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Evaluation of a Simulation Model for Deep-Bed Drying of Hybrid Rice Seeds

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ABSTRACT

This study evaluates a simulation model for drying hybrid rice seeds in deep-bed set-up. This model is based on a heterogeneous diffusion model for predicting grain moisture at different levels on a deep-bed drying set-up was developed. To evaluate this, hybrid rice seeds were dried in a laboratory dryer with a 50-cm depth test cell. Three drying setups (45°C, 55°C, and stepwise) were used. During drying, moisture content was measured at different levels of the cell and at specified time intervals. Around four months after storage, germination percentage of samples from different drying setting and grain locations were obtained. The drying experiment revealed that the fastest drying time is achieved with the 55°C drying temperature. Parameter estimation and model validation of the simulation have revealed that the model used can well predict the moisture content of the seeds across the deep-cell drying bin at any given time. This can be further supported by the mean relative error of the model which is below its acceptable values. Germination results have also shown that the drying procedures used have no negative effect on the seed quality. Thus, using the simulation model could be an accurate way to predict the moisture content with no effect on its seed quality.

Keywords: *hybrid rice, deep-bed drying, heterogeneous diffusion model, variable temperature drying, germination test*

INTRODUCTION

By 2028, the Philippine is projected to consume about 16.5 million tons rice. This is below the projected production of rice which is about 14.9 million tons (OECD/FAO, 2019). With this deficiency, the Philippines needs to do special measures to overcome this projection. Increasing the production of rice with the use of hybrid rice seeds is one of its solutions. Hybrid rice is a product of two-different cross-pollinated rice plants with superior qualities. It should inherit the qualities of the parents that could lead to higher yield and/or better quality than inbred varieties. The Philippines is slowly adapting the use of hybrid rice in rice farming. In 2016, the Philippines planted 388,827 ha with hybrid rice which is only about 16% of total area planted with rice (Litonjua et al, 2017).

Seeds that are harvested from field production needs to be processed such that it can be stored for a longer period without decreasing its quality. Drying is an important processing step which reduces the grain moisture to a level where there is minimum biological activity thereby increasing its storage life. The current drying air temperature used for rice intended for seed purpose should not exceed 43°C (IRRI, n.d.; PhilRice, n.d.). However, drying temperature of 45°C and 55°C was found to have potential since the germination percentage from the result of a study was found to be acceptable based on the Philippine National Standards (Bawar et al, 2023). Different variety of rice has different physical characteristics such as dimensions, awn length, and bulk density. Due to these differences, hybrid rice variety can also have distinct drying characteristics which could lead to significant difference on its drying rates.

In the Philippines, flatbed dryer is a common equipment being used in drying rice. They are mostly utilized by smallholder farmers in many parts of Southeast Asia. PHILMECH reported that there are 1,071 units of flatbed dryer nationwide (Manalili et al, 2015). These dryers are used for both rice intended to be milled and seeds. Using a 6-ton conventional flatbed dryer in Philippine condition would need 12 hours to dry rice from more than 24% to about 13 % MC_{wb} (Vinh and Gavino, 2011). Flatbed dryers that have capacity of 3 to 7 tons have 40 to 70 cm of grain layer. This thick grain layer causes moisture variation across the depth of a flatbed dryer. Based on the result of Hung et al (2019), moisture variation across the top and bottom layer of the flatbed is evident around the middle stage of drying using conventional flatbed dryer. This variation could be predicted with the use of simulation models. Dryers requires sensible heating to dry paddy rice. During sensible heating, heat is added to the moist air resulting in an increase in its temperature and lowering its relative humidity while maintaining its humidity ratio (Wang, 2001).

Simulation models have been developed and used as tools for describing complicated drying systems such as predicting moisture content within the drying bed to optimize drying processes and improve the grain quality. These models are necessary in designing and improving the control system of a drying operation (Sharon et al, 2016). Drying parameters are predicted by simulation models that assume that the deep-bed is composed of a series of thin-layers. Thus, the validity of deep-bed models is highly reliant on how well the thin-layer model that was used in the model (Misra and Brooker, 1980). **Table 1** shows some deep-bed drying for paddy grain

Table 1. Some deep-bed drying simulation studies for paddy grain.

DRYING TEMPERATURE (°C)	GRAIN DEPTH (cm)	THIN-LAYER MODEL USED	MEAN RELATIVE ERROR (%)	REFERENCE
33, 44	60	Page	Slightly higher simulated data	Wongwises and Thongprasert (2000)
45, 50	25	Wang and Singh	6.77 – 10.01	Zare et al (2006) Zare and Chen (2009)
40, 50, 60	25	Wang and Singh	2.88 - 8.06	Naghavi et al (2010) Torki-Harchegani et al (2014)
30, 32, 22-30	---	Hukill and Thorpe	Index of agreement = 99.1 - 99.6%	Lopes et al (2014)
41.6	25-60	Thompson	10 – 19	Hung et al (2019)

simulation models that have been published in recent years. These models had satisfactory results when they were used in simulation model of deep-bed drying of inbred rice. However, they have failed to check the effect on the quality of the dried seed. For many studies, a mean relative error of 10-15% is regarded as a satisfactory result (Zare and Chen, 2009).

The models used in **Table 1** can be considered homogenous. These empirical models can describe the mechanism of moisture exchange between the environment and grain surface. However, they do not consider the drying mechanism within the grain itself. The heterogeneous diffusion model could describe the exchange of moisture from within the grain onto the environment. A numerical model of heterogenous moisture diffusion in milled rice has been investigated by Perez et al (2013). They found that major routes and cracks induced rapid moisture movement in the grain which hastens as it's been exposed to higher temperature.

Reducing the drying time of hybrid rice seeds can reduce the overall cost of the operation. However, reduction of cost should never be in exchange for the quality of the seeds. A similar study has been conducted for paddy rice intended for milling (Xu et al, 2022). The researchers applied two-stage variable temperature drying which composed of a higher and a lower drying air temperature. They found out that these can reduce the cost of the drying process with improvement of quality of dried paddy rice through reduction of fissure rate resulting to higher head rice yield.

A basis for the reduction of drying time can be the glass transition property of rough rice. This is a property of amorphous materials in which they undergo transformation from a solid glassy state to viscous liquid state which happens at a specific temperature range called glass transition temperature. There is a dramatical change in the molecular mobility, physicochemical properties, and textural properties of food material and these happen during glass transition (Dogan and Kokini, 2007).

Figure 1 shows the relationship between moisture content and the glass transition temperature of brown rice. This indicates that as the moisture content of the rice grain increases, the glass transition temperature decreases. Dramatic changes on the physical properties of a rice kernel as the kernel temperature passed through the glass transition

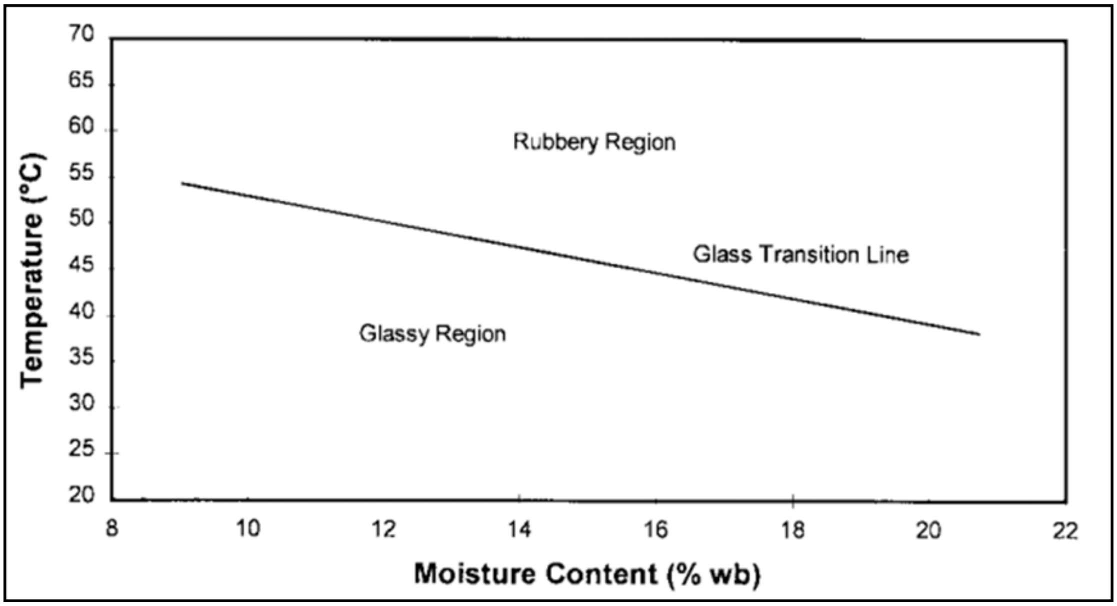


Figure 1. Glass transition relationship for variety Bengal brown rice.
Source: Perdon, 1999, as cited by Cnossen and Siebenmorgen, 2000

temperature was observed (Perdon, 1999, as cited by Cnossen and Siebenmorgen, 2000; Zhao et al, 2019). Studies had proven that drying the rice grains in the rubbery region and then cooled down immediately without being tempered decreases the head rice yield when milled (Cnossen and Siebenmorgen, 2000; Yang et al, 2003). Reduction in head rice yield is due to grain fissuring. Fissured kernels have weak structure and integrity, and milling leads to increased grain breakage (Bao, 2019). Since fissured seedlings significantly affect the germination rate of rice seeds (Menezes et al, 2012), glass transition could significantly affect the quality of seeds.

In this study, a simulation model for deep-bed drying of hybrid rice at constant temperatures and stepwise drying temperature was evaluated. Specifically, the study aimed to characterize the seed moisture dynamics across the deep cell; validate the simulation model; and determine the effect of drying treatment on seed quality based on seed germination rate.

METHODOLOGY

Sample preparation

Newly harvested hybrid rice seeds were used in the study. Initial moisture content of each drying run was determined. Drying was done up to the moisture at which it is safe for storage. Since the moisture content of the seed samples needs to be determined right away, rapid determination method in measuring moisture content is necessary. All moisture content data were measured using a GMK-303RS digital grain moisture meter G-won Hitech Co., LTD. This meter crushes 10-15 grain sample, has a resolution and accuracy of 0.1% and ±0.5%, respectively, and measures moisture using electrical resistance method.

Drying methodology

A laboratory dryer (**Figure 2**) was used in the drying experiments. It consists of a centrifugal fan, a heating section, the plenum chamber and

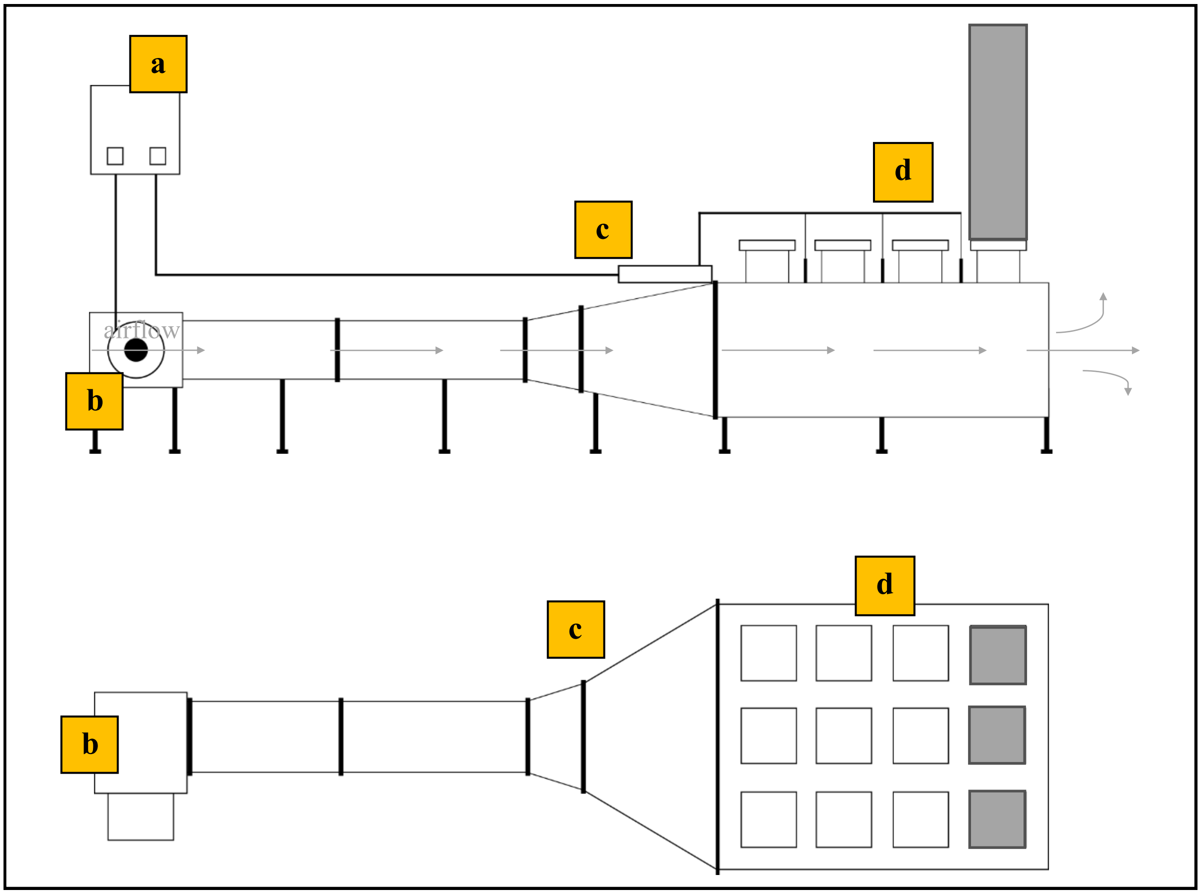


Figure 2. Schematic diagram of the convective flat-bed dryer used in the deep-bed drying experiment. (a) Power supply; (b) Blower; (c) Temperature controller; (d) Deep-cell drying bins.

three deep-cell drying bins. The centrifugal fan moves the heated air to the plenum chamber and through the drying bins. The deep-cell drying bins have a dimension of 150 mm x 150 mm x 600 mm, are made of galvanized iron sheets with a screened bottom. The deep-cell drying bins are covered with 12.7 mm insulation foam to minimize the heat loss at the sides of the bins. The initial sample depth inside the bin is about 60 cm. The drying air velocity was monitored using RS Pro RS-1340 hot-wire anemometer. It was set to about 0.5 m/s by changing the position of the damper in the inlet of the blower. Drying air temperature are adjusted thru a MC700-FK07-M-AN microcontroller of XNY International Limited attached to the nichrome wire in the heating section of the dryer. Drying was made both in daytime conditions with average RH from 61.41% to 79.02% and nighttime conditions with average RH from 83.94% to 91.26%. Once samples were placed in the dryer, moisture content and temperature data were gathered until the moisture content of about 11% have been reached or it is in equilibrium with the surroundings.

In this study, three drying air temperature settings are used. Two of the temperature settings: 45 °C (average RH of 46.32 ± 2.16%) and 55 °C (average RH of 31.81 ± 1.99%); utilizes constant temperature on the entire duration of the drying experiment. These temperatures are in accordance with the one used by the study of Bawar et al. (2023). The other temperature setting was named 'Stepwise' setting (average RH of 47.02 ± 16.49%) since drying air temperature increases in steps as the average moisture content of the grains being dried decreases (**Figure 3**). The two lines being followed in determining the temperature in this setting are the glass transition temperature and the temperature ensuring that the ΔM within the grain is less than 10%. The lower temperature between these two lines is the basis for the stepwise setting.

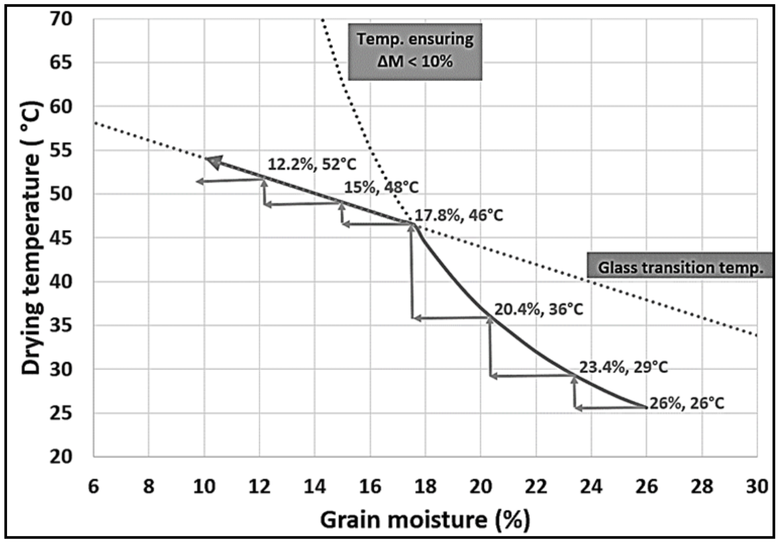


Figure 3. Air drying temperature for Stepwise setting.

Data acquisition

The moisture content and grain temperature were measured across the height of the deep-cell drying bin (**Figure 4**). Grain samplers were used to extract 50-60 grain samples from each site to measure the moisture. Three readings per cell per site per instance are obtained. Before moisture reading, seed samples were equilibrated with the surroundings for up to 10 mins in a desiccator so as the temperature would not affect the reading. Moisture reading was done on the first 30 mins of drying then time interval of 60 to 120 mins thereafter. Since moisture reading is a destructive sampling, the grain depth was initially set at around 60 cm so the grains would not be reduced to a height of below 50 cm before the end of the experiment.

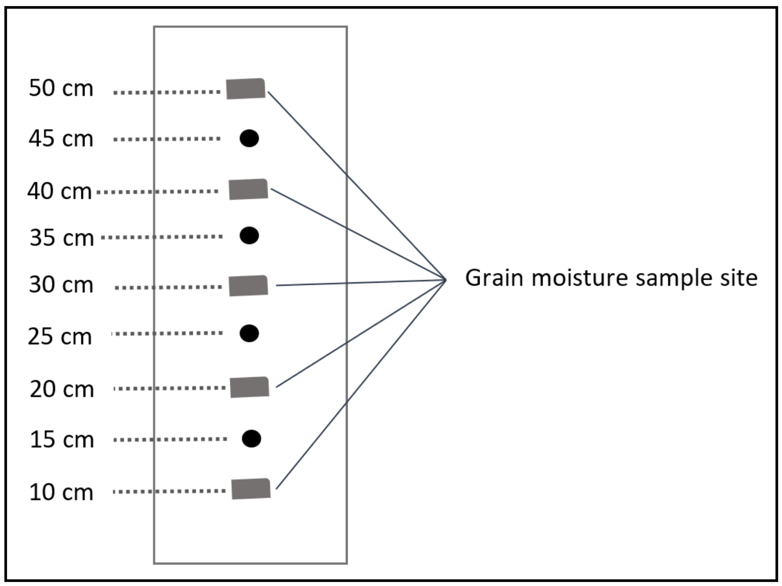


Figure 4. Sample sites of grain moisture across the deep-cell drying bin.

Hybrid rice drying simulation

In this study, heterogeneous diffusion model has been used in simulation. It was done using COMSOL Multiphysics with finite element method. The equations for the heterogenous diffusion model are a function of drying air temperature and moisture of the grain. These are presented below:

$$\frac{\partial M}{\partial t} = D_{eff}\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} + \frac{\partial^2 M}{\partial z^2}\right) \quad \textit{Equation 1}$$

D_{eff} is the internal moisture diffusion coefficient, which is defined as,

$$D_{eff} = a\exp\left(-\frac{E_a}{RT}\right) * (M_t - M_e)^2 + [b + c\,T_{air} + d(M_t - M_e)] \quad \textit{Equation 2}$$

where a, b, c, and d are constants, E_a is the activation energy, RT is the average kinetic energy, M_t & M_e are instant and equilibrium moisture content, and T_{air} is the drying air temperature. Constants are obtained using an experimental results trial.

A different set of trials were used in determining the accuracy of the simulation models. This was evaluated by calculating the percent mean relative error (MRE, %) by using Equation 3.

$$\boldsymbol{MRE = \frac{1}{N}\sum_{i=1}^{N}\frac{|M_{exp,i} - M_{pre,i}|}{M_{pre,i}} \times 100\%} \quad \textit{Equation 3}$$

In these equations, M_{exp} and M_{pre} represent experimental and predicted moisture content, respectively.

Germination test

For each drying run, dried hybrid rice seeds in the deep-cell drying bin were sampled for germination test. Three samples were obtained each from around 10-cm height, 30-cm height, and 50-cm height of the deep-cell. These samples were stored in ambient temperature for approximately 4 months of storage before it was subjected to germination test. The roll paper towel method was used for determining the germination rates of the dried hybrid rice seeds. In this method, for each sample, 100 randomly selected seeds were spread and placed at equal distance in a germination paper moistened with water. The whole unit was rolled before being placed in a plastic container and incubated for 7 days in an airconditioned room. Seedlings grown were counted as normal, abnormal and dead seeds. Percentage of germinated seeds was computed as the average number of normal seedlings in four replicates after seven (7) days.

RESULTS AND DISCUSSIONS

Drying Trials at Constant Temperature

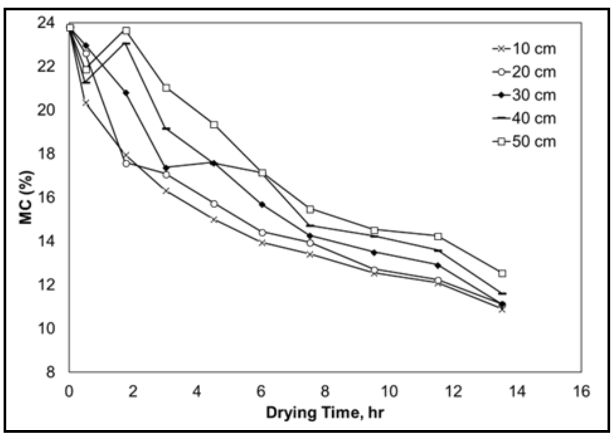
The summary of the drying trials that utilizes constant temperature drying air is shown in **Table 2**.

Figure 5 shows the moisture distribution across the height of the deep-cell for drying setpoint temperature of 45°C for three trials. The average drying time of the three trials was 13.6 hours where the fastest among the runs happens when the last part of the drying (grain moisture content is less than 15%) process is at the middle of the day. At this time, it approaches to the day's maximum temperature and minimum RH. The difference between the fastest and the slowest drying is about four hours. Equilibrium moisture content (EMC) value is a function of both air temperature and relative humidity. Air temperature has an inverse relationship with EMC while relative humidity has a direct relationship (Sadaka and Bautista, 2014).

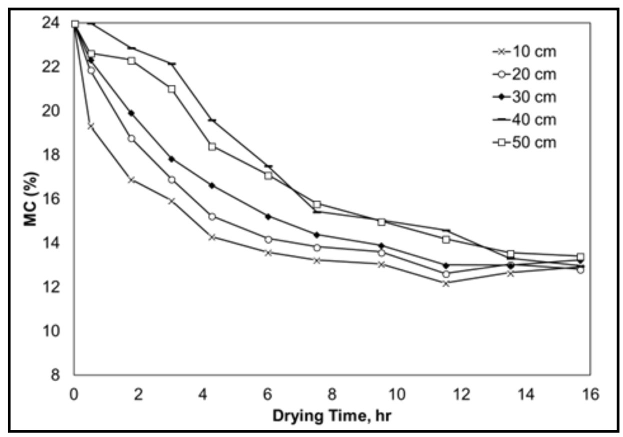
The maximum moisture difference across the depth of the deep-bed is at 105 to 115 mins of drying time with values of 4.71% to 5.71%. This happens when the moisture at 10-cm

Table 2. Results of Drying Trials utilizing Constant Temperature Drying Air.

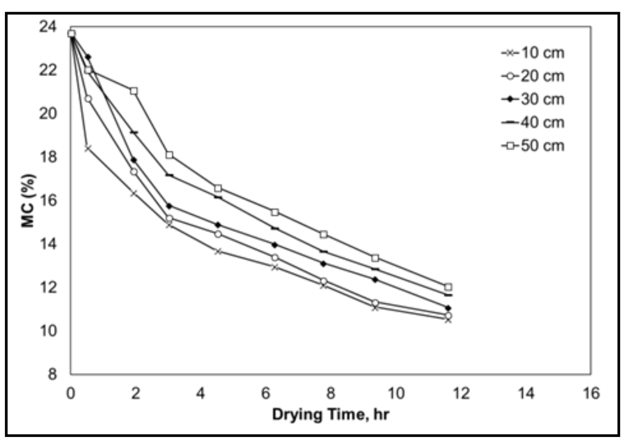
DRYING TEMPERATURE (°C)	TRIAL #	START OF TRIAL (date and time)	INITIAL MC (%)	FINAL MC (%)	DRYING TIME (mins)
45	1	11/05/2020 5:50PM	23.81	11.49	810
	2	16/05/2020 9:40AM	24.00	13.14	940
	3	17/05/2020 2:35AM	23.73	11.22	695
		Average	23.85	11.95	815
55	1	12/05/2020 8:45AM	23.13	11.22	345
	2	14/05/2020 8:20AM	22.40	11.87	360
	3	18/05/2020 7:30PM	22.42	12.60	345
		Average	22.65	11.90	350



(a)



(b)



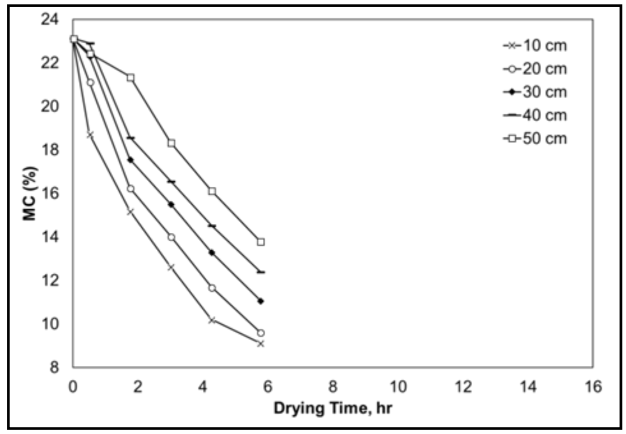
(c)

Figure 5. Moisture distribution across the deep-cell at 45°C for (a) trial 1, (b) trial 2 and (c) trial 3.

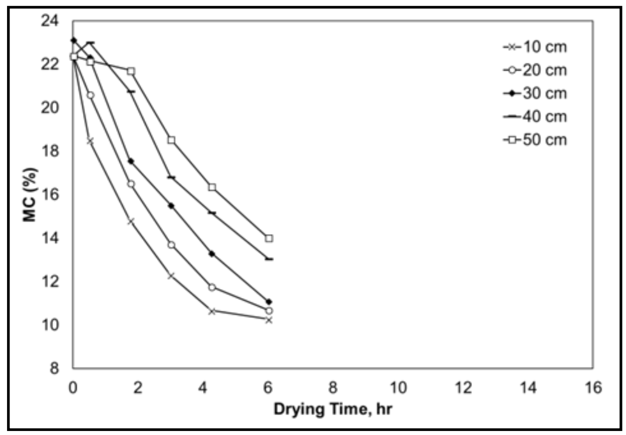
height is from 16.38% to 17.98%. For rice, moisture content of 18% is the end of constant rate period for drying (IRRI, 2013). Furthermore, the grain furthest from the air source will remain wet or may even be wetter due to condensation until the drying zone begins in that layer (FAO, 2011). Thus, the maximum moisture difference across the depth of rice happens when the moisture at 10-cm height is below the end of the constant rate period and the 50-cm height doesn't have any significant moisture loss yet. The final moisture content difference across the depth of the bed is 0.49% to 1.66%.

Figure 6 shows the moisture distribution across the height of the deep-cell for drying setpoint temperature of 55°C for three trials. The average drying time of the three trials was 5.8 hours. Unlike the drying setpoint of 45°C, drying using 55°C at the middle of the day and middle of the night seems to be similar as evident to the actual drying time for all the trials. Since drying utilizes sensible heating, increasing the setpoint temperature lowers relative humidity. This condition of high temperature and low relative humidity also has lower EMC which is much lower than the ambient temperature EMC. This condition makes drying using setpoint of 55°C not to be significantly affected with the change in the ambient condition.

The maximum moisture difference across the depth of the deep-bed for setpoint 55°C is at 105 mins of drying time with values of 5.01 % to 6.91%. The maximum moisture difference across the depth happens at almost similar drying time to drying setpoint of 45°C but its value is greater than the lower setpoint. This happens when the moisture at 10-cm height is from 14.27% to 15.20% which is lower than



(a)



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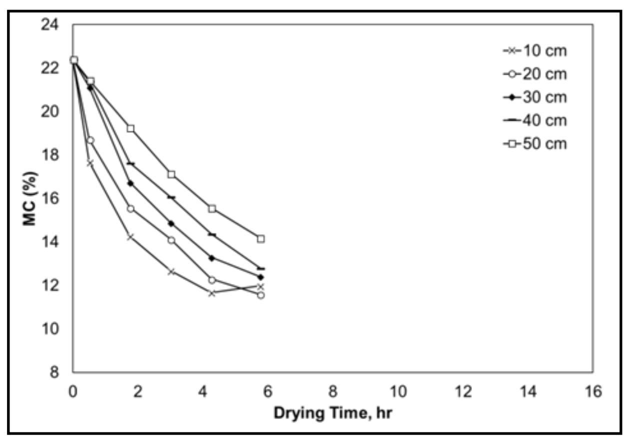

(c)

Figure 6. Moisture distribution across the deep-cell at 55°C for (a) trial 1, (b) trial 2 and (c) trial 3.

the value for the lower setpoint. These can be explained by the higher temperature which has better drying performance. The final moisture content difference across the depth of the bed is 2.21% to 4.68%.

Drying Trials at Stepwise Temperature

The result of drying trials that utilizes stepwise temperature drying air is shown in **Table 3**.

Figure 7 shows the moisture distribution across the height of the deep-cell for this setting. The average drying time of the three trials was 9.8 hours where the fastest run happens when the last part of the drying (grain moisture content is less than 15%) process is at the middle of the day while the slowest is when most of the drying happens during middle of the night. During the initial stage of drying in this setting, the setpoint temperature is at 33°C which is lower than the ambient temperature during the middle of the day. This significantly hastens the drying time as compared to middle of the night drying. Like the behavior of constant 55°C setpoint temperature, the time of day does not seem to affect the drying performance when the setpoint temperature was set to 55°C and 60°C.

Table 3. Results of Drying Trials utilizing Stepwise Temperature Drying Air.

TRIAL #	START OF TRIAL (date and time)	INITIAL MC (%)	FINAL MC (%)	DRYING TIME (mins)
1	13/05/2020 9:20AM	23.10	11.23	510
2	13/05/2020 6:50PM	23.40	11.08	750
3	18/05/2020 9:45AM	21.60	11.42	540
4	19/05/2020 2:05AM	22.18	10.94	600
5	20/05/2020 10:50AM	22.10	11.70	525
	Average	22.48	11.27	585

It should also be noted that the Stepwise setpoint temperature has faster drying time compared to constant 45°C which can be attributed to the increase in setpoint temperature for lower moisture content which is expected to have a slower drying rate.

Unlike the constant temperature drying, the maximum moisture difference across the depth of the deep-bed greatly differs between middle of the day and night drying. For the middle of the day drying, the maximum moisture difference is at 270 to 330 mins of drying time with values of 3.28% to 5.11%. This happens when the moisture at 10-cm height is from 13.58% to 16.11%. For the middle of the night drying, the maximum moisture difference is at 420 mins of drying time with values of 3.56% to 5.52%. This happens when the moisture at 10-cm height is from 12.11% to 13.88%. The variations of these values can be attributed to the different times when the setpoint was changed. The final moisture content difference across the depth of the bed 0.69% to 3.33%.

Simulation Results

The obtained constants for Equation 2 are shown in **Table 4** which were used as input to the simulation model. The simulation performance for model validation is shown in **Figure 8**. This resulted to R^2 of 0.9700 which could indicate that the simulation model well predicts a new set the experimental moisture data at any depth of the deep-cell bed and drying temperature. This validation has revealed that the model has a mean relative error of 3.88% ± 2.95% to a new set of data. This result is better than the

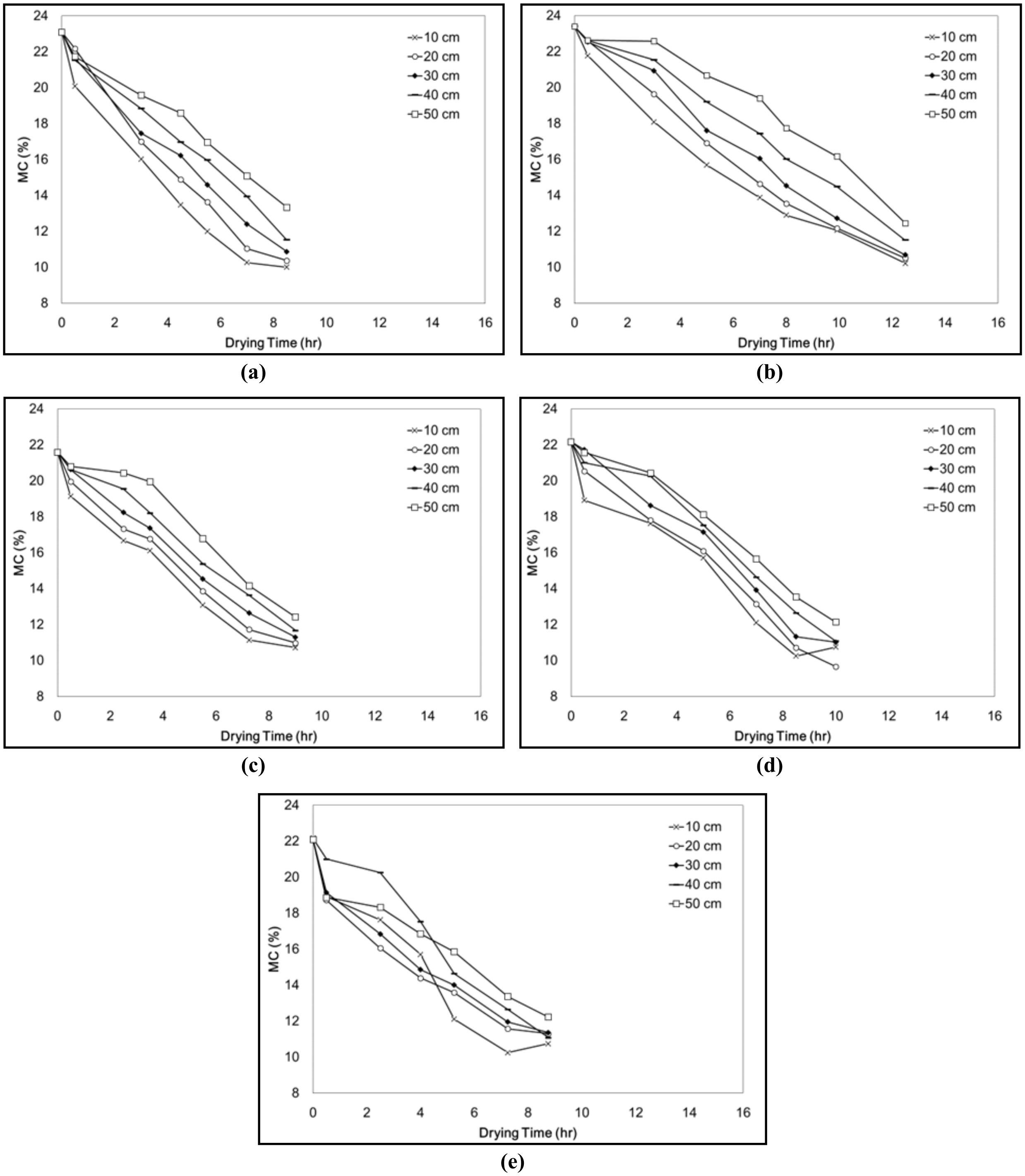

Figure 7. Moisture content profile across the deep cell during stepwise drying setting (a) trial 1, (b) trial 2, (c) trial 3, (d) trial 4 and (e) trial 5.

mean relative error regarded as satisfactory in many studies of 10-15% (Zare and Chen, 2009). However, it can be observed from **Figure 8d** that it is not good for predicting stepwise drying in a 2–4-hour region. Around this time, the moisture content is at its stage

Table 4. Obtained constants for D_{eff} using experimental results.

CONSTANT	OPTIMAL VALUE	LOWER BOUND	UPPER BOUND
a	0.999991	.0001	2
E_a	49592.6	30000	55000
b	3.23291E-11	-1E-09	1E-09
c	-6.85902E-10	-1E-08	0
d	1.08878E-14	-1E-11	1E-11

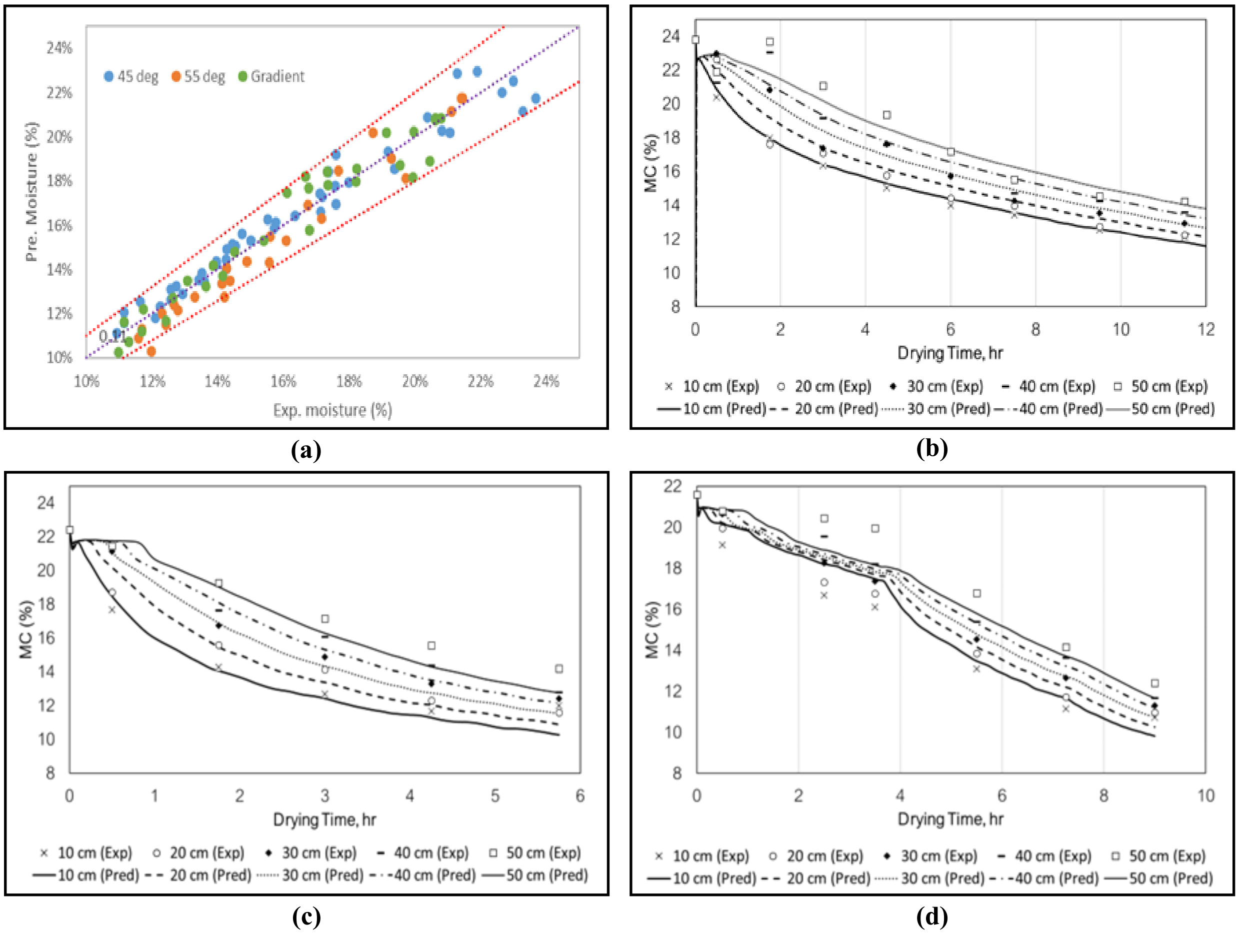

Figure 8. Simulation model performance for parameter estimation: (a) experimental moisture vs. predicted moisture; (b) 45°C; (c) 55°C; and (d) step-wise.

where the setpoint temperature was adjusted from 36°C to 46°C. This is a huge jump of 10°C increase in setpoint temperature which could affect greatly the moisture differential across the depth but was not compensated by the simulation model.

The simulation model performance for parameter estimation is shown in **Figure 9**. This resulted to R^2 of 0.9530 which could indicate that the simulation model could generally well predict the experimental moisture data at any depth of the deep-cell bed and drying temperature. This simulation has

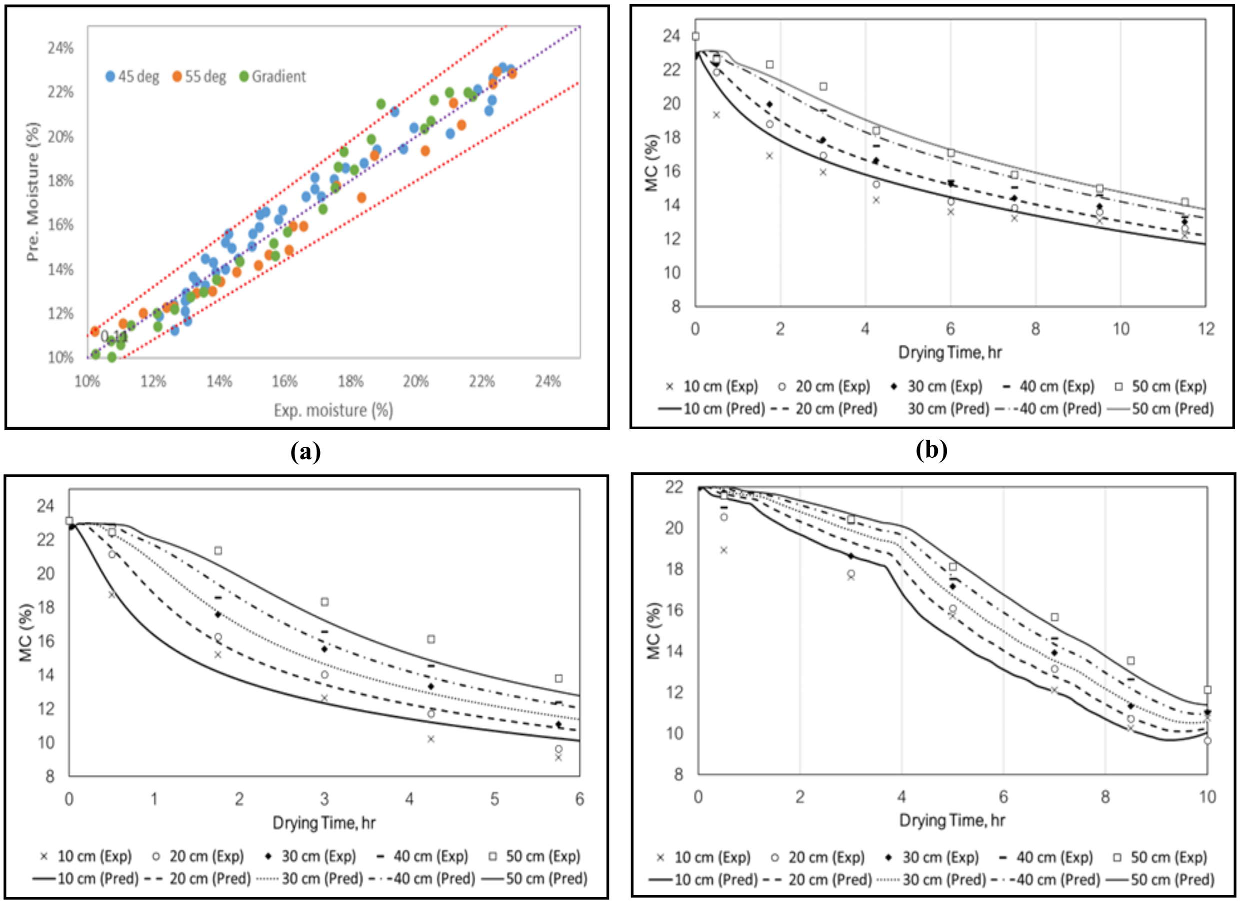

Figure 9. Simulation model performance for model validation: (a) experimental moisture vs. predicted moisture; (b) 45°C; (c) 55°C; and (d) step-wise.

revealed that the model has a mean relative error of 3.88% ± 2.88%. Like the result in parameter estimation, this result is better than the mean relative error regarded as satisfactory in many studies which is 10-15%.

Germination Results

Since this study is dealing with processing of hybrid rice as seeds, germination percentage is an important parameter that needs to be inspected. This could tell if a processing step is viable or not. The germination test is shown in **Figure 10**. The average germination percentage of dried hybrid rice seeds that undergone drying temperature of 45°C, 55°C, and stepwise set-up are 90.39%, 90.71%, and 90.44%, respectively. These values are above the allowable minimum for seed certification standard of 85% (Department of Agriculture, 2010) Statistical results revealed that there is no significant difference between the values of the germination percentage at different drying temperature set-up. There is also no significant difference in germination rate at different depths of the deep-cell. According to IRRI (n.d.), germination percentage of more than 80% is a good seed. Since the values for the germination percentage does not go below this value, this means that drying hybrid rice using any of the drying set-up will not affect the seed quality.

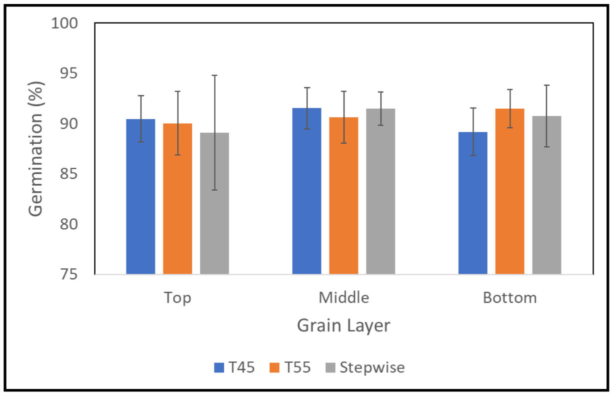

Figure 10. Germination test result of dried hybrid rice after about 4-months of storage.

SUMMARY AND CONCLUSION

Nowadays, drying practices used in seed production practices are based on studies for rice intended for milling and consumption. This difference, including the difference in the variety used can lead to a different drying rate that could affect its drying practice. There were also lots of simulation studies for rice but none of them have looked unto the effect to seed quality (Manuel et al, 2021). Thus, this study aims to evaluate a simulation model and develop a specific drying practice for hybrid rice seeds through seed moisture determination while drying and seed quality after drying.

The simulation model which was done using COMSOL is based on heterogeneous diffusion model. This was evaluated by drying hybrid rice seeds in a laboratory dryer with a test cell that has depth that can simulate the thickness of a flatbed dryer. Three drying temperatures (45°C, 55°C and stepwise) were used. Seed moisture was measured at specified intervals until it reached about 11%. Seed samples were obtained from top, middle and bottom layers of the test cell and stored for up to four month after which the germination test was performed.

It was revealed that the drying air temperature of 55°C has the fastest drying time. However, a large moisture gradient during the final stages of drying was observed between the top and bottom layer of the test cell. This is in contrast with the slower drying time for a drying temperature of 45°C but with relatively uniform moisture across the depth of the test cell. Stepwise drying offers a faster drying time than 45°C but with minimal moisture gradient across the depth of the deep-cell. This results offers a good trade-off but needs to have a technical person to be implemented on the field.

The simulation model based on heterogenous diffusion model was found to have a mean relative error of 3.88%. This proves that the model could well predict grain moisture while drying hybrid rice seed in a deep-bed set-up. Germination results have also shown that the drying procedures used have no negative effect on the seed quality. Thus, using the simulation model could be an accurate way to predict the moisture content with no effect on its seed quality.

RECOMMENDATIONS

The simulation model is recommended to be further verified in an actual flatbed dryer set-up. This verification could enable the simulation model to be used in an industrial set -up thereby a more impactful application of the model. Stepwise drying set-up is also recommended for further study, particularly, on development of a more responsive set-up by implementing with microcontrollers. This is a step closer to achieving smart dryer for hybrid rice. Conducting financial analysis and its applicability to actual drying practice is recommended to be done.

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