Drying Performance of Mobile Dryer and Physical Quality Assessment of Dried Shelled Corn

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***Abstract*—While drying an agricultural product is a challenging process, there is always a chance to improve the drying method and strategy in terms of preserving quality, decreasing cost, and also increasing capacity. A grain corn drying study was conducted with the objectives of evaluating the grain corn drying performance of a mobile dryer as well as the economic and quality aspects of the dried grain corn. The results indicated that the mobile dryer was capable of drying 3-3.4 tons of grain corn from 25 to 13% (w.b) moisture content. The study also compared drying performance during sunny and rainy conditions to get the optimum conditions for drying grain corn. The results suggest that the Stress Cracking Index (SCI) and the colour changes were acceptable. The drying cost analysis using a mobile dryer was also calculated. It can be concluded that the mobile dryer can be used for drying grain corn despite its deficiency.**

***Index Terms*—mobile corn dryer, grain drying, drying performance, dried shelled corn quality**

I. INTRODUCTION

Over the last few years, Malaysia's government under the Ministry of Agricultural and Agro-based Industry has given priority to the expansion of grain corn planting area to reduce the import of grain corn. Malaysia is currently importing up to 4 million tons of grain corn worth about RM3.1 billion a year [1]. The feedstock industry in Malaysia is predominantly dependent on the import of grain corn as the poultry and swine industries are almost totally based on cornmeal diet [2]. According to A.G. Wahab [3], most corn produced in Malaysia is sweet corn for human consumption. While the grain corn industry in Malaysia is still in its infancy, research and development in the whole value chain from seed production to harvesting and postharvest handling is crucial in producing high-quality grain corn.

The traditional sun-drying method has now slowly become limited in application because of the requirements for a large area and extended time, the tendency towards quality degradation, high level of dust and atmospheric pollution from the air, cloudiness and rain, interruption from animals and man, infestation caused by birds and insects, and inherent difficulties in controlling the drying process [4]. High-quality grain corn could not be produced unless the grains were properly harvested and dried. In tropical countries like Malaysia where grain corn is harvested, dried and stored under humid and warm climatic conditions which prone to rapid deterioration. A proper drying method preserves the quality, nutritional value and viability of the grain [5]. After harvesting, improperly dried corn grains are subjected to aflatoxin development which is a harmful mycotoxin not only for the animal but also for human health [6]. Yakubu [7] reported that fluctuations in temperature and relative humidity in tropical countries accelerate the multiplication of moulds and insects which facilitate the further spoilage of grain. Therefore, there is no doubt that drying is considered the most vital postharvest process that influences grain corn quality [8]. In modern agricultural practice, shelled corn is usually dried using a mechanical dryer with heated air to achieve the desired final moisture content.

To date, a considerable amount of work has been done on the drying of various agricultural products, including grain corn. In making mechanical dryers more practical and economical with less shelling damage, it was found necessary that the ear corn had been partially dried to a moisture content of less than 22% (w.b) by natural field drying [9]. Field drying is where ear corn is left standing unharvested in the field for some time after the maturity stage, which allows the ear corn to dry before harvesting.

There are many types of artificial or mechanical dryers available in the market and being used in the grain industries. For instance, the LSU dryer (LSU = Louisiana

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State University), mixed flow dryer, cross-flow dryer, fluidized bed dryer, spouted bed dryer, flatbed dryer and also inclined bed dryer. A study of shelled corn drying using the fluidized bed dryer by Soponronnarit *et al.* [10] showed that the inlet air temperature strongly influences moisture reduction whilst the air velocity and bed depth are relatively significant factors. Apart from that, the physical change was virtually found and the amount of corn tracing the stress crack, and the breakage significantly increased with the increased temperature [11]. In a previous work done by Thompson and Foster [12], the rate of drying (a function of air temperature and humidity) was correlated with the severity of stress cracking.

Nevertheless, Peplinski *et al.* [13] proved that the total number of kernel stress cracks did not change significantly over a range of drying temperatures from 25 ℃ to 100 ℃. In another study where the static drying approach of a mobile flatbed dryer was used to dry ear corn, Iqbal, J & Ahmad, M *et al.*, [14] reported that the drying time for four tons of ear corn was 9 hours from 25.5% to 19.4% (w.b). The average ambient air temperature was 39.1 ℃, whereas the average drying air temperature was 55.8 ℃. There was an attempt made by other researcher using flat bed dryer for drying shelled corn, Amir Syariffuddeen, M. A. *et al.*, [15] reported that drying at 70 ℃ displayed the highest single and multiple crack percentage and followed by 60 ℃ and 50 ℃.

Most of the dryers mentioned above are fixed type dryers. Very few studies have been done relating to mobile type dryers which have recently attracted the attention of small farmers. There have been many studies on modelling related to corn drying such as Suarez *et al.* [16], Tolaba and Suarez [17], Haros and Suarez [18], Lynch and Morey [19], and Li and Morey [20]. However, most of the modelling studies only involved thin layer drying and were on a laboratory scale. Therefore, the purpose of this study is to investigate the drying performance of a commercial circulating mobile corn dryer and the quality assessment of dried shelled corn in terms of stress cracking indexes and colour changes. The economic aspects of using a mobile corn dryer are also mentioned and discussed.

II. Materials and Method

A. Drying Procedure

The drying study using a mobile corn dryer owned by the Engineering Division of the Department of Agriculture, Malaysia was carried out at MARDI Seberang Prai, Penang since planting and harvesting are carried out at the same site. The drying experiments in MARDI Seberang Prai were carried out on 2nd and 3rd March 2018 where the drying conditions happened to be sunny and rainy days, respectively. The mobile corn dryer has a holding capacity of about 3-3.4 tons per batch. The dryer consists of a hopper for loading purposes, blower, motor and cylindrical drying chamber. The total height of the dryer and diameter of the drying chamber were 4.13m and 2.23m, respectively. The drying chamber is made of a perforated steel frame suitable for grain corn. It is also equipped with direct heating from a diesel burner to supply hot air for drying. This mobile dryer is tractor-driven in which mechanical power from the tractor's engine is transferred to the mobile dryer implement. At the same time, the grain corn is continuously circulated inside the chamber throughout the drying process. This mobile dryer required a minimum of 35 HP and 430 rpm of tractor PTO (power take-off). The inlet hot air temperature was set at 80 ℃. A side view of the mobile corn dryer is shown in Fig. 1.

Figure 1. Side view mobile corn dryer and sampling locations *a* and *b*.

Matured grain corns from *Dupont* variety were freshly harvested by a combine harvester. The harvesting was carried out when the initial moisture content of the shelled corn reached 22-25% (w.b). About one hectare of grain corn equivalent to 6-7 tons of shelled corn was dedicated for the drying experiments. The temperature and relative humidity of ambient air during drying were recorded. The ambient temperature and relative humidity were recorded using an EBRO data logger (EBI 20TH1) with accuracy ±0.5 ℃. The shelled corn kernel temperature was also monitored towards the end of drying using an infrared thermometer. A time interval of one hour was used at the beginning of drying (the first 12 hours) and reduced to 30 minutes intervals towards the end of the drying process. Triplicate samples consisted of 10 g per sample from two sampling spots were collected for moisture reduction as well as kernel temperature measurements, as shown in Fig. 1. The moisture content of the corn was analyzed in a moisture analyzer (SATAKE SS6, Japan) with ±0.5% accuracy and a measuring range of 10-40%. The moisture contents of the corn samples were measured immediately after sampling. The drying was stopped once the final moisture content of shelled corn reached 13-14% (w.b). Throughout the loading, drying and unloading process, the diesel consumption was monitored for both the tractor and mobile corn dryer. The moisture content in shelled corn is designated based on the weight of water. Equations (1) and (2) are the formulas that represent moisture content on a dry basis and wet basis, respectively, while the mass of water removed (M_w) from a wet product can be calculated by using Equation (3).

$$\%MC_{db} = \frac{W_w}{W_d}.100 \quad (1)$$

$$\%MC_{wb} = \frac{W_w}{W_w + W_d} . 100 \quad (2)$$

$$M_w = M_c \left[\left(W_i - W_f / 100 - W_f \right) \right] \quad (3)$$

where MC_{db} is the moisture content dry basis, MC_{wb} is the moisture content wet basis, W_w is the weight of water (g), W_d is the weight of dry matter (g), M_w is the mass of water loss, M_c is the mass of the product to be dried, W_i is the initial moisture content, and W_f is the final moisture content.

The drying performance of the dryer was determined by calculating the Moisture Extraction Rate (MER). MER is a formula to describe the mass of moisture removal per unit time and is calculated using the equation from the work of Karabacak and Atalay [21].

$$MER = \frac{M_w}{t} \quad (4)$$

where M_w is the mass of water evaporated from the product (kg) and t is the drying time.

B. Stress Cracking Indexes (SCI)

Stress cracking analysis was carried out on dried samples. Three randomly selected sub-samples of 100 medium flat-grains of dried shelled corn of each jumbo bag were inspected for stress cracks. The kernels were visually inspected for stress cracks using a light board, as shown in Fig. 2. Kernels were placed germ-side down on a light table and inspected from the top only. Each kernel was classified into one of four stress crack classes of undamaged, single and multiple as illustrated in Fig. 2 [22]. Each classified class of stress cracks was then expressed as a percentage divided by 100 kernels.

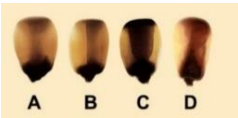

Figure 2. Stress crack classes (A: undamaged; B: single; C: double; D: multiple).

The Stress Crack Index (SCI) is a measure of the severity of damage in the corn. The SCI was calculated using equation 5 below:

$$\text{SCI} = 1\,(\%\text{ single cracked kernels}) + 3\,(\%\text{ double cracked kernels}) + 5(\%\text{ multiple kernels}) \quad (5)$$

C. Colour Measurement

Samples of dried corn grain were collected randomly from jumbo bags. Sound corn grains with no physical damage were selected to be measured. The colour of the dried corn grain was measured using a chromameter (model, Minolta). The L^*, a^* and b^* values indicated the brightness, greenness and yellowness respectively. The grain corn kernels were placed in Petri dishes until full and measured 3 times for replication.

D. Economic Engineering Evaluation

An evaluation of the economic engineering aspects of the mobile dryer was carried out to estimate the cost of drying per kg of corn grain. The calculation was done by considering the useful life of the dryer and fixed and variable costs.

III. Results and Discussion

A. Drying Performance

The samples for moisture reduction during drying were taken from two different locations in the mobile dryer. Fig. 3 illustrates the drying air and ambient temperatures during the sunny day. The average ambient and inside the drying chamber temperatures during the sunny day were 36 ℃ and 84 ℃. Kernel temperature was also measured, as shown in Fig. 4. The maximum kernel temperature was between 60-63 ℃. The average drying times for the mobile dryer in rainy and sunny conditions were found about 3.5 and 3.0 hours respectively. The drying rate of the mobile dryer during the sunny day was higher than the rainy day. Table I shows that the drying rate is between 3-4% per hour, where the drying rate is at an optimum level during the sunny day. This is proven by the moisture extraction rate (MER) of 152.62 kg per hour as compared to only 122.27 kg per hour during the rainy day.

Nevertheless, gas consumption was higher in the fall compared to the spring season. The mobile dryer was placed under shade to prevent from a rewetting of the grain corn during rain. This phenomenon also affected the fuel consumption of the drying process; hence the total drying time of the grain corn. As the grain corn moisture reached 13-14% (w.b), the burner was turned off while the grain continued to be circulated inside the drying chamber to cool down. It took almost one hour for the kernels to reach the ambient temperature of around 35-40 ℃. This cooling practice is important before loading the dried grain corn into the jumbo bags to prevent condensation. The total diesel consumption, including both the burner and PTO tractor, was between 70-84 L. In other words, the diesel consumption rate was between 17-19 L per hour for a full capacity of grain. The diesel consumption during rainy was 18.5% higher than the sunny day. The PTO tractor contributed to about 31% of the total diesel consumption. This figure includes the cooling, loading and unloading of the grain. Taking into account only the diesel consumption, the drying cost was about RM0.05-0.06 per kg of shelled corn.

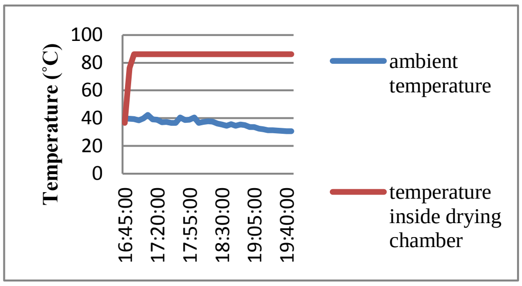

Figure 3. Ambient and drying chamber air temperatures during the sunny day.

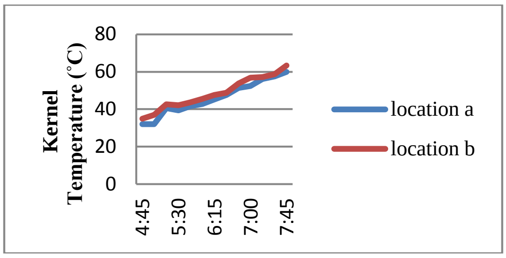

Figure 4. Kernel temperatures during drying at locations a and b in the mobile dryer.

TABLE I. TABLE DRYING PERFORMANCE OF MOBILE DRYER DURING SUNNY AND RAINY DAYS

Parameters	Sunny day	Rainy day
Initial mass (kg)	3216.0	3392.5
Final mass after drying (kg)	2686.5	2734.0
Recovery of dried shelled corn (%)	83.54	80.59
Average initial moisture (% w.b.)	25.3	23.8
Average final moisture (% w.b.)	12.9	12.8
Drying time duration (hour)	3	3.5
Dryer capacity (kg shelled corn/minute)	17.87	16.15
Cooling period (hour)	1	1
Total drying + cooling time (hour)	4	4.5
Drying rate 1 (%/hour)	4.13	3.14
MER (kg water removed/hour)	152.62	122.27
Diesel consumption of burner (L)	49	57.6
Diesel consumption of PTO tractor (L)	21.75	26.25
Total diesel consumption for complete drying + cooling (L)	70.75	83.85
Diesel consumption rate (L/hour)	17.69	18.63
Drying cost of diesel *RM 2.40/L (RM/kg shelled corn)	0.05	0.06

B. Stress Cracking Index (SCI)

Table II shows the stress cracking index of dried shelled corn that resulted from drying using the mobile dryer. The total average SCI of the dried sample at 80 ℃ is 254±17.52. Sonġul G. *et al.* [23] also reported that an increase in the drying rate could lead to an increase in the SCI. Meanwhile, a study reported by Joseph O. A. *et al.* [24] revealed that the SCI of using a solar dryer at 52.8 ℃ was only 160. Thompson and Foster [25] reported that an increase in the drying air temperature would increase breakage susceptibility and stress cracking and therefore reduce the milling quality of the grain corn. This proves that the drying temperature plays an important factor in raising the SCI value. The increase in SCI value can increase the breakage of the kernels during commercial and extensive handling as reported by Mohamed I. S. *et al.* [26]. Sone [27] revealed that broken maize and foreign materials promote the development of storage moulds as fungi is more easily penetrated broken kernels than the intact kernel.

TABLE II. STRESS CRACKING INDEX OF DRIED SHELLED CORN USING MOBILE DRYER

Jumbo bag No.	J2	J7	J8	J11	J14	Total average of SCI
Average Stress Cracking Index (SCI)	251.00 ±15.13	234.67 ±21.93	280.67 ±14.01	261.33 ±17.93	245 ±4.36	254.53 ±17.52

C. Colour Measurement

Table III indicates that there were no significant changes in colour between wet and dried grain corn, especially during the sunny day. Nevertheless, the value of greenness, *a** was found significant, which might be due to the long period of drying during the rainy day. The *L** values of fresh grain corn were in most cases higher than dried grain corn indicating a bright coloured product. Besides, the greenness and yellowness of dried grain corn were found to be higher compared to the fresh product. According to Ibrahim, D and Mehmet, P. [28], drying corn at 65 ℃ showed *L** values of 65.70 and 58.97 for treated and untreated corn.

TABLE III. COLOR CHANGES OF GRAIN CORN BEFORE AND AFTER DRYING

	Fresh kernels (before drying)			Dried kernels (after drying)		
	*L**	*a**	*b**	*L**	*a**	*b**
Sunny day	49.23^a ± 1.12	6.35^a ± 1.46	14.97^a ± 1.09	48.38^a ± 2.13	7.05^a ± 1.34	15.40^a ± 0.87
Rainy day	48.79^a ± 3.02	6.13^b ± 1.35	14.69^a ± 0.68	47.99^a ± 4.59	8.43^a ± 0.86	16.27^a ± 1.39

D. Engineering Economic Analysis

Table IV shows that the estimated cost of the dryer is RM 160,000, and the useful life is 15 years. The depreciation cost is calculated based on a straight-line method with interest on investment at 10% whereas repair and maintenance cost is 3%. The calculation is also based on annual usage, where the total tonnage of grain corn to be dried 6 tons per hectare. There is no electrical cost for the mobile dryer as it is meant to be mobile and fully operated by a diesel burner with a PTO-driven tractor.

TABLE IV. ECONOMIC ANALYSIS OF USING MOBILE DRYER

Initial investment of mobile dryer (RM)	160,000
Estimated useful life (years)	15
Expected usage per year (days)	30
Salvage value (10% of the investment)	16,000
Total tonnage grain corn to dry per hectare	6
Depreciation cost (RM/day)	320
Repair and maintenance cost (RM/day)	160
Diesel cost (RM/day)	316.80
Labour cost (RM/day)	59.70
Transportation cost (RM/dryer)	200
Cost per kg of drying grain corn (RM/kg)	0.176

The estimated cost of drying grain corn using the mobile dryer is RM 0.176 per kg. The variable cost includes diesel, labour and transportation. Labour cost involves one man to operate the dryer, and it is estimated to be RM8/hr. Transportation cost is estimated to be incurred for the logistics requirements of the mobile dryer. Nevertheless, the transportation cost is set to be minimum as it is expected to be shared by small farmers.

IV. CONCLUSION

In this study, the performance, quality and economic point of view of using a mobile dryer were investigated.

The mobile dryer was found to be capable of drying grain corn in relatively short drying time and producing an acceptable quality of dried grain corn. Nevertheless, the practicality of a mobile dryer is questionable, especially when dealing with unpredictable weather conditions and handling tons of grain corn in an open field. It also has setbacks in terms of logistics in such remote areas. This setback is unlikely to happen in stationary drying centres, where handling is done with proper facilities and not much affected by weather conditions. Therefore, it is recommended that a mobile dryer can be used as an alternative method provided that it has proper supporting facilities to handle the grain.

NOMENCLATURE

MC_{db} moisture content dry basis [%]
MC_{wb} moisture content wet basis [%]
W_w weight of water [g]
W_d weight of dry matter [g]
M_w mass of water loss [g]
M_c mass of product to be dried [g]
W_i initial moisture content [%]
W_f final moisture content [%]
t drying time [hr]
$L*$ brightness
$a*$ greenness
$b*$ yellowness
rpm rotational per minute
HP Horsepower
MER moisture extraction rate [kg/hr]
SCI Stress cracking index [dimensionless]
PTO Power take-off
LSU Louisiana State University

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

Yahya Sahari involved in planning the research, conducting experiments, analyzing results and writing the paper; Sharifah Hafiza Mohd Ramli involved in conducting experiments and reviewing the paper; Amir Syariffuddeen Mhd Adnan involved in conducting experiments and analyzing data; Mohd Shahrir Azizan involved in writing the paper and setting up the instruments; Afiqah Aina Rahim involved in conducting and assisting in data collection; Zainun Mohd Shafie involved in analyzing data and reviewing the paper and Nor Amna Aliah Mohammad Nor involved in economic analysis on the research findings. All authors had agreed and approved the final version of the manuscript for publication.

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