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Enhanced real-time paddy moisture content assessment in pneumatic drying using correction factor

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Abstract

Accurate and real-time monitoring of paddy moisture content during the drying process is critical to preserving rice quality and ensuring efficient post-harvest management. This research article presents the application of weather sensor (DHT22, AM2302, Aosong Electronics Co.,Ltd) that measures air temperature and relative humidity for evaluating paddy moisture content in drying process of a pneumatic dryer. Khao Dawk Mali 105 paddy with initial moisture content of 26%w.b. was dried by a constant drying air temperature of 70 °C and the drying air flow rate of 0.0631 m^3/s with paddy feed rate of 8.45 kg/min throughout the test. Two methods namely DHT-Prediction and DHT-Factor correction methods for evaluating moisture content of paddy were developed by mass balance equation and the result were compared with the reference paddy moisture content analyzed by hot air oven method. The results showed that the DHT-Prediction method gave high moisture measurement error compared to the reference paddy moisture content (R^2 between 0.274 - 0.359 and RMSE between 5.077 - 7.465). The DHT-Factor correction method gave the lowest discrepancy of paddy moisture content during the first 150 minutes of the drying with R^2 of 0.987 and RMSE of 0.515. This method also showed low discrepancy results over the entire drying period which indicated that it has high potential for evaluating the real-time paddy moisture content during drying process.

Keywords: Paddy moisture content, Drying, Non-destructive techniques, Measurement

1. Introduction

Rice is a staple food consumed globally, serving as a fundamental dietary component across many regions [1, 2]. Each region produces rice varieties with distinct characteristics, such as Thailand's Hom Mali rice, renowned for its unique taste and aroma [3]. This variety was awarded the title of "World's Best Rice" in both 2020 and 2021 [4]. In 2023, the Thai Department of Foreign Trade reported that Thai rice exports reached 8.76 million tons, reflecting a 13.62% increase, valued at approximately 5,144 million USD [5]. Consequently, the Thai rice industry plays a critical role in the nation's economy.

Rice is typically harvested at an optimal time to ensure a high-quality yield. Freshly harvested paddy rice generally possesses a moisture content ranging between 22% and 26% on a wet basis (%w.b.). However, this high moisture content necessitates reduction to an appropriate level for safe storage. Proper moisture reduction is essential to prevent potential damage and quality deterioration during storage. Without this crucial step, rice is susceptible to spoilage, mold growth, and a decline in overall quality. Therefore, moisture control is critical to post-harvest rice management, ensuring the preservation of the crop's value and usability over time [6, 7].

Moisture content also directly affects the weight of paddy rice, which is a key determinant of the buying price in transactions between farmers and buyers. Accurate moisture measurement is vital not only for trade but also prior to storage, where rice may be destined for use as seed or for consumption. Furthermore, controlling moisture content during the drying process is crucial, as prolonged exposure to elevated temperatures can degrade rice quality and ultimately impact its market price. Current moisture measurement techniques often require the extraction of samples for testing, with some methods relying on destructive techniques that can cause delays due to the time required to obtain results [8]. These delays hinder quality control during production and, in turn, affect the final product. Thus, the development of non-destructive moisture measurement methods, utilizing indirect physical properties, offers a promising solution to these challenges. This approach can streamline the process, improve quality control, and minimize adverse effects on rice pricing.

In recent years, non-destructive testing techniques have gained increasing attention in developing moisture measurement tools for grains. A review of previous studies highlights several approaches. Armstrong et al. [9] developed a moisture meter for corn and other grains, using relative humidity (RH) and temperature (T) measurements from small digital sensors embedded in the tip of a probe that

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can be inserted into grain bags. The accuracy of this device was comparable to that of the GAC 2100 moisture meter for corn with moisture content below 15%. Pathaveerat and Pruengam [10] introduced a low-cost, reusable method for measuring paddy rice moisture using cobalt chloride-coated paper, which changes color in response to the equilibrium relative humidity inside a container of moist rice. Lin et al. [11] developed a near-infrared (NIR) spectroscopy-based moisture sensor for rice, achieving a coefficient of determination (R^2) of 0.936 and a sum of squared errors (SSE) of 25.47 for rice with moisture content ranging from 13% to 30%. This device provided rapid and accurate results, making it suitable for real-time moisture monitoring during rice production.

Similarly, Makky et al. [12] developed moisture measurement tools for paddy rice using comparable techniques. Although these methods demonstrated high accuracy and compatibility with industrial systems, they are often expensive and complex to operate. As a result, the development of real-time moisture measurement methods using low-cost sensors for data collection and processing presents a viable alternative, especially for medium-scale drying systems. Such an approach has the potential to reduce costs while maintaining accuracy and efficiency, making it more suitable for widespread application in grain drying and processing industries.

This study aims to develop an accurate and cost-effective method for real-time moisture monitoring in paddy rice during the drying process. Utilizing a DHT22 sensor to measure air temperature and relative humidity, this research seeks to establish a reliable moisture evaluation system within a pneumatic drying setup. The experiment was conducted under controlled conditions, with the paddy rice initially having a moisture content of 26% w.b. and a constant drying air temperature of 70 ºC. Both the rice feed rate and airflow rate were maintained consistently throughout the process. This approach aims to enhance both the accuracy and economic feasibility of moisture measurement in medium-scale drying operations, offering practical applications for the rice industry.

2. Materials and methods

2.1 Sample preparation

In this study, Khao Dawk Mali 105 paddy rice was selected as the experimental sample. Before any testing, the paddy underwent a thorough cleaning process. The initial moisture content of the rice was determined using the hot air oven method at 105 ˚C for a duration exceeding 24 hours, following the AOAC standard [13], as illustrated in Figure 1(a). The moisture content was calculated using Eq. (1) and (2) [14, 15]. This data was then employed to calculate the required amount of water to be added back to the paddy to achieve the desired moisture content, using Eq. (3) [15]. The paddy was adjusted to an initial moisture content of 26% w.b. (or 35% d.b.). Subsequently, the water-added paddy was sealed in a container and stored in a cold room at a temperature of 2–5 ˚C for more than 24 hours, as shown in Figure 1(b), to ensure uniform moisture distribution throughout the storage container.

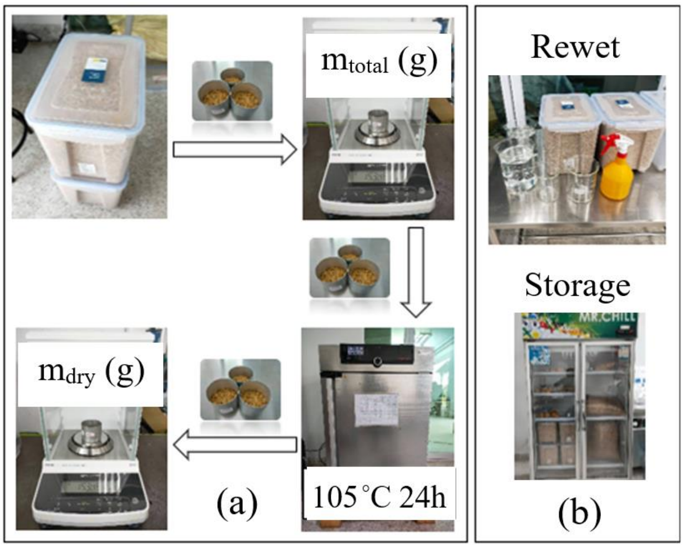

Figure 1 Sample preparation

$$MC_{wb} = \frac{m_{water}}{m_{total}} = \left(\frac{m_{total} - m_{dry}}{m_{total}}\right) \quad (1)$$

$$MC_{db} = \frac{m_{water}}{m_{dry}} = \left(\frac{m_{total} - m_{dry}}{m_{dry}}\right) \quad (2)$$

$$m_{water,add} = m_{dry,total}\left(MC_{target} - MC_{db}\right) \quad (3)$$

Where MC_{wb} is the paddy moisture content on wet basis (decimal), MC_{db} is the paddy moisture content on dry basis (decimal), MC_{target} is the target paddy moisture content on dry basis (decimal), m_{water} is the mass of water in paddy (kg), mtotal is the total mass of paddy (kg), m_{dry} is the mass of the dry matter (kg), $m_{water,add}$ is the mass of water to be added to the sample (kg), $m_{dry,total}$ is the total mass of dry matter of the prepared sample (kg).

2.2 Pneumatic dryer

The pneumatic dryer was used as the drying experimental equipment in this research. The various components of the pneumatic dryer are illustrated in Figure 2.

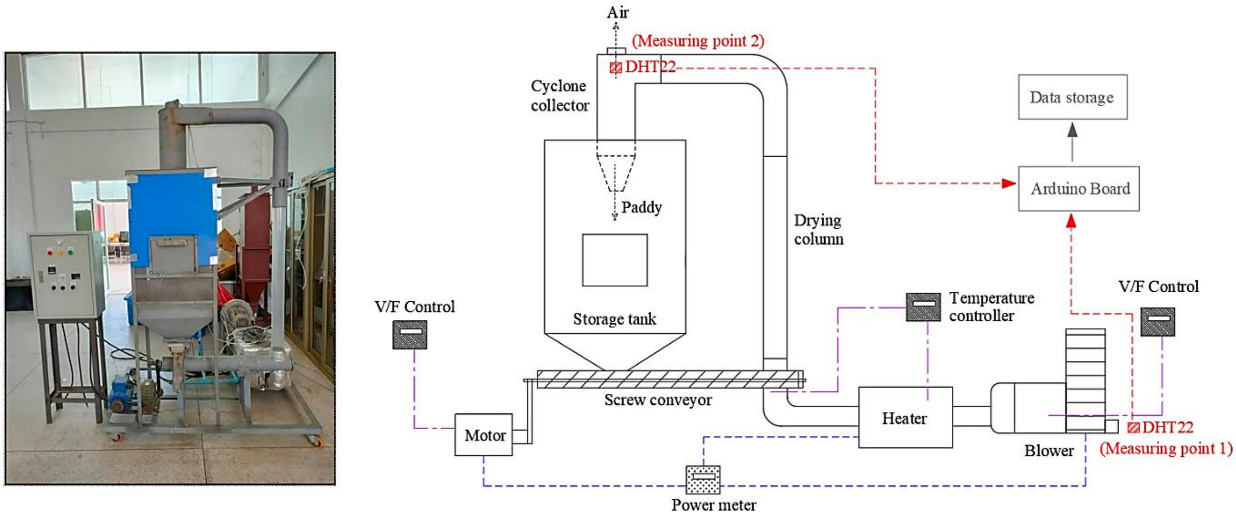

Figure 2 Diagram of pneumatic paddy dryer

The working principle of this dryer relies on heat generation from a heat generator 3 kW, which operates in conjunction with a temperature controller (RKG, model: REX-C100FK02) to regulate the drying temperature. A blower 1.5 kW is used to drive the hot air into the drying column. Simultaneously, paddy is fed from the storage tank via a screw conveyor powered by a motor 0.746 kW. The rotational speed of the conveyor and blower are controlled by inverters (Hitachi, model: WJ200, 2.2 kW). As the paddy is transported to the inlet of the drying column, it is exposed to hot air with low relative humidity, which facilitates the removal of moisture from the paddy grains. The hot air absorbs the moisture, resulting in an increase in relative humidity and a decrease in temperature. The paddy, along with the humid air, is then conveyed into a cyclone, where the humid air and paddy are separated. The paddy is collected in a storage tank, and the process repeats continuously until the moisture content of the paddy reaches the desired target level.

The calibrated DHT22 sensor (AOSONG, model: AM2302) was connected to an Arduino Microcontroller Board to read and record the air properties, as illustrated in Figure 3. The sensor was installed on the dryer, as shown in Figure 2, with two measurement points: the first at the fan inlet to measure ambient air condition (measurement point 1) and the second at the cyclone outlet to measure the humidified drying air after contact with the paddy (measurement point 2). The temperature and relative humidity readings from these two points were analyzed to determine the amount of moisture transferred from the paddy to the drying air. This was calculated as the difference in the moist mass of the paddy, based on the mass balance equation.

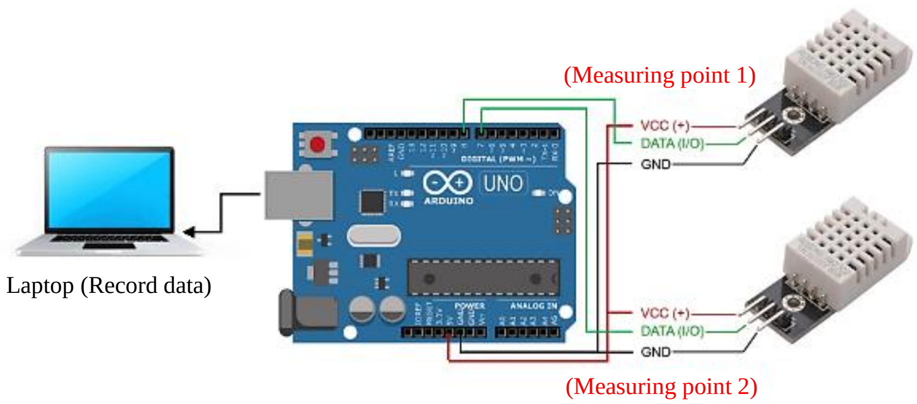

Figure 3 Sensor connection diagram

2.3 Experimental setup

The drying tests were conducted at a constant drying air temperature of 70 ºC, with a paddy feed rate of 8.45 kg/min and a drying air flow rate of 0.0631 m^3/s. The paddy rice, which had undergone initial moisture conditioning as outlined in Section 2.1, was dried in batches, each consisting of 20 kg and the experiment was three replications. During each test, three random samples of paddy were collected from the cyclone outlet, and the DHT22 sensor readings were recorded at 10-minute intervals until the paddy moisture content reached equilibrium. Once the equilibrium moisture content was achieved, the test was concluded.

The moisture content of the randomly selected paddy samples was then measured using the hot air oven method (Figure 1(a)), which served as a reference for evaluating the accuracy of the moisture assessment results.

2.4 Estimation of paddy moisture content through air property measurement using DHT22 sensor

When the DHT22 sensors at both positions read the temperature of the incoming and outgoing air from the dryer, the measured temperature values are first converted to Kelvin (K) before being used to calculate the saturation vapor pressure (P_{sv}) at both measurement points, according to Eq. (4) [16, 17]. Meanwhile, the relative humidity (RH) values obtained from the sensors are used to calculate the air vapor pressure (P_v) and the humidity ratio (ω) at both points, using Eqs. (5) and (6), respectively [16, 17]. The difference in the humidity ratio (ω_2-ω_1) is then used to determine the amount of moisture transferred from the paddy into the drying air at any given time, as described in Eq. (7) and (8) [16]. The cumulative moisture transfer is subsequently used to calculate the final moisture content of the paddy at various time intervals, as per Eq. (9) [6].

$$P_{sv} = e^{\left(\frac{C_1}{T}+C_2+C_3T+C_4T^2+C_5T^3+C_6 lnT\right)} \quad (4)$$

$$P_v = \frac{RH \times P_{sv}}{100} \quad (5)$$

$$\omega = \frac{0.621945 \times P_v}{P_{atm} - P_v} \quad (6)$$

$$\rho = \frac{P_{atm} - P_v}{287.042T} \quad (7)$$

$$m_{ma} = \dot{m}_{da}(\omega_2 - \omega_1)t = \frac{\rho \mathrm{Av}}{1+\omega_2}(\omega_2 - \omega_1)t \quad (8)$$

$$MC_{pred} = \frac{m_{total}MC_{wb}^{*} - 100m_{ma}}{m_{total} - m_{ma}} \quad (9)$$

where C_1 is -5.8002206×10^3, C_2 is 1.3914993, C_3 is -4.8640239 ×10^{-2}, C_4 is 4.1764768 ×10^{-5}, C_5 is -1.4452093×10^{-8}, C_6 is 6.5459673, P_{atm} is the atmospheric pressure (101,325 Pa), T is the dry bulb temperature (K), RH is the relative humidity (%), P_v is the partial pressure of water vapor in the air (Pa), ω is the air humidity ratio (kg_w/kg_{da}), P_{sv} is the saturated vapor pressure (Pa), ρ is the air density (kg/m^3), m_{ma} is the mass of water transferred to drying air (kg), A is the cross-sectional area of pipe at the considered point (m^2), t is time (s), MC^*_{wb} is the paddy moisture content on wet basis (percentage, %w.b.) and MC_{pred} is the estimated paddy moisture content (%w.b.).

2.5 Model validation

The moisture content of paddy rice at any given time was compared with the reference moisture content, which was determined using the hot air oven method in accordance with AOAC standards. The accuracy of the data between the reference set and the predicted set was evaluated using the coefficient of determination (R^2) and the root mean square error (RMSE), calculated as per Eq. (10) and Eq. (11), respectively [15, 17, 18]. An R^2 value close to 1 and an RMSE value close to 0 indicate high model accuracy and strong performance in predicting real-time paddy moisture content [18, 19]. Three experiments were carried out for the analysis, 102 data sets from experiments 1 and 2 were used as training sets, while 51 data sets from experiment 3 were used as validation sets. RMSEC represents the RMSE for the training set, while RMSEP represents the RMSE for the validation set.

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{i=n}\left(MC_{ref} - MC_{pred}\right)^2}{\sum_{i=1}^{i=n}\left(MC_{ref} - MC_{avg}\right)^2}\right) \quad (10)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{i=n}\left(MC_{ref} - MC_{pred}\right)^2}{n}} \quad (11)$$

where MC_{ref} is the reference moisture content, MC_{avg} is the average moisture content, and n is amount of data.

3. Results and discussion

3.1 Temperature and humidity measurements

The three replications temperature and relative humidity data collected from the DHT22 sensors at two measurement points are shown in Figure 4 and Figure 5. Measurement point 1 (T1 and RH1, located at the fan inlet) and measurement point 2 (T2 and RH2, located at the cyclone outlet) exhibited different temperature and humidity profiles throughout the drying process. These data were used to calculate the humidity ratio of the dry air at various measurement points as shown in Figure 6.

3.2 Humidity ratio difference over time

Figure 6 illustrates the humidity ratio difference (ω_2-ω_1) over time. It indicates the amount of mass transferred water from the paddy grain to the drying air [14, 17]. During the initial drying period, from minute 1 to minute 70, the humidity ratio difference remained high and stable. This period corresponds to the constant rate drying period, where moisture transfer from the paddy rice surface to the drying air is steady [20, 21].

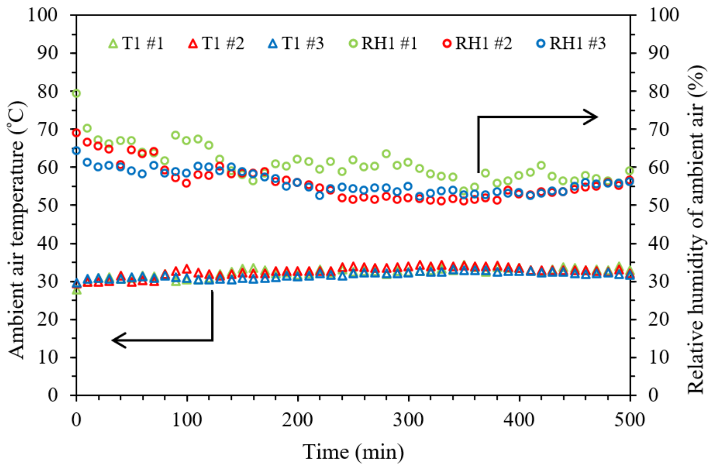

Figure 4 Temperature and relative humidity of the air at measurement point 1

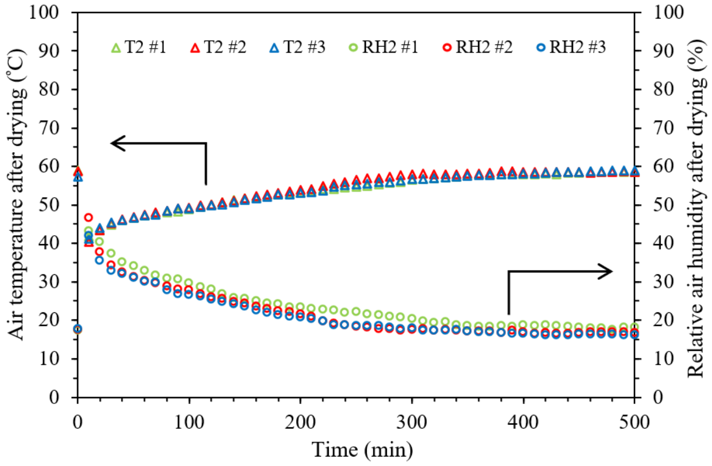

Figure 5 Temperature and relative humidity of the air at measurement point 2

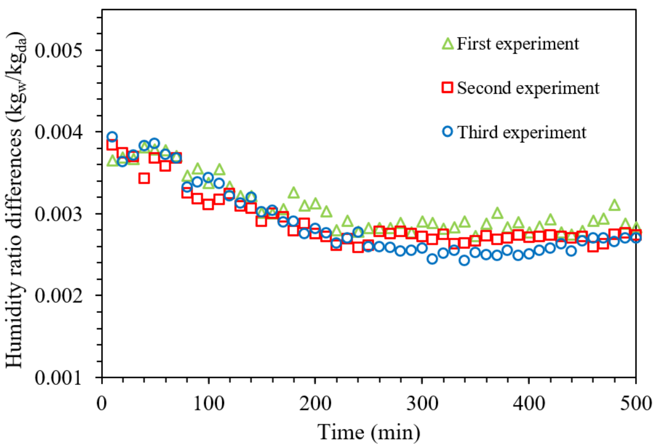

Figure 6 Differences in air humidity ratios during the process

As drying progresses, the difference in the air humidity ratio decreases over time, becoming negligible after the 300th minute. This indicates a reduction in moisture transfer to the air, suggesting that the drying air has reached a state of moisture saturation equilibrium. At this point, the paddy's moisture content aligns with its equilibrium moisture content. Using the method outlined in Section 2.4, the moisture content of the paddy (DHT-Prediction) was calculated at various time intervals, and the results are presented in Figure 7. The standard deviation values, derived from three replicates of the reference moisture content data set (MC-Reference), range between 0.122 and 0.844, while those from the DHT-Prediction data set range between 0.751 and 1.509. These results underscore the reliability of the experimental data and the consistency of the DHT-Prediction model with observed trends.

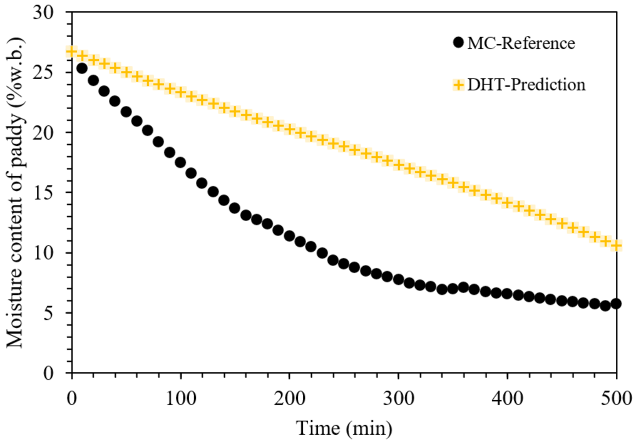

Figure 7 Paddy moisture content estimated from the method DHT-Prediction

3.3 Sensor accuracy and limitations

Considering Figure 7, the moisture content of paddy in the drying process can be predicted using the mass balance method according to Section 2.4 (DHT-Prediction) with data read from the DHT22 sensor causes prediction errors throughout the process, when compared to the reference moisture content (MC-Reference). The DHT22 sensor displayed limitations in high-temperature conditions, particularly after 340 minutes of drying, as seen from the residual data between minutes 340 and 500 (Consider from Figures 6 and 7). These readings indicate a sensor accuracy issue when operating at high temperatures, as residual moisture was still detected despite that equilibrium had been reached. Additionally, during the experiment, it was observed that some air escaped along with the rice at the outlet. This indicates inefficiencies in the cyclone's operation. This escaping air may contribute to the continuous drying of the paddy in the storage tank. Moreover, with each drying cycle, the temperature of the rice increased over time. It is likely that some moisture was transferred to the atmosphere while the rice was in the storage tanks, awaiting the next drying cycle. These observations and assumptions from the experiment contribute to inaccuracies in the predicted moisture content, as illustrated in Figure 7.

The study acknowledges the limitations of the DHT22 sensor, particularly its reduced accuracy at elevated temperatures, which compromises reliability during prolonged drying periods. Beyond the application of a correction factor, additional measures could mitigate these challenges. Strategic sensor placement, such as avoiding areas with turbulent airflow, may enhance measurement precision. Moreover, integrating supplementary sensors for cross-validation of data with the DHT22 sensor could further improve accuracy. Such a hybrid configuration holds potential to address the sensor's inherent limitations, particularly under extreme operating conditions.

3.4 Moisture prediction using correction factor

To address the limitations of the DHT22 sensor, a correction factor, termed Factor n, was introduced. This factor was adapted from previous research by Hemhirun and Bunyawanichakul [6], which employed a constant evaporation factor to estimate the moisture transfer rate. In this research, Factor n is a coefficient that is multiplied with the rate of water evaporation from the paddy to the air (denoted as m_{ma}). Factor n was calculated by comparing the reference paddy moisture content with data obtained from the DHT22 sensor, which measured the properties of moist air (derived from Eq. (8)). The relationship can be rewritten as Eq. (12). After that, the obtained values were used to study the pattern of relationship with time further.

$$Factor\ n = \frac{\sum_{t=0}^{t=N} m_{ma,ref}}{\sum_{t=0}^{t=N} m_{ma,sensor}} \tag{12}$$

where $m_{ma,ref}$ is the mass of water transferred to drying air from the reference data (kg), $m_{ma,sensor}$ is the mass of water transferred to drying air from the sensor data (kg), N is the drying time used for sampling.

The average experimental results revealed a logarithmic relationship between the factor (variable y) and drying time (variable x), as illustrated in Figure 8. The standard deviation of the data in Figure 8 ranged from 0 to 0.286, indicating the level of variability within the experimental dataset.

From the fitting of data, it was found that the regression line of the data was consistent with the function, with an R^2 value of 0.9659. When considering the relationship pattern from the equations that appear, it is found that the coefficients in front of the natural logarithm have similar values in all experiments and the constant values of all equations have slightly changed relatively. The trends and relationships were consistent across trials. The researcher therefore presents the use of factor n in the form of an average which is a function with time (t) by $y = -0.692\ln(t) + 5.6097$. It was applied to adjust the predicted moisture content by the times (DHT-Factor correction). This adjustment significantly improved the accuracy of moisture prediction, aligning the predicted values more closely with the reference data obtained from hot-air drying, as shown in Figure 9.

The approach of factor n brings the discussion to an important synthesis of existing knowledge. By adapting a method developed in previous studies to account for the evaporation dynamics in the drying process, this study successfully mitigated the discrepancies caused by sensor inaccuracies. This reflects the broader challenge in moisture content prediction, balancing cost-effectiveness with precision. In this case, by using factor n, the accuracy of moisture measurement improved significantly, indicating the potential for this method to be applied in other grain-drying systems or even adapted to other low-cost sensors for real-time assessment.

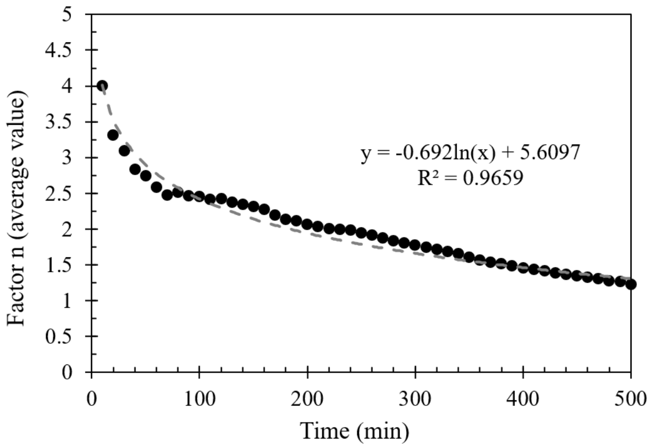

Figure 8 Relationship between Factor n and time

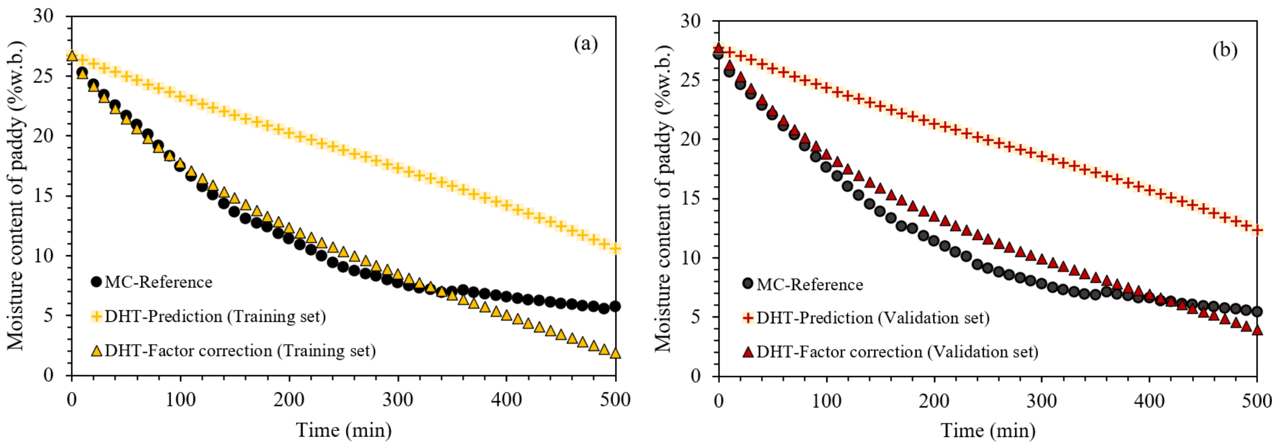

Figure 9 Evaluation of paddy moisture content (a) Training set (b) Validation set

3.5 Comparative of prediction methods

The evaluation of paddy moisture prediction results from the two approaches was conducted by dividing the drying period into 30%, 60%, and 100% of the time required for the paddy to reach equilibrium moisture content (approximately 500 minutes). The R^2 and RMSE values were used to assess consistency and discrepancies in the data, as shown in Table 1.

Table 1 Performance comparison of methods for evaluating paddy moisture content

Time division	Methods	Training set		Validation set	
		R^2	RMSEC	R^2	RMSEP
30%	DHT-Prediction	0.660	5.074	0.705	5.083
(150 mins)	DHT-Factor correction	0.997	0.502	0.996	0.549
60%	DHT-Prediction	0.250	7.826	0.254	7.774
(300 mins)	DHT-Factor correction	0.992	0.623	0.980	1.312
100%	DHT-Prediction	0.371	7.095	0.375	8.238
(500 mins)	DHT-Factor correction	0.907	1.814	0.963	1.241

For the validation of these methods, the data from the training set was provided initial model fitting while the validation data set assessed model robustness. During the initial 150 minutes period (30% of drying), the DHT-Prediction method achieved an R^2 of 0.660 and an RMSEC of 5.074 in the training set, with the validation set showing an R^2 of 0.705 and RMSEP of 5.083. In contrast, the DHT-Factor correction method showed superior performance, achieving an R^2 of 0.997 and an RMSEC of 0.502 in the training set and an R^2 of 0.996 and RMSEP of 0.549 in the validation set, highlighting minimal discrepancies between training and validation results.

As the drying period extended to 300 minutes (60%), the DHT-Prediction method displayed a decline in prediction accuracy, with an R^2 of 0.250 and RMSEC of 7.826 in the training set, and an R^2 of 0.254 with RMSEP of 7.774 in validation. The DHT-Factor correction method, however, maintained strong predictive accuracy, yielding an R^2 of 0.992 and RMSEC of 0.623 in training, with validation results of R^2 at 0.980 and RMSEP at 1.312.

For the full 500 minutes drying cycle, the DHT-Factor correction method continued to outperform, with an R^2 of 0.945 and RMSEC of 1.433 in the training set, compared to the DHT-Prediction method, which produced an R^2 of 0.371 and RMSEC of 7.095. The validation data reinforced these findings, with an R^2 of 0.963 and RMSEP of 1.241 for the DHT-Factor correction method, indicating strong consistency across both data sets.

This comparative analysis reinforces the effectiveness of the factor n correction method. While the DHT-Prediction method alone was prone to large errors due to sensor limitations and the complexity of the drying process, the factor n correction method significantly reduced these errors. The high R^2 values achieved with the factor n method, particularly during the initial drying phase, demonstrate its robustness in improving prediction accuracy. This suggests that similar correction factors could be developed for other sensor types or different drying processes, making this approach a valuable contribution to real-time moisture monitoring in both agricultural and industrial applications.

3.6 Comparison with previous studies

The results of this study align with previous research on moisture content estimation during the drying process. For example, the work by Hemhirun and Bunyawanichakul [6] employed a similar approach for moisture prediction, achieving a relative error of 4.3%. In contrast, the method proposed in this study, using the factor n correction, demonstrated improved accuracy, with a mean relative error of 2.75%. This comparison highlights the effectiveness of integrating correction factors to enhance prediction accuracy, particularly when using low-cost sensors like the DHT22.

Additionally, studies such as Armstrong et al. [9] and Lin et al. [11] have explored moisture measurement techniques for grains using various sensor technologies, including near-infrared spectroscopy (NIR) and relative humidity sensors. While these methods offered high accuracy, they were often more costly and complex to implement in medium-scale systems. The current study's use of the DHT22 sensor, combined with the Factor n correction, presents a more cost-effective alternative that still maintains competitive accuracy, particularly during the paddy drying process for stored.

Moreover, in comparison to the work by Pathaveerat and Pruengam [10], which utilized a low-cost reusable method for moisture estimation in paddy rice, this study offers a real-time, non-invasive solution that does not require manual sampling or colorimetric changes. The ability to continuously monitor moisture levels during the drying process represents a significant advancement in improving the efficiency of moisture control.

Although the correction factor can clearly help improve the results of predicting paddy moisture content in the pneumatic drying process, However, this method still has limitations in terms of specificity to the dryer, the type of agricultural material being studied, and the conditions under study. Expanding the results of this research to drying other agricultural materials with commercial dryers will require additional trials in a variety of conditions in the future.

Finally, the real-time monitoring approach in this study also reflects trends in precision agriculture, where non-destructive, continuous monitoring methods are gaining attention for their potential to enhance both quality control and operational efficiency. By developing a method that balances cost, accuracy, and ease of implementation, this study contributes to the ongoing efforts to improve moisture measurement technologies in grain drying systems.

4. Conclusion

The DHT22 sensor, when used for temperature and humidity measurements in a pneumatic paddy drying system, initially displayed significant errors in moisture estimation, particularly in high-temperature conditions. The DHT-Prediction method exhibited a low correlation with reference data, with R^2 values between 0.250 and 0.705 and RMSE values between 5.074 and 8.238. However, the introduction of the correction factor (DHT-Factor correction) significantly improved accuracy, particularly during the initial 150 minutes of the drying process. With this adjustment, the R^2 value rose to 0.997 and RMSEC dropped to 0.502 in the training set; similarly, an R^2 of 0.996 and RMSEP of 0.549 were achieved in the validation set. This enhanced prediction method was effective in reducing paddy moisture content to safe storage levels, demonstrating its potential for real-time moisture assessment in drying systems. Future research could explore the broader application of this method in other grain drying processes and drying periods at various experimental conditions.

5. Acknowledgements

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