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# Investigation of Drying Behavior of Glutinous Rice (*Oryza Sativa Var. Glutinosa*) in a Fixed-Bed Dryer

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**Abstract.** Small-scale glutinous rice processing facilities often rely on manual drying methods, with drying conditions typically determined by experience. Establishing an accurate drying profile of glutinous rice allows for optimal selection of drying conditions. This contribution investigated glutinous rice drying behaviors in fixed bed dryers at temperatures 40°C, 50°C, and 60°C. The Page model was determined to be the best-fit thin layer model for describing glutinous rice drying with $R^2$ of 0.953 (50°C). Experimentally determined drying information was fed into the Aspen Plus V14 simulator to produce a digital version of glutinous rice drying process. A combined constant and falling rate mass transfer coefficient specified in the process simulator produced a simulation output close to that of the Page model with an $R^2$ of 0.9843. Modeling and digitalization of glutinous rice drying in this work are instrumental to accurately predict the drying performance of glutinous rice or other food grains.

**Keywords:** Aspen Plus, Drying Kinetics, Fixed Bed Dryer, Glutinous Rice, Mass Transfer.

## INTRODUCTION

Rice is Malaysia's third most significant crop behind rubber and palm oil, contributing significantly to the country's agricultural sector. One of the most well-known rice cultivars is glutinous rice (*Oryza sativa var. glutinosa*), also referred to as sticky rice or waxy rice. Glutinous rice contains amylopectin, which is responsible for the sticky texture of the rice after being cooked. Glutinous rice is prevalent throughout the Malay festive seasons in Malaysia. Malaysia mainly imports glutinous rice from neighboring countries (i.e., Thailand) to meet local demand. It is worth pointing out that 15% of the 891,000 metric tonnes of rice imported to Malaysia is glutinous rice (Zainal *et al.*, 2021). When the grains have finished maturing, glutinous rice plants are harvested and threshed to separate grains from the stalks. The grains are subsequently dried to remove moisture, making them more storable. An ideal moisture content for glutinous rice to prevent fungal growth at 25°C is 12.9% (Abdullah *et al.*, 2000).

It is worth noting that regular rice

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contains amylose (15 - 25%) and amylopectin, while glutinous rice is almost entirely made up of amylopectin. Amylose is a linear starch while amylopectin is a branched starched. The high amylopectin content in glutinous rice makes it more moisture-absorbent, so it tends to retain moisture more strongly and dries more slowly than regular rice. While the drying of raw ordinary rice and glutinous rice may not appear drastically different at first glance, their differing starch compositions (amylose vs. amylopectin) influence how each behaves under drying conditions.

The drying requirements of any rice grains vary depending on the type of dryer used and the grain's drying profiles. The commercial paddy drying process uses mechanical-type dryers such as swirling fluidized beds, flatbeds, packed beds, and fixed bed dryers. Each type of grain responds differently to the types of dryers used. Moreover, differences in the chemical and physical properties of the grains generate different drying profiles. As such, developing an accurate model to describe the moisture transfer characteristics of glutinous rice inside a specific dryer type can significantly aid in the optimization and selection of glutinous rice drying conditions. Among the common models to describe grain drying processes is the thin-layer drying model, which describes the rate of moisture transfer from grains as they dry in the form of a thin layer. The Page, Weibull, Linear-Plus-Exponential, Henderson, and Pabis models are common thin-layer models (Dongbang *et al.*, 2015). An ideal model for characterizing the thin-layer drying kinetics of glutinous rice should have high coefficients of determination ($R^2$), low reduced sum square errors (RMSE), and low root mean square errors (MSE).

There are many works reporting paddy rice drying and its drying profile available in the literature. This is unsurprising, considering paddy rice is a staple in many nations, especially in Southeast Asia. Anuththara *et al.* (2019) investigated the drying kinetic of two types of parboiled paddy in a packed bed dryer at three different hot air temperatures (35°C, 45°C, and 55°C) by keeping bed height and hot air flow velocity constant at 0.15 m and 0.98 $m.s^{-1}$, respectively. RMSE showed that the Weibull model better fits experimental observation. Golmohammadi *et al.* (2012) conducted an experimental investigation on the intermittent drying properties of a heat-sensitive paddy rice variety (rough rice) in Iran. They found that a 5-hour tempering stage at a tempering temperature of 50°C can reduce 85% of the moisture gradient during drying.

Compared to paddy rice, research on glutinous rice drying is not well-established. Dongbang *et al.*, (2018) investigated drying of 'cooked/steamed' glutinous rice using microwave irradiation. They found that increasing microwave irradiation powers (300 – 500 W) and drying temperature (45 – 51°C) significantly reduced drying time. The best thin-layer model to accurately describe their experimental observation was the Page model with $R^2$ and RMSE values of 0.998 and 0.002, respectively. Limpaiboon *et al.* (2011) compared the drying kinetics of steamed glutinous rice in a free convective solar dryer with those dried in the open sun. They observed a sharper decline in moisture ratio for convective solar dryers than open sun drying. Handerson and Pabis's model best describes the process, with an $R^2$ value of 0.99 (MSE of $1.82 \times 10^{-5}$) for solar dryers and an $R^2$ value of 0.99 (MSE of $8.97 \times 10^{-6}$) for open sun drying. It is worth to mention that these two studies focus on the drying process of 'steamed/cooked' glutinous rice as opposed to the freshly harvested glutinous rice (with husk), which is the main focus of our work.

Producing a digital replicate of glutinous rice drying using process simulation software (e.g. Aspen Plus V14) can tremendously aid in the rapid evaluation of various drying settings/strategies to achieve desired moisture content in a virtual environment. Despite its prevalence, process simulation works of the glutinous rice drying process have not been explored that much. The experimental-to-digital transformation of the drying process using process simulator would go a long way as it enables users to estimate the drying performance quickly under various settings. Required specifications for the process simulator, such as dryer settings, drying profiles, and mass transfer coefficients, along with other relevant information, can be obtained experimentally. Combining these strategies opens up new possibilities for predicting the drying behavior and performance of glutinous rice and other grain crops.

This study investigates glutinous rice drying in a laboratory-scale fixed-bed dryer unit, which replicates the large-scale glutinous paddy drying process. This work aims to mathematically develop a thin-layer drying kinetic model of glutinous rice drying based on experimental observation and establish the relationship between the solid-to-gas (S/G) ratio and drying temperature with the mass transfer coefficient (MTC). MTC of glutinous rice is calculated as a function of S/G and drying time. Several thin-layer drying models were fitted to the experimental data, and the best models were selected based on the highest value of $R^2$. Digital replication of glutinous rice drying is performed by transferring experimentally collected data into the Aspen Plus V14 process simulator. Simulation models for glutinous rice drying can be developed to dry other grain crops such as wheat, rice, and rice barley.

## MATERIALS AND METHODS

### Materials

Glutinous rice with husk was kindly provided by Company X, a rice processing facility located in Sungai Besar, Malaysia.

### Drying of Glutinous Rice under Various Conditions (Effect of Air Temperature)

A schematic illustration of the lab-scale fixed bed dryer unit is shown in Figure. 1. Yisino DIY 2000W hot air gun was used to provide a constant flow of hot air (flow rate of 60 $L.min^{-1}$). Silicone tubing with a diameter of 1 cm was used to channel the hot air from the source to the bottom of the fixed bed column (a cylindrical shape column: volume = 50 mL and diameter = 0.05 m). A humidity meter, digital thermometer, and grain moisture analyzer MD7822 were placed at several locations along the height of the fixed bed column. The dryer setup was inspected for any potential leaks before use.

Drying temperatures of glutinous rice varied from 40 to 60°C, following specifications of the conventional paddy rice drying reported in most literature and temperature set at Company X. (42 – 45°C) (Taveesuvun *et al.*, 2022; Xu *et al.*, 2022). Three drying temperatures (i.e., 40, 50, and 60°C) were selected in this study. Before drying, around 100 g of glutinous rice (corresponding to a solid-to-air (S/G) ratio of 1.67 $g.L^{-1}.min^{-1}$) was soaked in 500 mL of water for 30 min at room temperature to evenly moist the grains. The initial moisture content of the glutinous rice was recorded using grain moisture analyzer MD7822. The hot air unit was switched on and the temperature was set at 40°C. The moistened glutinous rice was then transferred to the column. Grain moisture analyzer MD7822 was placed on the rice bed, and the moisture content of the grain was measured every 5 min for several hours, depending on the time taken for the grains to achieve a moisture content of 12% (Abdullah *et al.*, 2000). The experiment was repeated at temperatures of 50 and 60°C. Moisture content was continuously measured using a moisture analyzer with a probe placed at a specific location in the rice bed. This ensured no rice samples were removed and the S/G ratio was consistently maintained throughout the drying process.

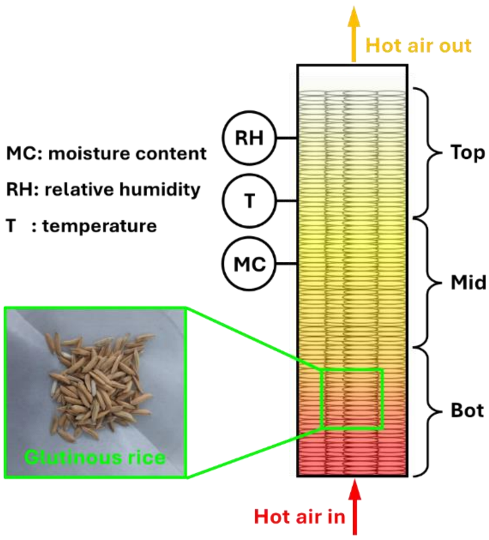



**Fig. 1:** Schematic illustration of lab-scale fixed bed dryer unit

### Drying of Glutinous Rice under Various Conditions (Effect of Solid-to-air Ratio)

Methods for observing drying behaviors of different glutinous rice loading were similar to those described in an earlier section. Quantities of glutinous rice selected were 50, 100, and 150 g, corresponding to the S/G ratios of 0.83, 1.67, and 2.50 $g.L^{-1}.min^{-1}$, respectively. The drying temperature was kept constant at 50°C. Grain moisture content was measured at an interval of 5 min until the grain reached a moisture content of 12%. A similar procedure was repeated for drying temperatures of 40°C and 60°C. Glutinous rice with husk was kindly provided by Company X, a rice processing facility located in Sungai Besar, Malaysia.

### Drying Kinetics Model Development

Experimentally determined moisture ratios for all data sets serve as the basis for determining the drying profiles of glutinous rice. Moisture ratio (MR) can be calculated using Eq. 1, where $MC_o$, $MC_e$, and $MC_t$ were the moisture contents at initial, equilibrium, and time = t, respectively.

$$Moisture\ ratio\ (MR) = \frac{MC_t - MC_e}{MC_o - MC_e} \qquad (1)$$

MR and drying time for data sets were then fitted into seven thin-layer drying kinetic models using the MATLAB 2021 curve fitting tool, and the drying curves were analyzed based on the calculated $R^2$ values. The thin-layer drying kinetics models considered in this work were empirical, including the Newton, Page, Henderson, Pabis, Logarithmic, Linear-Plus-Exponential, Midilli, and Weibull models.

The respective general equations for each model were manually specified in the curve fitting tool before plotting the MR against drying time data. Statistical analyses were used to evaluate and compare different thin-layer drying models. The statistical metrics $R^2$ and RMSE were used to assess the model's goodness of fit. The model with the highest $R^2$ and lowest RMSE values was chosen to characterize the drying curves with the maximum goodness of fit. The constants in the drying kinetics models were determined through the drying kinetics equation obtained from the curve fitting.

**Experimental Determination of Mass Transfer Coefficient**

Obtaining the mass transfer coefficient (MTC) of glutinous rice is an essential step, as the flowsheet development in the Aspen Plus V14 process simulator requires MTC as one of its input values. MTC describes the mass transfer of water molecules in the glutinous rice to the surrounding air, which, in this case, was calculated using Fick's Law-based model. Following Eq. (2), a linear plot of the natural log of MR against time was plotted following Eq. (2).

$$ln(MR) = ln(k_0) - kt \quad (2)$$

Where MR is the moisture ratio, $k_0$ is the lag factor, and t is time. The slope of the linear plot was used to calculate the drying constant, k. Then, effective diffusivity, $D_e$, can be estimated from the slope of Eq. (3).

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_e}{4z^2}\right)t \quad (3)$$

Next, the Dincer number ($D_i$) and Biot number ($B_{im}$) can be calculated using Eqs. (4), (5), and (6), respectively.

$$D_i = \frac{u}{kz} \quad (4)$$

$$B_{im} = \frac{24.848}{D_i^{0.375}} \quad (5)$$

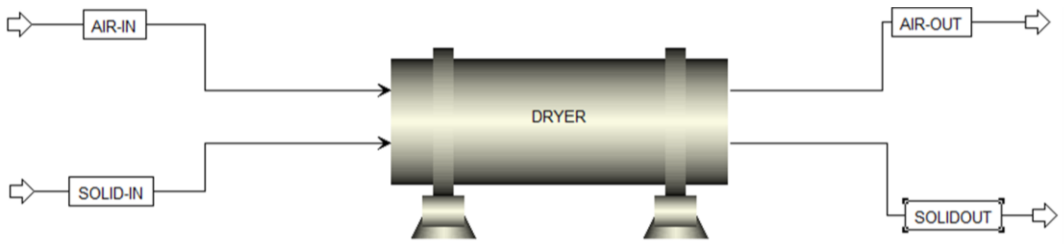
$$B_{im} = \frac{h_m z}{D_e} \quad (6)$$

Where, u, z, and $h_m$ are flow velocity, characteristic dimension, and convective MTC, respectively. MTCs for each parameter investigated were calculated assuming the drying process occurs in a single stage (case 1) or two stages (case 2). For case 1, MTC was calculated from t = 0 until the drying process was completed. On the other hand, MTC for two-stage drying (case 2) considers two drying stages: constant rate that occurs at the beginning of the drying process until the MR value drops by 1.5% and falling rate, which is the remainder of the drying process. In this case, two MTCs must be determined, as the drying rates differ at each stage. The calculated MTCs were then used to simulate the drying of glutinous rice in Aspen Plus V14.

**Simulation of the Drying Process in Aspen Plus V14**

Aspen Plus V14 process simulator was used to simulate the drying process of glutinous rice. Glutinous rice was specified as a 'non-conventional component', requiring the non-conventional properties such as component attributes, particle size distribution (PSD), density, heat capacity, etc., to be specified/estimated. In the Aspen Physical Property System, the built-in HCOALGEN model encompasses various correlations for the heat of combustion, heat of formation, and heat capacity. Meanwhile, the DCOALIGT model determines the true density of glutinous rice in its skeletal or solid phase. Though these models are best used for coal or char components, they were also frequently used for biomass samples.

Moreover, the parameter values were slightly adjusted to match the properties of glutinous rice. It is worth noting that HCOALGEN (option codes 1-1-2-1) and DCOALIGT models require component attributes (i.e., proximate, ultimate, and sulfur analysis) as input. Proximate, ultimate, and sulfur analyses of the glutinous rice were determined using a thermogravimetric analyzer (TGA Mettler Toledo) and CHNS Analyzer (LECO). Finally, the PSD of the glutinous rice was determined by measuring the sizes of individual glutinous rice grains. Seventy random glutinous rice grains were handpicked, and the length of each grain was measured manually.




| Block information | Details |
|---|---|
| Flow rate | Batch mode |
| Temperature | 50/100/150 g |
| Drying kinetics & MTC | Varies |

| Stream information | SOLID-IN | AIR-IN |
|---|---|---|
| Flow rate | 100 g | 60 L/min |
| Temperature | 32.1°C | Varies |
| Pressure | 1 bar | 1 bar |

| Proximate analysis | | Ultimate analysis | | Sulfur analysis | |
|---|---|---|---|---|---|
| Element | Value | Element | Value | Element | Value |
| Moisture | 0.1267 | Carbon | 0.38790 | Sulphate | 0.00979 |
| Fixed carbon | 0.1570 | Hydrogen | 0.06881 | - | - |
| Volatile matter | 0.6820 | Nitrogen | 0.38790 | - | - |
| Ash | 0.1610 | - | - | - | - |

**Fig. 2:** Process flowsheet of glutinous rice dryer unit along with block and stream information. Component attributes of glutinous rice to be specified in the simulator

Other components specified in the Aspen Plus V14 simulator were air and water (available in the simulator component database), which are defined as conventional components. The thermodynamic property method selected for the simulation was IDEAL. Stream class MIXNCSPD was selected, which requires the specification of the PSD of non-conventional components. Flowsheet development involved a DRYER unit (convective dryer in batch mode) operating without pressure drop with MTC and drying kinetics information to be manually specified in the block. A wet basis was chosen for the drying curve for solid moisture content. Critical and equilibrium solid moisture content, normalized solid moisture, and normalized drying rate were specified based on the experimental data. Stream and block information and process flowsheet of the drying process specified in Aspen Plus V14 are shown in Figure 2.

## RESULTS AND DISCUSSION

### Effects of solid-to-air (S/G) ratio and air temperature on glutinous rice drying

Glutinous rice (with husk) was dried in a homemade fixed-bed dryer unit, with the grain moisture content monitored regularly. Before drying, the glutinous rice is soaked in water to increase its moisture content (see Figure 2). The initial moisture content of glutinous rice measured using digital grain moisture analyzer MD7822 was around 32%, which is in the range for most grain crops (30% – 40%) (Baktash *et al.*, 2016; Lu *et al.*, 1994; Sun *et al.*, 1993). It is worth noting that the grains' initial moisture content may differ depending on the type of grain and the conditions it is collected. Due to their high moisture content, grains that require long storage time are susceptible to microbial growth and degradation. Therefore, reducing the grain moisture content to 12% – 14% before storage is critical (Abdullah *et al.*, 2000). 40°C – 60°C is a typical temperature range for drying grains. Meanwhile, a temperature range of 42°C – 45°C is well-known for drying rice grain (Hanisa *et al.*, 2022). In this work, the moisture content of glutinous rice grain is monitored every 30 sec until it is completely dried.

Maintaining an ideal S/G ratio and regulating drying air temperature is critical to maintaining a secure and effective drying process yielding excellent rice grain. A high S/G ratio creates an uneven drying environment as insufficient air evaporates the moisture, producing rice batches with inconsistent moisture content. On the other hand, low S/G results in ineffective or delayed drying since there will be too much air over glutinous rice. Low drying temperature requires long hours for completion, and glutinous rice may develop fungus or other damage during the process.

While high drying temperature significantly shortens drying duration, high temperature can cause the rice grain to break, compromising the rice's quality. Figure 3(b – d) present glutinous rice drying profiles (i.e., moisture content vs. time) at temperatures ranging between 40°C to 60°C and S/G ratios between 0.83 to 2.50. The hot air flow rate is maintained at 60 L.min$^{-1}$. For all cases, the moisture content of glutinous rice decreases over time but at different rates.

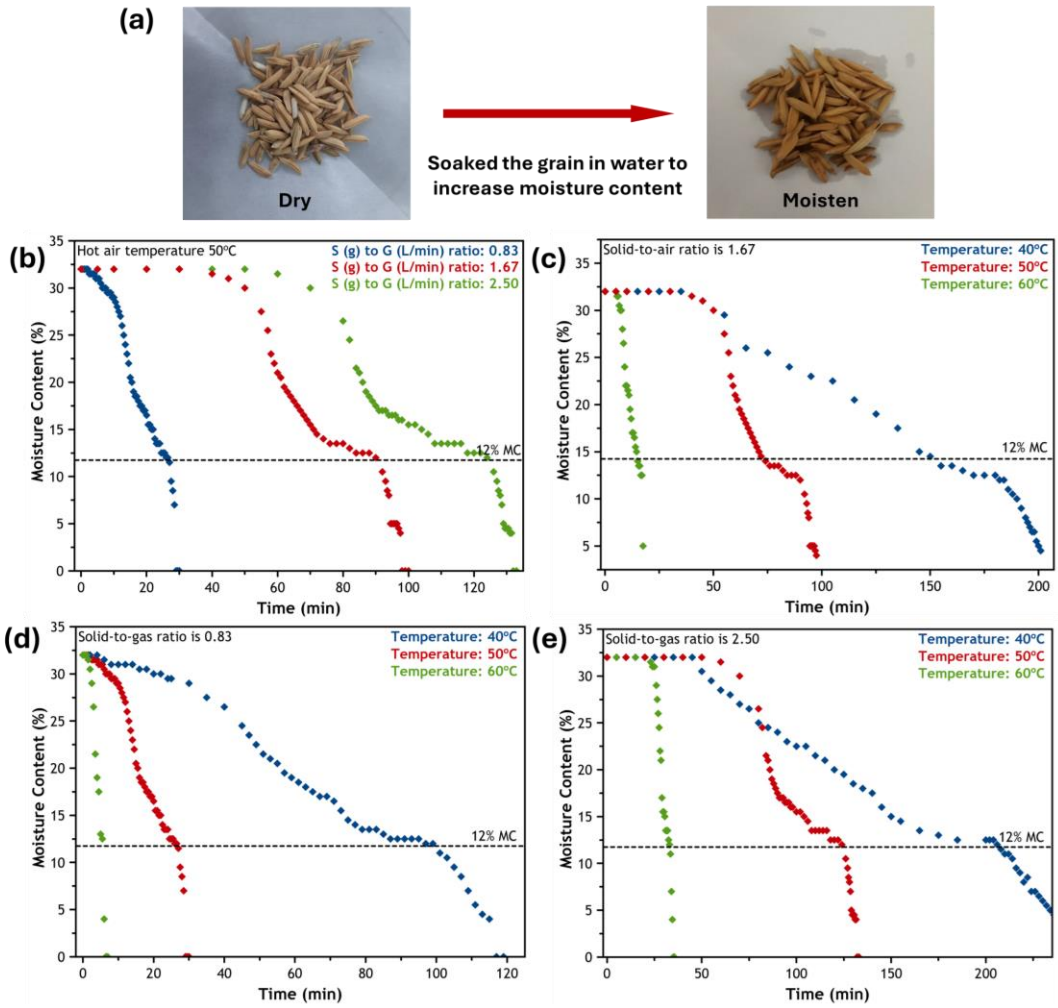



**Fig. 3:** (a) digital photographs of glutinous rice: dry and wet/moistened state. (b – d) A plot of moisture content against drying time: for different temperatures 40ºC, 50ºC, and 60ºC and S/G ratio 0.83, 1.67, and 2.50

At a constant S/G ratio of 1.67, drying time to achieve a final moisture content of 12% significantly decreases from 182 min to 12 min when drying temperature increases from 40°C to 60°C. High drying temperature increases moisture diffusion from the interior to the surface of glutinous rice grains, where it evaporates into the drying air. The rate of moisture diffusion from glutinous rice is sped up due to the rising temperature of drying air and rising water vapor pressure. As a result, total drying time is shortened since more moisture is extracted from the grains in a given time. Although drying time is accelerated at higher drying air temperatures, the quality of the grains could be compromised (Scariot *et al.*, 2020). For instance, (Maldaner *et al.*, 2021) observed a decrease in the yield of whole grains, an increase in the percentage of broken grains, and a retrogradation of the starch structure upon exposure to high drying temperatures.

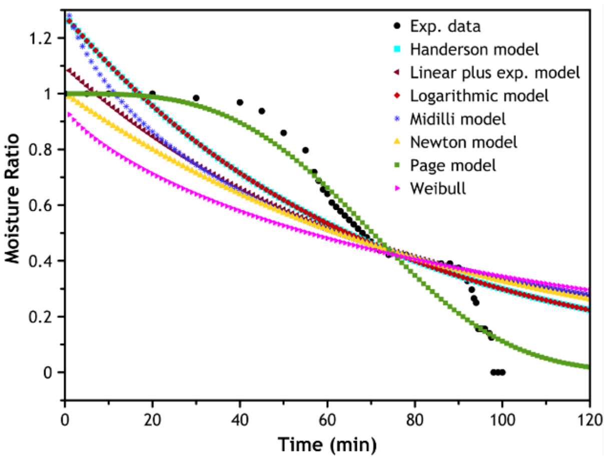



**Fig. 4:** Curve fitting of glutinous rice drying (S/G ratio of 1.67 and 50°C) for various thin-layer drying models. Experimental data points (black) are included for comparison.

Similarly, drying time is shortened from 124 to 26 min when the S/G ratio decreases from 2.50 to 0.83. This result is rather obvious, as lower quantities of grains require less time to dry (Coradi *et al.*, 2020). Watcharin Dongbang & Nuantong (2018) observed a similar decreasing trend, where increasing drying temperature and reducing the amount of 'cooked/steamed' glutinous rice inside a microwave dryer resulted in a shorter drying duration.

It is also worth mentioning that among the two parameters investigated, temperature variation has a more profound impact on grain moisture content reduction than the S/G ratio. Nonetheless, both parameters must be optimally selected to ensure the safety and quality of the dried grains.

**Thin-layer Drying Kinetic Models for Glutinous Rice Drying**

Drying results from all experiments were fitted into seven existing thin-layer drying kinetics models: the Newton, Page, Henderson, and Pabis, Logarithmic, Linear-Pus-Exponential, Midilli, and Weibull models. The most popular empirical models are the Page, Henderson, and Pabis, Midilli-Kucuk, and Logarithmic models (Benseddik *et al.*, 2018). The design and optimization of drying processes for various goods, including fruits, vegetables, cereals, and other food items, benefit significantly from using these models.

Thin-layer drying kinetic models describe the rate at which moisture is removed from a product as it dries in a thin layer. The model is based on mass transfer, where moisture is transported from a product's surface to the air around it by convection or diffusion. Representative curve fitting for all thin-layer models for glutinous rice drying (S/G ratio of 1.67) at 50°C is illustrated in Figure 4. Meanwhile, model equations along their $R^2$ values are listed in Table 1. The kinetic model that best describes the drying of glutinous rice is selected based on the highest $R^2$ value provided by the models.

Among the seven models considered, at an S/G ratio of 1.67 and an air temperature of 50°C, the Page model produces the best drying curves for glutinous rice, with an $R^2$ value of 0.9536. The model equations for all thin-layer drying kinetics, along with their coefficients of determination ($R^2$) for other drying conditions (i.e., S/G ratios of 0.83, 1.67, and 2.50, at temperatures of 50°C Table 1 – 3. Based on the data, the Page model best represents the drying behavior of glutinous rice, regardless of the S/G ratio and temperature applied.

The Page model, which incorporates a reverse sigmoidal curve, provided a better fit to the experimental data than other models, reflecting the decreasing drying rate over time characteristic of our drying process. (Abe *et al.*, 1997) also, the Page model was most suitable for describing thin-layer infrared radiation drying of 'rough rice'. (Iguaz *et al.*, 2003) also reached a similar conclusion when investigating the drying process of rough rice (Lido cultivar) at low drying temperatures ($R^2$ value of 0.949). In more recent work, (Dongbang & Nuantong, 2018) reported a Page model with an $R^2$ value as high as 0.998 to represent the drying process of 'cooked' glutinous rice in an infrared irradiation dryer.

**Table 1.** Developed model equations for all thin-layer drying kinetics (drying condition: S/G ratio = 1.67, temperature 50ºC).

| Drying model | Developed model with $R^2$ values |
|---|---|
| Henderson and Pabis | $MR = 1.279\exp(-0.01453t)$, $R^2 = 0.7363$ |
| Linear plus exponential | $MR = \exp(-0.01438t) + 2.653\times 10^{-14}t + 9.743 \times 10^{-2}$ |
| | $R^2 = 0.6809$ |
| Logarithmic | $MR = 1.279\exp(-0.01453t) + 8.146 \times 10^{-10}$, $R^2 = 0.7363$ |
| Midilli | $MR = 1.352\exp(-0.0544t^{0.7035}) + 2.337 \times 10^{-14}t$ |
| | $R^2 = 0.6359$ |
| Newton | $MR = \exp(-0.01117t)$, $R^2 = 0.6651$ |
| Page | $MR = \exp(-6.262 \times 10^{-7}t^{3.272})$, $R^2 = 0.9536$ |
| Weibull | $MR = 0.951\exp(-2.772 \times 10^{-2}t^{0.7819}) + 3.057 \times 10^{-4}$ |
| | $R^2 = 0.5587$ |

**Table 2.** Developed model equations for all thin-layer drying kinetics (drying condition: S/G ratio = 0.83, temperature 50ºC).

| Drying model | Developed model with $R^2$ values |
|---|---|
| Henderson and Pabis | $MR = 1.169\exp(-0.04253t)$, $R^2 = 0.90688$ |
| Linear plus exponential | $MR = \exp(-0.1624t^{0.554}) - 0.08958t - 0.05966$ |
| | $R^2 = 0.97958$ |
| Logarithmic | $MR = 234.8\exp(-0.000118t) - 233.8$, $R^2 = 0.95107$ |
| Midilli | $MR = 0.942\exp(-0.169t^{0.5471}) - 0.0876t$, $R^2 = 0.72827$ |
| Newton | $MR = \exp(-0.03292t)$, $R^2 = 0.83556$ |
| Page | $MR = \exp(-0.001338t^{2.097})$, $R^2 = 0.98385$ |
| Weibull | $MR = \exp(-0.04881t) + 0.1335$, $R^2 = 0.88355$ |

**Table 3.** Developed model equations for all thin-layer drying kinetics (drying condition: S/G ratio = 2.50, temperature 50ºC).

| **Drying model** | **Developed model with $R^2$ values** |
|---|---|
| Henderson and Pabis | MR = 1.305exp(-0.01077t), $R^2$ = 0.74253 |
| Linear plus exponential | MR = exp(-0.01076t) + 3.079× $10^{-14}$t + 0.1076, $R^2$ = 0.88401 |
| Logarithmic | MR = 204.4exp(-0.00003802t) - 203.2, $R^2$ = 0.81720 |
| Midilli | MR = exp(-0.008124t) + 2.221 × $10^{-14}$t, $R^2$ = 0.62800 |
| Newton | MR = exp(-0.008124t), $R^2$ = 0.66313 |
| Page | MR = exp(-2.006 × $10^{-7}t^{3.287}$), $R^2$ = 0.94353 |
| Weibull | MR = 1.072exp(-0.0001645$t^{1.862}$) + 4.963 × $10^{-6,}$ $R^2$ = 0.70543 |

**Convective Mass Transfer Coefficient (MTC) of Glutinous Rice Drying**

A metric used to measure the mass transfer rate in convective systems is the convective MTC, which, generally, describes how well mass is transferred from a fluid to a solid surface (Jain *et al.*, 2004). MTC value can be influenced by the physical characteristics of the fluid, such as viscosity, density, diffusivity, and thermal conductivity (Sokhansanj, 1987). In terms of flow characteristics, turbulent flow promotes better mass transfer than laminar flow due to greater mixing and fluid interactions (Larson *et al.*, 1973). MTC can also be influenced by a solid surface's size, shape, roughness, or an interface between two immiscible fluids (Zhao *et al.*, 2007). Larger surface areas or more interfacial contact encourage a higher mass transfer rate.

In this work, MTC is considered a bridge between the experimental and simulation of glutinous rice drying, as the calculated MTCs will later be used in the process simulation software. The curve fitting tool in MATLAB software is used to fit the convective MTC data concerning the S/G ratio and drying temperature. (Solomon *et al.*, 2021) have also used a similar method for modeling heat and mass transfer of Ethiopian fresh injera (Ethiopian staple food) inside the tunnel dryer. Several built-in models were used to fit the data and the model that best describes MTC was selected based on the highest $R^2$ value.

Impacts of the S/G ratio and drying temperature on the convective MTC of glutinous rice are represented as surface and contour plots in Figure 5. For both figures, the y-axis indicates the air's drying temperature (40 – 60°C), while the x-axis shows the mass of glutinous rice (50 – 200 g) and MTC is represented by the surface plot's z-axis (0 – 2.1 $m.s^{-1}$). A high area or peak seen on the surface plot denotes high MTC regions. As the S/G ratio and drying temperature change, the surface plot would show a steep gradient or slope, suggesting a considerable change in the MTC.

From the contour plot, decreasing the S/G ratio and increasing the drying temperature improve the mass transfer rate. The air flowing around each rice grain rises as the S/G ratio lowers. Greater MTC results from a faster moisture evaporation rate from the rice surface due to enhanced airflow. In other words, the rate at which moisture may evaporate off the surface of the rice increases when there are fewer grains of rice in each volume of air because there is more space for the air to circulate each grain of rice. This is the leading cause of the rise in convective

MTC when the S/G ratio decreases.

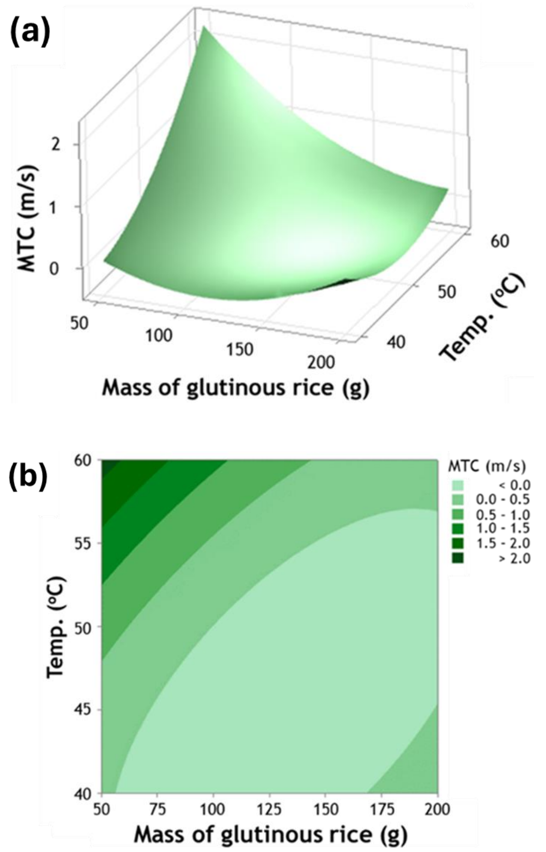



**Fig. 5:** Impacts of S/G ratio and drying temperature on MTC represented as (a) surface plot and (b) contour plot.

On the other hand, a rise in convective MTC of glutinous rice is observed with increasing temperature attributable to stronger driving forces for moisture transfer between the rice and surrounding air (Rong *et al.*, 2018). The air becomes less dense and more buoyant at higher temperatures, promoting convection (Malekan *et al.*, 2021). The plot shows that the MTC coefficient increases relatively fast at low solid loading, especially in the temperature region between 50 and 60°C. Meanwhile, variation in MTC is less apparent with changes in the S/G ratio, especially in the low-temperature region (<50°C). Therefore, these results indicate that temperature variation substantially affects MTC more than the S/G ratio.

**Aspen Plus Simulation of Glutinous Rice Drying**

Establishing a digital version of the glutinous rice drying process using process simulation software can greatly assist in evaluating different drying scenarios and selecting the most effective strategies to achieve the desired results in a virtual environment. Dryer setting, drying profiles, MTCs, and other information obtained experimentally were specified in the Aspen Plus V14 simulator to produce a digital version of the process. The particle size distribution (PSD) curve of glutinous rice specified in Aspen Plus V14 is produced by measuring the length of 70 randomly

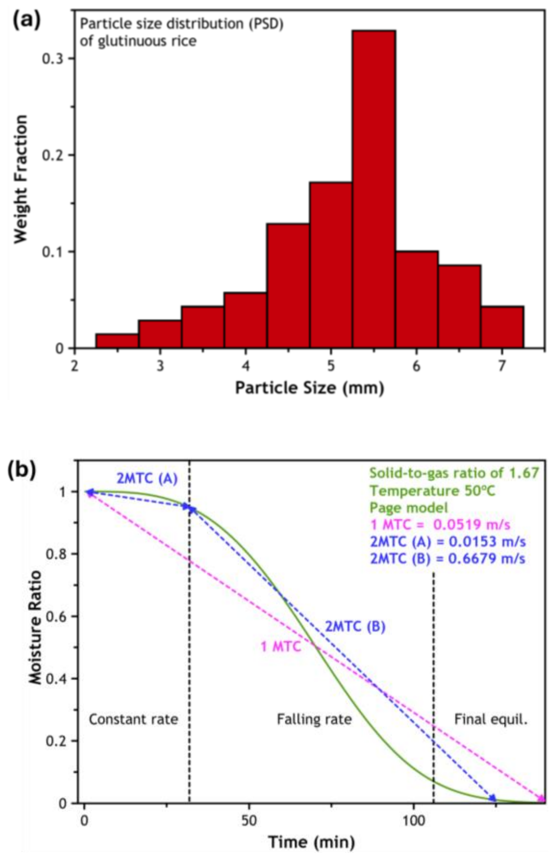



**Fig. 6:** (a) PSD of glutinous rice (b) Drying profile of rice in fixed bed dryer based on the Page model at 50°C and S/G ratio of 1.67. MTC values consider drying process occur in either one stage (1 MTC) or multiple stages (2 MTC)

handpicked rice grains. The PSD of the glutinous rice shown in Figure 6(a) produced a Gaussian distribution with 72% of the population having grain length between 4.0 and 6.5 mm.

Grain fissuring produces glutinous rice with smaller grain lengths (2.0 mm – 3.0 mm), accounting for roughly 5% of the population. On the other hand, information on component attributes (i.e., proximate, ultimate, and sulfur analysis) to be specified in the process simulator is obtained from thermogravimetric analysis (see Figure 2). It is worth mentioning that the component attribute values are slightly adjusted to fit simulation requirements in the simulator. In the drying process of food and agricultural goods, the statistics of normalized solid moisture and normalized drying rate are frequently employed (Li *et al.*, 2016).

The ratio of a solid material's actual moisture content to its starting moisture content, represented as a fraction or percentage, is known as normalized solid moisture (Delgado *et al.*, 2005). For glutinous drying at 50°C and S/G of 1.67, an overall MTC (1 MTC = 0.0519 $m.s^{-1}$) value was specified in the Aspen Plus for initial flowsheet development. A metric used to measure the mass transfer rate in convective systems is the convective MTC, which generally, describes how well mass is transferred from a fluid to a solid surface (Jain *et al.*, 2004). MTC values can be influenced by the physical characteristics of the fluid, such as viscosity, density, diffusivity, and thermal conductivity (Sokhansanj, 1987).

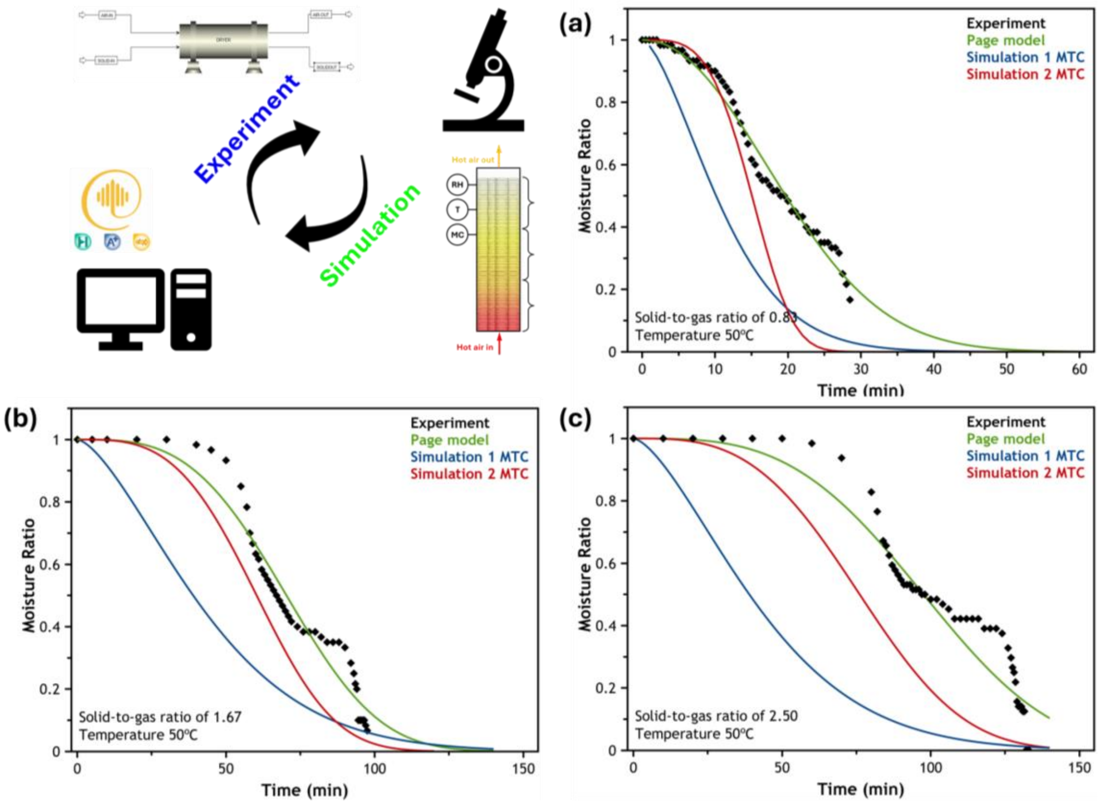



**Fig. 7:** Comparison between drying kinetics obtained from the experiment, Page model, simulation output using overall MTC (1 MTC), and simulation using falling and constant rate MTC (2 MTC) for S/G ratio of (a) 0.83 (b) 1.67, and (c) 2.50. Note that the drying temperature is 50°C.

(a)

**Mill/Plant Data**

| Spec | Mass flow (tons) | Air temp. (°C) | Air flow ($m^3.hr^{-1}$) | Time taken (hr) | Moisture content (%) |
|---|---|---|---|---|---|
| Value | 10 | 45 | 35,000 | 12 | 12 |

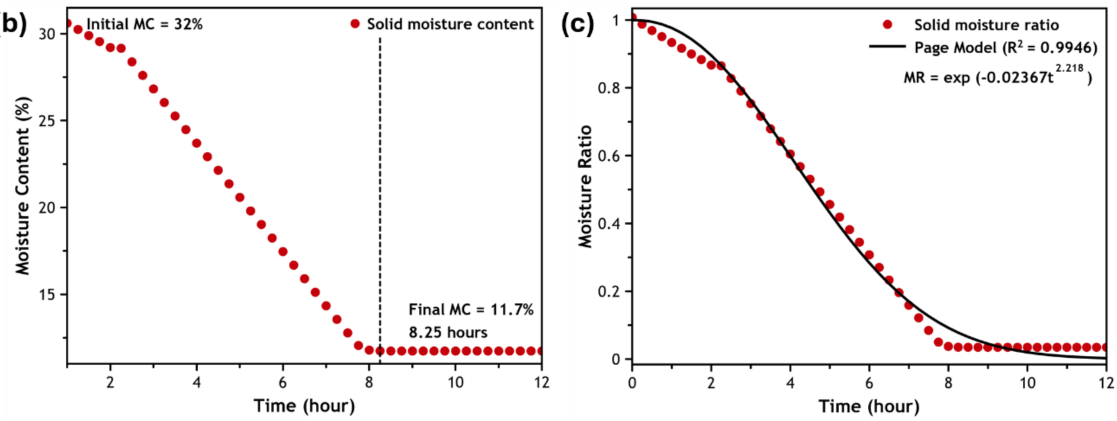



**Fig. 8:** (a) Mill/plant data at Company X. (b) Simulation output (moisture content) based on plant data (c) Page model equation based on the plant data output.

The simulation model's accuracy was assessed by comparing the simulation output with the Page model and experimental data. From Figure 6(b), the simulation model utilizing an overall MTC value (1 MTC) does not provide satisfactory drying prediction as it does not align well with the Page model or experimental data for all drying cases. 1 MTC value was calculated by accounting for the moisture ratio from the beginning of the drying process until completion. When the overall MTC (1 MTC) is specified in the simulation models, the drying rate is constant throughout the drying process, thereby producing data prediction with low accuracy. To further improve the simulation model, 2 MTCs (i.e., constant rate MTC and the falling rate MTC) were introduced in the simulation model, as shown in Figure 7.

It is worth mentioning that the constant rate MTC was calculated at time = 0 until time when the moisture ratio decreased by 1.5%. The simulation flowsheet utilizing constant and falling rate MTC (2 MTC) produces a better simulation output than 1 MTC to predict drying the behavior of glutinous rice in a fixed bed setup (result not shown). Three (3 MTC) and four-stage (4 MTC) drying processes were also considered in this study, but unfortunately, the simulation results were not accurate, hence excluded. Based on the optimized simulation models, Aspen Plus V14 can be used to calculate other important drying information.

We then proceed by testing the simulation for large-scale processing of glutinous rice (10 tons batch capacity). Mill/plant data at Company X., Malaysia, as specified in the simulator (plant data are shown in Figure 8(a)). Meanwhile, MTCs at 45°C were interpolated based on the experimental results. As shown in Figure 8(b), Aspen Plus simulation output calculated a drying time of 8.25 hours to achieve a grain moisture content of 11.7% as opposed to the 12-hour drying time reported by the mill operator, which is encouraging. Finally, we fit the simulation output for the 10-ton glutinous rice drying setup with the Page model ($R^2$ of 0.9946), as shown in Figure 8(c). Moving forward, we plan to improve the accuracy of the simulation for large-scale simulation estimation by including parameters not accounted for in the simulation (e.g., pressure drop, scale factor, bed geometry, and heat loss) and incorporating more mill data for fine-tuning.

## CONCLUSIONS

A general-purpose thin-layer drying kinetics has been established to model the glutinous rice drying process in a fixed-bed dryer unit. The models were evaluated for different air temperatures, ranging from 40 to 60°C, and S/G ratios between 0.83 and 2.50, with the initial grain moisture content of 32%. Experimental data were fitted to seven thin-layer models based on the initial, final, and equilibrium moisture contents. For all drying models considered, the Page model gave the best drying prediction with $R^2$ values all above 0.94 (e.g., model equation of [$MR = \exp(-6.262 \times 10^{-7}t^{3.272})$] for drying temperature of 50°C and S/G ratio of 1.67) for all parameter combinations. MTC values were mainly affected by temperature variation, as displayed in the surface plot. The application of Aspen Plus simulation software tremendously aids drying process computation, optimization, and determination of other drying parameters not provided by the Page model. Specifying constant MTC (0.0153 $m.s^{-1}$) and falling rate MTC (0.6679 $m.s^{-1}$) in the simulation flowsheet produced data reasonably close to the Page model with an $R^2$ value of 0.9843. To sum up, developing drying models, particularly Page models, and understanding moisture transfer characteristics can tremendously aid in determining optimal drying conditions for glutinous rice (potential applicability for other grain-based agricultural products).

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