1.918

(Means with same letter are not significant).

Table 8 shows that changing air velocity from 0.21 m/s to 0.27 m/s had no significant effect on neither moisture removal rate nor drying efficiency, since in all cases, the difference between the means were less than $LSD_{\alpha=0.05}$. The same applied to changing from 0.34 m/s to 0.41 m/s. However, changing air velocity from 0.27 m/s to 0.34 m/s had a significant effect on both moisture removal rate and drying efficiency, since in these cases, the difference between the means exceeded $LSD_{\alpha=0.05}$.

From Table 9, it is evident that changing from each of the grain layer levels to the next had a significant effect on MRR. However, while changing from 0.04 m to 0.06 m grain layer thickness had a significant effect on drying efficiency, changing from 0.02 m to 0.04 m, as well as 0.06 m to 0.08 m grain layer thicknesses did not.

Thus, it would be prudent to use an air velocity of 0.34 m/s since using 0.41 m/s would end up in greater power consumption without any significant advantage as far as drying efficiency and moisture removal rate are concerned. A grain layer thickness of 0.04 m would be preferable if drying efficiency were the major criterion, since using 0.02 m would reduce through-put without necessarily reducing drying efficiency. However, if moisture removal rate was the main consideration, a grain layer thickness of 0.02 would be preferred since it would result in the highest moisture removal rate.

3.2. Optimisation of Dryer in Laboratory Conditions

The Taguchi Approach, using the statistical software Minitab 17, was applied to determine the combination of drying air velocity, temperature and grain layer thickness that would result in greatest MRR and drying efficiency, if the dryer is used under controlled laboratory conditions. As shown in the Main Effects Plot in Figure 3, the greatest mean SN ratios were found to be at 0.41 m/s (level 3) for air velocity (Factor A), 45°C (level 1) for drying air temperature (Factor B) and 0.02 m (level 1) for grain layer thickness (Factor C). This would therefore be the best combination resulting in the highest MRR.

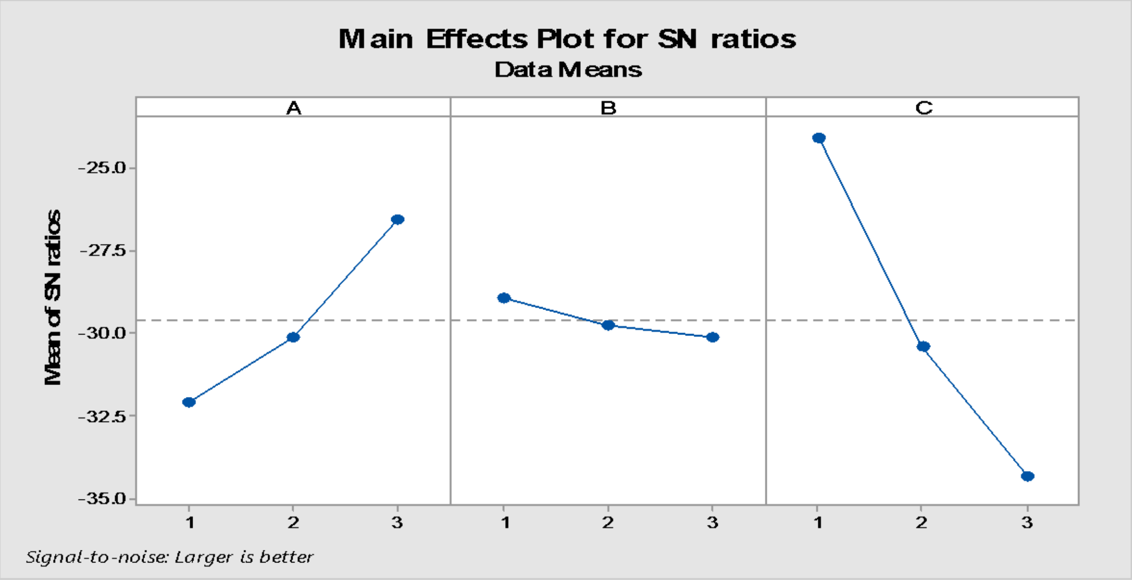

Figure 3. Main Effects Plot for MRR during Laboratory Drying

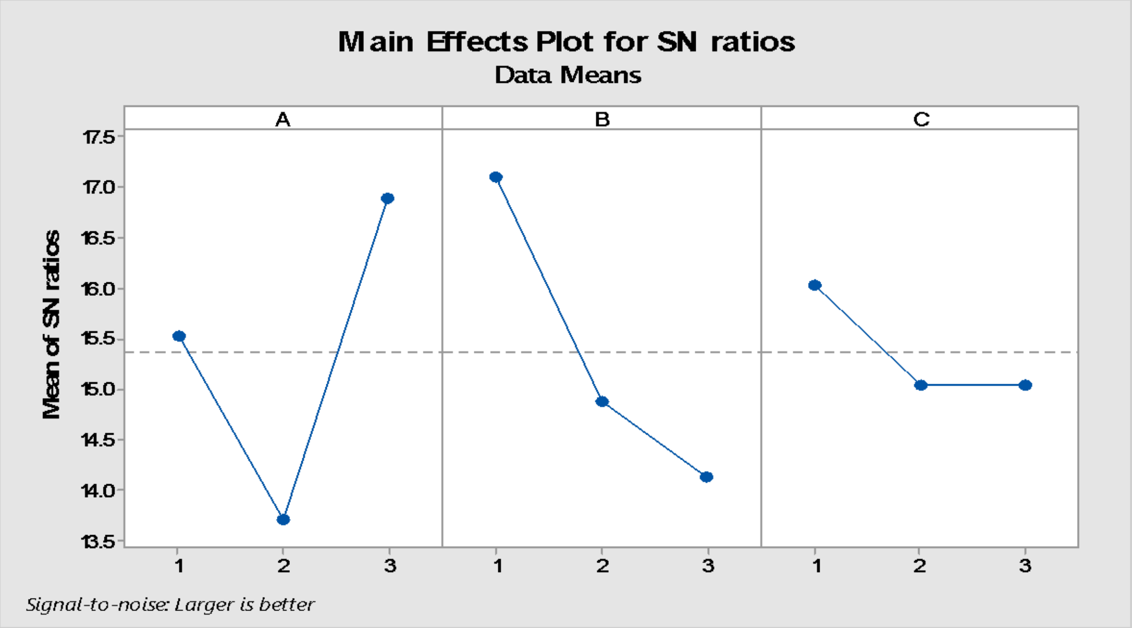

Figure 4. Main Effects Plot for Drying Efficiency during Laboratory Drying

Figure 4 shows that the best combination of parameters for greatest drying efficiency was found to be 0.41 m/s, 45℃ and 0.2 m/s.

3.3. Discussion of Results

The results in section 3.1 and 3.2 suggest that within the ranges of air velocity, temperature and grain layer thickness investigated, both high MRR and high drying efficiency are favoured by a combination of the greatest air velocity, lowest drying air temperature and lowest grain layer thickness. [28] reported that a combination of the highest temperature and highest air velocity resulted in lowest drying time (implying highest MRR) and lowest specific energy consumption (implying highest drying efficiency). [29] found that a combination of highest temperature, and lowest cube dimensions (implying lowest layer thickness) led to higher EUR (implying lower efficiency). Thus, the results of this research agree with [28] in as far as air velocity affects MRR and dying efficiency, and with [29] for effect of layer thickness on efficiency. However, there is disagreement with [28,29] concerning the optimal temperature. This could be because the different factors affect MRR and drying efficiency to varying extents, and therefore their combined effect would be dependent upon the specific factors interacting together. The combination of factors in this research were different from those in the studies by [28,29], the former having combined temperature, air velocity and peel to size ratio, while the latter combined temperature, cube size and bed depth. A better comparison would have resulted from an investigation involving the same factors in a similar dryer.

4. Conclusions

As a result of the application of the Taguchi approach, the optimal combination of grain layer thickness and air velocity were found to be 0.02 m and 0.41 m/s exit velocity respectively. However, on application of ANOVA and LSD it was found that there was no significant difference in MRR or drying efficiency when air velocity was changed from 0.34 m/s and 0.41 m/s. It is therefore recommended that an air velocity of 0.34 m/s is used if fan power is to be conserved. Also, changing from 0.02 m to 0.04 m layer thickness had a significant effect on MRR but no significant effect on drying efficiency. Thus the choice of grain layer thickness should depend on the criterion of importance. If the aim is to have a high MRR, then 0.02 m thickness should be used as using 0.04 m would significantly reduce it. If a high drying efficiency is desired, the 0.04 m should be used as this would result in a greater throughput with no significant effect on efficiency.

Following investigations with the dryer under laboratory conditions, it was found that applying air velocity of 0.41 m/s, drying air temperature of 45 ℃ and grain layer thickness of 0.02 m would result in greatest MRR and drying efficiency.

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Authors’ Contributions

The first author (also the corresponding author) carried out the research as part of his PhD project. The other three participated as supervisors.

Statement of Conflict of interest

The authors declare that there is no conflict of interest in this research.

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