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Developing a Lab-Scale Fluidized Bed Dryer System to Enhance Rough Rice Drying Process

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Developing a Lab-Scale Fluidized Bed Dryer System to Enhance Rough Rice Drying Process

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by

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Abstract

For more than half of the world's population, rice (*Oryza sativa L.*) is a staple meal. However, rice growers encounter difficulties supplying this demand, particularly in developing nations, where rice is susceptible to spoilage if the moisture content is not lowered to a safe level soon after harvest. As a result, traditional drying methods, such as sun drying and natural air drying, are commonly used by rice growers, particularly in underdeveloped nations. However, these procedures are time-consuming and can lead to rice spoilage. On the other hand, fluidized bed drying is a well-established technology that might give rice growers a rapid, practical, economical, and portable drying procedure. According to past research, the primary benefit of fluidized bed drying is the increased drying rate.

On the other hand, other research has expressed concerns about inferior rice quality, which is considered a significant weakness in fluidized bed drying. In the United States of America, the farmers and processors lack consensus and thus there is a mistrust to utilize fluidized bed drying for rice. As a result of the lack of agreement, an extensive study to understand the fluidized bed drying of rice is needed.

In the Mid-South region of the United States, high humidity ambient air is typical, resulting in stoppage of the in-bin rice drying process to avoid rewetting of rice. Ambient air dehumidification may be able to solve this problem and allow for a continual drying process. However, no study utilized desiccant for ambient air dehumidification for drying rice; through this study, an attempt was made to bridge the research gap and determine the benefits and practicalities of ambient air dehumidification to achieve continuous rice drying.

A lab-scale mobile batch fluidized bed dryer was constructed and used in this study. Several tests were done to improve the system that included designs, additions, and replacements of parts.

In a fluidized bed and fixed bed drying system, the effects of ambient air dehumidification, air temperature, and drying duration on rough rice quality was investigated. Energy and exergy analyses were done to determine the thermal efficiency of the drying system. Mathematical modeling was done to optimize the drying of rough rice.

Overall, it was found that fluidized bed drying technology can be utilized for drying rough rice without compromising the quality compared to the fixed bed drying. The air temperature used was between 40 to 50°C, and rice was dried for no more than 60 min. In addition, the ambient air dehumidification reduced the relative humidity of drying air and did not affect rice quality but increased the rice moisture removal, ultimately increasing the drying rate.

The study recommends using air temperatures below 50°C and a drying duration of less than 60 min to achieve effective rough rice drying with fluidized bed drying technique. In addition, ambient air dehumidification can be employed for reducing ambient air relative humidity by few points. However, more research must be done at the farm and industrial scale to check the accuracy of these findings at a large scale.

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Dedication

This dissertation is dedicated to the 3 most important women in my life: my mother, Swati Luthra Gogna, my mother-in-law, Anju Mishra, and my wife, Akshita Mishra.

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2. Chapter 3 (published)

Sadaka, S. S., Luthra, K., & Atungulu, G. G. (2018). Evaluation of the Performance of a Custom-Made Fluidized Bed Drying System. *Applied Engineering in Agriculture, 34*(6), 1027-1037.

3. Chapter 4 (published)

Luthra, K., Shafiekhani, S., Stephens, B., Sadaka, S., & Atungulu, G. G. (2019). Evaluation of the Performance of a Newly Developed Wireless Temperature and Moisture Sensor for Rice under Various Levels of Temperature, Moisture Content, and Dockage. *Applied Engineering in Agriculture, 35*(3), 311-318.

4. Chapter 5 (published)

Luthra, K., Sadaka, S., & Atungulu, G. G. (2018). Exploration of Rough Rice Head Yield Subjected to Drying and Retention Durations in a Fluidized Bed System. *Applied Engineering in Agriculture*, *34*(5), 877-885.

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Luthra, K., & Sadaka, S. (2021). Investigation of rough rice drying in fixed and fluidized bed dryers utilizing dehumidified air as a drying agent, *Drying Technology*, *39*:8, 1059-1073, DOI: 10.1080/07373937.2020.1741606

6. Chapter 7 (published)

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7. Chapter 8 (under review)

Luthra, K., & Sadaka, S. (2021). Impact of air dehumidification, air temperature, and drying duration on fluidized and fixed-bed systems' energy and exergy efficiencies during rough rice drying.

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8. Chapter 9 (under review)

Luthra, K., & Sadaka, S. (2021). Mathematical modeling of rough rice dehydration with dehumidified air in a fluidized bed drying system.

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Chapter 1: Introduction

1. Rice production

Rice grain (*Oryza sativa L.*) is considered the staple food and feeds more than 3 billion lives daily (Hashimoto et al., 2020; Sen et al., 2020). With a global annual production of around 740 MMT, rice is also considered the most critical food crop globally. Asia harvests and consumes around 90% of the world's rice crop. Few other countries outside Asia such as Brazil, Egypt, and the United States, produce rice in surplus. In 2020, the United States estimated annual production of rice was 11.6 MMT (USDA NASS, 2020). The U.S. domestic consumption is easily met, and most of the produced rice is exported. As a result, the United States was the fourth-largest among rice exporters in 2020. The Arkansas Grand Prairie, the Mississippi Delta (parts of Arkansas, Mississippi, Missouri, and Louisiana), the Gulf Coast (Texas and Southwest Louisiana), and the Sacramento Valley of California have historically produced most of the US rice supply (Atwill, 2015). Since 1973, Arkansas has been the most crucial rice-producing state in the United States, accounting for 5.5 MMT, i.e., 47.4% of total rice production in 2020 (USDA NASS, 2020).

Most of the grains are harvested at high moisture content levels, making them unfit for long-term storage (Sadaka and Atungulu, 2018). In addition, grain may develop mold due to the delayed drying process and the excessive moisture content. Grain drying on a modest scale on the farm is, therefore, necessary to lower grain moisture content to levels safe for storage (Reddy et al., 2008). In the Mid-South, rough rice is typically harvested around 14 to 22 percent moisture content (wet basis). Therefore, the rice should be dried to 12.5 percent moisture content (wet basis) as soon as possible after harvesting to reduce respiration rates and mold growth and prevent fungi and insect proliferation (Dillahunty et al., 2000).

2. Problems

2.1 Fluidized bed drying debate

Drying is a contemporary process that incorporates both heat and mass transfer, with the main forces being enthalpy and concentration changes. Farmers and producers dry rough rice on-farm to preserve it for sale at a higher price during the off-season. Rice drying off-farm is the most common drying method in the United States, where rice is dried after harvest in processing factories. According to Kunze and Calderwood (2004), around 20% of rice produced in the United States is dried on-farm with natural or low-temperature air. Typical weather circumstances may not allow the drying front to travel quickly enough within the grain mass with on-farm in-bin drying systems, where rice is progressively dried from the bottom to the top. Fluidized bed drying has developed some promise as a drying technology for rice due to increased output and unpredictable weather, directly influencing sun drying and natural air drying in developing nations (Proctor, 1994). However, there is an ongoing debate on using this technique for drying rough rice. Numerous studies support commercializing this rice drying technique because of the high drying rate, which may avoid rice spoiling and dry a considerable rice volume with high moisture content. On the other hand, several studies are opposed to adopting this method, citing the reduced head rice yield of rice dried using the fluidized bed drying process. No agreement on the effectiveness of this technique is available in the U.S., thus leading this technique untapped for rice drying benefits.

2.2 Humid ambient conditions

As mentioned above, that farmers in the United States utilize ambient air for on-farm in-bin drying. The main disadvantage of ambient air drying is its reliance on the weather. Humid, cold, or rainy circumstances halt the drying process and, in some instances, cause the rice to rewet, raising the drying cost and lowering the quality. Not many options are available to the producers. One of the few options includes costly ambient air heating, not preferred by the farmers. They are willing to stop the drying process for an eventual loss rather than using costly ambient air heating.

3. Research gaps & study aim

Following were the research gaps identified and addressed in this research:

1. There is a debate on utilizing fluidized bed drying of rough rice by weighing in the potential positive of high drying rate with the potential negative of low milling yield.
2. There is a need to develop a desiccant-based system for ambient air dehumidification integrated with the fluidized bed dryer.
3. No research has looked at the influence of FBD on rice pasting qualities using ambient air dehumidification.
4. There has not been much research on the energy and exergy of rough rice drying in a batch fluidized bed dryer. Furthermore, no research has been done on the energy and exergy of drying rough rice in fluidized beds with ambient air dehumidification.

This extensive research focused on addressing the abovementioned research gaps. In this work, to better understand the rough rice fluidized bed drying process, the laboratory size fluidized bed dryer was used to identify dried rice quality, pasting properties, and energy and exergy of the system. In addition, ambient air dehumidification was achieved with silica gel, and its effects on the drying process were evaluated. Modeling was also developed to optimize the system's performance. Thus, the overall aim of this study was to enhance the fluidized bed drying technology for use in the U.S. to dry rough rice by providing solutions for the dried rice quality reduction and humid ambient air leading to rice drying delays.

4. Objectives

This dissertation follows the "published/submitted papers" approach, with each chapter consisting of a manuscript that has been published or is currently under review in a peer-reviewed journal. Accordingly, the following are the precise objectives of each chapter of this dissertation:

Chapter 2

(1) to explore fluidized bed drying technology and details its advantages and disadvantages related to rice drying, (2) to understand the effects of the operating parameters involved in fluidized bed drying, i.e., rice moisture content, drying temperature, airflow rate, air velocity, drying duration, and tempering duration, on dryer performance and rice quality, and (3) to understand the past work on modeling of fluidized bed drying of rice and the energy and exergy efficiencies of fluidized bed dryers and suggests opportunities for research associated with fluidized bed drying of rice.

Chapter 3

(1) to study the effects of aspect ratio, drying temperature, and drying duration on wheat moisture content, drying rate, and drying efficiency, and (2) to develop two empirical models to predict the wheat moisture content and dryer efficiency as a function of the previously mentioned operating parameters.

Chapter 4

(1) to test the accuracy and precision of the probes for a practical range of on-farm drying air temperature, rough rice initial moisture content, and dockage levels; (2) to identify the

calibration equations for the probes based on the standard values of temperature and moisture content.

Chapter 5

(1) to determine the effects of drying and retention durations on the bed temperature profile, moisture content, head rice yield, and energy consumption per unit mass of water removed.

Chapter 6

(1) to investigate the effects of ambient air dehumidification and the air temperature on dried rice moisture content, drying rate, head rice yield, whiteness, and energy consumption in fixed and fluidized bed dryers.

Chapter 7

(1) to evaluate the effects of ambient air dehumidification, air temperature, and drying duration on rice quality and pasting properties using fluidized bed and fixed bed drying systems

Chapter 8

(1) to identify the effects of bed condition, air temperature, drying duration, and ambient air dehumidification on energy utilization, energy utilization ratio, and specific energy consumption, and (2) to identify the effects of bed condition, air temperature, drying duration, and ambient air dehumidification on exergy loss and exergy efficiency during rough rice drying.

Chapter 9

(1) to determine the best fit kinetic model of rough rice fluidized bed drying, (2) to evaluate the effects of air temperature and ambient air dehumidification on the model constants, and (3) to determine the effective moisture diffusivity and the activation energy of rough rice drying with dehumidification and without dehumidification of ambient air.

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Chapter 2: Challenges and opportunities associated with drying rough rice in fluidized bed dryers: a review

Contributing Authors: Kaushik Luthra and Sammy Sadaka

1. Abstract

Rice (*Oryza sativa L.*) is a staple food for more than half the world's population. World rice production reached approximately 732 million metric tons (MMT) in 2018 due to the ever-increasing demand driven by population and economic growth. Rice producers face challenges in meeting this demand, especially in developing countries where rice is prone to spoilage if the moisture content is not reduced to a safe level shortly after harvest. Rice producers, particularly in developing countries, typically use conventional drying methods, i.e., sun drying and natural air drying. These methods are time-consuming and environmentally dependent. On the other hand, fluidized bed drying, which is a well-established technology, could provide rice producers with an effective drying technique that is quick, practical, affordable, and portable. Several innovative designs for fluidized bed dryers have been developed that could be installed on-farm or off-farm at a reasonable cost. Some studies have mentioned that the main advantage of fluidized bed drying is the increase in drying rate and the reduction of rice spoilage after harvest. Conversely, other studies have raised alarms regarding low rice quality, which is seen as a significant flaw of fluidized bed drying. Due to this lack of consensus, there is a great need to review this drying technology objectively. Therefore, this review article explores fluidized bed drying and details its advantages and disadvantages related to rice drying. It also sheds light on the effects of the operating parameters involved in fluidized bed drying, i.e., rice moisture content, drying temperature, airflow rate, air velocity, drying duration, and tempering duration, on dryer performance and rice quality. Several fluidized bed numerical models are also reviewed and evaluated. Additionally, this review explores the energy and exergy efficiencies of fluidized bed dryers and suggests opportunities for research associated with fluidized bed drying of rice.

Keywords. Energy, Exergy, Fluidized bed drying, Fluidized bed modeling, Moisture content,

Rice quality, Rough rice, Tempering.

2. Introduction

Rice is the most common staple food in the world and is consumed by more than 3.5 billion people daily. The world's annual production of rice in 2018 reached approximately 732 MMT (USDA-ERS, 2018). About 90% of the world's rice production is harvested and used in Asia. Other areas of rice production include a few countries in South America, i.e., Brazil, Paraguay, and Uruguay, as well as the U.S. The U.S. was the fourth-largest exporter of rice in 2018, with an annual production of approximately 11.4 MMT. In the U.S., rice production occurs in the Central region (Arkansas, Mississippi, Missouri, Louisiana, and Texas) and the Sacramento Valley of California (Atwill, 2015). Arkansas has been the most crucial rice-producing state since 1973, with about 47.9% of total U.S. rice production in 2018 (USDA-ERS, 2018). Rough rice is typically harvested at a moisture content above 20% wet basis (w.b.) The high moisture content of freshly harvested rice should be reduced quickly to a safe moisture content of 13% (w.b.) to avoid spoilage (Benado and Rizvi, 1985; Reddy et al., 2008).

2.1 Fluidized bed technology

Rough rice is dried on-farm by producers to preserve rice for personal use or for selling at higher prices in the off-season. Off-farm drying of rice is prevalent in the U.S., where most rice is dried after harvest at processing plants. Kunze and Calderwood (2004) reported that only about 20% of rice produced in the U.S. is dried on-farm using natural air or low-temperature air. Typically, with on-farm in-bin drying systems, in which the rice is dried slowly from the bottom to the top of the bin, prevailing weather conditions may not allow the drying front to move quickly enough through the grain mass. To overcome this slow drying rate, several promising drying technologies have been introduced, including crossflow drying, layer drying, and fluidized bed drying. Fluidized bed (FB) drying is a well-established technology that has been in use for almost three decades for drying rough rice (Tirawanichakul et al., 2004; Karbassi and Mehdizadeh, 2008; Tuyen et al., 2009).

FB dryers are the most commonly used type of dryers for chemicals, fertilizers, pharmaceuticals, and agricultural produce (Srinivasakannan et al., 2012). FB dryers show reasonable drying rates in particulate handling industries. The reasons for adopting FB dryers are good gas contact with the wet particles, high heat transfer between the gas and particles, reasonable circulation rates, and fast drying with excellent product quality compared to conventional dryers. To enhance the drying process with minimal energy usage, various researchers have reported modified designs for FB dryers (Tahmasebi et al., 2014; Jafari and Zare, 2017; Yahya et al., 2017) and have conducted experiments and developed theoretical models with different design modifications (e.g., microwave, ultrasonic, and solar).

Specific to rice drying in the U.S., there has been a debate on the use of FB drying. Numerous studies are in favor of commercializing this technology for drying rice due to the high drying rate, which can prevent spoilage and can dry large amounts of high-moisture rice. On the other hand, several studies are against the use of this technology and point to the lower head rice yields that result from FB drying.

No consensus is available on the use of FB drying for rice in the U.S. Thus, there is a need for a comprehensive review of the FB drying technology used for drying rice in the U.S. Accordingly, this review article explores FB drying technology and details its advantages and disadvantages related to rice drying. It also sheds light on the effects of the operating parameters involved in FB drying, i.e., rice moisture content, drying temperature, airflow rate, air velocity, drying duration, and tempering duration, on dryer performance and rice quality. Several FB numerical models are also reviewed and evaluated. Additionally, this review explores the energy and exergy efficiencies of FB dryers and suggests opportunities for research associated with FB drying of rice.

2.2 The debate about FB drying of rice

As mentioned previously, FB drying is not new and is used commercially in Asia to dry rough rice (Sutherland and Ghaly, 1990). Research in Asia has recommended the use of FB drying of rice without compromising rice quality (Soponronnarit and Prachayawarakorn, 1994). However, due to the differences in climate, rice varieties, and the amount of throughput, FB drying of rice has not yet gained equivalent acceptance in the U.S. (Ondier et al., 2010). There are also differences in the results and recommendations of different researchers, as discussed in the following sections.

3. Factors affecting fluidized bed drying of rice

For any perishable food product, drying for safe storage depends on several factors. Studies have short-listed a few factors that play a significant role in FB drying of rice. These factors include air temperature, air relative humidity, airflow rate, air velocity, initial moisture content of rice, drying and tempering duration, and the FB design (Banaszek and Siebenmorgen, 1990; Brook, 1992; Prakash and Pan, 2011; Sharada, 2013). Representative studies of FB drying of rice are summarized in table 1.

3.1 Air Temperature

The drying air temperature is the temperature at which the drying of rice occurs. The temperature of the rice bed equalizes with the heated air temperature in a short time. The inlet air temperature is inversely proportional to the drying time (Gazor and Mohsenimanesh, 2010). During the drying process, the air temperature affects the diffusion of moisture. At higher temperatures, the particles absorb more heat for water evaporation than at lower temperature, and hence the evaporation rate increases. The drying rate depends on the resident temperature of the solids in the bed (Da Silva et al., 2012). Reay and Baker (1985) reported that the bed temperature had a significant effect on the drying rate with both large and small particles. Giner and Calvelo (1987) performed FB drying of wheat and found that increasing the bed temperature from 40°C to 70°C decreased the drying duration by a factor of four. Sadaka et al. (2018) reported that the grain temperature increased, and the drying duration decreased, with an increase in air temperature.

For rice, several studies have used very high air temperatures (up to 150°C) with FB drying and found that the drying rate increased with increasing air temperature (Soponronnarit, 1999; Taweerattanapanish et al., 1999; Karbassi and Mehdizadeh, 2008). Bonazzil et al. (1997) studied the effect of thermal shock on rice quality. They reported that no loss in rice quality occurred with temperatures ranging from 30°C to 90°C. Similarly, Soponronnarit and Prachayavaracorn (1994) found that any air temperature less than 115°C was suitable for drying rice. However, some researchers have reported otherwise. Cnossen and Siebenmorgen (2000) mentioned that any temperature above 60°C reduced the head rice yield (HRY).

Table 1. Studies of fluidized bed (FB) drying of rice along with their operating parameters and findings.

Dryer Type	Study Objective	Operating Parameters	Findings	Reference
FB	To select the best model for drying rough rice and determine the effects of operating variables on drying characteristics.	Air temperature (50°C, 60°C, and 70°C), air velocity (2.3, 2.5, and 2.8 m s^{-1}), and solids holdups of 0.66 and 1.32 kg.	The Midilli et al. (2002) model was best for describing the drying characteristics of rice. Drying rate increased with increase in air temperature and air velocity.	Khanali et al. (2012)
FB	To examine effects of high-temperature FB drying and tempering on pasting, gelatinization, crystalline, and microstructural properties of long-grain rice.	Air temperature (80°C and 90°C), drying duration (2.5 and 3 min), tempering temperature (75°C and 86°C), and tempering duration (0, 30, 40, and 60 min).	Pasting properties and gelatinization enthalpy decreased with increasing temperature and tempering duration, while the pasting and gelatinization temperature increased.	Truong et al. (2019)
Solar-assisted FB	To introduce a less expensive drying option for drying rice.	Air temperature (100°C to 150°C), bed depth (10 to 11 cm), and air velocity (1.6 to 2.3 m s^{-1}).	FB drying with ambient air ventilation achieved dried rice quality similar to the local practice.	Jittanit et al. (2010)
Cross-flow FB	To develop a mathematical model and simulation of the rice drying process.	Air temperature (50°C to 60°C) and feed rate 1000 kg h^{-1}.	The experimental results fitted well with the developed mathematical model.	Izadifar and Mowla (2003)
Vibrating FB	To examine the effect of FB drying of rice and how the Page equation fits the drying data.	Air temperature (160°C to 240°C).	Discoloration of rice was noted at about 240°C air temperature. The Page model fit well with the experimental data.	Ramesh and Rao (1996)
Inclined bed FB	To determine the effect of inclined bed drying after FB drying of rice.	Dryer bed area, air temperature, air relative humidity, and air velocity.	Inclined bed drying with FB drying helped to increase rice quality.	Sarkar et al. (2014)
Plug-flow FB	To develop a sequential method to model continuous plug-flow FB drying of rice.	Initial moisture content of rice, air temperature and velocity, and particle flow rate.	The developed model was highly accurate in predicting the final moisture content of rice.	Bizmark et al. (2010)
FB	To investigate the cooking and pasting properties of waxy rice after FB drying.	Air temperature (90°C to 150°C).	Thermal degradation of amylopectin granules at higher temperatures was noted and led to easy digestion of the starch.	Jaiboon et al. (2011)
FB	To determine the effects of initial rice moisture content, drying temperature, and tempering on head rice yield (HRY).	Initial moisture content of rice (25%, 30%, and 35% d.b.), air temperature (110°C, 130°C, 150°C, and 170°C), and drying time (1, 2, 3, and 4 min).	Initial moisture content and tempering had significant effects on HRY, and drying temperature should not be greater than 150°C after the first stage of drying.	Poomsa-ad et al. (2005)
FB	To investigate the effects of FB drying using superheated steam and hot air on the physical properties of soaked rice.	Fluidization velocity (1.3 to 1.5 min) and soaking time in water (3 to 4 h).	HRY and whiteness of rice were superior with superheated steam compared to hot air in FB drying.	Rordprapat et al. (2005)

Thus, there is no explicit agreement on the optimum drying air temperature for rough rice. Previous studies have clearly shown that the highest acceptable drying temperature, that does not compromise rice quality, depends on the specific variety of rice.

3.2 Air Relative Humidity

The humidity of the inlet air has an inverse effect on the drying rate; it should be as low as possible for faster drying. Moisture in the air also has intense effects on the rate of evaporation and the temperature profile (Reyes et al., 2007). For drying to occur, the relative humidity of the drying air must be low enough so that the air can absorb moisture from the rice. Heating the air is the simplest way to lower its relative humidity. Brook (1992) reported that increasing the air temperature by 11°C reduced the relative humidity by about half. The heated air increases the temperature of wet rice, increasing the vapor pressure of the moisture within the rice, and thereby accelerating the evaporation of moisture to the heated air (Brook, 1992). When heating the air is not possible, the airflow can be increased to remove moisture at the required rate. Alternatively, the air relative humidity can be reduced by passing the humid air through a desiccant that absorbs moisture from the air; the desiccant can be regenerated thermally, as reported by Luthra and Sadaka (2019).

3.3 Airflow Rate and Velocity

The airflow rate, or the volume of air blown into the FB for drying, depends on the static pressure of the FB. The static pressure is estimated based on the rice depth and pressure losses, and thus the airflow rate can be determined (Brook, 1992; Sadaka, 2014). An increase in airflow rate in general increases the drying rate; as more air flows through the rice, more moisture is removed. Airflow is an essential factor in understanding FB behavior. The airflow should be determined carefully if the freeboard region has an open end. With a continuous FB drying system, an air collection system should be incorporated. Huynh et al. (1991) reported that a 0.3 m grain bed depth, which presented a static pressure of 1.3 cm of water, required an airflow rate of 6.5 m^3 min^{-1} m^{-2}. Reay and Baker (1985) reported that the drying rate for smaller particles was directly proportional to the airflow rate in FB drying. For solid by-products from an olive oil mill, Liebanes et al. (2006) suggested that increasing the airflow rate and air temperature increased the drying rate for FB drying. Topuz et al. (2004) found that the drying rate decreased with increasing airflow during FB drying of hazelnuts. Accordingly, the discharge of air through the blower should be optimum.

The minimum fluidization velocity is affected by the properties of the particles and of the air; thus, it is an essential factor for the design and operation of FB dryers. The moisture content of the particles decreased rapidly at higher air velocities (Djaeni et al., 2013). An increase in air velocity may also lead to an increase in bubble size in the FB. Particles are easily fluidized at high air velocities. As a result, mass transfer and heat transfer can easily occur in the bed. Unexpectedly, the air velocity, rather than the temperature, dominates the performance of FB dryers (Villegas et al., 2008).

3.4 Drying and Tempering Durations

The drying duration is directly proportional to the moisture removed from the rice. Therefore, the drying duration depends on the initial moisture content and the targeted final moisture content of the rice. The drying duration also depends on the air temperature, relative humidity, and airflow rate.

Tempering reduces the moisture content gradient between the surface and center of the rice kernels that develops during drying. Many studies have reported a positive effect of tempering on HRY. Cnossen et al. (2003) tested three different drying conditions; for all conditions, the HRY increased with increasing tempering duration. Schluterman and Siebenmorgen (2007) tested tempering durations of 0 to 160 min for rough rice and found that the HRY increased with increased tempering duration. Poomsa-ad et al. (2001) and Soponronnarit (1999) showed the positive effect of tempering duration on rice quality using a fluidization technique.

3.5 Initial Moisture Content

The initial moisture content of rough rice also plays a significant role in determining the final moisture content and rice quality. Schluterman and Siebenmorgen (2007) showed that the final moisture content of dried rice is directly proportional to the initial moisture content of harvested rice. The drying rate of rice decreased with a decrease in moisture content. The drying rate also decreased with FB drying, as mentioned by Luthra et al. (2018) and Sadaka et al. (2018). The decrease in drying rate occurs because of the lack of surface water or free water during the later phase of drying. The bound water present in the later phase of drying requires more time to evaporate, and thus the drying rate decreases with a decrease in the initial moisture content of rice.

3.6 Particle Size and Density

Fluidization depends on the properties of the particles, i.e., particle size and bulk density (Gong et al., 1997). Fluidization is smooth and homogenous for small and low-density particles. It can occur with a low airflow rate, and the growth and speed of the bubbles can be controlled.

Different varieties of rough rice have significant variation in their dimensions, as reported by Bagheri et al. (2013). Short grain rice, medium grain rice, long grain rice, and extra-long grain rice have kernel lengths of $L < 5.5$ mm, 5.5 mm $\leq L < 6.5$ mm, 6.5 mm $\leq L < 7.5$ mm, and $L \geq$ 7.5 mm, respectively. The bulk density of rough rice generally varies between 300 and 600 kg m^{-3}, depending on the cultivar (Bagheri et al., 2013; Patel et al., 2013). The particle size and density change with different rice varieties (short, medium, long-grain, and extra-long), which in turn changes the drying rate in FB dryers because the contact surface area changes. Ulku and Uckan (1986) reported that the drying rate increased in FB drying with an increase in the contact area or size of the particles.

3.7 Solids Holdup

Solids holdup is the amount of drying material in the FB. In a study on granular materials modeling, the drying rate decreased with an increase in solids holdup (Proctor, 1994). An increase in solids holdup decreases the bed temperature because there is more material to be dried, and therefore the drying rate decreases. Srinivasakannan and Balasubramanian (2006) studied FB drying of ragi, a cereal crop grown in Asia and East Africa, and concluded that the drying rate increased significantly with a decrease in solids holdup and an increase in air temperature.

3.8 Interdependent Factors

Several of the previously mentioned factors, i.e., air temperature, relative humidity, airflow rate, air velocity, drying duration, tempering duration, and initial moisture content of rice, are dependent on each other. Many studies have reported the interdependency and correlation of these factors with each other. Brook and Foster (1982) reported that the drying duration increased with an increase in grain depth and a decrease in initial moisture content. Drying from 15% to 12.5% (w.b.) moisture content can be done for any desired period (Mrema et al., 2012). Mrema et al. (2012) reported that rice below 15% (w.b.) moisture content can be safely stored for an extended period, as long as an airflow of at least 2.7 $m^3\ min^{-1}\ t^{-1}$ is applied, which is satisfactory for maintaining rice quality. For wetter rice and unfavorable conditions, an airflow of 3.5 $m^3\ min^{-1}\ t^{-1}$ is required.

Supplemental heat has been used to increase the air temperature during cold weather or at night to keep the relative humidity low. Supplemental heat also reduced the drying time by 25% to 65% compared with using airflow without supplemental heat (Mrema et al., 2012). Misra and Brooker (1980) suggested that the air temperature had the most significant effect on the drying rate, whereas airflow and air relative humidity had minor effects. They even suggested that air relative humidity can be ignored as a factor in determining the drying rate for thin-layer modeling. Bonazzil et al. (1997) found similar results, i.e., the drying time for rice was 20 times faster at 80°C than at 30°C and seven times faster than at 45°C. They also reported that drying increased with lower relative humidity of the air; however, similar to Misra and Brooker (1980), they considered relative humidity to be much less important than air temperature.

4. Advantages and disadvantages of fluidized bed dryers

FB drying has many advantages, including: (1) The rice is thoroughly mixed, which leads to homogeneity of the thermal treatment and ensures uniform drying with a high drying rate (Wimberly, 1983; Avidan and Yerushalmi, 1985; Kassem et al., 2011). (2) The turbulence in the bed creates high heat and mass transfer rates, which allow a shorter drying duration (Richardson, 1971; Avidan and Yerushalmi, 1985). (3) Large amounts of rice can be moved quickly in the fluidized state, which improves product handling (Avidan and Yerushalmi, 1985). (4) FB drying can accommodate varying particle sizes (Avidan and Yerushalmi, 1985). (5) FB drying can significantly reduce the drying duration compared to conventional drying methods (Sutherland and Ghaly, 1990; Srinivasakannan and Balasubramaniam, 2006). (6) FB drying requires a reasonable initial investment compared to some conventional methods (Wimberly, 1983; Sopanronnarit et al., 1998; Gazor and Mohsenimanesh, 2010).

Notwithstanding the above advantages, there are also a few disadvantages of FB drying, which include: (1) The design and structure of FB dryers are more complicated compared to conventional dryers (Avidan and Yerushalmi, 1985). (2) Scale-up of FB drying can be challenging (Avidan and Yerushalmi, 1985). (3) Erosion of the FB dryer walls can be an issue and can require maintenance (Avidan and Yerushalmi, 1985). (4) FB drying produces an increased amount of particle breakage (Kunze, 1983) (5) High energy costs are associated with FB dryers. (6) The dried rice requires tempering before further processing, i.e., milling (Villegas et al., 2010).

5. Challenges with FB drying of rice

Apart from the abovementioned advantages and disadvantages, there are some challenges associated with the application of FB drying technology for rice. Feeding of rice into the FB drying column can be challenging because the entire column cannot be filled at once. Separation of the dried rice from the incoming wet rice is another challenge, especially when the FB dryer is operating with high airflow. At high airflow, the moving grain creates more wear on the dryer walls; thus, dryer maintenance can be a challenge. An additional challenge is dust blown upward due to the higher airflow. Dust production increases due to kernel-to-kernel and kernel-to-wall friction. Consequently, managing the dust can be a challenge, and there is a risk of dust explosion. Kauffman (1987) reported that dust explosions can cause injuries, disrupt the drying and milling process by affecting the equipment, and cause financial loss.

Another challenge is the scaling-up of laboratory FB dryers for commercial use (Matsen, 1996; Daud, 2008). A limited number of theoretical models exist for FB drying that can replace the expense of numerous pilot-plant trials. Theoretical modeling of a scaled-up FB dryer is difficult because the bubbling characteristics and mixing behavior differ greatly with the variation in size from laboratory scale to industrial scale. This limitation requires testing at both laboratory scale and pilot-plant scale to formulate a scaling-up plan for the dryer. Thus, it is essential to determine a method for reducing the costs of pilot-plant experiments (Knowlton et al., 2005).

6. Heat transfer in FB dryers

Heat transfer in FB dryers can occur in two ways. The first form of heat transfer occurs between the air and the solid particles, as in many other processes. The second form of heat transfer occurs between the bed phases, i.e., bubbles, clouds, and emulsion, which exist only in FB systems. The bubbles in FB systems act like liquid bubbles with low viscosity. FB systems are characterized by excellent heat transfer between the fluidized layer and the heating surfaces (Roy and Sarma, 1970).

7. Drying rice in FB dryers

Various designs of FB dryers have been developed. Based on their structural design, there are four FB categories: static, vibrating, circulating, and annular (Hemis et al., 2019). Novel techniques are also used in combination with FB drying, such as microwave-assisted or infrared-assisted FB drying, solar-assisted FB drying, inclined bed drying combined with FB drying, impinging steam combined with FB drying, and continuous plug-flow FB drying (Wimberly et al., 1983).

Solar FB dryers can work on-farm, with their energy requirements met by solar energy, providing a solution for off-grid farmers in developing countries (Sopanronnarit et al., 1998; Yahya, 2016). Jafari and Zare (2017) used ultrasound with FB drying to investigate the drying effects on rice quality. Meeso et al. (2004) used far-infrared irradiation to dry rough rice with FB drying. The irradiation time was 0.5 to 1.0 min with a radiative intensity of 0.310 to 0.707 W cm^{-2} and 1 to 2 min of tempering. Temple et al. (2000) used multi-stage FB drying with air recirculation. Kozanoglu et al. (2013) studied the drying kinetics of rough rice in a reduced superheated steam FB system and found that the drying rate increased with an increase in drying air temperature. Sarker et al. (2017) studied rice quality during the drying process using an inclined FB. Ramesh and Rao (1996) used a vibrating FB dryer to dry rice at temperatures ranging from 160°C to 240°C. Rordprapat et al. (2005) used superheated steam in FB dryers to investigate the physical properties of rough rice during drying. An airflow rate of 1.3 to 1.5 times the minimum fluidization velocity was used with 3 to 4 h of soaking time in water. The results showed that HRY and whiteness improved with the use of superheated steam as compared to hot air.

Stakic and Urosevic (2011) studied a vibrating FB dryer experimentally and with simulations using fine-grained materials. They reported that the temperature differences in the bed were almost negligible (±1.0°C) due to the mixing of particles. Comparison of the drying kinetics, experimentally and numerically, showed that a higher airflow rate and temperature increased the drying rate. This effect was pronounced for deeper beds because of the greater amount of grain to be dried using the equivalent drying capacity. In a study on jasmine rice, Atthajariyakul and Leephakpreeda (2006) adapted a fuzzy logic technique optimized for quality control with FB drying. They concluded that a drying temperature of 150°C with 33% initial moisture content and 90 min of tempering were the best conditions for drying.

7.1 Research supporting FB drying of rice

Wiset et al. (2001) dried rough rice with two different FB drying treatments. The first treatment involved drying at 90°C for 11 min, and the second treatment was two-stage drying: fluidization until 18% (w.b.) moisture content, followed by drying in storage using ambient air. For the second treatment, the HRY did not decrease, as in the first treatment. Poomsa-ad et al. (2001) included tempering in their experimental design and showed that tempering helped in achieving an acceptable HRY with FB drying. Thakur and Gupta (2006) compared FB and fixed bed drying of rough rice and concluded that the energy use could be reduced by half and the drying rate enhanced with FB drying, without compromising rice quality. Sarker et al. (2017) reported acceptable HRY and whiteness for rice dried in an inclined bed FB dryer. Wetchacama et al. (2000) reported a 5% greater HRY in a commercial-scale FB dryer as compared to fixed bed ambient air drying. Using Vietnamese rice varieties, Tuyen et al. (2009) tested the effects of high-temperature FB drying along with tempering. They found that the HRY increased tremendously with tempering for 40 min, and the hardness of the rice kernels was greater with FB drying as compared to thin-layer drying. Improved HRY was also reported by Meeso et al. (2004). They used far-infrared irradiation and tempering with FB drying and achieved a 58% maximum HRY, which was higher than the control samples. Rattanamechaiskul et al. (2016) reported an increase in HRY for purple rice using hot-air FB drying; the maximum HRY reported was 46%. Sarker et al. (2013) reported no difference in the HRY using ambient air drying and FB drying. Jafari and Zare (2017) studied the drying behavior and energy consumption for rough rice using an ultrasonic FB dryer. Their objective was to study the influence of high-power ultrasound on FB drying of rice based on the relationships of drying kinetics, grain quality (kernel bending strength and percentage of cracked kernels), and specific energy consumption. Application of high-power ultrasound in conjunction with traditional FB drying resulted in a 23% decrease in drying time as well as enhanced grain quality, as measured by percentage of cracked kernels and kernel bending strength.

Parboiling of rough rice is a process that requires drying. Parboiling increases the nutritional value, improves the quality of cooked rice, and decrease the breakage of milled rice. Parboiling is conducted in three stages: soaking, steaming, and drying. Prachayawarakorn et al. (2018) combined microwave and hot-air FB (MWFB) to produce parboiled rice. They tested the effects of bed depth, drying temperature, and microwave power on drying time. Their results showed that the drying time was shorter with a shallower bed, higher drying temperature, and higher microwave power. The drying temperature, bed depth, and microwave power strongly affected the gelatinization of rice starch. The parboiled rice produced by MWFB resulted in insignificant broken kernels (1% to 2%). Increasing the drying time, initial grain temperature, drying temperature, and microwave power decreased the whiteness and increased the specific energy consumption. The researchers recommended MWFB for producing parboiled rice with a complete degree of starch gelatinization without the need for steaming. Production of parboiled rice with the FB at 170°C, initial grain temperature of 32°C, and bed depth of 5 cm had a 32% lower specific energy consumption than the conventional parboiling process.

Soponronnarit et al. (2006b) tested a pilot-scale superheated-steam FB dryer for parboiled rice. They found that a fluidization velocity of 1.3 to 1.5 times the minimum fluidization velocity had no significant effect on the drying rate. The drying temperature had a significant effect on the parboiled rice quality, as measured by whiteness, water adsorption, and pasting viscosity. The starch gelatinization during drying resulted in higher HRY for the parboiled rice as compared with raw rice. The energy consumption for reducing the moisture content of rough rice from 43% to 22% (d.b.) reached 7.2 MJ kg^{-1} water evaporated. Similarly, Taechapairoj et al. (2003) recommended FB drying of rice using superheated steam as an alternative to hot air. The mass transfer mechanism for drying rough rice with an initial moisture content of 25% to 44.5% (d.b.) was significantly affected by the movement of moisture inside the kernels. The researchers reported that the drying rate and drying time were functions of the drying temperature and bed depth. They stated that the HRY with superheated steam drying was superior to the HRY obtained with hot-air drying. On the other hand, the color of the rice was darker with superheated steam drying, which is an inferior quality attribute.

Srimitrungroj et al. (2019) investigated the drying characteristics and quality of rough rice dried with hot air and with humidified hot-air fluidization. They soaked rough rice with an initial moisture content of 14% (d.b.) in hot water at a temperature of 70 °C for 5 h. They then dried the rice with air temperatures of 130°C, 150°C, and 170°C, relative humidity in the range of 0.3% to 12%, air velocity of 3.9 m s^{-1}, and bed height of 10 cm. The rice quality was determined based on the HRY, degree of gelatinization, and color of the dried rice. The results showed that humid hot-air drying required more time than hot-air drying. The degree of starch gelatinization was significantly higher with humid hot-air drying as compared with hot-air drying because the former method provided a higher grain temperature and slower drying rate. The HRY was also higher with humid hot-air drying than with hot-air drying. However, the color of the dried rice obtained with humid hot-air drying was browner for the drying temperature range used. The researchers recommended that humid hot-air drying could be performed at temperatures of up to 170°C, relative humidity of 6%, and a degree of milling of 10% to produce parboiled rice.

7.2 Research against FB drying of rice

The concept of glass transition, introduced by Cnossen and Siebenmorgen (2000), suggests that fissuring of rice kernels occurs if the kernels are heated above 60°C. This finding questions the use of FB drying with air temperatures above 60°C, which is common. Soponronnarit (1999) used an air temperature of 115°C for FB drying of rough rice and reported a reduction in rice quality. Karbassi and Mehdizadeh (2008) performed FB drying of rough rice at 140°C for 2 min and found that the HRY decreased, along with cooking properties and nutritional quality. Jaiboon et al. (2009) found that the HRY of waxy rice was less with FB drying than with shade drying, and tempering did not improve the HRY. Ramesh and Rao (1996) used a vibrating FB dryer at temperatures between 160°C and 240°C to dry rice and reported that a substantial color change occurred in the rice.

Prasad et al. (1994) conducted drying experiments on parboiled rough rice in stationary, semi-fluidized, and fluidized drying conditions. They tested bed thicknesses of 10, 15, and 20 cm at drying air temperatures of 40°C to 80°C for the three drying conditions. They reported that the stationary bed with 20 cm depth achieved a maximum overall thermal efficiency of 47.4% at a drying air temperature of 80°C. The parboiled rough rice could be dried in semi-fluidized conditions without any significant milling loss, and the drying time was reduced as compared to stationary bed conditions. A high drying rate was obtained at lower bed thicknesses with semi-fluidized conditions. An extensive loss in HRY in milling and higher energy consumption were found with fluidized conditions. The researchers recommended that parboiled rough rice should not be dried in FB dryers due to extensive loss in HRY and higher energy consumption.

Soponronnarit et al. (2006a) used a superheated steam fluidization method for parboiling of brown rice. The influence on product quality of soaking temperature, time, steaming temperature, and bed depth was evaluated based on HRY, whiteness, and viscosity of the rice flour. The initial moisture content of the rice was 12.8% (d.b.). The researchers tested soaking temperatures of 70°C to 90°C, soaking times of 0.5 to 2.0 h, steam temperatures of 120°C to 160°C, steam velocity of 3.9 m s^{-1}, and bed depths of 8 to 12 cm. They reported that lower HRY was observed when the final moisture content was reduced below 28%.

8. Fluidized bed modeling

For rice drying in FB dryers, environmental factors, such as air temperature and humidity, are essential, and the FB dryer parameters (i.e., aspect ratio, bed temperature, airflow rate, and minimum fluidization velocity) and grain parameters (i.e., initial moisture content, size, and density) must also be considered. Drying models, also referred to as mathematical models, are essential for understanding the impacts of the factors that affect the drying process. Drying models are used as tools to explain the drying phenomena using mathematical equations (Gunhan et al., 2005).

There are two broad classifications of models in any area of research: empirical models and theoretical models. Empirical models are developed by fitting experimental data to a mathematical equation (Chen and Wu, 2000). Empirical models for rice drying are mostly based on exponential equations. Empirical models can be easy to implement; however, they are restricted to the range of operating conditions for which they were developed. On the other hand, theoretical models are developed using heat and mass transfer equations (Wu et al., 2004). These models can be applied to a wide range of operating conditions; however, they are complex to implement.

Empirical models, i.e., kinetic models, describe the drying kinetics of rice, which generally occurs in two phases: a falling rate period and a constant rate period. The constant rate drying period is modeled using correlation models between the drying rate and the influencing parameters or by using coefficients for heat and mass transfer between solids and fluids (Srinivasakannan and Balasubramanian, 2008). Tahmasebia et al. (2014) performed a kinetic study on microwave and FB drying. The drying kinetics with nitrogen FB, superheated steam FB, and microwave drying were investigated. The microwave drying data were best described by the Page model, indicating a difference in kinetics between the two drying methods. This difference was attributed to different heat transfer mechanisms between conventional and microwave drying.

Zare et al. (2012) established a comprehensive dimensionless model of rough rice drying from a validated partial differential equation (PDE), applying the dimensional analysis of the Buckingham theorem. This comprehensive dimensionless model used all the drying parameters in one equation to predict grain moisture content during the drying process. Statistical measures, including the coefficient of determination (R^2), chi-square (χ^2), mean relative deviation (MRD), and root mean square error (RMSE), were used to compare the validated PDE model with the dimensionless model. The researchers reported that the data from the PDE model fitted well with the generalized dimensionless model. They also found good agreement between the generalized dimensionless model and experimental drying data. The results indicated that the generalized dimensionless model could predict the rough rice moisture content with reasonable accuracy.

Because the generalized dimensionless model was simple and considered all the drying parameters in one equation, it was easy to use for the prediction of grain moisture content.

Numerical models have also been widely used by researchers because of their accuracy. The two most common types of numerical FB models are single-phase models and multi-phase models. In a single-phase model, the FB is considered as a single mass. Heat and mass balances are used for the FB, and the particles are assumed to be perfectly mixed (Martinez-Vera et al., 1995). On the other hand, multi-phase FB models comprise a bubble phase (dilute phase) and a suspension phase (dense phase). Some researchers have assumed that the suspension phase is composed of the particles and the intermediate gas phase (Zahed et al., 1995; Burgschweiger et al., 1999). Fick's equation has been used in FB drying studies, and it assumes that all the rice kernels are exposed to standard conditions (Srinivasakannan and Balasubramanian, 2008). However, this assumption has been questioned by researchers due to the reported dependence of the shape of the drying column and the amount of drying mass on the effective diffusivity. In recent years, Fick's laws of diffusion have been used to model the moisture gradient within a single rice kernel. These models describe the average moisture content of a single kernel as well as the moisture gradient between the surface and center of the kernel. These single-kernel models are useful for understanding the problem of rice fissuring. A few studies have used heat transport phenomena in their models (Yang et al., 2002; Meeso et al., 2007). These models differ based on the varieties of grain used due to differences in thermal, physical, and quality-related properties (Basunia and Abe, 1998).

Researchers have discussed numerical models for FB drying. Gong et al. (1997) proposed a two-dimensional finite element model using one-dimensional cylindrical geometry to model wheat particles. They accurately described the heat and mass transfer of wheat in a rotating jet spouted bed. Villegas et al. (2008) used a lumped mechanistic model to estimate the temperature and moisture content of particles in a batch FB dryer. Inaba et al. (2007) developed an energy and exergy FB model to investigate the effects of heat and mass transfer on the drying efficiency of wheat and corn. They found that the energy and exergy efficiency decreased with a decrease in moisture content. Nejadi and Nikbakht (2017) developed a single-phase numerical model to predict the moisture content of corn and to describe the heat and mass transfer in an infrared-assisted FB dryer, assuming the bed to be continuous. Izadifar and Mowla (2003) used a cross-flow continuous FB dryer to develop a numerical model for simulating the drying process in which relative humidity, air temperature (50°C to 60°C), initial moisture content, and feed rate (1000 kg h^{-1}) were the variables. Good agreement was obtained between the model output and experimental results. Bizmark et al. (2010) developed a sequential model for a continuous plug-flow FB dryer using initial moisture content, airflow, and particle flow rate as variables. Their model estimated the final moisture content of rough rice with less than 4.5% inaccuracy.

Khanali et al. (2014) conducted simulations and experiments on a plug-flow FB dryer using inert dry solids to determine the outlet gas humidity and temperature. Their model was extended to determine the mass and energy transfers between solid and gas phases in dynamic conditions. Drying of rough rice in a laboratory-scale plug-flow FB dryer was investigated in dynamic conditions to validate the model. A very acceptable agreement between the simulated and measured results was achieved. Additionally, Xiao et al. (2012) performed CFD modeling, simulation, and experiments on the drying characteristics of rapeseed using a superheated steam FB dryer. The simulated drying curve obtained from the drying model was in good agreement with the experimental results. A negative drying rate occurred in the first period, caused by initial steam condensation that lasted for about 6 s, and the moisture content of the material increased to a maximum.

9. Energy and exergy efficiencies of FB dryers

Several studies have reported the energy and exergy efficiencies of FB dryers of various designs and with various bed materials. However, there is a lack of studies on the energy and exergy analysis of rice drying in FB dryers, so this section presents a general discussion of the energy and exergy efficiencies of FB dryers. Energy efficiency is defined as the energy used for moisture evaporation divided by the energy consumed in the drying air for the extent of the drying duration. This definition emphasizes moisture removal, and it excludes the temperature of the material. Exergy efficiency is used to assess the drying parameters throughout the duration of drying. The exergy efficiency is usually less than the energy efficiency because of entropy. However, it follows the same trend.

Nazghelichi et al. (2011) analyzed the energy and exergy performance of FB drying. Their drying experiments used carrot cubes with dimensions of 4, 7, and 10 mm^3, inlet air temperatures of 50°C, 60°C, and 70°C, and bed depths of 30, 60, and 90 mm. The effects of the drying variables on energy utilization, exergy utilization ratio, exergy loss, and exergy efficiency were studied. The exergy efficiency was found to be in the range of 10.3% to 70.7%. The results showed that the exergy efficiency had its maximum value with higher drying air temperature, small cube size, and shallower bed depth. Karagüzel et al. (2012) recommended FB drying based on exergy and energy analyses of chickpea and bean drying. The drying process was evaluated at different temperatures and air velocities for both products. Exergy analysis was used to determine the exergy efficiency during drying based on the second law of thermodynamics. The parameters that influenced the exergy efficiency were determined, and the exergy efficiency was shown to be proportional to the drying air temperature and velocity. The exergy efficiency for the same drying air temperature (47.1°C) was 56% to 65% for bean and 45% to 62% for chickpea. Yogendrasasidhar and Setty (2018) performed energy and exergy analyses with a wall-heated batch FB dryer using kodo millet grain and fenugreek seed. The energy and exergy analyses were performed by changing the wall temperature, air velocity, bed height, and initial moisture content of the bed material in the wall-heated FB dryer. The energy utilization ratio, exergy loss, and exergy efficiency of kodo millet and fenugreek seed were reported. The exergy efficiencies for kodo millet and fenugreek seed ranged from 40% to 72% and from 40% to 75%, respectively. The exergy efficiencies increased for both kodo millet and fenugreek seed with increasing wall temperature, air velocity, and drying time and decreased with increasing bed height and initial moisture content.

Ozahi and Demir (2013) developed a model to analyze the exergy of a batch FB dryer. An innovative model for thermodynamic analysis of a batch FB dryer was proposed by considering two distinct systems, i.e., the drying air medium and the particles to be dried. The energy and exergy efficiencies evaluated using the proposed model were compared with those in previous studies. The researchers found good conformity with an acceptable error margin of 9%. A relationship was developed with a mean deviation of 10% to evaluate the energy efficiency of corn drying as well as the drying processes for other particles at an air temperature of 50°C. The researchers concluded that exergy analysis, along with energy analysis, is necessary to estimate optimum FB conditions.

Correspondingly, Assari et al. (2013) used a two-fluid simulation model for a batch FB dryer to analyze the energy and exergy of the dryer. The two-fluid model was used to optimize the input and output and maintain the product quality. The two-fluid model was based on a continuum postulation of the two phases. Two sets of conservation equations were applied for the solid and gas phases and were considered as an interpenetrating range. This study also considered two-dimensional, axisymmetric cylindrical energy and exergy equations for both phases, and numerical simulation was performed. The effects of the inlet gas velocity, inlet gas temperature, and particle size diameter on the energy and exergy efficiencies were studied. The two-fluid model prediction indicated good agreement between the reported non-dimensional correlations and experimental results. At the beginning of the drying process, the energy efficiency was higher than the exergy efficiency for a short duration. However, these efficiencies became close to each other in the final stage of the drying.

Azadbakht et al. (2017) performed energy and exergy analyses using artificial neural network (ANN) modeling for FB drying of potato cubes. Drying was modeled with inlet air temperatures of 45°C, 50°C, and 55°C, air velocities of 0.05, 0.11, and 0.15 m min^{-1}, and bed depths of 1.5, 2.2, and 3.0 cm. The effects of these factors on energy utilization, energy efficiency, utilization ratio, and exergy loss and efficiency were evaluated. Furthermore, the ANN was used to predict the energy and exergy parameters. The thermodynamic drying process was also simulated using the model. The results showed that the energy utilization, efficiency, and utilization ratio increased with increasing bed depth and air velocity. The energy utilization and efficiency also increased with increasing temperature. The exergy loss and efficiency increased with increasing bed depth, air velocity, and temperature.

Various researchers (e.g., Srinivasakannan et al., 1994; Srinivasakannan and Subramanian, 1998; Choi et al., 2002) have conducted studies on multistage FB dryers to determine the drying behavior of materials such as ragi and millet. This energy and exergy research on continuous multistage FB dryers may encourage more research on different types of continuous dryers to ensure good product quality with lower energy use.

Yahya et al. (2017) designed and evaluated a hybrid, solar-biomass FB dryer. Their FB drying system included a solar collector and a biomass furnace. The solar-assisted FB dryer and biomass furnace were used to study the drying kinetics of rough rice. The average temperature of the drying air was 61°C and 78°C. Rough rice with a moisture content of 20% (w.b.) was dried to 14% (w.b.) during 13.3 to 21.3 min, and exergy efficiencies of 47.6% and 49.5% were reported for the temperatures of 61°C and 78°C, respectively. The researchers suggested that most of the drying occurred in the falling rate period. The performance of the FB drying system was evaluated based on energy and exergy efficiencies. The specific energy consumption and drying time were lower with the solar-biomass FB drying system in comparison with solar dryers. Likewise, Sarker et al. (2015) determined the energy and exergy performance of an industrial FB dryer using rough rice. The maximum throughput of the dryer was 22 t h^{-1}. Energy and exergy models, which were developed by applying the first and second laws of thermodynamics, were used to estimate the exergy efficiency during the drying process. The analysis showed that the energy utilization ratio varied from 5.24% to 13.92%. On the other hand, the exergy efficiency varied from 46.99% to 58.14%. A pure exergy balance revealed that only 31.18% to 37.01% of the exergy was used for drying rough rice, and the large amount of remaining exergy was wasted. The researchers were hopeful that the exergy can be increased in future studies, if sufficient insulation is installed on the dryer housing and the exhaust air is recycled.

As mentioned above, there are detailed studies on energy and exergy analyses of batch FB dryers, and a few studies on the energy and exergy efficiencies of continuous FB dryers.

However, the available literature in this area is limited. Continuous FB dryers are more important for industrial applications because they can handle large throughputs.

10. Research opportunities in FB drying of rice

As discussed above, FB drying could be a solution to the problem posed by the vast production of rough rice in the U.S. that needs rapid drying after harvest. The major shortcoming of FB dryers, as pointed out, is the development of moisture gradients during drying, which leads to rice fissuring and lowers the HRY. Therefore, the on-going debate among researchers on the effects of FB drying on rice quality requires thorough studies that focus on product quality. The following topics could be explored in future research on rice drying with FB dryers:

1. Determine the maximum acceptable drying temperature that does not compromise rice quality, along with the corresponding rice variety. No explicit agreement on the optimum drying air temperature for rough rice can be concluded from the current literature.

2. Study the use of moisture absorbents, rather than heating the air, to decrease the relative humidity of the drying air, which might enhance the drying rate during FB drying of rice.

3. Explore the energy and exergy efficiencies during FB drying of rice. There is limited research on the energy and exergy efficiencies of FB dryers.

4. Develop comprehensive numerical models for FB drying of rice that include the change in moisture on the surface of the kernels as well as within the kernels. There is currently a lack of such models, and such models could further support, or oppose, the use of FB drying for rice.

11. Conclusions

With increasing rice production in the U.S., post-harvest drying technology must be enhanced. FB drying technology for drying rice was reviewed, and this technology was found to have many advantages, including faster drying rates. This review also revealed that previous studies have reported a decrease in rice quality with FB drying; however, studies have suggested that drying temperatures below 60°C could help maintain rice quality. Other heating technologies, such as microwave and solar, and different structures to assist FB drying have had positive effects on the product quality and drying rate. Mathematical models have been developed to describe the FB drying of rice, but there is a lack of theoretical models that describe the internal and surface moisture kinetics of rice kernels. Thus, further research is needed to model the FB drying process to determine the optimum drying conditions. Research is also needed on the exergy and energy efficiencies related to FB drying of rice to further support, or oppose, the use of this drying technology in the U.S.

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Chapter 3: Evaluation of the performance of a custom-made fluidized bed grain dryer

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Abstract

Laboratory and farm-scale fluidized bed dryers are not available to purchase. Additionally, a deliberation is presently continuing regarding the beneficial and damaging effects of drying grain in a fluidized bed. Therefore, the goal of this research was to develop and test a custom-made small-scale fluidized bed dryer, suitable for moderate farms and capable of drying small and large size grains from high moisture content to a safe storage moisture content. The customary fluidized bed dryer was developed and constructed in the Rice Research and Extension Center, Stuttgart, AR, USA. The fluidized bed dryer was used to dry wheat from an initial moisture content of 23.3% db. The effects of the aspect ratio (bed height to bed diameter ratio) of 2, 3 and 4 m/m, the furnace temperature of no heat, 100, 150 and 200^{o}C and drying duration of 10, 20, 30, 40, 50 and 60 minutes on the wheat moisture content, drying rate, and dryer efficiency were investigated. The lowest wheat moisture content of 16.3% db was observed at the lowest aspect ratio of 2 m/m, the highest furnace temperature of 200^{o}C and the longest drying duration of 60 minutes. Conversely, the highest wheat moisture content of 19.0% db was observed at the highest aspect ratio of 4 m/m, and the no heat condition. The drying rate of 0.47%/min was observed at the lowest aspect ratio of 2 m/m and the furnace temperature of 200^{o}C after 10 minutes. The maximum dryer efficiency of 63.2% was achieved at the aspect ratio of 4 m/m, the furnace temperature of 200^{o}C. Two empirical models were developed to predict the moisture content of wheat and the dryer efficiency as affected by the aspect ratio, the furnace temperature and the drying duration with the adjusted coefficient of determination of 0.91 and 0.88, respectively. Although, the developed fluidized bed dryer is a lab-scale system, the experimental results provided an exceptional indication to scale up the drying system to dry grains.

Keywords.

Dryer efficiency, Drying rate, Fluidized bed, Moisture content, Wheat-drying.

1. Introduction

The high production of cereal grains in developing countries from small size farms, and the limited availability of on-farm drying systems, has created a major challenge for grain producers in the world. Moreover, there is an on-going debate among researchers on the effects of some drying techniques *i.e.* fluidized bed drying on grain quality (Taweerattanapanish et al., 1999; and Tirawanichakul et al., 2004). These tasks steered to a pressing need of fabricating and testing a custom-made lab-scale fluidized bed grain dryer. The dryer should be capable of drying various grains of different sizes and a wide range of initial moisture content.

Cereal grains *i.e.* corn, wheat, rice, barley, and sorghum, have been a primary source of diet for humans for thousands of years. Major cereal grain world production reached 2,355 million metric ton in 2010 (Awika, 2011). India and Africa produced about 8.50% and 4.25%, respectively, of grains annually (Shukla, 2001; and Macauley and Ramadjita, 2015). Most of these grains are typically harvested at high moisture contents (MC) levels that are not safe for long time storage (Sadaka and Atungulu, 2018). For example, in Vietnam, a major exporter of rice; the rice is harvested in the wet season with a moisture content around 46.7% db (Tuyen et al., 2009). Another example, in India, Sri Lanka and East Africa, farmers harvest high moisture content ragi, a cereal crop, in the winter season and stack them to be dried in the summer (Goswami et al., 2015). Due to the delay of the drying process and the high moisture content, grain might develop molds. Therefore grain drying on the farm at a small scale is essential to reduce grain moisture content to levels safe for storage which lead to the minimization of respiration rate and microbial growth (Compton et al., 1993; and Champ et al., 1996).

Drying is a contemporary process involving both heat and mass transfer with the driving force being enthalpy and concentration differences. Unfortunately, conventional fixed-bed dryers take a longer time to reduce the moisture content to safe storage levels (Proctor, 1994). Thus, farmers in developing countries are looking for on-farm drying alternatives such as fluidized bed drying (FBD) to dry their grain immediately after harvest (Srinivasakannan and Balasubramaniam, 2006; and Tuyen et al., 2009). Another reason that leads small farms in developing countries to adopt FBD is to avoid the high capital cost of drying grains using conventional methods (Gazor and Mohsenimanesh, 2010; Sivakumar et al., 2016; and Yahya, 2016). FBD is one such alternative to time-consuming and highly unpredictable conventional drying methods. FBD is a relatively old technique that offers the same amount of heat to almost all the particles in it. The solid particles are mixed rapidly, and this leads to more uniform isothermal conditions in the bed. Additionally, the heat and mass transfer rates in the fluidized bed are high as compared to other modes of contact between solids and gas. Researchers reported that fluidized bed-drying techniques result in less variation of the moisture content in solid particles. Also, the fluidized bed drying could overcome the diffusion limitations of other conventional drying methods due to various residence times of grains. They are simple and have minimal moving parts, which might lead to less maintenance costs (Mujumdar and Devahastin, 2003). Studies have also proposed that FBD can work on the farm with the energy requirements being met by solar energy (Sopanronnarit et al., 1998; and Yahya, 2016). This could provide the solution to electricity issues at farms in most developing countries. FBD could also be designed to dry the majority of grain types, thus having a broader application and use compared to the conventional fixed-bed dryers.

Uckan and Ulku (1986) reported that the FBD resulted in 15% and 54% higher drying rates at low and high temperatures of 20ºC and 65ºC, respectively, than stationary bed drying at the same temperatures when drying corn. They postulated the increase in the drying rate corresponding to fluidization to the increase in the contact of air with the drying products. Huynh et al. (1991) studied the hydrodynamics and mass transfer characteristics of a venturi bubble column at low superficial velocities of up to 0.35 m/s. The gas hold up increased to 150% and the volumetric mass transfer coefficient was tripled. Reay (1985) studied the effect of bed depth, gas velocity, particle size, and temperature on the drying rate in a fluidized bed dryer. For large size materials, increasing the bed height produced a proportional increase in the drying rate. The drying rate of smaller diameter material was directly proportional to gas velocity. Experiments with both large and small materials showed that bed temperature has a substantial effect on the drying rate. It is essential to note that the material being processed dictates the maximum allowable temperature to be used. Giner and Calvelo (1987) concluded that for wheat, increasing the temperature of fluidized bed from 40ºC to 70ºC decreased the drying time by a factor of four. Topuz et al. (2004) found that in FBD of hazelnuts, drying rate decreased with increasing flow rate. Niamnuy and Devahastin (2005) suggested that using a temperature of 120ºC and inlet air velocity of 5.94 m/s had the best drying rate for coconut in a FBD with market-accepted quality. Liebanes et al. (2006) studied FBD of solid olive oil mill by-products. They concluded that FBD improved the efficiency with drying rate increasing with air temperature and flow rate. Srinivasakannan and Balasubramaniam (2006) investigated FB drying on ragi, a common cereal crop in Asia and East Africa; they concluded that drying rate increased significantly with increase in temperature and marginally with increase in flow rate and decreased with increase in solids holdup. Similar results were found by Sandeepa et al. (2013) for sorghum. Thakur and

Gupta (2006) compared fluidized bed drying and stationary bed drying on paddy and concluded that by using FBD, power usage can be curtailed by half and drying rate improved with no decrease in rice quality. Murthy and Joshi (2007) found that FB drying method at 80^{o}C and 1.9 m/s air velocity had the minimum drying time of 120 min, and also maintained the essential nutrients in Aonla, the Indian gooseberry. Darvishi et al. (2015) concluded that drying soybean in a fluidized bed with increased temperature and air velocity from 80^{o}C to 140^{o}C and 1.8 m/s to 4.5 m/s, respectively, reduced the drying time from 380 to 50 min. Prakash et al. (2004) showed that fluidized bed dried samples of carrot had better color, overall quality, and hydration properties than microwave oven and solar drying. In drying tea leaves, multi-stage fluidized bed drying with re-circulation was found to be the best method and was adopted widely by the tea industry (Temple et al., 2000). Using the FB for drying garlic, Souraki and Mowla (2008) concluded that heat and mass transfer coefficients were better than the conventional dryers.

Despite having the abovementioned advantages of fluidized bed dryers, there are some limitations. The central drawback of fluidized bed drying is particle breakage, that means the particles to be dried must have sufficient mechanical resistance (Jangam et al., 2011). Breakage of particles produces a significant number of fines in the final product, which could be unacceptable in some markets. To date, insufficient consideration has been given to the development of pilot scale fluidized bed dryers, which are presently needed in developing countries. Small capacity dryers are also needed in food processing, chemicals, and other industries, which are at a growing stage in developing countries. Laboratory scale or small farm size fluidized bed dryers are hardly available and are often expensive to purchase and operate. Therefore, it would be beneficial to design and construct a relatively inexpensive and an easy to control lab-scale fluidized bed dryer to carry out the drying research of various grains. This fluidized bed dryer should be capable of drying grain samples of different initial moisture content to safe levels for storage, while concurrently lessening kernel-to-kernel final moisture content variability. The primary objective of this study was to develop, construct and evaluate a lab-scale fluidized bed dryer that could be used as an educational outreach tool and to be capable of drying grain samples. The specific objectives were: (1) to study the effects of aspect ratio, drying temperature, and drying duration on wheat moisture content, drying rate, and drying efficiency, and (2) to develop two empirical models to predict the wheat moisture content and dryer efficiency as a function of the previously mentioned operating parameters.

2. Materials and methods

2.1 Wheat collection and characterization

Soft red winter wheat (*OAKES*) was procured in early June 2015 from a local farm located in the Northeast of Arkansas, USA. Following, it was transported to the Rice Research and Extension Center, Stuttgart, Arkansas. A wheat sample of 100 kg was visually inspected to avoid any foreign materials or damaged wheat grains. The sample was placed initially in four polyethylene bags in refrigerator at 4°C. The initial moisture content was determined using the standard method ASAE S352.2 (ASAE, 2008) and was found to be 15.2% db. To achieve the target moisture content level of 24.0% db, the required amount of distilled water was calculated and added to the wheat in the polyethylene bags with the help of spray bottles. Following the addition of distilled water, the samples were mixed vigorously to ensure uniform distribution of the added water. These bags were stored in the refrigerator at 4°C for 24 hours. Following, the moisture content of wheat samples was determined using the previously mentioned standard method ASAE S352.2 (ASAE, 2008) and found to be 23.3% db. The basic dimensions (length, width, and thickness) of fifty wheat kernels were measured using a steel digital caliper (General Ultratech, Series – 147, Secaucus, NJ, USA) with 0.02 mm accuracy. The geometric mean diameter was calculated by taking the cube root of the multiplication of the three basic dimensions. A similar method was used by Bande et al. (2012) in measuring different melon seed sizes. Wheat bulk density was measured with a Cox Funnel-29 (Seedburo, Des Plaines, IL) following the standard test weight procedure (Boerner, 1922). The bulk density of wheat was determined by dividing the mass of grains by the volume they occupy (average of 5 samples at 15.2% db moisture was 740.5 kg/m^3). Subsequently, it was found that the amounts of wheat needed to obtain aspect ratios (bed height to bed diameter) of 2, 3, and 4 m/m were 3.50 kg, 5.25 kg and 7.00 kg, respectively. After that, twelve subsamples were collected in well-sealed plastic bags according to the following sequence: bags 1 through 4 were filled with 3.50 kg each; bags 5 through 8 were filled with 5.25 kg each; and bags 9 through 12 were filled with 7.00 kg each. All samples were stored in a refrigerator at 4^{o}C until needed.

Table 2 shows the characteristics of fresh wheat samples including moisture content, bulk density, weight of 1000 kernels, and minimum fluidization velocity (five replications each). It also shows the average length, width and thickness of fifty kernels. These parameters are necessary to characterize the fluidization process. The moisture content of wheat samples was 15.2% db. The average geometric mean diameter and bulk density of fresh wheat samples were determined to be 3.72 mm and 740.5 kg/m^3, respectively. The average geometric mean diameter was lower than previously found as 4.26 mm for Iranian irrigated and dryland wheat (Tabatabaeefar, 2003). Murthy et al. (2008) found the bulk density of raw soft white wheat to be 833 kg/m^3 which is higher than the value obtained in the present study. This difference is possibly due to the moisture differences as was previously reported that the bulk density of rewetted wheat samples varies depending on the moisture content values. The present study showed that the weight of 1000 wheat kernels is 36.3 g which is in agreement within the values obtained in the literature (35.8 - 45.4 g) by Rajabipour et al. (2006) for several varieties of irrigated Iranian wheat. The minimum fluidization velocity of the fresh wheat (moisture content of 15.2% db) was found to be 0.76 m/s, whereas Giner and Calvelo (1987) obtained the minimum fluidization velocity of wheat as 1.2 m/s at 25% moisture content db. This difference is attributed to differences in the moisture content of wheat.

Table 2. Characteristics of wheat samples.

Property	Unit	Value
Moisture Content*	% (d.b.)	15.2±0.8
Wheat Dimensions		
Length**	mm	6.40±0.41
Width**	mm	3.22±0.23
Thickness**	mm	2.52±0.19
Geometric mean diameter**	mm	3.72±0.14
Bulk density*	kg/m3	740.5±17.7
Weight of 1000 kernels*	g	36.3±0.6
Minimum fluidization velocity (at 15.2% d.b.)*	m/s	0.76±0.12

*Values are average of five replicates.
** Values are average of fifty kernels dimensions.

2.2 Fluidized bed drying system

The fluidized bed dryer consisted of four basic components: an air supply system, an air heating system, a drying column and measuring systems as shown in Figure 1.

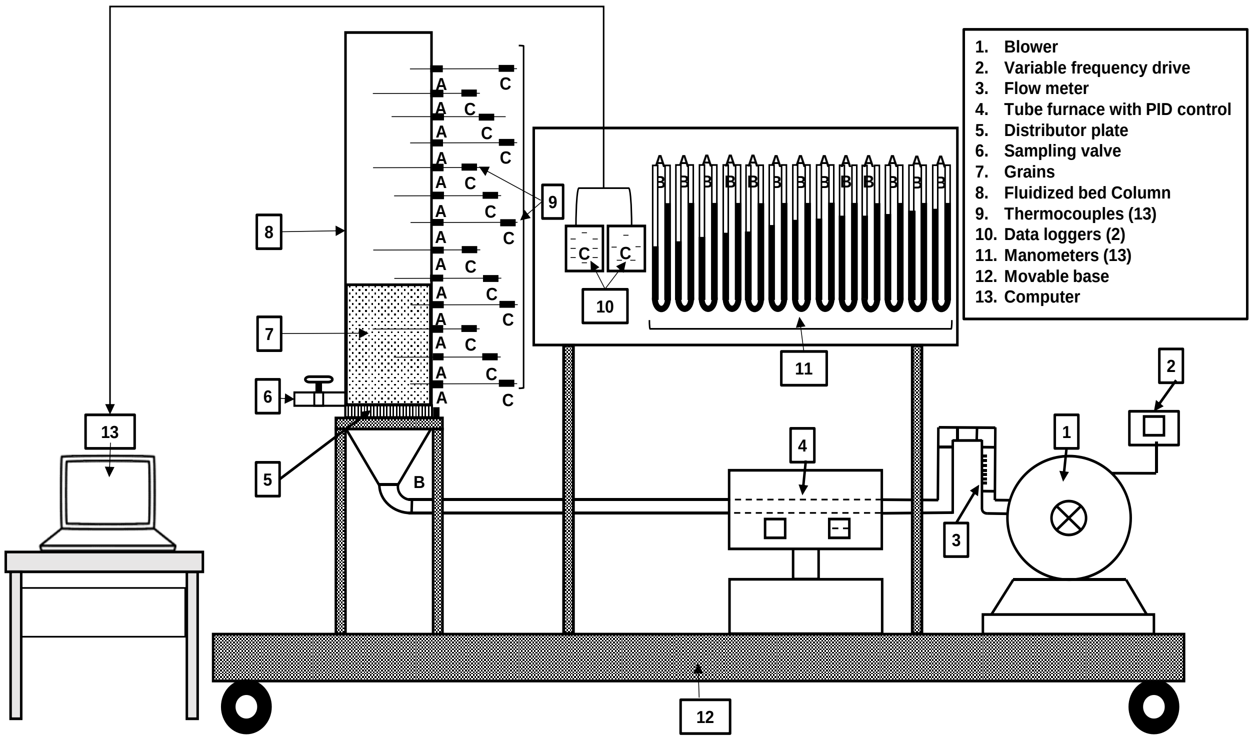

Figure 1. A schematic diagram of the fluidized bed dryer system.

The air supplying system consisted of a 3kW regenerative blower (SCL k05-MS MOR, FBZ, Italy) controlled by a variable frequency drive [VFD] (ACS350, ABB Ltd, Switzerland) and connected to an air flow meter (7510 series, KING Instrument Company, Garden Grove, CA), which has the range of 0 - 1.70 m^3/min. The centrifugal fan was selected to ensure enough static head to fluidize the material in the column. Also, the airflow meter was used to determine a wide range of airflow that enable to sufficiently fluidize various quantities of materials. It should be mentioned that the airflow meter was used to measure the airflow rate which was controlled by the VFD. Prior to the experiments, the airflow rates were measured and recorded as a function of the number of hertz on the variable frequency drive.

In the air heating system, air was passed through a 2.5 cm steel pipe in a tube furnace (Fisher Scientific, Single Set Point 120v 50/60 Hz, Hampton, NH) that had a single set point to control the desired temperature. Air was supplied continuously until the temperature reached a steady state.

The drying column consisted of a plexiglass cylinder (15 cm in diameter and 150 cm in height, rated at 180^{o}C) with the bottom closed by a perforated distributor plate (High-Strength PVC Plastic Perforated Sheets). The perforated distributor plate used in this study had 2 mm diameter orifices with a total open area of 15%. This might simulate floor dying systems.

The top of the column was kept open to discharge exhaust air and allow an easy access to load wheat samples. A 3.8 cm ball valve was installed above the distributor plate to allow collection of the samples at the desired drying durations, and to allow emptying the FB column at the end of each experimental run. A transparent column was selected to support extension activities by allowing producers to visualize and comprehend the FBD technology.

To evaluate the performance of the FBD, it was essential to measure the air temperature, air relative humidity, pressure drop, and wheat moisture content to determine the drying efficiency. Air temperature readings, in various locations, were measured by using type J thermocouples connected to data logger (OMEGA TC-08, Norwalk, CT). Thirteen thermocouples were inserted horizontally into the fluidizing column (10 cm apart), to measure the temperature profile in the vertical direction. The tip of thermocouples 1, 4, 7 and 10 were located at a 2.5 cm from the wall, thermocouples 2, 5, 8, 11 and 13 were located at a 7.5 cm from the wall and thermocouples 3, 6, 9 and 12 were located at a 12.5 cm from the wall to measure the horizontal temperature profile as well. Two OMEGA data loggers (PicoLog data logger software, Norwalk, CT) were used to monitor and record the bed temperature readings during the experimental runs. The two data loggers were connected to two USB connection ports on a PC.

Air relative humidities, of the inlet air and outlet air, were monitored by a hand held relative humidity meter (Dew Point Meter, 5 to 95 Range, Norwalk, CT). Exit air velocity was measured using an air velocity meter (EXTECH, Anemometer, 0.4 to 30 m/s, Norwalk, CT) by placing the meter at the top of the FBD column. The air velocity was measured at the exit of the fluidizing column in three locations including one measurement at the center of the column and two measurements close to the walls of the column. Pressure drop system consisted of 13 U-tube manometers with one side of all the U-tubes connected to each other via a manifold whereby the manifold was attached to the bottom of the fluidizing column via a 1.27 cm hole under the distributor plate. The other end of each U-tube was connected to a port on the column located next to the thermocouple. The moisture content values of fresh and dried wheat samples were measured using an AM 5200 Grain Moisture Tester (PERTEN Instrument, Hägersten, Sweden). To determine the minimum fluidization velocity of wheat, a sample of 5 kg was discharged into the fluidized bed. The air velocity was increased by changing the frequency on the variable frequency drive (VFD). Once the wheat particles were suspended in the airstream (fluidize), the minimum fluidization velocity was determined and used as the smallest velocity at which fluidization (balance of gravity, drag and buoyant forces) occurs. Similar technique was used by Giner and Calvelo (1987) to determine the minimum fluidization velocity of wheat kernels.

2.3 Experimental design

In order to test the effect of the aspect ratio, drying temperature, and drying duration on the performance of the fluidized bed dryer, the experimental design was carried out as shown in Table 3.

Table 3. Experimental design.

Experiment No.	Aspect Ratio m/m	Furnace Temperature ºC	Drying Duration min.
	2	No heat	0 - 60, 10 min. intervals
		100	0 - 60, 10 min. intervals
		150	0 - 60, 10 min. intervals
		200	0 - 60, 10 min. intervals
	3	No heat	0 - 60, 10 min. intervals
		100	0 - 60, 10 min. intervals
		150	0 - 60, 10 min. intervals
		200	0 - 60, 10 min. intervals
	4	No heat	0 - 60, 10 min. intervals
		100	0 - 60, 10 min. intervals
		150	0 - 60, 10 min. intervals
		200	0 - 60, 10 min. intervals

Three moisture content measurements were obtained for each drying duration.

2.4 Determination of drying rate

The drying rate of wheat samples was calculated by dividing the difference of the moisture content of two consecutive samples by the drying duration as shown in Eq. 1.

$$DR = \frac{MC_i - MC_{i+1}}{t} \tag{1}$$

Where,

DR = the drying rate (%/min),

MC_i = the moisture content at time i (% db),

MC_{i+1} = the moisture content at time i+1 (% db),

t = the drying duration (min).

2.5 Determination of dryer efficiency

The thermal dryer efficiency (η_{th}) is useful for evaluating the actual evaporation of moisture from the grain inside the drying system (Balbine et al., 2015). This is expressed as the ratio of energy used to evaporate water from the grain (E_w) to the energy provided to the air during drying (E_a) where the energy consumed to evaporate moisture can be calculated as follows:

$$E_w = M_w \times L_w \tag{2}$$

Where,

E_w = the water evaporation energy (kJ),

M_w = the mass of water evaporated (kg),

L_w = the latent heat of water vaporization (kJ/kg).

The energy consumed to heat the air can be calculated as follows:

$$E_a = M_a \times C_p \times \Delta T \tag{3}$$

Where,

E_a = the energy provided to heat the air (kJ),

M_a = the mass of air (kg),

C_p = the specific heat of air (kJ/kg °C),

ΔT = the temperature difference (°C)

Therefore, the thermal dryer efficiency, η_{th}, can be calculated as follows:

$$\eta_{th} = \frac{E_w}{E_a} \times 100\% \tag{4}$$

2.5 Experimental procedure

The centrifugal fan was turned on and the airflow rate was adjusted to the pre-calibrated rate by setting the variable frequency drive. The air velocity was selected to be 1.5 times the minimum fluidization velocity to ensure higher fluidization of the bed. The tube furnace was turned on and the temperature was adjusted to the pre-selected level using the PID on the furnace. The system was kept for 60 minutes to ensure adequate heating. Subsequent, the air temperature reached a steady state (monitored on the computer screen from the OMEGA software), the required amount of wheat was discharged into the drying bed from the top. Pressure drop readings were obtained from the U-tube manometers. The room temperature was measured using a handheld thermometer placed at the inlet of the blower. The inlet and exit air relative humidity values were determined using a handheld relative humidity meter. After ten minutes, a plastic bag was attached to the side pipe of the ball valve. The ball valve was turned on and a sample was allowed to discharge to the bag. Two more bags were filled by wheat samples as well. The moisture contents of the three samples were measured using the grain moisture tester. The three plastic bags were emptied back (within 3 minutes of sampling) into the drying bed from the top port to maintain the wheat weight constant throughout the experiment. Moisture content sampling procedure was repeated every 10 minutes until the end of the experimental run. Drying bed temperatures were measured with the shielded thermocouples. By the end of the experiment, the drying bed was emptied from the side port and moisture content of the dried wheat sample was measured. Subsequently, the samples were stored in a refrigerator at 4°C. Microsoft Excel Software (Microsoft Corporation, Redmond, WA) was used for graphing and analyzing the data.

3. Results and discussions

3.1 Effects of aspect ratio, furnace temperature and drying duration on air temperature

The temperature values in the drying bed were recorded every 30 seconds. Figure 2 presents the effects of the aspect ratio, furnace temperature and drying duration on the temperature profile in the drying bed. Each temperature point represents the average measurements of the temperature readings from the thermocouples that were immersed in the grain bed. The readings of remaining thermocouples were not included as they were located in the freeboard. The graph shows that the temperature dropped instantaneously after adding wheat to the drying bed. Afterwards, the air temperature in the drying bed started to rise during the first 20 minutes until it almost reached steady state. The drop in the air temperature could be attributed to the grain temperature, which was stored and introduced at room temperature. It should be mentioned that the room temperature ranged between 18.0 and 22.5°C during all experiments. Increasing the aspect ratio decreased the temperature in the drying bed. The temperature decrease is attributed to the increase in the mass of wheat corresponding to the increase in the aspect ratio. This is an acceptable result as it matches the basics of heat transfer since the heat transfer and the specific heat of wheat are constant. Therefore, increasing the mass of wheat, or in other words the aspect ratio, results in a decrease in the drying bed temperature. Sghaier et al. (2009) presented an experimental and numerical study of humid air drying of a fixed bed of moist porous particles. They reported that the bed with the thinnest depth reached the highest gas temperature and remained at this temperature for the shortest amount of time. Conversely, increasing the furnace temperature and the drying duration increased the temperature values in the bed. This phenomenon was anticipated as the input energy provided to heat the air was increased. Henneberg et al. (2003); and Giner and Calvelo (1987) also reported that increasing the drying duration increased the bed temperature profoundly in the first few minutes until the bed temperature reached almost steady state conditions.

At the no heat added test (room temperature), there was only a small difference in the final temperature among the studied aspect ratios particularly in the last 30 minutes. Interestingly, the air temperature rose from room temperature to 41.2^{o}C without external heat addition. This temperature rise is attributed to the effects of air compression with the centrifugal force of the blower as well as air friction within the pipes and the pipe fittings. At the furnace temperatures of 100, 150 and 200^{o}C, the final air temperatures reached 46.1, 46.9 and 50.2^{o}C, respectively, at the aspect ratio of 2 m/m. After 60 minutes of drying, the minimum air temperature reached 41.2^{o}C at the aspect ratio of 3 m/m and no heat addition whereas the maximum air temperature reached 50.2^{o}C at the aspect ratio of 2 m/m and the furnace temperature of 200^{o}C. Differences in the final air temperatures among the three aspect ratios were highest at the furnace temperature level of 200^{o}C. This could be attributed to the larger differences in the mass of grain corresponding to the differences in aspect ratios.

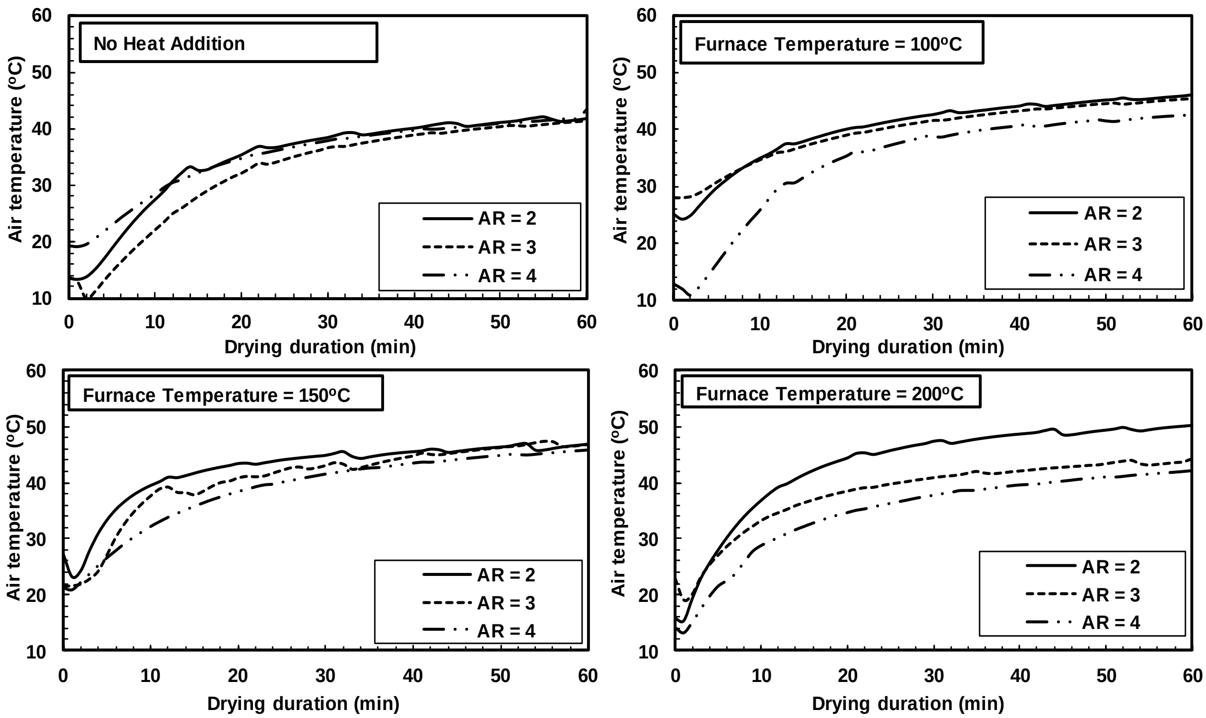

Figure 2. The effects of aspect ratio (AR), furnace temperature and drying duration on the average air temperature.

3.2 Effects of aspect ratio and furnace temperature on the pressure drop across the distributor plate.

Monitoring the pressure drop readings around the distributor plate are imperative because it reflects the quality of fluidization inside the bed. The effects of the aspect ratio and the furnace temperature on the pressure drop across the distributor plate are presented in Figure 3. It should be mentioned that the pressure drop readings were observed while the fluid in the manometer was fluctuating due to the fluidization phenomenon. Increasing the aspect ratio and/or the furnace temperature increased the pressure drop across the distributor plate. The highest-pressure drop of 3.48 kPa was observed at the aspect ratio of 4 m/m and the furnace temperature of 200^{o}C. In comparison, the lowest pressure drop of 2.24 kPa was observed at the aspect ratio of 2 m/m and the furnace temperature of 150^{o}C, which was slightly lower than the pressure drop observed at the no heat level. Deomore and Yarasu (2017) also reported an increase in fluidized bed pressure drop corresponding to the increase in the bed temperature for corn and wheat. The data in their study were more noteworthy than the present study as they measured the pressure drop across the freeboard and 3 cm above the distributor plate.

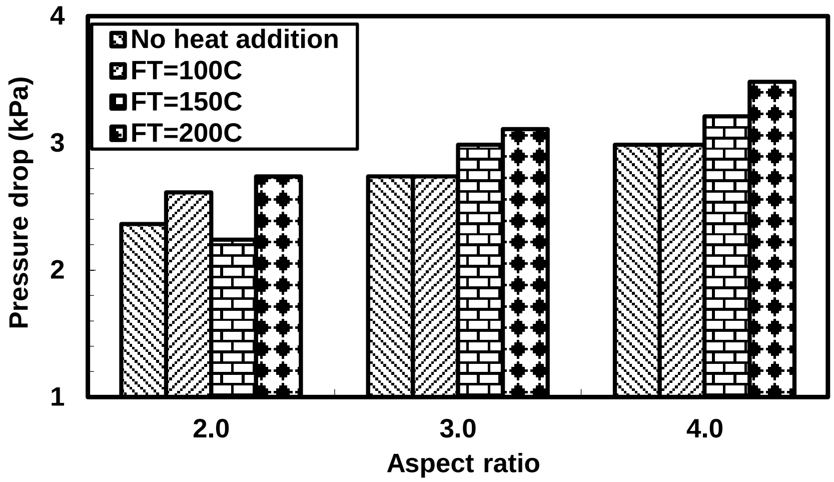

Figure 3. The effects of aspect ratio and furnace temperature (FT) on the pressure drop around the distributor plate.

3.3 Effects of aspect ratio, furnace temperature and drying duration on the wheat moisture content

The moisture content of conditioned wheat samples was found to be 23.3% db. Samples were taken every ten minutes during a one-hour drying duration. The moisture content as affected by the aspect ratio, the furnace temperature, and the drying duration is illustrated in Figure 4. Results showed that moisture content decreased slightly with the aspect ratio and an increase of furnace temperature and drying duration. The minimum moisture content of 16.3% db (a 7.0% point reduction) was observed at the aspect ratio of 2 m/m, furnace temperature of 200°C and drying duration of 60 minutes. In contrast, the highest moisture content of 19.0% db (a 4.3% point reduction) was observed at the aspect ratio of 4 m/m, no heat condition and drying duration of 60 minutes. Although the three aspect ratios showed the same trend, there were some differences in the final moisture content after the same drying duration. The final moisture content varied from one aspect ratio to another based on the bed mass and the amount of air resistance to go through the deepest bed. The results showed that at the same condition, the higher the aspect ratio the lower the moisture content. This phenomenon can be postulated to the large amount of moisture at the beginning corresponding to the larger mass in the bed and the challenging quality of fluidization. Increasing the aspect ratio increased the bed material, which resulted in a large amount of moisture in the bed yielding in less amount of moisture migration.

At the no heat condition as well as the furnace temperatures of 100 and 150^{o}C, the moisture content of wheat decreased almost linearly (Figure 4) whereas at the furnace temperature of 200^{o}C, the moisture content decreased profoundly with the three tested aspect ratios predominantly in the first 10-20 minutes. At the beginning of the test, the reduction of moisture content was due to the concentration difference between the moisture content within wheat kernels and air, which increased the moisture migration from the center of the wheat kernel to its surface and then from the surface to air by convection mass transfer. Then, the release of moisture from wheat kernels became more difficult due to the reduction of moisture within the kernels. In other words, the difficulty of removing more moisture is due to smaller difference between the air relative humidity and the wheat moisture content. Corresponding moisture reduction trends were observed by Oluleye et al. (2012) while drying rice and wheat from the initial moisture content of 30% and 49% db in a fluidized bed at a bed temperature of 115^{o}C. They observed 11.18% and 9.67% Points of moisture reduction of rice and wheat, respectively in 35 minutes drying duration. Their results are considerably higher than the value observed in the current study. The difference could be attributed to the higher temperature levels used in their study. Also, Ondier et al. (2010) observed a reduction of 4 to 10% moisture points during the drying of rough rice in a fluidized bed under 60 to 90^{o}C and 1-hour drying duration.

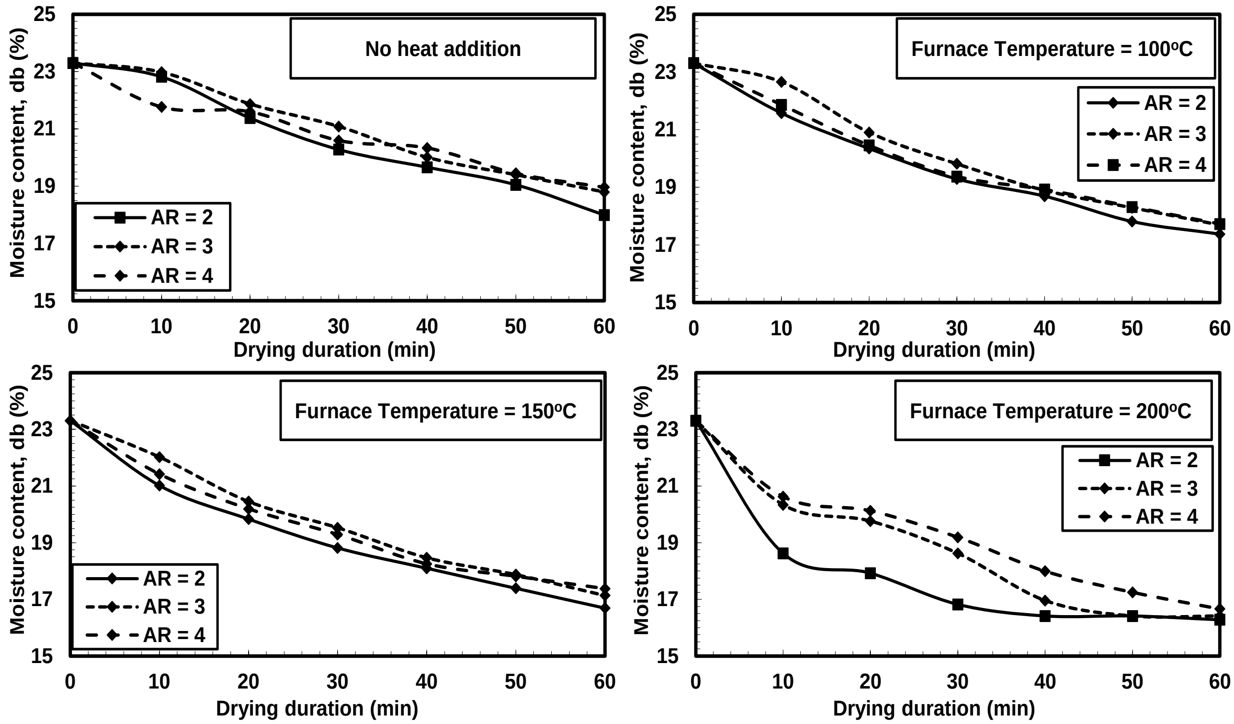

Figure 4. Effects of aspect ratio (AR), furnace temperature, and drying duration on the wheat moisture content (db).

3.4 Effects of aspect ratio, furnace temperature and drying duration on the drying rate

Table 4 shows the drying rate as affected by the aspect ratio, furnace temperature, and drying duration as well as the overall drying rate after 1 hour of the drying duration. The values shown in the table were calculated based on equation 1. In all cases, the first 20-minute period showed the highest drying rates. The highest drying rate of 0.468%/min was observed at the aspect ratio of 2 m/m, the furnace temperature of 200^{o}C and the drying duration between 0-10 minutes. Whereas the minimum drying rate of 0.000%/min was observed in the two cases of the aspect ratio of 2 m/m, the furnace temperature of 200^{o}C and the drying duration between 40-50 minutes and the aspect ratio of 3 m/m, the furnace temperature of 200^{o}C and the drying duration between 50-60 minutes. The results are in agreement with the results obtained by Sandeepa at al. (2013), who also reported that the drying rate was higher at the early stage of drying while the drying rate reduced as the late drying stages. There is no solid trend of the effects of aspect ratio, furnace temperature and drying duration on the drying rate particularly after 20 minutes of the drying duration as indicated by the fluctuations of the drying rate values. The reduction of the drying rate with time can be postulated to the reduction of the moisture amount contained in the bed. Additionally, the drying rate was found to increase significantly with an increase in temperature which is in agreement with Sandeepa at al. (2013). Increasing the air temperature increased the drying rate due to the temperature difference between air and kernels, which increased the mass and heat transfer coefficients. Further explanation could be the fact that with increase in air temperature, the relative humidity and/or the vapor pressure of the air decrease, thus enhancing the water absorbing capacity of the air.

On the other hand, the overall drying rate (last column) showed a very clear trend of the effects of the aspect ratio and furnace temperature on the overall drying rate. The results showed that decreasing the aspect ratio and increasing furnace temperature increased the drying rate. The highest overall drying rate of 0.117%/min was observed at the aspect ratio of 2 m/m and the furnace temperature of 200^{o}C, whereas the lowest overall drying rate of 0.072%/min was observed at the aspect ratio of 4 m/m and no heat during the one-hour drying duration. The increase in drying rate corresponding to the decrease in the aspect ratio allows the same amount of heat to remove more moisture during the one-hour drying. The reduction of drying rate resulted from increasing the aspect ratio can be postulated to the high moisture level within the bed and the reduction of quality of fluidization. In an investigation into the heat transfer in shallow fluidized beds by McGaw (1976), the results revealed that the gas to particle heat transfer coefficient, in addition to being a function of the Reynolds number, is also a strong function of the bed depth. Moreover, the higher the air temperature the more moisture removal from the wheat kernels as more energy was provided to the kernels, and the moisture holding capacity of the air increases with increase in temperature.

Table 4. Effects of furnace temperature and drying duration on drying rate (%/min).

Furnace Temp. °C	Aspect Ratio m/m	Drying duration (min) 0 to 10	10 to 20	20 to 30	30 to 40	40 to 50	50 to 60	Overall drying rate
No heat	2	0.048	0.144	0.110	0.062	0.061	0.106	0.088
	3	0.032	0.111	0.078	0.108	0.061	0.060	0.075
	4	0.154	0.017	0.100	0.026	0.089	0.049	0.072
100	2	0.173	0.123	0.106	0.059	0.088	0.044	0.099
	3	0.065	0.175	0.109	0.092	0.060	0.060	0.094
	4	0.144	0.141	0.107	0.045	0.060	0.059	0.093
150	2	0.229	0.119	0.102	0.072	0.071	0.070	0.110
	3	0.129	0.157	0.092	0.106	0.060	0.074	0.103
	4	0.189	0.123	0.090	0.104	0.044	0.044	0.099
200	2	0.468	0.070	0.110	0.041	0.000	0.014	0.117
	3	0.297	0.058	0.114	0.166	0.054	0.000	0.115
	4	0.268	0.050	0.093	0.120	0.074	0.059	0.111

3.5 Effects of aspect ratio, furnace temperature and drying duration on the dryer efficiency

The thermal efficiency of the dryer was calculated based on equation 4. Figure 5 shows the effects of aspect ratio and furnace temperature on the thermal efficiency of the fluidized bed dryer. Although the four heating conditions showed the same trend, there were some differences in the dryer efficiencies after the one-hour drying duration. Increasing the aspect ratio and the furnace temperature increased the dryer efficiency. This can be attributed to more wheat and energy associated with the increase in the aspect ratio and furnace temperature, respectively. As mentioned earlier, the air flow rate remained constant. The variable that changed overtime was the total amount of water removed from the wheat kernels.. The highest dryer efficiency of

63.2% was achieved at the aspect ratio of 4 m/m and the furnace temperature of 200^{o}C, whereas the minimum drying efficiency of 22.5% was observed at the aspect ratio of 4 m/m and the furnace temperature of 200^{o}C. There is no profound difference between the dryer efficiencies at the aspect ratio of 2 m/m for all the studied heating conditions. Adding supplemental heat from the no heat condition to 200^{o}C decreased the dryer efficiency slightly from 25.1% to 22.5%. This phenomenon could be postulated to the smallest amount of wheat in the fluidized bed as compared with other aspect ratios. In other words, the smaller the amount of wheat, the smaller the amount of water to be evaporated from the wheat kernels. As a comparison, increasing the aspect ratio from 2 to 4 m/m at the furnace temperature of 200^{o}C almost tripled the dryer efficiency (from 22.6% to 63.2%). This may support the findings of the highest drying rates at the furnace temperature of 200^{o}C. Similar results were observed by Balbine et al. (2015) when they studied the dryer efficiency during the drying of mango under various temperature levels of 40, 50, and 60°C. They reported that the higher the air temperature the faster drying rate and the shorter drying time. The observed dryer efficiencies were lower than these obtained by Oluleye et al. (2012). They reported that the fluidized bed dryer efficiency reached 89% and 90% for rice and wheat, respectively. The lower dryer efficiency in the current study may be due to the utilization of more air to dry wheat. The larger amount of air could be translated to higher energy input to the system.

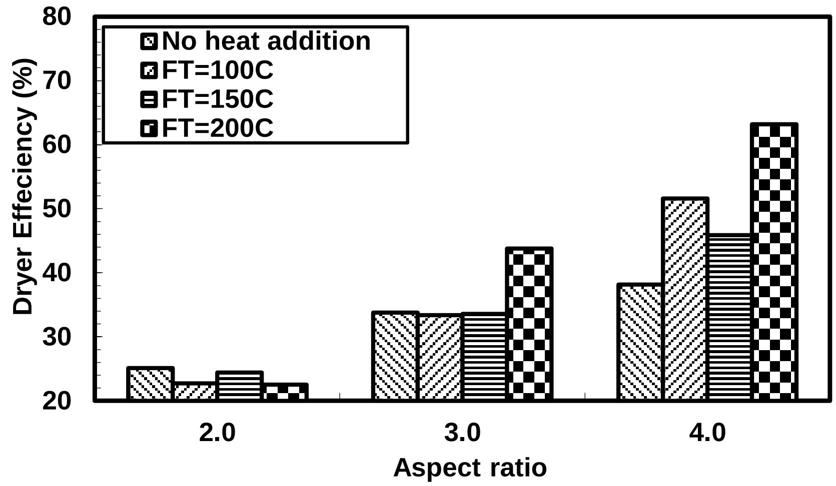

Figure 5. Effects of aspect ratio, furnace temperature (FT), drying duration on the drying efficiency.

3.6 Empirical models

Multiple regression techniques were used to develop an empirical correlation to predict wheat moisture content (% db) as a function of the aspect ratio, the furnace temperature and drying duration. Figure 6 shows the measured moisture content versus predicted moisture content. Equation 5 shows the moisture content of wheat to decrease with an increase in the drying temperature and/or the drying duration. It also shows that the moisture content of wheat kernels to increase with the increase in the aspect ratio. This empirical equation is valid under the specific conditions of drying wheat subjected to the studied conditions of aspect ratio, drying temperature and drying duration with the adjusted coefficient of determination and the root mean square error (RMSE) of 0.91 and 0.7%, respectively.

$$\mathrm{MC} = 23.228 + 0.275 \times \mathrm{AR} - 0.012 \times \mathrm{T} - 0.095 \times \mathrm{t} \quad (5)$$

Where,

MC = the moisture content of wheat (% db),

AR = the aspect ratio (m/m),

T = the furnace temperature (°C),

t = the drying duration (min).

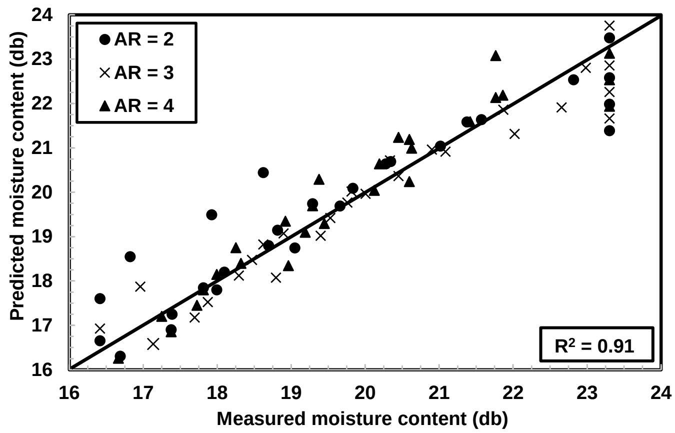

Figure 6. Measured moisture content versus predicted moisture content.

Another empirical equation was developed to determine the dryer efficiency as a function of the aspect ratio and the drying temperature. The values of the maximum air temperature were used rather than the values of furnace temperature. Multiple regression techniques were also used to develop the empirical correlation as presented in Equation 6. Figure 7 shows the determined dryer efficiency versus those predicted. It should be mentioned that the dryer efficiency is not a function of the drying duration in this case as the determination of the dryer efficiency took place after one hour. Equation 6 shows that the dryer efficiency to increase with the increase in the aspect ratio and/or the drying temperature. This empirical equation is valid under the conditions of drying wheat subjected to the studied conditions of aspect ratio and drying temperature with the adjusted coefficient of determination and RMSE of 0.88 and 4.6%, respectively.

$$\mathrm{DE} = -12.48 + 14.28 \times \mathrm{AR} + 0.06 \times \mathrm{T} \qquad R^2 = 0.88 \tag{6}$$

Where,

DE = the dryer efficiency (%)

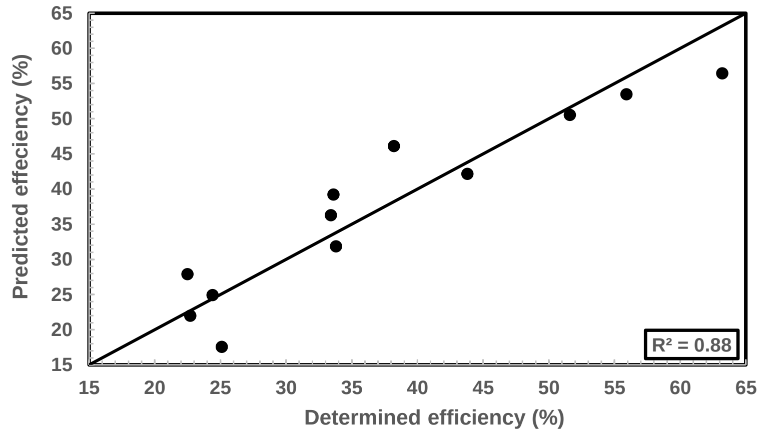

Figure 7. Determined dryer efficiency versus predicted dryer efficiency.

4. Conclusions

A fluidized bed dryer system was developed and tested to successfully dry wheat kernels. The drying characteristics of wheat had been evaluated in the fluidized bed dryer with respect to various operating parameters. The effects of aspect ratio, furnace temperature and drying duration on the dryer performance were determined. The following conclusions can be made from this study:

- The fluidized bed dryer system proved to be an exceptional tool to dry wheat kernels as well as having the potential to dry other commodities.
- The lowest moisture content of wheat reached 16.3% db at the aspect ratio of 2 m/m, the furnace temperature of 200^{o}C, and the drying duration of 60 minutes.
- The drying rate ranged between 7.0% and 4.3% moisture points per hour.
- The highest overall drying rate reached 0.117%/min at the aspect ratio of 2 m/m, the furnace temperature of 200^{o}C and the drying duration of one hour.
- The dryer efficiency reached 63.2% at the aspect ratio of 4 m/m and the furnace temperature of 200^{o}C.

- Two correlations between the wheat moisture content and the dryer efficiency as functions of the aspect ratio, the drying temperature and the drying duration were developed with adjusted coefficient of determination of 0.91 and 0.88, respectively.

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Chapter 4: Evaluation of the performance of a newly developed wireless temperature and moisture sensor for rice under various levels of temperature, moisture content, and dockage.

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Abstract

Monitoring on-farm, in-bin natural air-drying process of rice is critical to achieve optimum milled rice quality, milling yields and maximize profits to growers and processors. Engineering tools such as temperature/humidity cables with sensors for grain condition monitoring, and mobile applications have emerged to provide significant improvements in quality control and automation of the drying process. This research seeks to improve the performance of a recently developed, novel wireless probe for sensing temperature and moisture content of rice. The specific objective is to test the accuracy and precision of the measurements over a wide range of rice temperature (20°C to 60°C), moisture content (13% to 25% wet basis) and dockage levels (0 to 10% by weight). Wireless probes designed and built-in collaboration with Deacon Technologies LLC were used in this study. The probes were calibrated against thermocouple readings for temperature measurements and standard oven method measurements for moisture content. Experiments were performed in triplicates using three different probes and three metal containers with rice samples to check the accuracy of the probes and to determine the variability amongst different probes. The probes were accurate due to the strong regressions found between the measured and true values of temperature and moisture content. The ANOVA analysis showed that there was no significant difference within different probes both for temperature ($p = 0.17$) and moisture content ($p = 0.48$) measurements. Calibration equations were developed to further reduce the variance in the probe measurements. Both for temperature and moisture content measurements, the calibration equation coefficients were statistically significant with positive slopes and small standard errors (less than 0.5). Thus, these probes could be handy for on-farm in-bin rice temperature and moisture monitoring, with the merits of portability, easy set-up, and tear down, low initial and maintenance cost, and precise and accurate

measurements.

Keywords.

Rough rice, On-farm in-bin drying, Temperature, Moisture content, Wireless probe, Dockage, Calibration

1. Introduction

Rice has emerged as the most important cereal in the world, with 21% of world per capita caloric intake and 85% of the production used for direct human consumption (Awika, 2011). It is considered as the staple carbohydrate source of more than half the world's population (Atwill, 2015). The US is the fourth largest exporter of rice and the state of Arkansas produces approximately 47% of the U.S. rice (USDA, 2016). Thus, rice in general has great social and economic importance. Rice is harvested at high moisture contents (19-21% wet basis) and must be dried immediately following harvest to maintain the grain quality. Many factors can lead to grain deterioration during drying and storage, which include grain germination, mold growth, discoloration, insect infestations, and rodent attack (Boumans, 2012; Shafiekhani et al., 2018). For the modern bins and even the small-scaled structures in developing countries, control of temperature and air humidity is crucial to attain the safe grain storage moisture content (Mrema et al., 2012), for rice, it is 13% wet basis (Benado and Rizvi, 1985; Reddy et al., 2008). The grain moisture and temperature have been cited to play a significant role in the rate of the grain quality deterioration (Proctor, 1994). Therefore, it is vital to develop a technology capable of continuous monitoring of these two parameters during drying and storage (Asefi et al., 2015).

A variety of practices are used to monitor rice temperature and moisture content during drying and storage. These practices vary in the degree of sophistication. Manual inspection of rice temperature and moisture content was used in the past and is still being practiced in some developing countries (Maier et al., 2010). Visual inspection, scooping rice with hands, and smelling from the top of the bin allowed farmers or processors to make a judgment on the temperature, moisture content, mold growth and insect activities (Maier et al., 2010). However, this method is time-consuming, dangerous, and oftentimes unreliable (Freeman et al., 1998). Electronic sensors have been developed and installed in bins to automate the manual inspection process. The sensors measure physical entities that could be used to make a judgment about the condition of the grain (Lees, 2003). Sensors available in the industry allow monitoring and control of grain temperature and moisture (Folk, 2016), carbon dioxide, odor, dust levels and acoustics (Neethirajan and Jayas, 2007).

A major transformation in the grain sensing occurred with the introduction of the second generation technology which is more robust and dependable. The most common system of grain temperature and moisture sensing in the bins involves the use of a network of sensors integrated together on multiple cables (cabling technology). These cables use thermocouples and moisture sensors sensing dielectric properties of grain for temperature and moisture measurements, respectively (Neethirajan and Jayas, 2007). The cables holding the sensors are suspended from the ceiling of the bin and are uniformly spread throughout the bin width. The length of the cables and the number of sensors on each cable are dependent on the dimensions of the bin and the specific monitoring requirement of the user. These cables expose the sensors to the environment through an opening on the cables. The data is either transmitted to the computer connected to the cables or there can be remote transmission of data (Armstrong, 2003; Neethirajan and Jayas, 2007). Though these cables are most used and can incorporate multiple sensors on a cable, initial and maintenance cost can prove costly to a small-scale farmer in the US (Armstrong, 2003). The stirring mechanism cannot be used during the drying process as the cables will be damaged. Also, if a breakdown occurs during drying, not only it takes a long time to fix the cables which compromises grain quality but also the cost of maintenance is high.

Deacon Technologies, LLC collaborated with the University of Arkansas, Fayetteville to develop the temperature and moisture content probe (Grain Deacon, Deacon Technologies, LLC, AR, USA) used in this study. Similar probes were presented in the study by Armstrong et al. (2017) and they evaluated the measurement of probes to be used in the developing countries where bag storage is common. However, the probes used in this study is developed majorly for on-farm bin setting and can also be used for bag storage and other arrangements with a smaller scale on-farm setting. The novel probe is less costly, portable, low-maintenance, and capable of wireless transfer of temperature and humidity data. Compared to "cabling technology", installation of the new probes in the bins is simpler. The probes may not jeopardize drying processes that employ stirrers because they can be easily disassembled. Anecdotally, as per developer, the cost for monitoring standard rice bins in the United States is $600 per bin which is approximately 1/10th the cost for monitoring by the temperature and moisture cables; hence may suit economics of scale for smallholder grain producers. Another major advantage of these probes is that they do not require AC electricity. Each probe is battery powered and a solar panel is available to power the hub (a medium that transmits the data from probes to a computer). The solar panel has a built-in battery that stores power for the hub for use during periods of darkness. The solar panel can provide enough power to run the system for 5 days in total darkness and can fully recharge the battery in 2 hours.

Previous studies have reported that rice is harvested at a wide range of initial moisture content ranging from 14-26% wet basis (Inprasit and Noomhorm, 2001; Wiset et al., 2001;

Ambardekar and Siebenmorgen, 2012) and contain average of 2% of dockage coming into the US on-farm rice bins (Atungulu et al., 2013). High levels of dockage restrict air flow within a drying bin and determine characteristics of the grain in the proximity of sensors; such may impact the accuracy of temperature and moisture sensing. Thus, the objectives of this study are (1) to test the accuracy and precision of the probes for a practical range of on-farm drying air temperature, rough rice initial moisture content, and dockage levels; (2) to identify the calibration equations for the probes based on the standard values of temperature and moisture content.

2. Materials and methods

All experiments were performed in a laboratory at the department of food science, University of Arkansas, Fayetteville, AR.

2.1 Probe construction and measurement

The probe developed by Deacon Technologies, LLC., consists of temperature and humidity sensors. The sensors are shielded in 1.59 cm (5/8th in) diameter aluminum pipe. The probe is 1.04 m (41 in) long, has a hexagonal base which provides a base to mount battery powered electronic circuit (fig. 8-A & B). The temperature and humidity sensors are placed inside the aluminum tapered tip at the other end from the flat hexagonal base (fig. 8-C). Temperature sensor is a linear active thermistor IC (Model-MCP9700A, Microchip Technology Inc., Chandler AZ), whereas humidity sensor is a low voltage relative humidity sensor with near linear output (Model-HIH-5031, Honeywell International Inc., Morristown, NJ). These sensors outputs are read by analog to digital convertor using inputs from a transceiver (Model-900HP FM, XBee, Minnetonka, MN). The sensors are connected from the circuit at the base through the wires, the aluminum duct prevents dust and other foreign materials. The sensor board (circuit at the base) measures the temperature and relative humidity of environment around the probe immersed in the grain. The software considers the grain size and type and makes adjustments before reporting the grain moisture content on the mobile application (Grain Deacon, Deacon Technologies, LLC). Based on the effects of bulk density and air temperature, grain moisture content can further be refined for greater accuracy and precision, which is the primary goal for the current study.

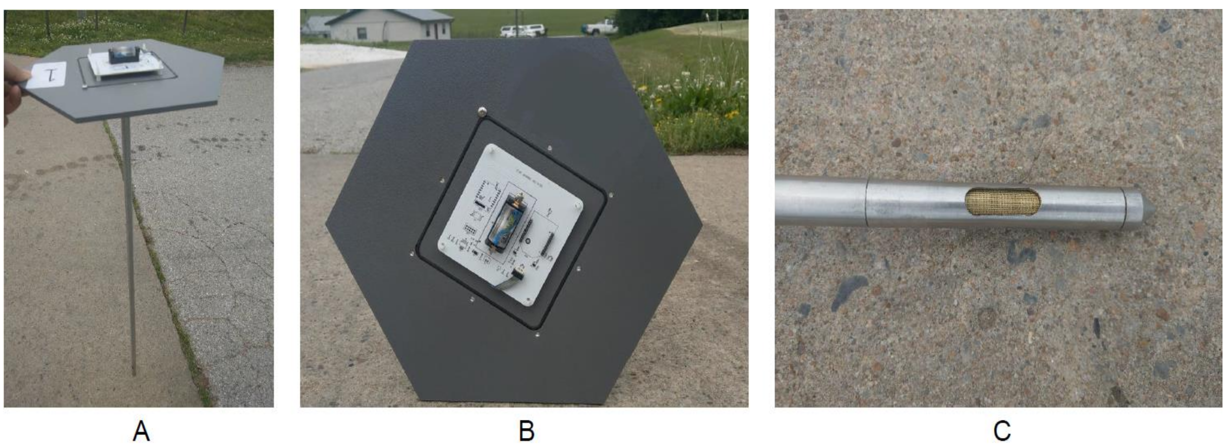

Figure 8. Moisture content probe visual description: (A) probe length wise in an upside-down position, (B) hexagonal base with the circuit mounted, (C) temperature and moisture sensors located near the tip of the probe.

2.2 Sample Preparation

Medium-grain rice (cv. Jupiter) which was at an initial moisture content of 20.3% wet basis (w.b.) was used in this experiment. The rice was harvested from a commercial farm in the Northeast region of Arkansas during the month of October in 2017. Harvested rice was cleaned with a dockage tester (Model XT4, Carter-Day, Minneapolis, MN). After cleaning, rough rice was gently dried in a conditioned environment (26°C, 56% relative humidity). Dried samples were then dehulled with an impeller husker (Model FC2K, Yamamoto, Yamagata, Japan) to obtain husk, which was used as dockage in the experiments. Rough rice and dockage moisture content were 18% w.b. as measured following the procedures of American Society of Agricultural Engineers (ASAE) standard S352.2. It involved heating 15 g of the sample in an oven at 130°C for 24 h (fig. 9-A & B). For moisture content measurements, rough rice and dockage were divided into four sub lots and were either re-wetted or dried to attain moisture contents of 13%, 17%, 21%, and 25%. However, for temperature measurements, rough rice and dockage were dried to attain moisture content of 18% (w.b.). Re-wetting was done by spraying the amount of water estimated using the difference between the initial and desired moisture content. Drying was done by spreading rice and dockage on the floor of a conditioned room as mentioned above. After attaining the desired moisture content, the rice and dockage were kept in a cooler at 4°C for 7 days.

A B

Figure 9. Standard moisture content measuring procedure: (A) tin cups are used to hold 15 g of samples and the cups are placed on a tray; (B) tray with cups is kept in the oven at 130°C for 24 hours.

2.3 Experimental Design

Three identical probes were tested in the laboratory for accuracy and precision of rice temperature and moisture content measurements at varying levels of air temperature, moisture, and dockage. Accuracy is defined as the degree of equality of any measured quantity to a known standard, while precision is defined as the degree of deviation of measurement from the mean (Taylor, 1997). The ranges of air temperature, sample moisture content and the dockage were similar to the practical ranges as observed in on-farm drying and storage rice bins.

To check the accuracy and precision of probes for temperature and moisture content measurements, two sets of experiments were performed with different experimental design and procedures, respectively. For temperature experiments, three levels of air temperature (20°C, 40°C and 60°C) and four levels of dockage to rough rice ratio (0:1, 1:49, 1:16, and 1:9 kg/kg) were tested (table 5). These experiments were performed inside an oven (Fisher Scientific Isotemp Oven, Model 516G, Hampton, NH) to vary air temperatures as shown in table 5.

Table 5. Experimental design for checking accuracy and precision of probes to measure the temperature of rice.

Exp. No.	Air temperature °C	Dockage to rough rice ratio kg/kg	Replication/probe number
1	20	0:1	1, 2, 3
2	20	1:49	1, 2, 3
3	20	1:16	1, 2, 3
4	20	1:9	1, 2, 3
5	40	0:1	1, 2, 3
6	40	1:49	1, 2, 3
7	40	1:16	1, 2, 3
8	40	1:9	1, 2, 3
9	60	0:1	1, 2, 3
10	60	1:49	1, 2, 3
11	60	1:16	1, 2, 3
12	60	1:9	1, 2, 3

For moisture content experiments, combinations of desired moisture contents (13%, 17%, 21% and 25% w.b.) and four dockage to rough rice ratio (0:1, 1:49, 1:16, and 1:9 kg/kg) were tested (table 6). These experiments were performed at controlled room temperature (25°C) using thermostat settings for the HVAC system in the laboratory; the data logger was used to verify the same (Hobo U23 Pro v2, Onset Computer Corporation, Bourne, MA). Both sets of experiments were performed in triplicates using three different probes to check the accuracy of the probes and to determine the variability amongst different probes.

Table 6. Experimental design for checking accuracy and precision of probes to measure the moisture content of rice.

Exp. No.	Desired moisture content % (w.b.)	Dockage to rough rice ratio kg/kg	Replication/probe number
1	13	0:1	1, 2, 3
2	13	1:49	1, 2, 3
3	13	1:16	1, 2, 3
4	13	1:9	1, 2, 3
5	17	0:1	1, 2, 3
6	17	1:49	1, 2, 3
7	17	1:16	1, 2, 3
8	17	1:9	1, 2, 3
9	21	0:1	1, 2, 3
10	21	1:49	1, 2, 3
11	21	1:16	1, 2, 3
12	21	1:9	1, 2, 3
13	25	0:1	1, 2, 3
14	25	1:49	1, 2, 3
15	25	1:16	1, 2, 3
16	25	1:9	1, 2, 3

2.4 Experimental Procedures

One-gallon metal containers were used to hold the samples in each experiment as described in table 5 and 6. Three containers, one each for one probe were used. A hole was drilled at the center of the lid of container having the same diameter as the probe i.e. 1.59 cm (5/8th inch). For all experiments, probes are inserted 15 cm (6 inch) into the rice as shown in figure 10. Serial number (1, 2, and 3) was labeled on the probes and the containers. For temperature and moisture content experiments, different arrangements were made as described in the experimental design and further explained in the following two paragraphs.

For temperature, a container without a lid was filled with the sample and was kept in the oven. After 30 minutes of exposure, the temperature readings were taken. The 30 minutes allowed the rice temperature to reach a steady state after the initial rise (estimated using a test run and monitoring on the computer screen from the data logger software). The probe attached with a thermocouple was inserted upside-down through the hole on top of the oven as shown in figure 10-A & 10-B. Standard air temperature readings were measured using type J thermocouple connected to a data logger (OMEGA TC-08, Norwalk, CT). The data logger was attached to a computer as shown in figure 3-A, and the thermocouple readings were retrieved using data logger software (OMEGA). The mobile application was used to retrieve probe temperature data, the hub communicates to the probe and data was downloaded on a computer. The temperature measurements were taken at the same time from both the probe and thermocouple to check the accuracy of the temperature measured by the probe.

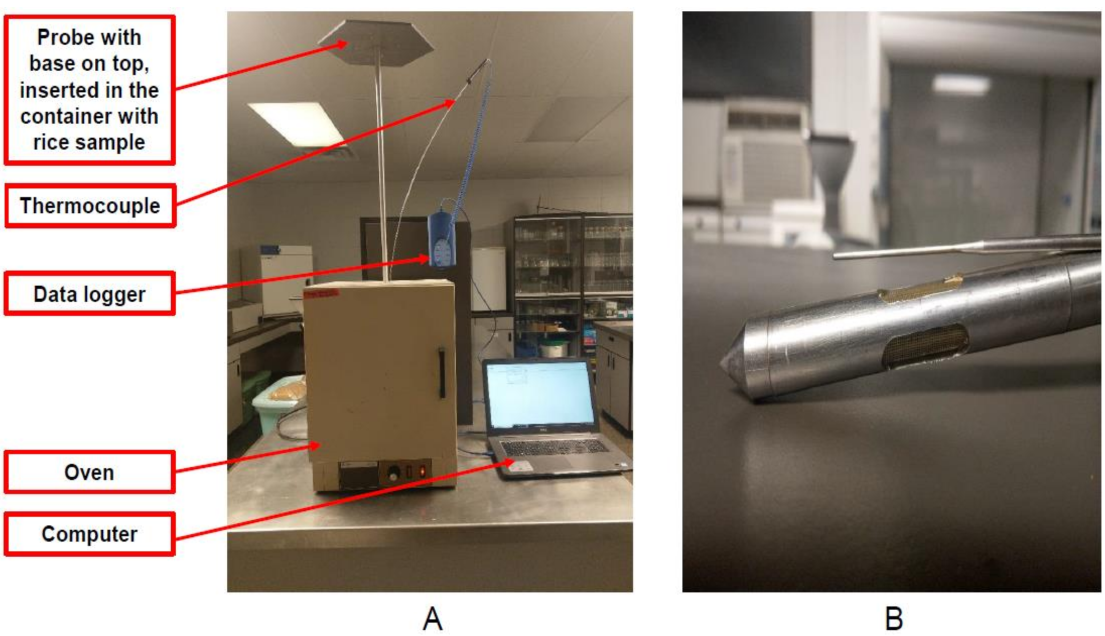

Figure 10. Experimental setup to measure the temperature of rough rice samples using probes: (A) full setup with rice samples in a metal container kept in the oven at the desired air temperature for 30 minutes before readings were taken from the probe and the thermocouple, (B) probe sensors near the tip and thermocouple tip were kept close together by taping the probe and thermocouple in the middle.

For moisture content, the complete setup of the experiment is depicted in figure 11. The containers were filled with the samples at the required level of dockage to rough rice ratio and desired moisture content. Moisture content data was recorded every 30 seconds, the probes were inserted upside-down through the hole in the lid with the tip inside the samples. Each experiment was run for 15 minutes, recording a total of thirty moisture content data points. The arithmetic average was taken to obtain the experimental moisture content (w.b.). To measure the standard moisture content (w.b.) for calibration purposes, the same samples were used after each experiment for measuring the moisture content using ASAE standard S352.2 (fig.9-A & 9-B). The probe moisture data was downloaded using the mobile application. The bulk density of the samples for each experiment was also obtained by measuring the sample weight of a known volume using a measuring flask.

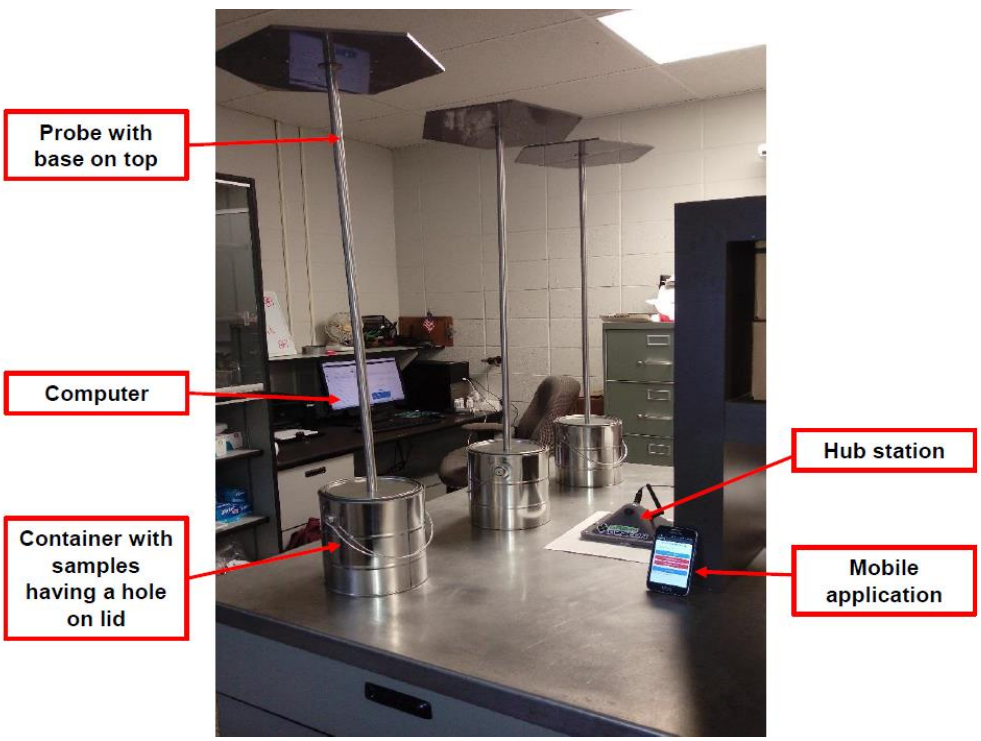

Figure 11. Experimental setup to measure the moisture content of rough rice samples using probes.

2.5 Data Analysis

Data were analyzed for analysis of variance (ANOVA) with complete randomized block design using JMP Pro 13 (SAS Institute Inc., Cary, NC) to see any effect of changing dockage to rough rice ratio on accuracy and precision of probe measurements. The experimental values and the standard values of rice temperature and moisture content (w.b.) were used to compare the accuracy of the probes. Moreover, the precision of the probes was checked using the three replications obtained using three different probes. The calibration curve and equation were obtained to make any further adjustments in the experimental readings based on the standard readings.

3. Results and Discussion

3.1 Rice Temperature

The experimental and standard rice temperature for different dockage to rough rice ratio and air temperature are presented in table 7.

Table 7. Mean data with standard errors for all temperature experiments.

Air temperature °C	Dockage to rough rice ratio	Experimental rice temperature °C	Standard rice temperature °C
20	0 to 1	20.03±0.07	19.87±0.09
20	1 to 49	20.03±0.09	20.03±0.07
20	1 to 16	19.93±0.03	19.93±0.07
20	1 to 9	20.03±0.07	20.03±0.15
40	0 to 1	36.70±0.10	36.77±0.09
40	1 to 49	36.67±0.07	36.50±0.06
40	1 to 16	36.87±0.03	37.13±0.09
40	1 to 9	36.90±0.06	37.17±0.03
60	0 to 1	55.43±0.09	55.13±0.07
60	1 to 49	55.53±0.03	55.50±0.12
60	1 to 16	55.50±0.06	55.73±0.17
60	1 to 9	55.50±0.06	55.70±0.06

The ANOVA results for temperature experiments with experimental rice temperature as a response variable are shown in table 8. Only air temperature as a factor was statistically significant, using samples at different air temperature was reported different by the probes. There was no significant effect of dockage to rough rice ratio on the rice temperature measurement (p = 0.4185), the dockage in the rough rice did not change the rice temperature measurement by the probes. Thus, the farmers can use the probes to monitor the rice temperature without error due to the presence of dockage in rice.

Table 8. ANOVA table for checking the statistical significance of the variables in the temperature experiment.

Factor	Degree of freedom	P-value
Air temperature	2	<0.0001*
Dockage to rough rice ratio	3	0.4185
Replication/probe number	2	0.1731
Air temperature * Replication/probe number	4	0.2659
Dockage to rough rice ratio * Replication/probe number	6	0.4719

* Statistical significance checked at $\alpha = 0.05$.

3.2 Precision of probes

The precision of the probe was verified by checking differences in temperature measurement of the three different probes. Table 8 suggests that there was no overall difference in the temperature measurements between the three probes used for the experiments (p = 0.1731). The precision was also verified by looking at the interactions of the probe number (replication) with changing air temperature and dockage to rough rice ratio. No statistical significance was found for the interactions suggesting that the probes were highly precise for practical ranges of air temperature and dockage to rough rice ratio. Due to the high precision of probes for temperature measurements, the individual probe can be considered interchangeable for rice temperature monitoring as there was no difference in the data measured by different probes.

3.3 Accuracy of probes and calibration

Every equipment measuring any physical entity (rice temperature and moisture content in this study) involves some systematic errors in measurement. The experimental/measured value reported by the equipment needs to be corrected to minimize error and is done through calibration. It involves comparing the experimental/measured value with a standard/true value and formulating a calibration equation to obtain a prediction of true value (Peters, 2001; Barwick, 2003). Thus, to check the accuracy of the probes for temperature measurement, probes were compared to the standard value as determined by thermocouples. The calibration line was plotted with the experimental values on the horizontal axis and the standard values on the vertical axis (fig. 12).

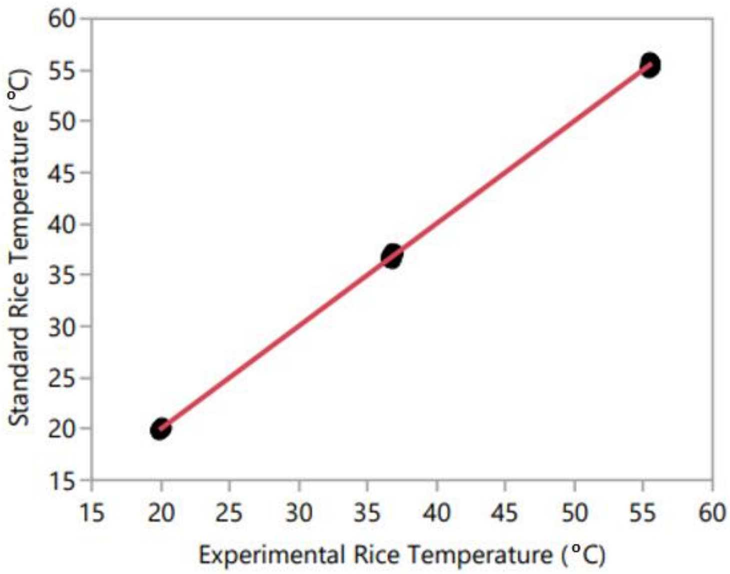

Figure 12. Calibration line fitted between the experimental and standard rice temperature (°C).

The coefficient of determination (R^2) value is 0.988 which means that 98.8% of the total variability is explained by the calibration line, a good line of fit for the prediction of true rice temperature. Moreover, it indicates a strong positive correlation between the experimental and the standard value (r = 0.99). Thus, it can be reported that the probes are accurate for rice temperature measurements, however, it is advisable to use the calibration equation for better accuracy. Equation 1 is the calibration equation for the probes to find true rice temperature (°C) based on the measured (experimental) rice temperature (°C).

$$True\ rice\ temperature = (1.002 * Measured\ rice\ temperature) - 0.04 \tag{1}$$

The slope (1.002) and intercept (-0.04) coefficients are statistically significant at 99% level of significance. The standard error with the slope and intercept coefficients are ±0.003 and ±0.11, respectively. Thus, the calibration equation is dependable due to small standard errors for equation coefficients, R^2 close to 1, and a small p-value (<0.0001).

3.4 Rice moisture content

The experimental and standard moisture content (w.b.) along with the bulk density for all the experiments are reported in table 9.

Table 9. Mean data with standard errors for all moisture content (MC) in wet basis (w.b.).

Desired MC % (w.b.)	Dockage to rough rice ratio	Bulk Density (kg/m3)	Experimental MC % (w.b.)	Standard MC % (w.b.)
13	0 to 1	612.13 ± 5.32	12.77 ± 0.06	12.75 ± 0.04
13	1 to 49	581.33 ± 7.75	12.64 ± 0.06	12.61 ± 0.06
13	1 to 16	490.30 ± 10.37	12.65 ± 0.04	12.59 ± 0.06
13	1 to 9	452.47 ± 18.99	12.68 ± 0.06	12.75 ± 0.07
17	0 to 1	632.33 ± 5.43	16.51 ± 0.05	16.96 ± 0.05
17	1 to 49	593.50 ± 2.18	16.81 ± 0.19	17.03 ± 0.04
17	1 to 16	534.03 ± 8.79	17.16 ± 0.18	17.18 ± 0.01
17	1 to 9	466.40 ± 12.49	17.32 ± 0.13	17.19 ± 0.06
21	0 to 1	652.13 ± 5.56	20.30 ± 0.02	20.93 ± 0.03
21	1 to 49	596.33 ± 9.23	20.36 ± 0.00	21.02 ± 0.05
21	1 to 16	521.77 ± 14.83	20.28 ± 0.00	20.84 ± 0.05
21	1 to 9	453.67 ± 24.10	20.19 ± 0.02	20.67 ± 0.00
25	0 to 1	645.73 ± 7.71	22.61 ± 0.05	24.89 ± 0.12
25	1 to 49	609.70 ± 4.17	22.43 ± 0.01	24.67 ± 0.10
25	1 to 16	536.23 ± 14.29	22.44 ± 0.04	24.89 ± 0.06
25	1 to 9	466.73 ± 8.96	22.47 ± 0.06	24.67 ± 0.10

The analysis of variance (ANOVA) results for moisture content experiments are shown in table 10. The table shows that only desired moisture content was statistically significant, thus, samples with different initial moisture content showed different moisture content readings from the probes. There was no significant effect of dockage to rough rice ratio on the moisture content measurements ($p = 0.5389$), the dockage in the rough rice did not change the probe moisture content measurements. Thus, the probes are dependable for error-free on-farm in-bin monitoring of rice moisture content at levels of dockage studied.

Table 10. ANOVA table for checking the statistical significance of the variables in the moisture content experiments.

Factor	Degree of freedom	P-value
Desired moisture content	3	<0.0001*
Dockage to rough rice ratio	3	0.5389
Replication/probe number	2	0.4820
Desired moisture content * Replication/probe number	6	0.6202
Dockage to rough rice ratio * Replication/probe number	6	0.9264

* Statistical significance checked at $\alpha = 0.05$.

3.5 Precision of probes

The precision of the probes was verified by checking differences in moisture content measurements by three different probes. Table 10 suggests that there was no overall difference in moisture content readings of the three probes used for the experiments ($p = 0.4820$). Interactions of the probe number (replication) with changing desired moisture content and dockage to rough rice ratio were likewise not significant. Thus, the probes were precise for a practical range of moisture content and dockage to rough rice ratio. Because of the high precision of these probes, individual probes can be used interchangeably without any bias occurring due to the difference in probes.

3.6 Accuracy of probes and calibration

To check the accuracy of the probes, moisture content measured by the probes was compared to the standard moisture content value as determined by ASAE Standard S352.2. The calibration line was plotted between the experimental moisture content and the standard values (fig. 13).

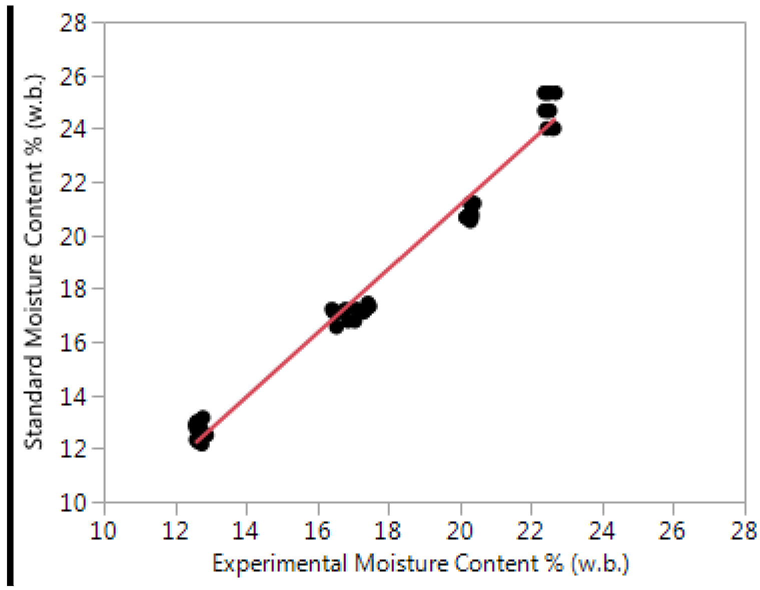

Figure 13. Calibration line fitted between the experimental and standard moisture content (w.b.).

The coefficient of determination (R^2) value is 0.979, thus, 97.9% of total error is explained by the calibration line which makes it a good line of fit for the prediction of true moisture content. A strong positive correlation between the experimental and the standard value (r = 0.989) is also noticed. Therefore, it can be reported that the probes are highly accurate, however, it is advisable to use a calibration equation for better accuracy. The calibration equation for the probes to find a true moisture content (w.b.) based on the measured (experimental) moisture content (w.b.) is given in equation 2.

$$True\ moisture\ content = (1.202 * Measured\ moisture\ content) - 2.914 \quad (2)$$

The above calibration equation is dependable due to R^2 close to 1, slope (1.202) and intercept (-2.914) coefficients are statistically significant, and the standard error with slope and intercept coefficients are small i.e. ±0.03 and ±0.48, respectively.

4. Conclusions

Rice growers in the U.S. use sensor cables to monitor the temperature and moisture levels in the on-farm drying and storage bins to avoid rice spoilage. Simple, portable and wireless probes are introduced. These probes run on battery and solar energy which provide growers with ease of operations and maintenance. The accuracy and precision of probes were examined for rice temperature and moisture content measurements over a wide range of rice temperature, moisture content and dockage levels. ANOVA showed that there is no significant effect of varying dockage amount in the accuracy of both rice temperature and moisture content measured by the probes. There was no statistical difference in probes for rice temperature and moisture content measurements, thus the probes were highly precise. Strong correlation between measured and standard values ($r = 0.990$ for temperature and $r = 0.989$ for moisture content) also indicated good accuracy of the probes, however, it is advisable to use calibration equations which give predicted true values by further reducing variance in the measurements. The findings from this study provide useful information regarding the accuracy and precision of the tested novel probe.

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Chapter 5: Exploration of rough rice head yield subjected to drying and retention durations in a fluidized bed system.

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Abstract

Several researchers have reported that drying freshly harvested rough rice to safe storage moisture content of 13% w.b. in fluidized bed dryers resulted in a decrease in head rice yield, as compared with traditional drying methods. This phenomenon was attributed to the high thermal stress that affects rice kernels. The present study hypothesized that drying rough rice in fluidized bed dryers subjected to retention period would maintain the rice quality as it may reduce the thermal stress. Therefore, the goal of this research was to investigate the effects of heating and retention durations on the dried rice quality and energy consumption in a fluidized bed dryer. A bench scale fluidized bed dryer was developed and tested. The effects of drying duration of 10, 20 and 30 minutes and the retention duration of 0, 15, 30, 45 and 60 minutes on rough rice moisture content, drying rate, head rice yield, and energy consumption were investigated. During the retention period, paddy released a considerable amount of moisture. This moisture reduction, achieved during retention period, was obtained without any additional heating cost and was a supplement to the overall drying process. The retention period helped with thermal stress management within rice kernels and resulted in maintaining the head rice yield as compared to the rice dried without retention. Considering all the studied heating and retention durations, the head rice yield values of rice samples varied from 46.0 % to 51.0 %. The lowest energy consumption was achieved at the heating duration of 10 minutes and the no retention duration. This value represents 144% of the theoretical energy required to remove 1 kilogram of moisture from organic matter.

Keywords.

Drying, Energy Consumption, Head rice yield, Retention duration, Moisture Content, Rough rice.

1. Introduction

Rice (*Oryza sativa* L.) is a favorite staple food with consumption by more than half the world's population (Atwill, 2015). The U.S. is considered the fourth largest exporter of rice (Childs, 2016) which accounts for around 4 million metric tons of rice produced in 2016 (USDA, 2016). In the US, rice production occurs in the Central region (Arkansas, Mississippi, Missouri, Louisiana, and Texas) and the Sacramento Valley of California (Childs, 2016). Arkansas is the most crucial rice-producing state since 1973 with around 47% of the total US rice production in 2016 (USDA, 2016). Rough rice is typically harvested at moisture content above 20%. The high moisture content of freshly harvested rice should be reduced quickly to the safe moisture content of 13% wet basis (w.b.) to avoid any degradation of rice quality due to the growth of mycotoxins. Kunze and Calderwood (1985) reported that about 20% of rice production in the United States is dried on-farm using natural air or low-temperature air. Typically, with on-farm in-bin drying systems, where rice is slowly dried from the bottom to the top, prevailing weather conditions may not allow the drying front to move quickly enough within the grain mass. Accordingly, producers started to utilize the fluidized bed drying technique to dry rough rice which has been in practice for almost three decades (Tirawanichakul et al., 2004; Karbasi and Mahdizadeh, 2008; Tuyen et al., 2009). Due to a gradual increase in production of rice and reducing moisture in a short time for safe storage, fluidized bed drying started to be one of the most convenient methods of drying rice in several parts of the world (Karbasi and Mahdizadeh, 2008).

The fluidized bed drying technique is one of the most widely used technologies in industries for chemicals, fertilizers, pharmaceuticals, and agricultural produce (Srinivasakannan et al., 2012). This method fluidizes the bed of particulate material by blowing air at high speeds to support the weight of the substance in a fluidized state (Yang, 2003). The intrigue transfer phenomenon removes the moisture by evaporation from the grains; heat is supplied for the evaporation through convection from the surrounding medium to the surface of the grain, and then from the surface through conduction to the center of the grain (Sutar and Sahoo, 2011). The moisture travels in the opposite direction to finally evaporate in the environment through convection (Sutar and Sahoo, 2011). In recent times, fluidized bed drying has found an increasing amount of applications in the grain drying industry due to optimized bed designs suited to dry the coarse grains, which were believed hard to fluidize (Srinivasakannan et al., 2012). This fluid-like behavior enables grains to be handled like fluids providing ease of loading and unloading (Daud, 2008; Ondier et al., 2010; Sutar and Sahoo, 2011; Khanali et al., 2013). The intense mixing of grains provides a uniform grain temperature with uniform drying and better control of the drying process (Yang, 2003; Daud, 2008; Ondier et al., 2010; Khanali et al., 2013). It also enhances the heat and mass transfer rates due to increased contact between grains and air, thus reducing the drying time as compared to the conventional hot air drying (Yang, 2003; Daud, 2008; Ondier et al., 2010). Fluidized bed dryers can dry different grains by varying the drying parameters like air flow, temperature, and bed height (Jaiboon et al., 2009).

Kozanoglu et al. (2013) studied the drying kinetics of paddy in a reduced superheated steam fluidized bed. It was observed that the drying rates increased with an increase in operating temperatures. Higher degrees of superheated steam generated lower equilibrium moisture contents in this case. Sopanronnarit et al. (1998) developed a fluidized bed paddy dryer with a drying capacity of 2.5-4 t/h and were able to reduce the moisture of paddy from 32.6% to 25.8% dry basis (d.b.) with a bed velocity of 2.8 m/s and an average drying temperature of 144°C. Sarker et al. (2017) studied the effect of fluidized bed drying assisted with inclined bed drying on quality aspects of rice, they concluded that the technique yielded acceptable head rice yield and rice whiteness. Jafari and Zare (2017) investigated the effect of ultrasound radiations assisted fluidized bed drying of rice, they found that drying time reduced by 23% and specific energy consumption decreased by 22% compared to fluidized bed drying without ultrasound radiations. Rordprapat et al. (2005) investigated fluidized bed paddy drying using hot air and superheated steam; and reported that for the same duration of drying, the drying rates of paddy dried by superheated steam were less than those dried with hot air due to initial steam condensation in case of superheated steam. Tirawanichakul et al. (2004) studied the effect of fluidization bed drying temperature on quality attributes of two varieties of paddy. They found the head rice yield was significantly affected by inlet drying air temperatures and initial moisture content in one of the varieties. The whiteness of both the varieties decreased slightly with an increase in the drying air temperature and initial moisture content. Wetchacama et al. (2000) developed a commercial scale fluidized bed dryer and reported 5% more head rice yield than the paddy dried in ambient air.

The key concerns in drying rice with fluidized bed drying are the decreasing head rice yield with an increase in the inlet air temperatures, and also the effect on the whiteness of the rice (Wetchacama et al., 2000). Drying rice at very high temperatures induces stress in the grains, which is the primary cause of the breakage while milling, and affects head rice yield. The rapid moisture removal creates a high moisture gradient within the rice kernels which develops stress inside the rice kernels. The physical stress leads to rice fissuring; fissured rice cracks during the milling process, thus reducing the head rice yield. The lower the head rice yield, the lower the value of rice, since broken rice reduces its commercial value (Tirawanichakul et al., 2004; Jaiboon et al., 2009; Tuyen et al., 2009; Ondier et al., 2010).

Therefore, many studies have suggested using an intermediate tempering stage to improve the head rice yield. In tempering, dried rice is maintained for a specified period without air-flow, at the grain temperature to which the rice was heated in the initial drying stage. The internal moisture equilibrates in the rice kernel, thus relieving some of the stress developed in the rice kernels (Tirawanichakul et al., 2004; Jaiboon et al., 2009; Tuyen et al., 2009).

Thakur and Gupta (2006) examined both stationary versus fluidized bed drying of high moisture paddy with a rest period. They reported that introduction of a rest period between the first and second stage of drying improved the drying rate, lowered the energy requirement, and increased the head rice yield. There was no remarkable difference found in head rice yield from fixed and fluidized bed experiments, though discontinuous drying with rest periods improved head rice yield as compared to continuous drying. Tuyen et al. (2009) evaluated the effect of high-temperature drying and tempering on Vietnamese rice varieties. The head rice yield had improved significantly by extending the tempering time to 40 min. They found that the hardness and stiffness of sound rice kernels were higher in case of fluidized bed drying as compared to those dried by thin layer drying. Jaiboon et al. (2009) investigated the effect of fluidized bed drying temperature and tempering time on the quality of waxy rice. The fluidized bed drying, in their case, resulted in lesser head rice yield than shade drying even when tempering was performed. In contrast to other studies, they found higher drying times lead to higher head rice yield and tempering had no significant effect on it.

As mentioned earlier, many studies (Tirawanichakul et al., 2004; Jaiboon et al., 2009; Tuyen et al., 2009) claimed that tempering stage allowed moisture to diffuse from the core to the surface of rice and the overall effect reduced the problem of rice fissuring. However, the problem of lower head rice yield in fluidized bed drying still exists even after incorporating the tempering stage. Accordingly, the current study hypothesized that utilizing a retention duration following the drying duration could expedite the drying process and maintain the quality of rice. Unlike the tempering duration, air flow will remain constant without heat addition in the retention duration. Not many studies have been done, and uncertainty prevails over the effect of retention duration on dried rice quality. Therefore, the objective of this research was to study the effects of drying duration and retention duration on the bed temperature profile, moisture content, rice quality, and energy consumption.

2. Materials and methods

2.1 Rice collection and characterization

Rough rice (cv. Jupiter) was collected from an Arkansas farm located in the northeast region of the state. The required amount of rough rice was gently homogenized in a large container to ensure representative sampling during the experimental runs. The initial moisture content of rough rice was measured using the standard oven method (ASABE, 2008) and found to be 21.5% w.b. The rough rice bulk density was determined according to the standard method ASTM E873-82. The rice was then stored at 4°C in the cooler until the start of the experiment. The basic dimensions of the rough rice (length, width, and thickness) were measured using a steel digital caliper (General Ultratech, Series – 147, Secaucus, NJ) with an accuracy of 0.02 mm. Table 11 shows the characteristics of rough rice.

Table 11. Characteristics of rough rice.

Parameter*	Units	Rough Rice
Moisture content	%, w. b.	21.5±1.4
Bulk Density	Kg/m^3	634.7±7.9
Dimensions		
Length	mm	7.66±0.25
Width	mm	2.10±0.22
Thickness	mm	1.95±0.42

* Average of three readings, ± the standard deviations.

2.2 Fluidized bed drying system

The fluidized bed dryer consisted of four basic components: an air supplying system, an air heating system, a drying column and measuring systems as shown in figure 14.

Figure 14. A photo of the fluidized bed dryer system.

The air supplying system consisted of a 3kW regenerative blower (SCL k05-MS MOR, FBZ, Italy) controlled by a variable frequency drive (ACS350, ABB Ltd, Switzerland) and connected to an air flow meter (7510 series, KING Instrument Company, Garden Grove, CA), which has the range of 0 - 1.70 m3/min. In the air heating system, heating the drying air was achieved by passing a 1” steel pipe in a tube furnace (Fisher Scientific, Single Set-Point 120v 50/60 Hz) that had a single set point to control the air temperature whereby the furnace was set to the desired temperature, and then air was supplied continuously until the air temperature reached a steady state. The drying column was a cylindrical shape, 15 cm in diameter and 150 cm in height. It was made of Plexiglas with the bottom closed by a perforated distributor plate. A 1.5" ball valve was installed above the distributor plate to allow collection of the samples at the desired drying durations, and to allow emptying the fluidized bed column at the end of the experimental run.

To evaluate the performance of the fluidized bed drying, it was essential to measure the air temperature, air relative humidity, pressure drop, rice moisture content, and determine the drying efficiency. Air temperature readings, in various locations, were measured by using type J thermocouples connected to a data logger (OMEGA TC-08, Norwalk, CT). Thirteen thermocouples were inserted horizontally into the fluidizing column (10 cm apart), to measure the temperature profile in the vertical direction. The tip of thermocouples 1, 4, 7 and 10 were located at a 2.5 cm from the wall, thermocouples 2, 5, 8, 11 and 13 were located at a 7.5 cm from the wall and thermocouples 3, 6, 9 and 12 were located at a 12.5 cm from the wall to measure the horizontal temperature profile as well. Two OMEGA (PicoLog data logger software, Norwalk, CT) was used to monitor and record the bed temperature readings during the experimental runs. The two data loggers were connected to two USB connection ports on a PC. Air relative humidities, of the inlet air and outlet air, were monitored by a handheld relative humidity meter (Dew Point Meter, 5 to 95 Range). Exit air velocity was measured using an air velocity meter (EXTECH, Anemometer, 80 to 5906 fpm). Pressure drop system consisted of 13 U-tube manometers with one side of all the U-tubes connected to each other via a manifold whereby the manifold was attached to the bottom of the fluidizing column via a hole under the distributor plate. The other end of each U-tube was connected to a port on the column located next to the thermocouple. The moisture content values of fresh and dried rough rice samples were measured using an AM 5200 Grain Moisture Tester (PERTEN Instrument, Hägersten, Sweden).

2.3 Experimental design

In order to test the effect of the heating duration, and retention duration on the performance of the fluidized bed dryer, the experimental design was carried out as shown in Table 12.

Table 12. Experimental design.

Exp. No.	Heating duration (min)	Retention duration (min)	Total drying duration (min)
	10	0	10
	20	0	20
	30	0	30
	10	15	25
	20	15	35
	30	15	45
	10	30	40
	20	30	50
	30	30	60
	10	45	55
	20	45	65
	30	45	75
	10	60	70
	20	60	80
	30	60	90

2.4 Determination of drying rate

The drying rate of rough rice samples was calculated by dividing the difference of the moisture content of two consecutive samples by the drying duration as shown in equation 1.

$$DR = \frac{MC_i - MC_{i+1}}{t} \tag{1}$$

where,

DR = drying rate, %/min,

MC_i = moisture content at time i, %, d.b.,

MC_{i+1} = moisture content at time i+1, %, d.b., and

t = drying duration, min.

2.5 Determination of the energy consumption

The energy consumption values required to dry rice during the heating time and hold up time were calculated as follows (Eq. 2)

$$EC = \frac{HE + FE}{MWR} \tag{2}$$

where,

EC = energy consumption during the heating and retention durations, MJ/kg $_{\text{water removed}}$,

HE = energy consumption during the heating duration, MJ,

FE = energy consumption during the retention duration, MJ, and

MWR = mass of water removed kg.

2.5 Experimental procedure

The centrifugal fan was turned on and the airflow rate was adjusted to the pre-calibrated rate by adjusting the variable frequency drive. The tube furnace was turned on and the temperature was adjusted to 100^{o}C using the PID on the furnace. Once the air temperature reached a steady state (monitored on the computer screen from the OMEGA software), the required amount of rough rice (7 kg) was discharged into the bed from the top. Pressure drop readings were obtained from the U-tube manometers. The room temperature was measured using a handheld thermometer placed at the inlet of the blower. The inlet and exit air relative humidity values were determined using a handheld relative humidity meter. After the desired heating duration had reached, the tube furnace was turned off and the blower allowed to purge air for the desired retention duration. Following, rice sample was collected to determine the moisture content of rice. The bed temperatures were measured with the shielded thermocouples for both the heating duration and the retention duration. By the end of the experiment, the bed was emptied from the side port. Following, the samples were stored in the fridge at 4^{o}C.

3. Results and discussion

3.1 Temperature profile

The temperatures in the fluidized bed were recorded every 30 seconds. Figures 15 (A) and 15 (B) present the effects of the heating duration and retention duration on the temperature profile in the bed, respectively. Each temperature point represents the average measurements of six temperature readings in the bed. The graph shows that the temperature dropped instantaneously after adding rough rice to the bed. Following, the bed temperature started to rise again. The drop in the air temperature could be postulated to the addition of rough rice which was stored at room temperature. Increasing the heating duration increased the temperature in the bed. At the heating duration of 10, 20 and 30 minutes, the bed temperature reached 33.0, 41.3, and 43.8^{o}C, respectively. The higher bed temperature of the bed corresponding to the longer heating duration as compared to the shortest heating duration (a 32.7% increase) could be attributed to the longer time that allows air to capture more energy from the heated tube.

Figure (15-B) shows that increasing heating time from 10 to 20 minutes, increased the bed temperature from 38.1 to 45.2^{o}C at the end of the retention duration. After 25 minutes of the retention duration, there was no noticeable difference between the two curves of the heating duration of 20 and 30 minutes. Interestingly, the air temperature in the bed during the retention time did not show any observable decrease while the tube furnace was turned off. This temperature stability could be attributed to the effects of air compression in the blower as well as air friction within the pipes and the joints. These effects helped to maintain the air temperature at a constant level. Rattanamechaiskul et al. (2013) reported that increasing the drying duration increases the bed temperature of the brown rice in a fluidized bed. Henneberg et al. (2003) for γ–Al_2O_3 particles (Geldart group D) also reported that increasing drying duration resulted in an increase in the bed temperature in a fluidized bed system.

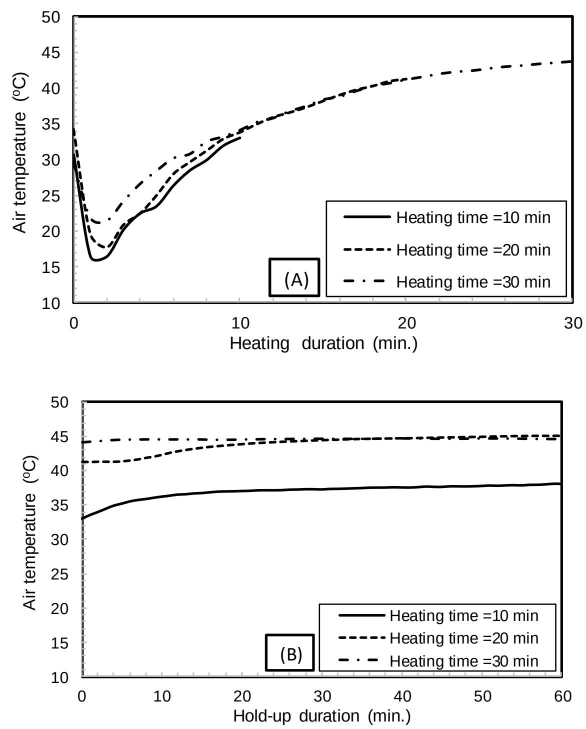

Figure 15. The effects of (A) heating duration and (B) retention duration on the temperature profile in the fluidized bed dryer.

3.2 Pressure drop

Monitoring the pressure drop readings around the distributor plate is imperative because they reflect the quality of fluidization inside the bed. The effects of the retention duration on the pressure drop across the distributor plate are presented in Figure 16. Increasing the heating duration from 10 to 30 minutes increased the pressure drop across the distributor plate from 1.62 to 1.74 kPa as is shown at 0 min of the retention duration. The rise was expected as the air temperature continued to rise with the increase in the heating time. Increasing the retention duration, slightly increased the pressure drop across the distribution plate for the three tested heating durations. After 30 minutes of the retention duration, there was no noticeable difference between the heating duration curves of 20 and 30 minutes.

The highest-pressure drop of 1.87 kPa was observed at the heating time of 20 and 30 minutes, particularly after 30 minutes. On the other hand, the lowest pressure drop of 1.62 kPa was observed at the heating time of 10 minutes and 0 minutes of the retention duration. The slight increase in the pressure drop corresponding to the increase in the retention duration could be attributed to the slight increase in the air temperature. The increase in the air temperature increased the air velocity, which in turn increased the pressure drop across the distributor plate. Pressure drop data in fluidized bed drying system was reported Sadaka et al. (2002). They reported that the pressure drop increased with increases in the air temperature.

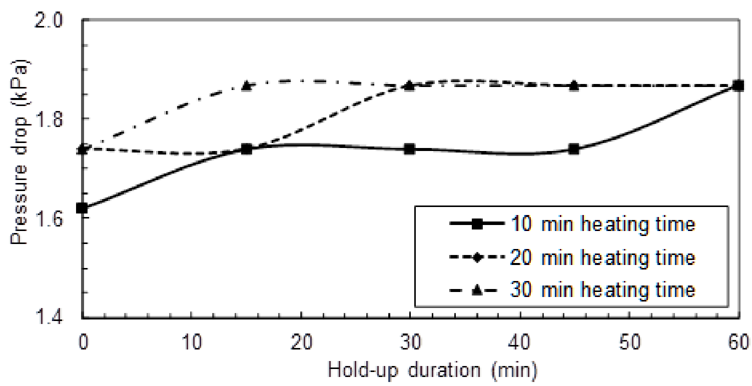

Figure 16. The pressure drop across the distribution place as affected by the retention duration.

3.3 Rice moisture content

The initial moisture content of rice samples was found to be 21.5% w.b. Samples were taken after the heating durations of 10, 20, and 30 minutes as well as by the end of the retention durations. Figure 17 shows the effects of retention duration on the moisture content of rough rice samples. Increasing the heating duration from 10 to 30 minutes (at 0 minutes of retention duration) decreased the rice moisture content from 19.3% to 17.4% w.b. A maximum of 4.1 moisture point's reduction was observed at the end of the longest heating duration of 30 minutes.

The minimum moisture content of 15.8% w.b. was observed at the end of the retention duration (60 minutes) for the heating duration curve of 20 minutes. Whereas the highest moisture content of 19.3% w.b. (only 2.2% points of moisture reduction) was observed at the end of the retention duration (60 minutes) for the heating duration of 10 minutes. There was a small difference in the moisture content of the three heating duration curves predominantly after 30 minutes of the retention duration.

At the beginning of the test, the reduction of moisture content was due to the concentration difference between the moisture content within the kernels and air, which increased the moisture migration from the center of the kernel to its surface and then from the surface to air by convection mass transfer. Then, the release of moisture from the kernels became more difficult due to the reduction of moisture within the kernels. As mentioned earlier, the results showed that in the same condition, the higher the heating time, the lower the moisture content. This phenomenon can be postulated to a large amount of moisture at the initial stages of the retention duration. Janas et al. (2010) also reported that increasing the drying time decreased the grain moisture content while drying corn in a fluidized bed. Similar results were observed by Tirawanichakul et al. (2004) while drying rice in a fluidized bed. They observed approximately 6% points of moisture reduction during tempering and retention period, which is slightly higher than the one observed in the current study. The difference could be attributed to the higher temperature levels used by Tirawanichakul et al. (2004) with a maximum temperature of 150°C.

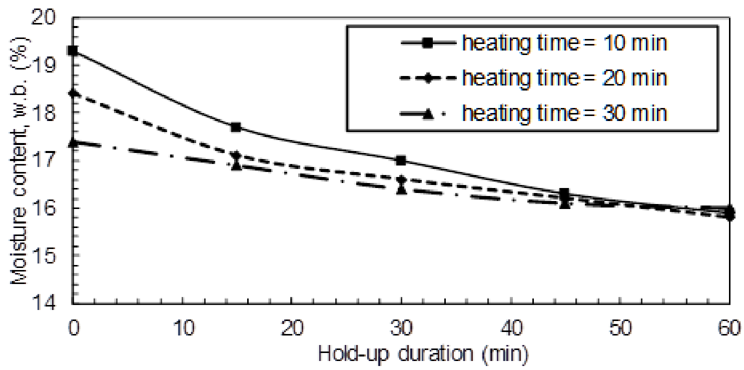

Figure 17. The effects of retention duration on the moisture content of rough rice.

3.4 Drying rate

Figure 18 shows the drying rate as affected by the heating duration and the retention duration. The values shown were determined based on equation 1. After the heating duration of 10, 20, and 30 minutes (at 0 minutes of retention duration) the moisture content of rice dropped to 19.3, 18.4 and 17.4%, respectively. These values could be translated to a drying rate of 0.220, 0.155, and 0.137%/minutes corresponding to the heating durations of 10, 20, and 30 minutes, respectively. Unpredictably, the results showed that the shorter the heating duration, the higher the drying rate. This phenomenon could not be attributed to the smaller reduction of the moisture points but the longer drying duration (at the denominator). In all the studied cases of the effects of retention time on the drying rate, the first 15 minutes showed the highest drying rates. The highest drying rate of 0.107%/min was observed after the heating duration of 10 minutes and at the retention duration of 15 minutes. On the other hand, the lowest drying rate of 0.007%/min was observed after the heating duration of 30 minutes and at the retention duration of 60 minutes. The results also showed that the longer the retention duration, the smaller the drying rate for all the studied heating durations. This could be attributed to the reduction of the moisture content of the kernels and the difficulties of migrating more moisture from the kernels to the surrounding air. Poomsaad et al. (2005) also reported that the drying rate of rice decreased for increasing period of ambient air ventilation.

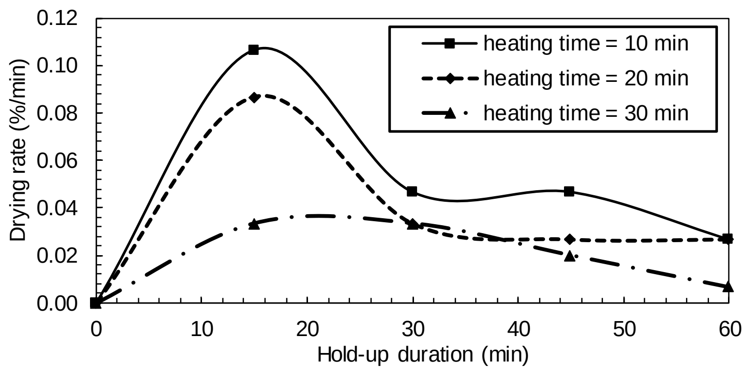

Figure 18. The effects of retention duration on the drying rate of rough rice.

3.5 Head rice yield

The HRY as affected by the retention duration did not vary meaningfully. Figure 19 shows the effects of retention duration on the head rice yield. The results showed a very slight decrease in the head rice yield as affected by the retention duration. The values of HRY at the heating duration of 10, 20, and 30 minutes (at 0 minutes retention duration) were 51.0, 50.0 and 49.5, respectively. Considering all the studied heating durations and retention durations, the HRY values of rice samples varied from 46.0% to 51.0%. The highest HRY reduction of 4.0% points was observed at the heating duration of 20 minutes whereas the lowest HRY reduction of 1.5% points was observed at the heating duration of 30 minutes. Thus, HRY was maintained at a higher value for retention durations using 30 min heated duration (bed temperature of 43.8°C). Tumpanuvatr et al. (2018) reported that pregerminated rice should be dried using a hybrid fluidized bed dryer at 45°C for higher HRY. It is not known why some HRY values were very low during that specific season. Sun and Siebenmorgen (1993) studied the milling characteristics of rough rice kernels thickness and found that HRY had a wider range between 30.0% and

73.0%. Counce et al. (2005) reported that the HRY could vary between 46.6% and 62.4% while testing the effects of high temperature on head rice yield using a controlled climate. According to these values, the present study showed HRY within an acceptable range.

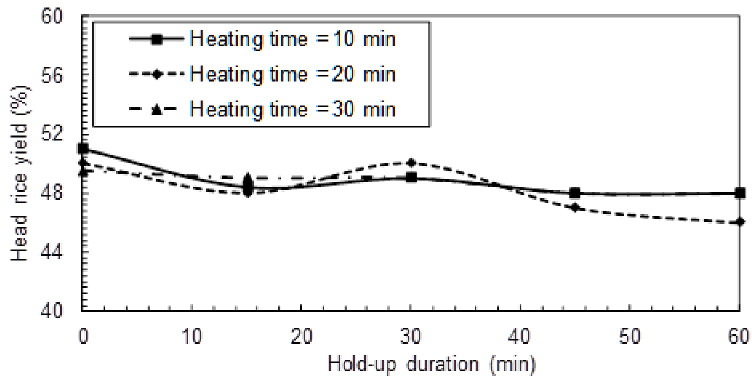

Figure 19. The effects of retention duration on the head rice yield of rough rice.

3.6 Energy consumption

Figure 20 illustrates the effects of heating duration and retention duration on the energy consumption per unit mass of water removed. Energy consumption, in the studied case, includes the energy consumed to heat the furnace as well as the energy required to drive the motor. Increasing the heating time and/or the retention time increased the energy consumption per kilogram of water removed. The lowest energy consumption of 3.31 MJ/kg $_{\text{water removed}}$ was observed at the heating duration of 10 minutes and at no retention duration. On the other hand, the highest energy conservation of 17.04 MJ/kg $_{\text{water removed}}$ was achieved at the heating duration of 30 minutes and the retention duration of 60 minutes. In a 100% efficiency dryer, the thermal energy required to remove 1 kg of moisture from organic matter was reported to be 2.3 MJ (Day et al., 1998). Accordingly, the observed energy consumption values, in the present study, are in the range of 1.4-fold and 7.4-folds as compared with the theoretical energy consumption to remove 1 kg of water. It was predicted that the energy consumption would increase with the increase in the heating time due to increase in bed temperature as reported by Darvishi et al. (2017). Increasing the heating time from 0 to 30 minutes increased the energy consumption from 3.31 to 7.76 MJ/kg $_{\text{water removed}}$ (a 134% increase) and from 12.87 to 17.04 MJ/kg $_{\text{water removed}}$ (a 32.4% increase) at the no retention duration and the 60 minutes retention duration, respectively. The significant increase in the energy consumption corresponding to the increase in the retention duration could be attributed to the larger energy consumption to run the 3-kW motor.

The results showed that there are noteworthy amounts of water removed during the retention duration. This could be attributed to the energy stored in the rice kernels during the heat up duration. The stored energy was released during the retention duration and continued to trigger more moisture removal. The moisture removal during the retention duration could be also attributed to the effects of air flow through the grain during this duration. As mentioned earlier, the retention duration represents turning off the tube furnace and maintaining the fan running. Additionally, the heat loss from the system could be higher, as the tube furnace is heating the air due to the allothermal effects.

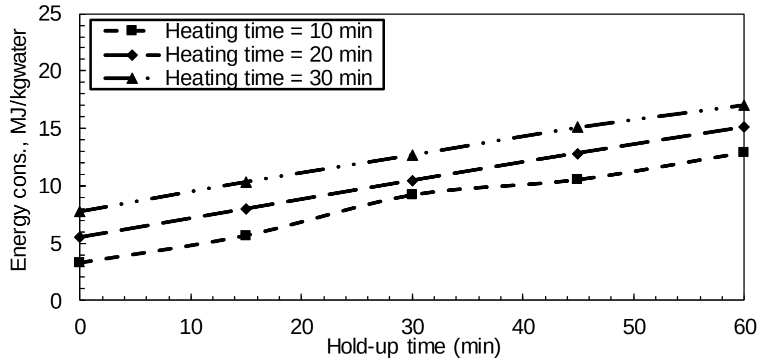

Figure 20. The effects of retention duration on the energy conservation per unit mass of water removed.

4. Conclusions

The suitability of drying rough rice in a fluidized bed subjected to heating duration and retention duration was investigated. The effects of the heating duration of 10, 20, and 30 minutes and the retention duration of 0 to 60 minutes with intervals of 15 minutes on the temperature profile, moisture content, drying rate, and the head rice yield were obtained. The bed temperature reached 43.8°C at the heating duration of 30 minutes. Increasing the heating duration increased the bed temperature whereas increasing the retention duration did not profoundly change the bed temperature. Increasing the heating duration from 10 to 30 minutes increased the pressure drop which denotes good fluidization. Increasing the heating duration from 10 to 30 minutes decreased the rice moisture content by 2.2%, and 4.1% points, respectively. The minimum moisture content of 15.8% w.b. was observed at the end of the retention duration (60 minutes) for the heating duration of 20 minutes. The drying rate reached 0.220, 0.155, and 0.137%/minutes corresponding to the heating durations of 10, 20, and 30 minutes, respectively. The shorter the heating duration, the higher the drying rate. The highest drying rate of 0.107%/min was observed after the heating duration of 10 minutes and at the retention duration of 15 minutes. The values of HRY varied from 46.0% to 51.0%. The highest HRY reduction of

4.0% points was observed at the heating duration of 20 minutes whereas the lowest HRY reduction of 1.5% points was observed at the heating duration of 30 minutes. Accordingly, the fluidized bed drying system was found to be a good tool to dry rough rice without meaningfully compromising the quality of rice. The results suggested that a wider range of tube furnace temperature should be investigated. Also, the milled rice yield and rice whiteness should be determined.

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Chapter 6: Investigation of rough rice drying in fixed and fluidized bed dryers utilizing dehumidified air as a drying agent.

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Abstract

The high initial moisture content of freshly harvested rice accompanied by high relative humidity ambient air as well as no external heating source utilized for on-farm in-bin drying increase the risk of rice deterioration. Air dehumidification could be among the best management practices for rice drying in the high relative humidity environment. The current study aimed to explore the possibility of using silica gel to dehumidify the humid ambient air for drying rice in a fixed bed and fluidized bed. A dehumidification unit was added to the previously developed lab-scale fluidized bed dryer before the blower inlet to help dehumidify the moist inlet air. The effects of bed conditions, i.e., fixed or fluidized, dehumidification environment, i.e., with and without dehumidification, and air temperature, i.e., 40^{o}C or 60^{o}C on the dryer performance, were investigated.

The fluidized bed dryer removed more moisture from rough rice as compared with a fixed bed dryer. Explicitly, under the conditions of a fluidized bed, no dehumidification and at 60^{o}C, the moisture removed was 1.5% moisture points more than under the same conditions for fixed bed. Dehumidifying the humid air removed between 0.2% and 1.6% moisture points from rough rice more than the environment of no dehumidification. Moisture content profile showed that about 87% to 90% of the moisture was removed during the first 30 minutes of the drying process. The maximum head rice yield achieved 66.7% during the drying in a fixed bed and with no dehumidification at 40°C. However, it achieved its maximum of 64.6% during the drying in fluidized with dehumidification, and under 40^{o}C. The maximum rice whiteness of 41.8 was attained for fluidized with no dehumidification, and at 60°C. The dryer energy consumption decreased with the use of air dehumidification techniques. Through this study, ambient air

dehumidification using desiccant showed the noticeable potential to be used for on-farm in-bin ambient air drying, particularly during humid conditions.

Keywords.

Dehumidification, Fixed bed, Fluidized bed, Rice drying, Rice quality, Silica gel.

1. Introduction

Rice is one of the principal crops produced in Arkansas, which accounts for more than 40% of U.S. production. Rice is harvested at 14-26% moisture content (wet basis) (Ondier et al., 2010). The moisture content of rice needs to be reduced to 13% wet basis for safe storage. Farmers use ambient air for drying rice to safe storage moisture content. Arkansas is prone to experience high temperatures and high relative humidity during the harvest and drying season. Therefore, a significant problem of rewetting the stored rice during the period of high ambient humidity could occur and daunts the farmers. Rewetting of rice creates fluctuations in the final moisture content of rice that leads to variable milled rice quality (Ondier et al., 2011). Increase of airflow rate by increasing the horsepower of the blower and heating the ambient air can be two possible solutions (Mukhopadhyay and Siebenmorgen, 2018). However, both management practices are costly for farmers to be included in their drying system. Bins equipped with programmed and controlled fans were introduced to the farmers that can stop the airflow during humid conditions and save the rice from rewetting. However, bins with wet rice without airflow even for a few hours can decrease the shelf life of rice tremendously. Accordingly, the high humidity of ambient air could be reduced by desiccant to achieve continuous drying.

Desiccants have been used earlier for drying the agro-products. Some of the common desiccants are silica gel (SiO_2), (Danziger et al., 1972; Yamaguchi and Kawasaki, 1994; Li et al., 2002a; Li et al., 2002b) bentonite (Sturton et al., 2002), crop by-products such as paddy husk

(Sadaka and Atungulu, 2018), and ash (Akpaetok, 1974). Silica gel, an inert material, is one of the most common desiccants used for drying crops. It is popular amongst researchers due to various qualities such as high absorbency up to 27% (Ondier et al., 2011), ease of regeneration at a high temperature above 100°C (Koh, 1977), and availability in the market at a relatively lower price than other desiccants (Ondier et al., 2011). A research group dried soybean to a safe storage level of moisture using silica gel and soybean intimate mixture in a fixed bed condition (Li et al., 2002a). Rough rice was dried to a safe storage level of moisture using silica gel packets and rough rice mixture in a closed environment (Obrien et al., 2006). They reported no loss in dried rice quality as compared to the control (rice with no silica gel). Danziger et al. (1972) demonstrated improvement in corn quality when dried with silica gel at ambient temperature. The upper layer of corn in-bin was dried with no lag period using packets of superabsorbent polymer (Roman et al., 2009). Desiccant drying of corn achieved in chamber yields not only high drying efficiency but also acceptable dried corn quality (Agarwal and Yadav, 2019). Potisate et al. (2014) used blanched *Moringa oleifera* leaves that were dried by four different drying techniques, including hot air tray drying, heat pump–dehumidified air drying, microwave drying, and freeze-drying. The heat pump–dehumidified drying- was found to be the fastest drying technique. Wang et al. (2013) reported the overview of desiccant drying in a rotary desiccant dryer and the potential uses of the drying technology overall. Hanif et al. (2019) reported that desiccant drying with wheat used less energy and had low drying cost as compared to the conventional heated drying. The previously mentioned studies mixed silica gel with a moist crop for drying purposes.

Similarly, Itodo et al. (2019) dried the humid air with desiccant and reported a higher drying rate as compared to sun drying. The literature search showed that not many studies had used silica gel packets to dry the ambient air to increase the drying capacity of the air used for drying rough rice. The approach of using a desiccant, not mixed with the actual product, could save the cost of separating desiccant from the crop and could diminish the risk of contamination.

Drying rice with the use of desiccants in a closed environment can be a prolonged exchange of moisture. Therefore, there is a necessity to study the effects of desiccants on drying air along with the effects of a rapid drying system such as a fluidized bed dryer. Fluidized bed drying is seen as one of the most available technologies to achieve a higher drying rate (Karbassi and Mehdizadeh, 2008; Luthra et al., 2018). In this technique, the air is blown at high speed to support the weight of the drying material and drying takes place in a fluidized state (Yang, 2003). In a fluidized bed, moisture is removed by evaporation from the grain kernels; heat is supplied for evaporation through convection from the drying air to the surface of the grain, and through conduction, the heat is supplied to the center of the grain (Sutar and Sahoo, 2011). Moisture travels in the opposite direction and evaporates in the environment through convection. Fluidized bed drying offers many advantages that include ease of handling of grains, uniform drying, and enhanced drying rate (Passos et al., 1989; Daud, 2008; Sadaka et al., 2018).

Factors resembling the mass of desiccant to rough rice, initial moisture content of both desiccant, and rough rice can affect the rice final moisture content (Raghavan et al., 1988). Also, drying duration, airflow, and ambient air conditions can be other sources of variation in rice final moisture content and milling quality (Witinantakit et al., 2006). Accordingly, the main goal of the present project was to use the silica gel in high ambient humidity conditions and observe silica gel's effects on the evaporating capacity of the drying air. Moreover, to ultimately evaluate the performance of the fluidized bed dryer equipped with a dehumidification system using head rice yield and whiteness as the rice quality parameters. Therefore, factors such as initial moisture content of rough rice, drying duration, airflow rate, and ambient conditions (air temperature and relative humidity) were constant in the present study. Thus, the goal of the present study was to investigate the effects of ambient air dehumidification and the air temperature on dried rice moisture content, drying rate, head rice yield, whiteness, and energy consumption in fixed and fluidized bed dryers.

2. Materials and methods

Laboratory experiments were performed in the Rice Research and Extension Center (RREC), Stuttgart, AR. A custom-made laboratory-scale batch fluidized bed dryer was developed by Sadaka et al. (2018) and used in this study. The following sections elucidate the materials and methods used in the present study along with the system development.

2.1 Rice samples

Rough rice (cv. Diamond) was harvested and obtained from a farm in Northeast Arkansas. Obtained rough rice was cleaned with a dockage tester (Model XT4, Carter-Day, Minneapolis, MN). Rough rice needed in the experiments was gently homogenized in a large container to have a representative sampling during the experiments. A sample of 1000 kernels was obtained using an automatic seed counter (Model SLY-C, Hinotek, China). The weight of the sample was obtained using a scale (Ohaus SP-2001 Scout Pro Balance, Parsipanny, NJ). Standard oven method (ASABE, 2008) was used to determine the initial moisture content of rough rice and was found to be 23.4% d.b. Bulk density was determined using the standard method ASTM E873-82 (Table 13). Basic dimensions that include length, width and thickness were determined using the digital caliper (General Ultratech, Series – 147, Secaucus, NJ) having an accuracy of 0.02 mm. The geometric mean diameter of rice was obtained by taking the cube root of the product of all three basic dimensions (Bande et al., 2012; Sadaka and Atungulu, 2018) (Table 13). Rough rice samples were sealed and then stored at 4°C in a cooler until the start of the experiment. Samples were brought to ambient conditions by allowing the sealed container 24 hours sitting time in the ambient condition just before the start of the experiment.

Table 13. Rough rice sample characteristics

Parameter	Units	Rough Rice
1000 Kernel weight*	g	26.1±0.16
Moisture content*	%, d. b.	23.4±1.2
Bulk density*	kg/m^3	620.8±2.28
Dimensions**		
Length	mm	8.75±0.53
Width	mm	2.40±0.14
Thickness	mm	1.14±0.14
Geometric Mean Diameter	mm	3.43±0.15

* Average of three readings, ± the standard deviations
** Average of fifty readings, ± the standard deviations

2.2 Fluidized bed dryer enhanced with dehumidification system

The fluidized bed dryer system, developed by Sadaka et al. (2018), was used in the present study. The system consisted of four essential components: air-supply system, air-heating system, drying column and measuring systems., The system was enhanced by adding a dehumidification system before the inlet of the blower to facilitate the fluidized bed dryer with ambient air dehumidification as shown in figure 21-A & 21-B. For the air-supply system and especially for ambient air dehumidification, several designs were tried, and the best design was selected based on ease of use and proper functioning as described below. The air-supply system consisted of a desiccant pipe that holds forty-eight 50-gram silica gel packets that were tied to a rope (maximum possible) using plastic ties, and the rope was hung inside the desiccant pipe from the top end. The desiccant pipe is a 10.4 cm in diameter with the top end connected to a duct pipe that sucks the humid ambient air (70-80% RH) from top of an industrial humidifier (AIRCARE

MA1201, coverage up to 334 square meters, USA). The purpose of using the higher relative humidity range was to simulate the ambient humid condition in real life, although the relative humidity greater than 80% was not achievable due to the large laboratory size. Air flowing through the silica gel packets works as the input to a 3-kW regenerative blower (SCL k05-MS MOR, FBZ, Italy). A variable frequency drive (ACS350, ABB Ltd, Switzerland) controls the airflow with an airflow meter (7510 series, KING Instrument Company, Garden Grove, CA) assembled in line. The flow meter has a range of 0.0 - 1.70 m^3/min. The air-heating system consists of a tube furnace (Barnstead/Thermolyne Corporation type 21100 tube furnace, Dubuque, IA) which heats the air flowing in a 2.5 cm diameter steel pipe. The tube furnace was set to the desired temperature to attain the air temperature at the required steady-state temperature. The drying column is 150 cm in length and 15 cm in diameter, made up of plexiglass. A 3.8 cm diameter ball valve was installed above the distributor plate to allow sampling and emptying the drying column after the end of each experimental run. The measuring system consists of various sensors to measure rice and air temperature, pressure drop, air relative humidity, rice moisture content, and air velocity. The air temperature was measured using 13 J-type thermocouples inserted horizontally in the drying column and spread (10 cm apart) along the length of the column. The thermocouples were connected to the data loggers (OMEGA TC-08, Norwalk, CT), which were connected to a PC for real-time recording of air temperature in the drying column. The moisture content of the rough rice was monitored and recorded using novel probe-type sensors (Grain Deacon, Deacon Technologies, LLC, Prairie Grove, AR) that were previously used by Luthra et al. (2019) These probes allowed to create a moisture content profile of rough rice for the experimental duration.

Air relative humidity of the inlet and outlet air was measured by a relative humidity dew point meter (HI 9565, 5% to 95% Range, Hanna Instruments Ltd, Bedfordshire, England, UK). The exit air velocity was measured using an air velocity meter (Anemometer, 80 to 5906 fpm, EXTECH, Nashua, NH). The pressure drop system consisted of 10 U-tube manometers and three digital manometers (Series 475, Dwyer Instruments INC, Michigan City, IN). One side of each manometer was connected to a manifold, and the other end was connected to a port next to the thermocouples drilled in the drying column. The manifold was attached to the bottom of the fluidizing column via a hole under the distributor plate. Digital manometers, along with the U-tube manometers, helped in taking readings, as it was a challenge sometimes to take readings visually from U-tube manometer alone due to constant fluctuations during the fluidization conditions. The initial and final moisture content values of rough rice samples were measured using a moisture meter (AM 5200 Grain Moisture Tester, PERTEN Instrument, Hägersten, Sweden).

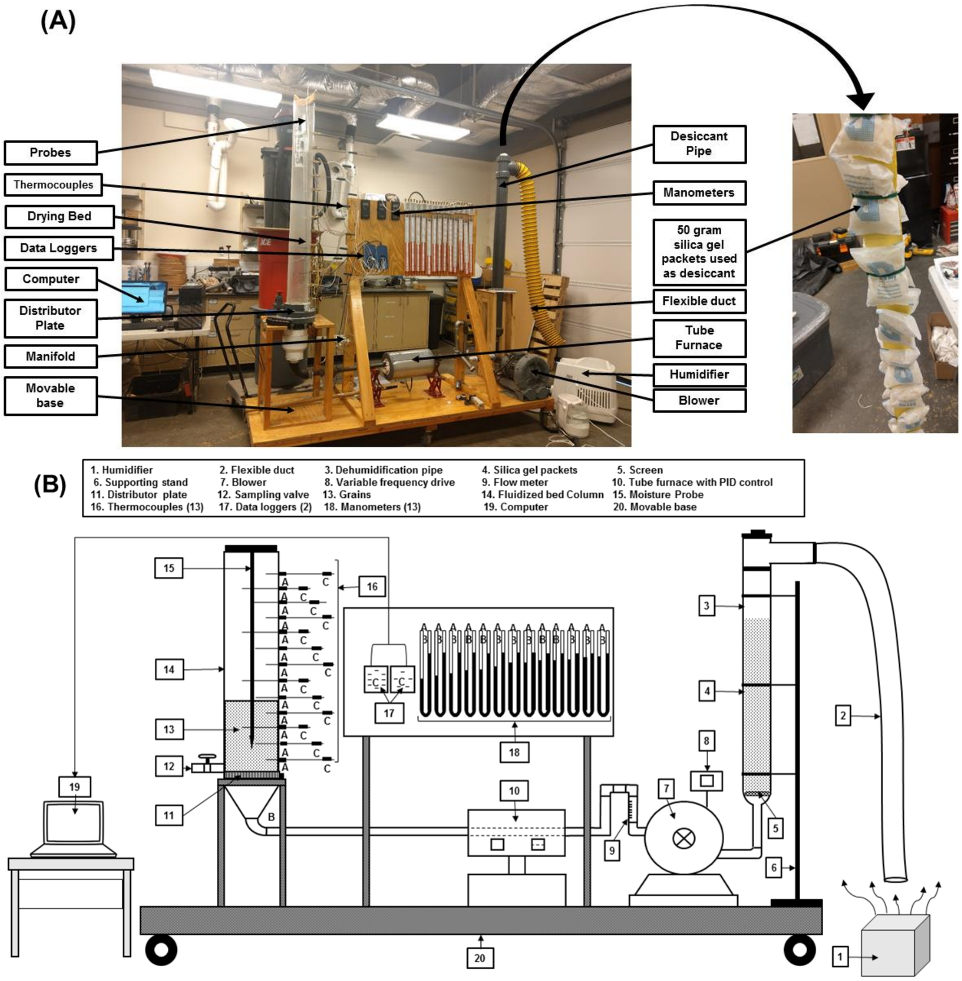

Figure 21. (A) Pictorial representation of the fluidized bed dryer and the desiccant used in this study and (B) Schematic diagram showing the fluidized bed dryer and the air dehumidification setup.

2.3 Experimental design

In the current study, a total of 24 experimental units were tested. We tested the effects of drying bed conditions (fluidized or fixed), ambient air or dehumidified air, and air temperature (40°C and 60°C) on the rice moisture content, drying rate and rice quality (head rice yield and whiteness), as well as energy consumption per unit mass of water, removed. All the factors along with their respective levels are itemized in Table 14. The fixed bed was used as a control for the bed condition. Also, no desiccant in the desiccant pipe was used as the control for the dehumidification factor. The level of an air temperature of 40°C simulated the scenarios of on-farm ambient air bin drying, and the higher temperature (60°C) was used to simulate the scenario when heating is employed for drying rice. In earlier trials, we determined that by supplying ambient air with a temperature of about 23°C to the system, the air temperature rises and stayed constant at about 40°C. The friction provided by the steel pipe to the high-velocity air, which heats the air, is speculated as to the reason for the rise in temperature. The higher temperature of 60°C was selected, as previously mentioned by Cnossen and Siebenmorgen (2000). They reported that the temperature up to 60°C could be used with no effect on the milling quality of rice. There were three replications for each combination of factors. Complete randomization was done for the experiments; analysis of variance (ANOVA) was done using JMP Pro 14 (SAS Institute Inc., Cary, NC). Desiccant effectiveness was evaluated statistically based on the experimental design. Physically, the weight gained by the silica gel packets was recorded after the 60 minutes duration of the experiment. The average weight gained per silica gel packet was 5.15 grams, which were 10.3 % of its original weight of 50 grams.

Table 14. Experimental design.

Factors	Levels	Total number of experiments
Bed condition	Fixed, Fluidized	
Dehumidification	No, Yes	$2\times2\times2\times3 = 24$
Air temperature	40°C, 60°C	
Replication	1, 2, 3	

2.4 Experimental procedures

Rough rice samples were taken out from the cooler 24 hours before the start of the experiment to acclimatize the ambient conditions. For the experiments with air dehumidification, silica gel packets (new or regenerated in the oven) were weighed and inserted in the desiccant pipe with a rope attached for secure handling (fig. 21-A). The blower was turned on, and the airflow was adjusted using the variable frequency drive to the desired level to achieve the fluidized or fixed bed conditions. In a separate experiment, the airflow selected to achieve fixed bed conditions and fluidized bed condition were 0.95±0.1 m/s and 1.75±0.1 m/s, respectively. For the fixed bed, we turned down the frequency on VFD to 30Hz, which is the minimum possible to start the blower. The air velocity was measured at the top of the column. The air velocity reached 0.95 m/s. For fluidized bed conditions, the air velocity was increased by changing the frequency of the VFD. Once the rice bed started to fluidize, the minimum fluidization velocity was determined. A similar method was used by Giner and Calvelo (1987) and Sadaka et al. (2018) To ensure higher fluidization of the bed, the air velocity was adjusted to about 1.45 times of the minimum fluidization velocity.

The tube furnace was turned on, and the air temperature was monitored; 4.5 kg of rough rice was discharged in the drying column after the desired air temperature was achieved. The experimental duration for all the experiments was fixed to 60 min that begins once the rough rice sample was poured from the open end of the drying column. Pressure drop readings were determined from the manometers. Temperature readings were recorded continuously during the experiment at every 30 seconds. Moisture content was measured every 10 minutes using the Grain Deacon mobile application that interacts with the probes inserted in the rice sample from the open end of the drying column. Ambient air temperature, as well as relative humidity, were measured using the handheld meters at the beginning, after 30 min, and at the end of the experiment. The ambient relative humidity was maintained within the range of 70% to 75% using the humidifier. After the end of the experiment, three dried rough rice samples were obtained from the ball valve; moisture content was measured using the moisture meter. The drying column was emptied and cleaned. Silica gel packets were weighed. The dried rough rice samples were taken to a chamber and further dried (25°C, 55% relative humidity) to the safe milling moisture level of a 13% wet basis. Then, the rough rice was milled to obtain head rice yield and whiteness to determine the rice quality. Silica gel packets were regenerated for the following experiment in a conventional oven at 120°C for 2 hours (as recommended by the manufacturer).

Head rice yield was obtained using a 100-g rice sample at 13% moisture content that was milled and sorted using a laboratory mill (PAZ-1 DTA, Zaccaria USA, Anna, TX). Whiteness is dependent on the physical characteristics and milling degree. The whitening process includes removing the bran and silver layer with some polishing (Ranalli et al., 2002). The milled rice whiteness is usually reported as an index of grain surface whiteness. In the current study, a portable whiteness meter (MBZ-P, Zaccaria USA, Anna, TX) was used; the relative index ranges from 20 to 50 (dimensionless), with 20 being the typical value of brown rice, whereas 50 represents well-milled white rice.

2.5 Determination of drying rate

The drying rate of rough rice samples was calculated by dividing the difference in moisture content during the experimental duration. It is described in equation 1 below.

$$DR = \frac{MC_i - MC_{i+1}}{t} \qquad (1)$$

where,

DR = drying rate (% d.b./min),

MCi = moisture content at time t (% d.b.),

$MCi+1$ = moisture content at time i+1 (% d.b.), and

t = drying duration (min).

2.6 Determination of energy consumption

Energy consumption to dry rice should include the energy consumption by the dryer, the heater as well as the energy consumption to regenerate the absorbent. Energy consumption by the dryer was determined in this study and defined as the energy consumed by the heater and the blower only to evaporate a unit mass of water from the rice. A 5.2-kWh oven, available in the lab, was used to regenerate the desiccant due to the shortage of available smaller oven. A smaller oven could be used for the laboratory scale experiment. Thus, the energy consumed in the regeneration of silica gel packets was not included in the current study. Accordingly, the energy consumption was calculated as follow (Eq. 2),

$$EC = \frac{HE + BE}{MWR} \tag{2}$$

where,

EC = energy consumption to remove water from rice for 60 min of experimental duration, MJ/kg water removed,

HE = energy used by 1 kW tube furnace during 60 min of experimental duration, MJ,

BE = energy used by 3 kW blower during 60 min of experimental duration, MJ, and

MWR = mass of water removed, kg.

3. Results and discussion

3.1 Effects of bed conditions, air dehumidification, and air temperature on the bed temperature profile

The bed temperatures were recorded every 30 seconds using the thermocouples. Figure 22 presents the effects of the bed conditions, *i.e.*, fixed bed or fluidized bed, air dehumidification, *i.e.*, no dehumidification and with dehumidification, bed temperature and drying duration on the temperature profile. Each temperature point plotted on the graph represents the average measurements of eighteen temperature readings from six thermocouples that were inserted in the rice bed as well as the three replicates. The graph shows that there was a temperature drop after adding rough rice to the drying bed. The temperature drop can be associated with the addition of rough rice that was initially at room temperature of 23°C. Approximately, within 6-8 min, the bed temperature started to rise again due to the supply of heated air to the bed. The temperature increased when the drying time increased until it reached an almost steady state. Luthra et al. (2018) reported that after an initial drop, the temperature increased with the increase of the heating duration for rough rice dried in the fluidized bed dryer.

Figure 22 (A through D) shows that fixed bed temperature and fluidized bed temperature profiles increased with drying duration. It could be visually observed that there was a gradual increase in the bed temperature, followed by a minor increase in the bed temperature until it reached an almost steady state. Under the fluidized bed condition, the bed temperature reached the plateau condition faster than under the fixed bed subjected to no dehumidification and with dehumidification environments. Fluidization of rice helped in achieving a uniform temperature of rice due to the vigorous mixing. Rattanamechaiskul et al. (2013) dried partially parboiled brown rice in a humidified hot air fluidized bed dryer and observed that the bed temperature increased with time. Bed condition and air dehumidification did not show profound differences in the bed temperature profile under the same tested level of air temperature. This observation could be owed to the small range of tested temperatures.

On the other hand, the air temperature had a profound effect on the bed temperature profile. Increasing the air temperature from 40^{o}C to 60^{o}C increased the bed temperature under both fixed and fluidized bed, air dehumidification, and no dehumidification. The vital point to notice was that the air temperature rises to about 40°C from room temperature of 23°C without any external heating. It can be attributed to the high friction and compression of the drying air that had been forced through the 2.54 cm (1 inch) steel pipes from the blower.

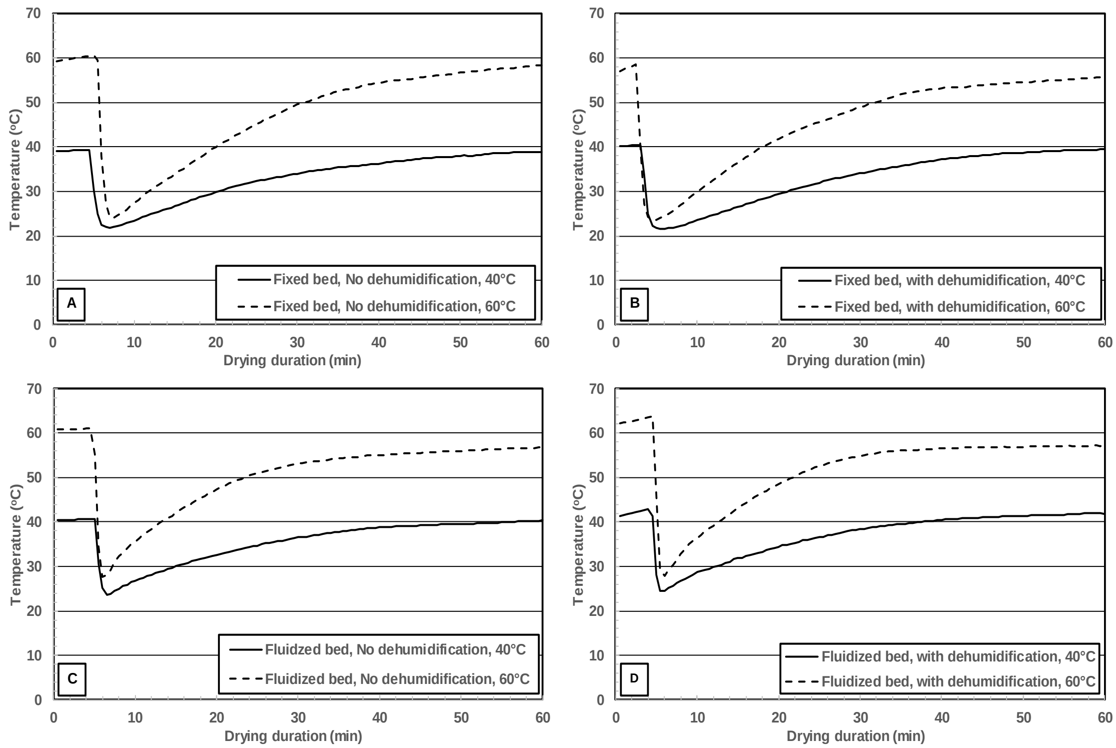

Figure 22. The average temperature profile of (A) fixed bed with no dehumidification, (B) fixed bed with dehumidification, (C) fluidized bed with no dehumidification, and (D) fluidized bed with dehumidification. Temperature averages were obtained for thermocouples within the rice bed and for three replications.

3.2 Effects of bed conditions, air dehumidification, and air temperature on bed pressure drop

The pressure drop in the drying bed was monitored to understand the movement of drying air and the rough rice in the bed. Figure 23 shows the effects of bed conditions (fixed or fluidized), the air dehumidification, and air temperature on the bed pressure drop. The maximum pressure drop of 1.82 kPa was noticed at the fluidized bed condition, no dehumidification, and the bed temperature of 60^{o}C. On the other hand, the least pressure drop of 1.58 kPa was observed at the fixed bed condition, no dehumidification, and a bed temperature of 40^{o}C.

It was observed that the pressure drop values in fluidized bed were higher than the fixed bed pressure drop values under the no dehumidification and dehumidification cases, and the two tested temperatures of 40^{o}C and 60^{o}C. It can be inferred to the higher airflow rate used in the fluidized bed drying as compared to the airflow rate used in a fixed bed. A similar observation of higher pressure drop with increasing airflow was reported by Banooni et al. (2018) while working on pneumatic and flash drying. Dehumidification of the air showed an exciting trend. Air dehumidification increased the pressure drop in the fixed bed and decreased the pressure drop in the fluidized bed under the two tested temperatures of 40^{o}C and 60^{o}C. The cause of this observation is not known, which might lead to further studies. The results clearly showed that increasing the bed temperature from 40^{o}C to 60^{o}C increased the pressure drop under all the tested bed conditions and dehumidification environments. This phenomenon could be postulated to the increase in the air volume as affected by increasing the bed temperature, which in turn increased the pressure drop. Chuwattanakul and Eiamsa-ard (2019), Luthra et al. (2018), and Sadaka et al. (2002) also reported that the pressure drop in fluidized bed dryer increased with an increase in air temperature.

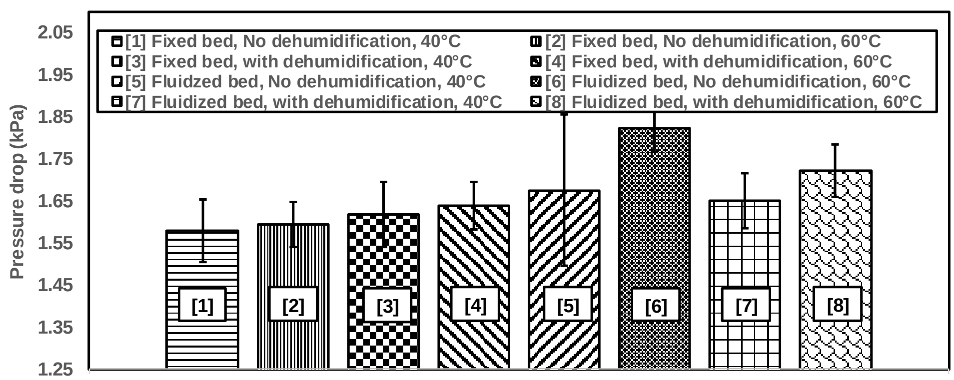

Figure 23. The pressure drop as affected by the bed conditions, air dehumidification, and air temperature.

3.3 Effects of bed conditions, air dehumidification, and air temperature on moisture content profile

Figure 24 shows the effects of bed conditions, air dehumidification, bed temperature, and drying duration on the moisture content profile of rough rice. The results showed an initial profound decrease in the moisture content with time, followed by a minor decrease in moisture content for all experiments. Final moisture content was determined using the moisture meter after the end of each experimental unit. Statistical analysis was performed on the experimental data to study the effects of the bed conditions, *i.e.*, fixed or fluidized, dehumidification environment, *i.e.*, without and with dehumidification, and bed temperature of 40^{o}C and 60^{o}C, as well as their interactions, on the moisture removed. A completely randomized factorial experiment with three replicates was carried out. Table 15 shows the results of the analysis of variance performed on the moisture removed as affected by bed conditions, dehumidification environment, and bed temperature. LSMeans Students' t-test was performed on the moisture removed data to test the difference among the levels of each variable at 0.05 level of significance. The results are shown in Table 16. The bed conditions, dehumidification environment, and bed temperature had significant effects (at 0.0001 level) on the moisture removed. There appear to be some interactions (at 0.05 level) among these variables.

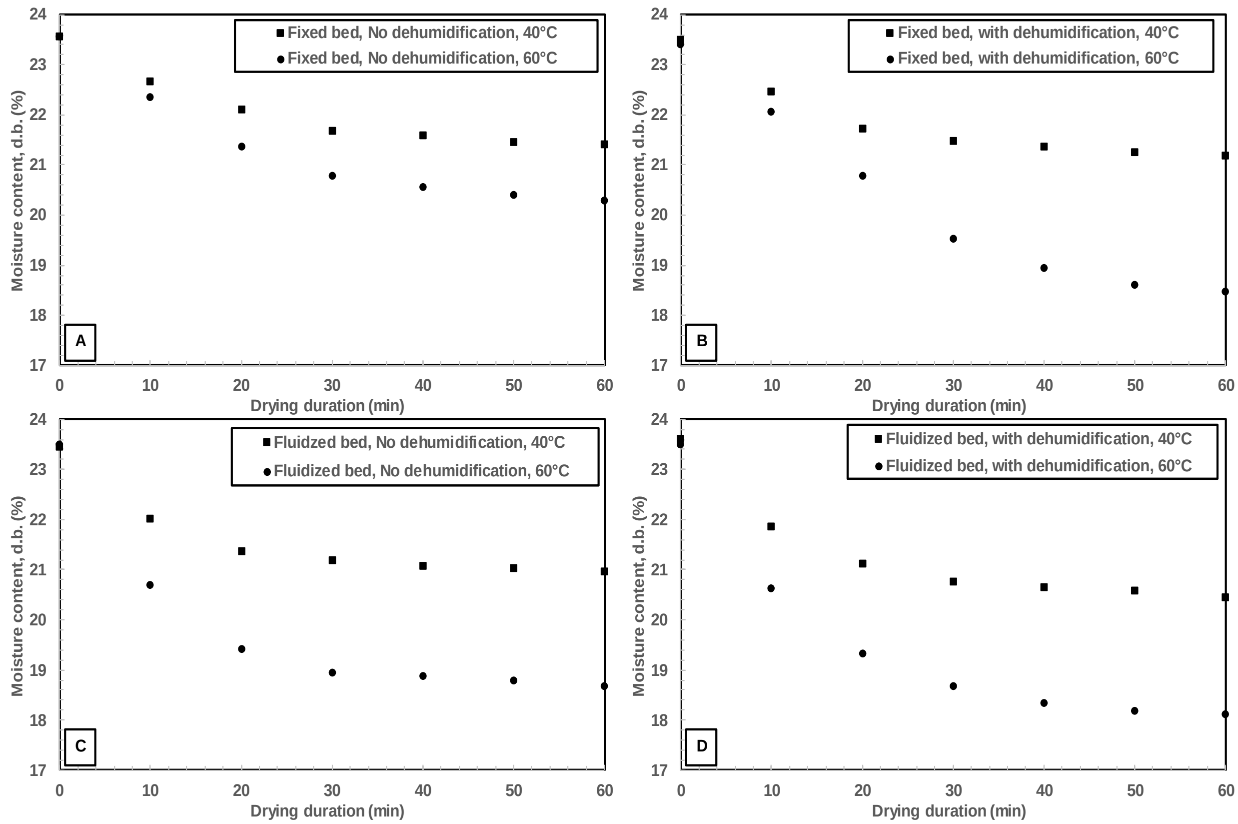

Figure 24. Moisture content profile of (A) fixed bed with no dehumidification, (B) fixed bed with dehumidification, (C) fluidized bed with no dehumidification, and (D) fluidized bed with dehumidification.

The highest moisture reduction of 5.4% moisture points (d.b.) was observed under fluidized bed conditions with air dehumidification and at 60°C. Conversely, the lowest moisture reduction of 2.1% moisture points (d.b.) was observed under the fixed-bed condition without dehumidification and at 40°C. The highest moisture reduction after 30 minutes reached 4.8% moisture points (d.b.), which was observed under fluidized bed conditions with air dehumidification and at 60°C. On the contrary, the lowest moisture reduction of 1.9% moisture points (d.b.) was observed under the fixed-bed condition, without dehumidification, and at 40°C after the same drying duration of 30 minutes. As seen from the results, about 87% to 90% of the moisture was removed during the first 30 minutes. The results demonstrated the fact that the free water on the outer layer of the kernels would be removed faster and with more accessibility than the water inside the kernels, which in turn showed higher moisture removal during the first 30 minutes.

Trivial moisture removal was observed during the last 30 minutes of all experimental runs. This phenomenon could be attributed to the lower moisture content of rice after 30 minutes, which increased the difficulty of removing more water from rice. Darvishi et al. (2017) reported that the energy required to evaporate moisture from food product per unit mass would increase over time as the free water in the food product decreases. Sadaka et al. (2017) mentioned that during fixed-bed drying, the drying front moves from bottom to top, allowing samples at the bottom end to dry first, which could lead to non-uniform drying as in the current study.

Fluidized bed dryer removed more moisture from rough rice as compared with fixed bed dryer under the no dehumidification and dehumidification status and the two tested temperatures of 40^{o}C and 60^{o}C. For instance, under the conditions of a fluidized bed, no dehumidification and at 60^{o}C, the moisture removed was 1.5% moisture point more than under the fixed bed, no dehumidification, and at 60^{o}C. This result could be confirmed from table 15 as shown by the significant difference between the fixed bed and fluidized bed (P-value of 0.0001). The higher airflow rate under fluidization condition as compared with the fixed bed condition increased the moisture removal from rough rice. Hamoud-Agha and Allaf (2019) reported that with higher pressure drop during drying of food particles, more moisture was removed. Thus, the study aligns with the present study trend that fluidized bed drying that had a higher airflow rate experienced more moisture removal.

Dehumidification of the drying air also showed a positive effect on the moisture removal for the two tested factors of bed conditions and bed temperature. Table 3 shows a significant difference between the no dehumidification and dehumidification environments (P-value of 0.0001). Excess rice moisture removed due to dehumidification overall ranged from 0.2% to 1.6% d.b. moisture points as compared to the drying with no dehumidification (Table 16). The highest value of 1.6% moisture points removed was achieved under fixed bed conditions and at the bed temperature of 60^{o}C. This occurrence can be explained by the increase of the drying air capacity as its relative humidity decreased during the dehumidification process. Bhardwaj et al. (2018) found similar results for drying fenugreek seeds in a desiccant solar dryer. Dehumidification reduces the moisture from the input air, thus, increasing the drying capacity of the air. Gill et al. (2014) used a desiccant dryer at 38°C to dry chilly, paddy, cilantro, fenugreek, and radish seeds. They achieved a significant amount of drying, which was not possible with no air dehumidification at that temperature.

The results also exhibited that the higher the air temperature, the more extensive the moisture removal from rice. There was a significant difference between the moisture removal under the air temperature of 60^{o}C and 40^{o}C (P-value of 0.0001). Under the fixed bed condition and with dehumidification, by increasing the air temperature from 40^{o}C to 60^{o}C, the moisture removal increased from 2.3% d.b. moisture points to 4.9% d.b. moisture points, a difference of 2.6% d.b. moisture points. Increasing the air temperature increased its volume, which in turn reduced its relative humidity. As a result, the air capacity of carrying more moisture from rice had been increased. Ondier et al. (2010) and Sadaka et al. (2018) observed a similar trend as they also reported a decrease in moisture content with an increase in air temperature at the same time while drying grain in a fluidized bed. The drying air at a higher temperature supplied extra heat; thus, more moisture was removed. Sadaka et al. (2018) reported a 4.3% point reduction in moisture content (d.b.) during the drying process of wheat with no heat addition in a fluidized bed dryer. The current study reported a 5.4% point reduction in moisture content (d.b.), which is comparatively a more significant removal of moisture. Ondier et al. (2010) observed a similar trend as they reported a decrease of 4.0% and 10.0% moisture (d.b.) at 60°C and 90°C air temperature for 1 hour of drying in a fluidized bed. The higher moisture could be attributed to the higher drying temperature used.

Table 15. Analysis of variance for checking the statistical significance of factors with moisture removed as the response variable.

Factor	Degree of freedom	P-value
Bed condition	1	<0.0001*
Dehumidification	1	<0.0001*
Air temperature	1	<0.0001*
Replication	2	0.1743
Bed condition × Dehumidification	1	0.0535
Dehumidification × Air temperature	1	0.0002*
Bed condition × Air temperature	1	0.0078*
Bed condition × Dehumidification × Air temperature	1	<0.0001*

* Statistical significance checked at $\alpha = 0.05$.

Table 16. Moisture removed from fixed and fluidized bed drying with and without dehumidification.

Bed condition	Air temperature (°C)	Moisture removed (% d.b.)* with no dehumidification	Moisture removed (% d.b.)* with dehumidification	Excess moisture removed due to dehumidification (%)
Fixed	40	2.1 ± 0.1^{A}	2.3 ± 0.0^{AB}	0.2 ± 0.2
	60	3.3 ± 0.1^{C}	4.9 ± 0.1^{D}	1.6 ± 0.2
Fluidized	40	2.5 ± 0.3^{B}	3.2 ± 0.2^{C}	0.7 ± 0.1
	60	4.8 ± 0.2^{D}	5.4 ± 0.2^{E}	0.6 ± 0.1

* Average of 3 replication ± the standard deviations. Letters are used in superscript to differentiate amongst moisture removed for all entries.

3.4 Effects of bed conditions, air dehumidification, and air temperature on drying rate

Figure 25 shows the drying rate as affected by bed conditions, air dehumidification, and air temperature. The values shown were calculated based on equation 1. The results showed that the maximum drying rate of 0.288% moisture points/min was observed under fluidized bed condition, with dehumidification, and at 60°C after the 10 minutes of drying time. A clear trend was observed when a comparison took place between the drying rate values under fixed bed conditions and fluidized bed conditions. Fluidization of the bed resulted in increasing the drying rate under the environment of no dehumidification, with dehumidification and under the two tested temperatures of 40^{o}C and 60^{o}C. This observation could be attributed to the higher airflow rate associated with a fluidized bed as compared with the airflow rate associated with a fixed bed. A similar observation was reported by Kalita et al. (2018) for rice drying using a fluidized bed dryer while maintaining a temperature of 58 to 62°C. For instance, by changing the bed conditions from fixed bed to fluidized bed under the no dehumidification environment and at 60^{o}C, the maximum drying rate increased by 0.161% moisture points per minute (0.121 to 0.282 % d.b. moisture point per minute). Air dehumidification increased the drying rate under the fixed bed and fluidized bed conditions. This occurrence can be attributed to the increase in the drying capacity of the dehumidified air that boosts the rice drying. A higher drying rate was also associated with higher air temperature. The higher air temperature supplied high energy to the rough rice, which in turn energized the moisture removal from rice faster which is supported by the findings of Bertotto et al. (2019).

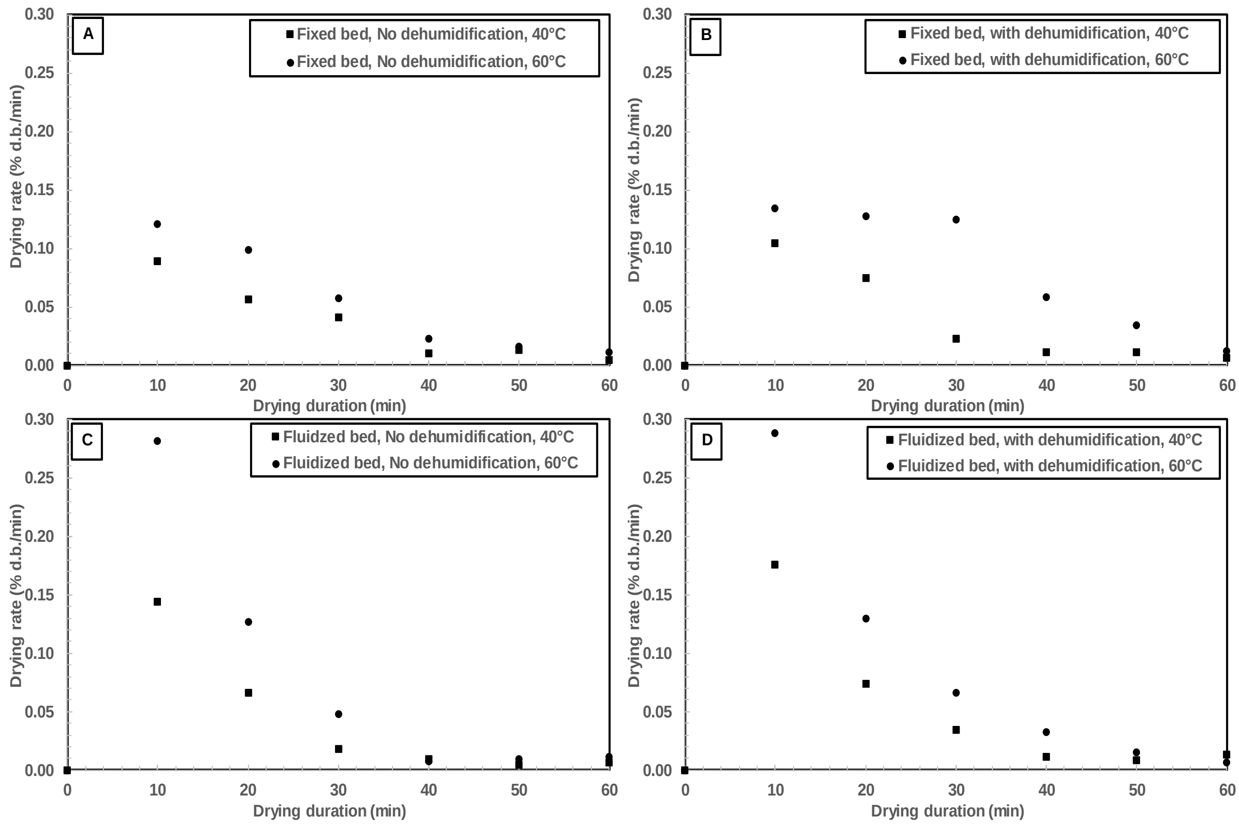

Figure 25. Drying rate profile of (A) fixed bed with no dehumidification, (B) fixed bed with dehumidification, (C) fluidized bed with no dehumidification, and (D) fluidized bed with dehumidification.

Under all studied conditions, the first 10 min showed the maximum drying rates. After the heating duration of 30 minutes, the drying rate dropped to less than 0.06 % d.b./minute associated with all tested conditions. The only exception to this observation was found under the fixed bed condition with dehumidification and at 60^{o}C. The significant reduction of the drying rate signifies the fact that no effective drying took place after almost half the experimental duration. This observation could be reasoned to the moisture reduction of the kernels and the lack of more moisture to be moved out from the kernels to the surrounding air. Luthra et al. (2018) and Poomsa-ad et al. (2005) also reported that the drying rate of rice decreased with increasing the period of rice drying. By increasing the drying duration, the drying rate values declined until they reached their minimum values after 40 to 50 minutes.

3.5 Effects of bed conditions, air dehumidification, and air temperature on head rice yield

Head rice yield for different levels of bed conditions, dehumidification environment, and air temperatures are mentioned in Table 17. This table shows the results of the analysis of variance. LSmeans Students' t-test was performed on the head rice yield data to test the difference among the levels of each variable at 0.05 level. The results are presented in Table 18. The air dehumidification environment and bed temperature had significant effects (at 0.05 level) on the head rice yield. Conversely, bed conditions, i.e., fixed bed or fluidized bed, had insignificant effects on the head rice yield. There appear to be some interactions (at 0.05 level) among these variables. The maximum head yield of 66.7% was achieved with fixed bed drying at 40°C with no dehumidification. For fluidized bed drying, 64.6% was the maximum head yield that was achieved at 40°C with dehumidification. The minimum head rice yields were 34.9% and 45.5% under no dehumidification and at 60°C for fixed bed and fluidized bed conditions, respectively.

Table 17. Analysis of variance for checking the statistical significance of factors with head rice yield as the response variable.

Factor	Degree of freedom	P-value
Bed condition	1	0.2526
Dehumidification	1	0.0002*
Air temperature	1	<0.0001*
Replication	2	0.0856
Bed condition × Dehumidification	1	0.0387*
Dehumidification × Air temperature	1	<0.0001*
Bed condition × Air temperature	1	0.0099*
Bed condition × Dehumidification × Air temperature	1	0.0004*

* Statistical significance checked at $\alpha = 0.05$.

Table 18. Head rice yield for different bed conditions, air temperature, and dehumidification condition.

Bed condition	Air temperature (°C)	HRY with no dehumidification (%)*	HRY with dehumidification (%)*	Change in HRY due to dehumidification (%)* #
Fixed	40	66.7 ± 0.8 A	64.1 ± 0.5 A	-2.7 ± 0.7
	60	34.9 ± 2.4 B	51.5 ± 6.6 C	16.5 ± 5.6
Fluidized	40	62.8 ± 1.1 A	64.6 ± 1.2 A	1.8 ± 0.2
	60	45.5 ± 0.3 D	48.9 ± 1.3 CD	3.4 ± 1.0

* Average of 3 replication ± the standard deviations. Letters are used in superscript to differentiate amongst head rice yield for all entries.
# Change in HRY due to dehumidification was calculated by subtracting HRY with no dehumidification from HRY with dehumidification.

No clear trend was observed when rough rice was dried in a fixed bed or a fluidized bed as measured by head rice yield, as shown in Table 17 by the insignificant difference between the two tested bed conditions. Air dehumidification had a significant (P-value <0.05) and positive effect on the head rice yield; however, for the fixed-bed condition at 40°C, the head rice yield with dehumidification was less than with no dehumidification. It could be postulated to the difference in moisture removal behavior of the less humid air as compared to the more humid air as pointed out by Ondier et al. (2010). They dried rough rice at a temperature range of 26 to 34°C using air dehumidification and observed that the head rice yield was similar to drying with no air dehumidification. Table 17 also shows significant differences (P-value < 0.0001) among the two tested temperatures. The head rice yield decreased with an increase in temperature from 40°C to 60°C. It can be postulated that due to higher moisture gradient developed in the rice kernel at higher temperature lead to the development of rice fissures. During milling, the developed fissures may have caused more rice breakage and thus less head yield. Similar results of less head rice yield for an air temperature of 60°C were reported by Bertotto et al. (2019), Cnossen and Siebenmorgen (2000) and Litchfield and Okos (1991).

3.6 Effects of bed conditions, air dehumidification, and air temperature on milled rice whiteness

As mentioned earlier whiteness values of milled rice are the relative index that ranges from 20 to 50 (dimensionless) with 20 being the typical value of brown rice, whereas 50 represents well-milled white rice. The maximum whiteness of 41.8 was achieved by fluidized bed condition with no dehumidification at 60°C, whereas the minimum whiteness of 38.3 was found for the fixed-bed condition with no dehumidification of ambient air at 60°C (Table 19). Fluidized bed drying, overall, had slightly higher whiteness than fixed bed drying. It can be postulated to the uniform drying of rice by the fluidized bed condition as compared to the fixed bed. On the other hand, under the fixed-bed drying, the drying front moves from bottom to top, allowing samples at the bottom end to dry first, which could lead to non-uniform drying (Sadaka et al., 2017). Taweerattanapanish et al. (1999) reported an acceptable level of milled rice whiteness for fluidized bed drying. The whiteness with dehumidification was slightly lower than with no dehumidification except under the fixed bed and the temperature of 60°C. Increasing the bed temperature from 40°C to 60°C showed a minor positive effect on the milled rice whiteness except for a fixed bed and no dehumidification of the air. Dillahunty et al. (2001) reported reduced whiteness for rice kernels at temperatures higher than 50°C and the experimental duration of 12 hours or more. Also, Chen et al. (2017) reported a reduced appearance of rice after drying by air at high temperatures (<80°C) for a short duration. However, in the present study, the experimental duration was 60 min, and two levels of air temperature were 40°C and 60°C, which could be the reason for the contradiction.

Table 19. Milled rice whiteness for different bed conditions, air temperature, and dehumidification condition.

Bed condition	Air temperature (°C)	Whiteness with no dehumidification*	Whiteness with dehumidification*
Fixed	40	39.6 ± 0.7^{AB}	38.8 ± 0.4^{BC}
	60	38.3 ± 0.8^{C}	39.3 ± 0.4^{AB}
Fluidized	40	41.4 ± 0.4^{D}	39.9 ± 0.3^{A}
	60	41.8 ± 0.8^{D}	40.1 ± 0.1^{A}

* Average of 3 replication ± the standard deviations. Letters are used in superscript to differentiate amongst whiteness for all entries.

3.7 Effects of bed conditions, air dehumidification, and air temperature on energy consumption by the heater and the blower per unit water mass removal

Table 20 illustrates the energy consumption by the dryer to remove a kilogram of moisture from the rice under different bed conditions, dehumidification environment, and air temperature. The energy consumption for the drying process includes the energy used by the heater and the blower. It should be mentioned that for the 40°C, no external heating was needed as the air temperature rose due to the heating produced by the air friction in pipes and fittings.

The lowest energy consumption per unit water mass removal of 86.8 $MJ/kg_{water\ removed}$ was observed for fluidized bed conditions with air dehumidification and at 60°C. Conversely, the highest energy consumption of 227.9 $MJ/kg_{water\ removed}$ was attained for the fixed-bed condition with no dehumidification and at 40°C. Energy consumption for the fluidized bed condition was significantly lower as compared to the fixed bed condition. More moisture removed could be attributed to the higher airflow. Higher airflow was attained at the expense of a similar amount of energy as used by the fixed condition or lower airflow. Energy consumption decreased under all conditions with dehumidification as compared to no dehumidification. This can be postulated to the fact that the dry air has more capacity to extract more water from the kernels as compared to the humid air at the same temperature. The observed energy consumption values in the present study are at a higher-end as compared to the values reported by Luthra et al. (2018) The later used 7 kg of rice and the heating duration varied from 0 min to 30 min. Darvishi et al. (2017) reported that energy consumed per unit mass of water removed would increase over time as the free water in the food product decreases, and more energy is consumed to remove the bound water from the product. Therefore, in the current study, energy consumption has much higher values. Additionally, the heat loss from the system could be higher, as the tube furnace is heating the air due to the allothermal effects. The high energy consumption in the current study could be attributed to the massive size blower utilized.

It should be mentioned that the energy consumption by the heater was 0.0% of the total energy under the drying temperature of 40^{o}C, for the fixed and fluidized bed with and without dehumidification as no extra heat was needed. On the other hand, the energy consumption by the heater reached 25.0% of the total energy under the drying temperature of 60^{o}C for fixed bed and fluidized bed with and without dehumidification. As a reminder, the energy consumed in the regeneration process of silica gel packets was not included in the current study.

Table 20. Energy consumption for different bed conditions, air temperature, and dehumidification condition.

Bed condition	Air temperature (°C)	Energy consumption with no dehumidification (MJ/kg$_{water\ removed}$)*	Energy consumption with dehumidification (MJ/kg$_{water\ removed}$)*
Fixed	40	170.9 ± 14.4 ^{A}	156.1 ± 11.4 ^{B}
	60	146.3 ± 6.1 ^{C}	95.1 ± 2.5 ^{D}
Fluidized	40	145.1 ± 14.2 ^{C}	113.4 ± 6.5 ^{E}
	60	97.1 ± 3.5 ^{D}	86.8 ± 2.9 ^{D}

* Average of 3 replication ± the standard deviations. Letters are used in superscript to differentiate amongst energy consumption for all entries.

4. Conclusions

The current study was performed to investigate a new technique of dehumidification of the drying air to allow continuous on-farm in-bin drying process even with high humid ambient air. Accordingly, a custom-made fluidized bed dryer was developed by installing a dehumidification unit containing silica gel that was used in the current study as a desiccant. The experimental design was completely randomized, with 24 experimental units. Three factors were tested, including bed condition (fixed and fluidized), dehumidification environment (without and with dehumidification), and air temperature (40°C and 60°C) in triplicates.

Of most significant, the three measured parameters of bed conditions, dehumidification environment, and bed temperature have a significant effect on the moisture removed from rough rice. Air dehumidification showed a maximum of 1.6%±0.2 moisture removal higher than no dehumidification environment. The highest moisture reduction reached 4.8% moisture points (d.b.), which was observed under fluidized bed conditions with air dehumidification at 60°C and after 30 minutes.

Of secondary importance, air dehumidification had a positive and significant effect on head rice yield for the majority of the experimental runs. Thirdly, the whiteness of milled rice ranged between 38.3 and 41.8, with the maximum value reported for rice dried under the fluidized bed.

Finally, dehumidification of air can be a handy method to be used for on-farm in bin drying of rice during high ambient air relative humidity. However, some technical challenges need to be studied, such as how silica gel can be regenerated for sustaining the continuous drying of rice.

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Chapter 7: Effects of ambient air dehumidification, air temperature, and drying duration on rough rice quality and pasting properties using fluidized bed and fixed bed dryers

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Abstract

High humidity ambient air is a common phenomenon in the USA's midsouth, resulting in a delay in the drying process to avoid rewetting rough rice. Ambient air dehumidification could have the potential to overcome this challenge and result in a continuous drying process. Therefore, the present study explored the effects of ambient air dehumidification, air temperature, and drying duration on rough rice quality and pasting properties in fluidized bed and fixed bed drying systems.

A fluidized bed and a fixed bed drying systems were used to study the effects of dehumidification settings (with and without), air temperature (40°C, 45°C, and 50°C), and drying duration (30 min, 45 min, and 60 min) on rice quality and pasting properties in triplicates. Silica gel was used as a desiccant for ambient air dehumidification. The results showed that the range of moisture removal to be 4.5 to 7.1 (%, dry basis) for 1 hour in a fluidized bed rice drying. The maximum water absorbed by air achieved 0.382 and 0.434 kg for fluidized bed and fixed bed dryers, respectively, after 60 minutes of drying, at 50°C, and with air dehumidification. The results showed that head rice yield and rice whiteness did not reduce in fluidized bed drying than the fixed bed drying. Ambient air dehumidification improved moisture removal from rice and can be employed during humid conditions. Head rice yield was negatively correlated with rice whiteness. Pasting properties also supported the notion of attaining good quality rice from fluidized bed drying of rice compared with fixed bed drying. The peak viscosity was lower for all fluidized bed experiments (2712.8 cP) than the fixed bed drying experiments (2815.8 cP). Head rice yield was positively correlated with the peak and trough viscosities signifying the increase in milling yield with the rice water-absorbing capacity and resistance to cooking textural breakdown.

Keywords

Dehumidification, Fixed bed, Fluidized bed, Rice drying, Rice pasting quality.

1. Introduction

In the U.S., farmers use ambient air on-farm in-bin drying if they plan to wait for an off-season increment in the rice's selling price (Luthra and Sadaka 2020a). The major challenge with ambient air drying is its dependency on weather. Humid, cold, or rainy conditions stop the drying and sometimes lead to rice rewetting, thus increasing the drying cost and reducing the quality. An alternative technique that promises to achieve a higher drying rate that can reduce weather interference during the rice drying season is fluidized bed drying (FBD) of rice. A significant drawback of FBD is the physical quality reduction due to particle breakage (Kunze, 1983), higher energy consumption as compared to conventional fixed-bed drying (Avidan and Yerushalmi, 1985), and impediment in upscaling the design (Avidan and Yerushalmi, 1985). Many Asian countries use fluidized bed drying of rice; however, there is a dispute in the U.S., as pointed out by Luthra and Sadaka (2020a). Researchers in the U.S. are debating the significant disadvantage of fluidized bed drying, i.e., the quality reduction due to rice breakage.

FBD of rice generally happens at high temperatures. Wiset et al. (2001) used FBD for rough rice using air at 90°C for 11 minutes and then air drying in storage bins. They reported the rice moisture content decreased to an 18% wet basis. They found that the head rice yield of rice did not decrease. Thakur and Gupta (2006) found that FBD could reduce energy usage and enhance drying rate without a significant rice quality change than the fixed bed drying. Sarker et al. (2013) found no significant difference in the head rice yield using fluidized bed and ambient air fixed bed drying. Cnossen and Siebenmorgen (2000) reported a decrease in rice quality above 60°C, so they did not recommend FBD of rice. Jaiboon et al. (2009) reported a reduction in head rice yield using FBD compared to the shade drying and tempering period after FBD did not improve the quality. Another study reported head rice yield, nutritional, and cooking quality reduction after drying rice in a fluidized bed at 140°C for 2 minutes (Karbassi and Mehdizadeh, 2008).

Rice pasting properties give insight into rice functionalities by providing detailed information about rice starch behavior using force and temperature changes over time (Lanning et al., 2012; Bruce et al., 2020). It helps in selecting the right end-use for the rice. Lanning et al. (2012) studied the effect of air temperature fluctuation on six rice cultivars' pasting properties. They reported the changes in pasting properties of rice with the change in air temperature. Specifically, peak viscosities and gelatinization temperatures increased with an increase in air temperature, whereas setback viscosities decreased. Bruce et al. (2020) studied the rice broken size variation, drying temperature differences, and the effect of commingling practice on the rice pasting properties. They found drying temperature and size of broken had a significant effect on rice pasting properties, whereas commingling did not change the pasting properties. Similarly, Mukhopadhyay and Siebenmorgen (2017) studied rice fissuring's effect that generates different sized broken rice and its effect on their pasting properties. They found that the peak, setback, and final viscosities were greatest for head rice and reduced significantly with decreasing broken rice size.

Fluctuations in ambient air's relative humidity that affect rice farmers who use on-farm in-bin drying systems are common in Arkansas. As the rice moisture content approaches storage moisture content, i.e., 13% wet basis, there is a high risk of rewetting the rice, thus, reducing milling quality (Ondier et al., 2011). Also, with high humidity, freshly harvested rice can take time to dry, or the worst-case scenario is no drying at all. Thus, farmers are forced to stop the airflow causing spoilage risks. Using external heaters can help reduce the ambient air's relative humidity; however, it increases the cost of drying a lot and is not preferred by the farmers. Using desiccants is an alternative to heaters that can be comparatively cheaper for ambient air dehumidification. Most of the past research has used desiccant with the product as an intimate mixture to achieve drying (O'brien and Siebenmorgen, 2006).

Luthra and Sadaka (2020b) used ambient air dehumidified air and compared fluidized bed and fixed bed drying of rice. They did not find a significant reduction in rice quality by FBD as compared to fixed bed drying. They reported that there is still a need to study the effects of ambient air dehumidification on rice quality and pasting properties under the medium levels of air temperature in a fluidized and fixed bed dryer. To our knowledge, no study has deliberated the effect of FBD of rice utilizing ambient air dehumidification on its pasting properties. Thus, this study evaluated the effects of ambient air dehumidification, air temperature, and drying duration on rice quality and pasting properties using fluidized bed and fixed bed drying systems.

2. Materials and Methods

The fluidized bed dryer and the ambient air dehumidification system, developed by Sadaka et al. (2018) and Luthra and Sadaka (2020b), were used. Rough rice samples (cv. Diamond) were used in all the experiments that were harvested at a farm in Northeast Arkansas. The experiments were performed in a laboratory in the Rice Research and Extension Center (RREC), Stuttgart, AR. The rough rice was cleaned using a dockage tester (Model XT4, Carter-Day, Minneapolis, MN), physical characteristics identified (Table 21), and was sealed and stored in plastic bags in a refrigerator at 4°C until used for experiments. The required amount of rice for the experiment was taken out to room conditions 24 hours before starting the experiment to restrict any dew formation on the rice surface. The rice's initial moisture content was 24.3% dry basis, measured by the ASABE standard oven method (ASABE, 2008). An automatic seed counter (Model SLY-C, Hinotek, China) and a scale (Ohaus SP-2001 Scout Pro Balance, Parsipanny, NJ) were used to determine the 1000 rice kernel weight. Bulk density and physical dimensions were determined using the standard method ASTM E873-82 and digital caliper (General Ultratech, Series – 147, Secaucus, NJ). Geometric mean diameter was calculated using the cube root of the product of length, width, and rice kernel thickness (Sadaka et al., 2018).

Table 21. Rough rice sample characteristics.

Parameter	Units	Rough Rice
1000 Kernel weight*	g	26.1±0.16
Bulk density*	kg/m^3	620.8±2.28
Initial Moisture content*	%, d. b.	24.3±1.1
Rice Kernel Dimensions**		
Length	mm	8.75±0.53
Width	mm	2.40±0.14
Thickness	mm	1.14±0.14
Geometric Mean Diameter	mm	3.43±0.15

* Average of three readings, ± the standard deviations
** Average of fifty readings, ± the standard deviations

2.1 Drying system

The drying system was a custom-made laboratory-scale constructed by Sadaka et al. (2018) and modified by Luthra and Sadaka (2020b). It consists of five subunits: air dehumidification unit, air supply unit, air heating unit, drying column and measuring systems. Figure 26 shows the drying system used in the present study. A detailed description of the system was reported by Luthra and Sadaka (2020b).

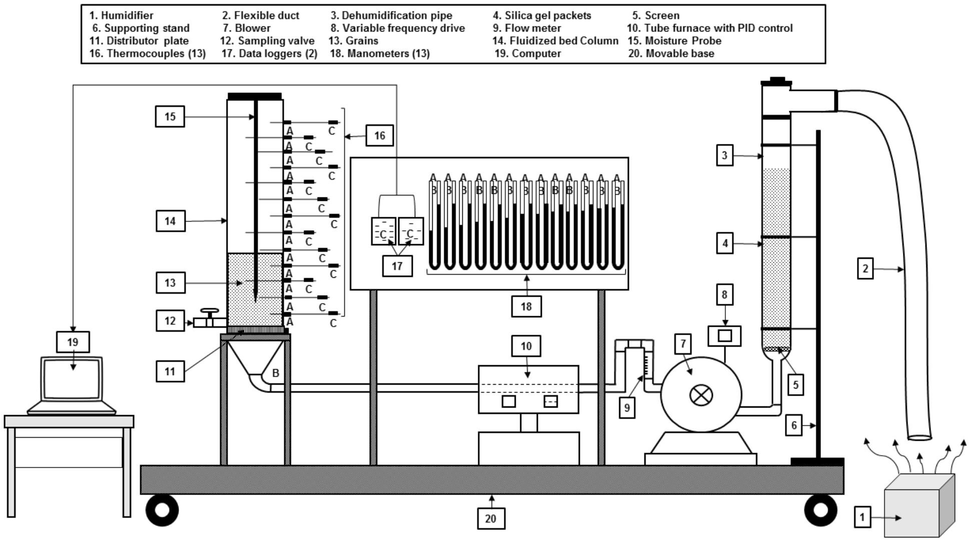

Figure 26. A schematic diagram of the drying system used in the present study.

2.2 Experimental design

The effects of bed conditions (fluidized bed and fixed bed), dehumidification settings (with and without dehumidification), air temperature (40, 45, and 50^{o}C), drying duration (30, 45, and 60 min) on moisture content, drying rate, water removal, head rice yield, rice whiteness, and pasting properties were studied. The experiments were performed in triplicate, yielding a total of 108 experimental runs. To avoid high drying temperatures, air temperatures below 60^{o}C were selected. Silica gel was used as a desiccant to dehumidify the ambient air during the dehumidification experiments. The experimental design was a complete randomized design.

A custom design on JMP software (SAS, 2016) was used to decrease the number of samples regarding the pasting properties. This analysis is known for reducing the number of runs without removing any factors for significance testing. A total of 20 sample analyses were carried out that were selected by the software.

2.3 Experimental procedures

Before starting each experiment, 4.5 kg of rough rice was brought to room temperature by keeping it out of the refrigerator for 24 hours. The blower was turned on and using a variable frequency drive, and the airflow was adjusted to attain the fluidized bed (1.75±0.10 m/s) or fixed bed conditions (0.95±0.10 m/s). The furnace was powered on, and the desired air temperature was attained within a few minutes. If the experiment required ambient air dehumidification, silica gel packets tied to the rope were installed in the desiccant pipe after the initial weight was recorded. Rough rice was loaded from the open end of the drying column. An Omega-8 datalogger (Norwalk, CT) was connected to a set of thermocouples to record the bed temperature every 30 seconds. Inlet and outlet air relative humidity and pressure drop readings were manually reported using a relative humidity dew point meter (HI9565, 5% to 95% Range, Hanna Instruments Ltd., Bedfordshire, England, UK).) and three digital manometers (Series 475, Dwyer Instruments INC, Michigan City, IN), respectively. The data was recorded in a sheet every 10 minutes. After the experiment's end, the final moisture content of rough rice was measured using a moisture meter (AM 5200 Grain Moisture Tester, PERTEN Instrument, Hägersten, Sweden), and three 200-gram samples were collected for rice quality analysis; they were stored in a labeled plastic bag in a refrigerator. The data files were stored, and the blower and furnace were shut down; the drying column was emptied and cleaned for the next experiment. Silica gel, if used were pulled out and weighed to determine the weight gain during the experiment. Silica gel packets were then regenerated by keeping the packets in a conventional air oven at 120°C for 2 hours (Luthra and Sadaka, 2020b). During the dehumidification and the no dehumidification settings, the amount of water carried by the inlet and exit air was determined periodically (every 10 minutes) by determining the air relative humidity and temperature. The Psychrometric chart was used to determine the mass of water in the air. During the dehumidification settings, the amount of water absorbed by the silica gel was determined by measuring the silica gel weight before and after the experimental run. Following the amount of water carried by air was determined.

2.4 Determination of dried rough rice quality

Dried rough rice quality was quantified using head rice yield, rice whiteness, pasting properties, including peak, breakdown, setback, final viscosities, peak time, and pasting temperature. The methods used are mentioned in the following sections.

2.4.1 Head rice yield

The rough rice samples were kept in an environmentally controlled chamber at 25°C temperature and 55% relative humidity for seven days to bring down the moisture content to 13% wet basis. Then 100 grams of rough rice was milled using a laboratory scale milling and sorting machine (PAZ-1 DTA, ZaccariaUSA, Anna, TX). The settings as recommended by the manufacturer were set to attain the standard surface lipid content of 0.5% while milling the rice. Head rice was sorted and weighed to determine the head rice in grams. The ratio of head rice to the total weight (100g) in percentage gives the sample's head rice yield.

2.4.2 Milled rice whiteness

Milled rice whiteness measures the degree of rice whitening. It includes removing the bran and silver layers with some polishing (Ranalli et al., 2002). A portable whiteness meter (MBZ-P, Zaccaria USA, Anna, TX) was used in the current study. The whiteness is reported as a relative index ranging from 20 to 50 (dimensionless). Brown rice is 20 on the index of whiteness, whereas 50 represents well-milled white rice.

2.4.3 Pasting properties

Pasting properties were determined using the rice flour with a rapid visco analyzer (RVA) (Newport Scientific, Warriewood, NSW, Australia) according to AACC international approved method 61-02.01. The paste was prepared by mixing 3.0 g of rice flour with 25.0 mL of deionized water in an RVA canister. The paste was heated to 50°C and then was held for 1.5 min. Next, the paste was heated to 95°C at 12.2°C/min and held for 2 min. Subsequently, the paste was cooled to 50°C at 12.2°C/min and was held for 1.5 min.

2.5 Statistical analyses

Data were analyzed using JMP Pro 15 (SAS Institute Inc., Cary, NC). Analysis of variance was conducted to determine the main effects of bed condition, dehumidification, temperature, and drying duration. Tukey's test's interactive effects were used to differentiate any significant factors. The level of confidence was set at 95% for checking the statistical significance.

3. Results and Discussion

3.1 Rice moisture content, drying rate, and the amount of water removed

Table 22 shows the final moisture content (MC) of rough rice as affected by the dehumidification setting, air temperature, and drying duration in a fluidized bed and fixed bed dryers. The results showed that increasing the air temperature and the drying duration decreased the final MC of rough rice under the tested air dehumidification settings and bed conditions. It could be postulated to reduce the inlet air relative humidity, which positively increased its capacity to carry out more rice moisture. Also, increasing the drying duration allows more air to carry out a more considerable amount of moisture from the rice. The final MC was lower under the air dehumidification settings than the no dehumidification and was lower under the fluidized bed conditions than the fixed bed conditions. More moisture was removed from rice due to the vast amount of air purged to sustain the fluidization status in the fluidized bed dryer compared to the fixed bed dryer. The minimum MC reached 17.2±0.1% (a 7.1% points reduction) after 60 min of drying in a fluidized bed at 50°C air temperature with ambient air dehumidification. In contrast, the maximum MC has attained at 21.9±0.2%, only a 2.4% point reduction, after 30 minutes of drying in a fixed bed, at 40°C, and without ambient air dehumidification. This finding is in line with Ondier et al. (2010b) results. They reported that the moisture reduction of 4 to 10% d.b. for fluidized bed drying of rice at 60°C to 100°C for 1 hour of drying. Similar results were reported by Thakur and Gupta (2006) and Luthra and Sadaka (2020b). It can be postulated that more airflow and better rice mixing during drying allow more moisture removal. The present study found the range to be 4.5 to 7.1 (% dry basis) for 1 hour of fluidized bed rice drying. The present study achieved rice drying at lower temperatures than the Ondier et al. (2010b) due to ambient air dehumidification and a different dryer design. Table 23 illustrates the significant differences in final moisture content's response variable as affected by bed condition, dehumidification settings, air temperature, and drying duration. All the studied parameters, i.e., bed condition, dehumidification settings, air temperature, and drying duration, were significantly different (P-value < 0.0001) except for the replicates.

Table 22. Effects of dehumidification settings, air temperature, and drying duration on final moisture content (%, d.b.) of rough rice in the fluidized bed and the fixed bed dryers.

Dehumidification	Air temperature	Fluidized bed			Fixed bed		
		30 min	45 min	60 min	30 min	45 min	60 min
No	40°C	19.8 ± 0.1	19.6 ± 0.1	19.0 ± 0.3	21.9 ± 0.2	21.8 ± 0.1	21.6 ± 0.3
	45°C	19.6 ± 0.1	19.5 ± 0.2	18.8 ± 0.1	21.3 ± 0.1	20.9 ± 0.2	20.3 ± 0.1
	50°C	19.2 ± 0.3	19.0 ± 0.1	18.5 ± 0.1	20.5 ± 0.1	19.8 ± 0.2	19.4 ± 0.1
Yes	40°C	19.1 ± 0.3	18.9 ± 0.2	18.2 ± 0.3	21.4 ± 0.2	20.8 ± 0.1	20.5 ± 0.3
	45°C	18.9 ± 0.1	18.7 ± 0.1	17.9 ± 0.2	20.2 ± 0.1	20.0 ± 0.1	19.2 ± 0.2
	50°C	18.6 ± 0.2	17.8 ± 0.1	17.2 ± 0.1	20.1 ± 0.1	19.1 ± 0.1	18.3 ± 0.1

Each reading represents the average of nine values (3 reading per experiment and three replicates) combined with its standard error value.

Table 23. Significance differences for the response variables of final moisture content, head rice yield, and rice whiteness as affected by bed condition, dehumidification settings, air temperature, and drying duration.

Factors	Levels	P-value*	Moisture content (%, d.b.)#	P-value*	Head rice yield (%)#	P-value*	Rice whiteness#
Bed condition	Fixed	<0.0001	20.4 ± 0.04^{a}	0.2439	63.3 ± 0.3^{a}	0.3761	37.7 ± 0.2^{a}
	Fluidized		18.8 ± 0.04^{b}		63.6 ± 0.3^{a}		37.4 ± 0.2^{a}
Dehumidification	Yes	<0.0001	19.1 ± 0.1^{c}	0.1383	63.6 ± 0.2^{a}	0.4978	37.5 ± 0.2^{a}
	No		20.1 ± 0.1^{d}		63.3 ± 0.2^{a}		37.6 ± 0.2^{a}
Drying duration	30 min	<0.0001	20.1 ± 0.1^{d}	0.3016	63.5 ± 0.4^{a}	0.2082	37.9 ± 0.1^{b}
	45 min		19.7 ± 0.1^{e}		63.2 ± 0.4^{a}		37.4 ± 0.1^{a}
	60 min		19.1 ± 0.1^{c}		63.6 ± 0.4^{a}		37.4 ± 0.1^{a}
Air temperature	40°C	<0.0001	20.2 ± 0.05^{d}	<0.0001	63.8 ± 0.2^{a}	0.0089	38.0 ± 0.3^{b}
	45°C		19.6 ± 0.05^{e}		63.9 ± 0.2^{a}		37.6 ± 0.3^{abc}
	50°C		19.0 ± 0.05^{c}		62.6 ± 0.2^{b}		37.0 ± 0.3^{c}
Replication	1	0.3096	19.7 ± 0.6^{de}	0.5470	63.6 ± 0.3^{a}	0.3531	37.5 ± 0.2^{a}
	2		19.7 ± 0.5^{de}		63.3 ± 0.3^{a}		37.3 ± 0.2^{ac}
	3		19.5 ± 0.5^{cde}		63.4 ± 0.3^{a}		37.8 ± 0.2^{ab}

*p-values less than 0.05 show the factors' statistical significance at a 95% level of significance.# Average and standard deviation values. All values in the same column not having a common letter in the superscript are statistically different.

The effects of dehumidification settings, air temperature, and drying duration on rough rice drying rate in the fluidized bed and the fixed bed dryers are presented in Table 24. Increasing the air temperature and decreasing the drying duration increased the drying rate under all other studied cases. Fluidized bed conditions and dehumidification statuses showed a higher drying rate than the fixed bed condition and the no dehumidification settings. The maximum drying rate achieved were 0.190%/min and 0.140%/min for fluidized bed and fixed bed dryers, respectively, after 30 minutes of drying, at 50°C, and ambient air dehumidification. On the other hand, the minimum drying rate of 0.088 and 0.045%/min for fluidized bed and fixed bed dryers were attained, after 60 minutes of drying, at 40°C, and without ambient air dehumidification. The reason could be that the higher airflow rate in the fluidized bed enhanced more moisture to be removed from rice in a shorter time.

Table 24. Effects of dehumidification settings, air temperature, and drying duration on rough rice drying rate (%, d.b./min) in the fluidized bed and the fixed bed dryers.

Dehumidification	Air temperature	Fluidized bed			Fixed bed		
		30 min	45 min	60 min	30 min	45 min	60 min
No	40°C	0.150	0.104	0.088	0.080	0.056	0.045
	45°C	0.157	0.107	0.092	0.100	0.076	0.067
	50°C	0.170	0.118	0.097	0.127	0.100	0.082
Yes	40°C	0.173	0.120	0.102	0.097	0.078	0.063
	45°C	0.180	0.124	0.107	0.137	0.96	0.085
	50°C	0.190	0.144	0.118	0.140	0.116	0.100

Each reading represents the average of nine values (3 reading per experiment and three replicates)

Furthermore, the air dehumidification status increased the difference between rice's moisture content and the air's relative humidity, which increased its ability to move more moisture faster. This can be due to reducing the drying air's relative humidity by the desiccant, thus enhancing the drying air's moisture removal capacity. Also, with an increase in air temperature and drying duration, the moisture removed increased significantly, as shown in Tables 23 and 25 as reported by Luthra and Sadaka (2020b). With an increase in drying air temperature, more heat was supplied by the air to the rice, and therefore more moisture was removed. Moreover, with an increase in drying duration, the rice was exposed to the drying air for a longer time and thus reached lower moisture levels.

As mentioned earlier, the airflow rate was higher in the fluidized bed condition (0.031 m^3/min) than with the fixed bed (0.017 m^3/min). Accordingly, for better comparison, the amounts of water removed per unit mass of rough rice and per unit volume of airflow during the drying process were calculated and presented (Table 25). The maximum water removed reached 0.822 g/kg $_{rice}$ m^3 $_{air}$ after 30 minutes of drying in the fluidized bed at 50°C with ambient air dehumidification. However, the minimum amount of water removed was 0.195 g/kg $_{rice}$.m^3_{air}, attained after 60 minutes of drying in the fixed bed, at 40°C, and without ambient air dehumidification. Increasing the air temperature and decreasing the drying duration increased the amount of water removed per unit mass of rough rice and per unit volume of airflow. Generally speaking, the amount of water removed was higher in all dehumidification cases than without dehumidification settings. Correspondingly, the fixed bed drying technique exhibited lower water removed per unit mass of rough rice and per unit volume of airflow than the fluidized bed technique. It could be due to the enhanced mixing of the rice in fluidized bed compared to rice's stationary status in the fixed bed. With the increase in air temperature, the fluidized bed drying had more potential to dry rice. With an increase in air temperature, the water's overall removal per kg rice and per m^3 of air increased. This is because of the enhanced capacity of drying air as the temperature of the air is increased. With ambient air dehumidification, a similar trend was observed. The difference in the amount of water removed per kg rice and per m^3 of air by fixed and fluidized bed increased with an increase in air temperature.

Table 25. Effects of dehumidification settings, air temperature, and drying duration on amount of water removed (g/kg $_{rice}$.m^3$_{air}$) in the fluidized bed and the fixed bed dryers.

Dehumidification	Air temperature	Fluidized bed			Fixed bed		
		30 min	45 min	60 min	30 min	45 min	60 min
No	40°C	0.649	0.452	0.382	0.346	0.240	0.195
	45°C	0.678	0.461	0.397	0.433	0.327	0.288
	50°C	0.735	0.509	0.418	0.548	0.433	0.353
Yes	40°C	0.750	0.519	0.044	0.418	0.336	0.274
	45°C	0.779	0.538	0.461	0.591	0.413	0.368
	50°C	0.822	0.625	0.512	0.606	0.500	0.433

Each reading represents the average of nine values (3 reading per experiment and three replicates)

The amount of water carried out by air was used to indicate the effectiveness of the dehumidification process. Table 26 shows the effects of dehumidification settings, air temperature, and drying duration on the amount of water carried out by the exit air. The average amount of water absorbed by the silica gel reached 0.151±0.038 kg, 0.199±0.19 kg, and 0.216±0.024 kg after 30, 45, and 60 minutes, respectively, and under the fluidized bed conditions. On the other hand, the average amount of water absorbed by the silica gel reached 0.152±0.008 kg, 0.190±0.057 kg, and 0.212±0.041 kg after 30, 45, and 60 minutes, respectively and under the fixed bed conditions. The difference between the measured water absorbed values in fluidized bed drying, and fixed bed drying could be attributed to the manual relative humidity equipment's response. During the ambient air dehumidification, silica gel absorbed moisture from 7.6 to 10.8% of its adsorptive capacity. It is around 30% of its total water adsorbing capacity, as Ondier et al. (2011) reported.

Table 26. Effects of dehumidification settings, air temperature, and drying duration on the amount of water added to the air (kg) in the fluidized bed and the fixed bed dryers.

Dehumidification	Air temperature	Fluidized bed			Fixed bed		
		30 min	45 min	60 min	30 min	45 min	60 min
No	40°C	0.131	0.207	0..233	0.113	0.131	0.295
	45°C	0.144	0.244	0.358	0.234	0.238	0.404
	50°C	0.167	0.206	0.333	0.192	0.344	0.436
Yes	40°C	0.234	0.263	0.329	0.214	0.266	0.406
	45°C	0.147	0.250	0.352	0.146	0.348	0.374
	50°C	0.221	0.283	0.382	0.125	0.275	0.434

Each reading represents the average of nine values (3 reading per experiment and three replicates)

Increasing the drying duration increased the amount of water carried out by the air for the fluidized bed and the fixed bed drying during the two settings of dehumidification and without dehumidification. Dehumidification settings showed a higher amount of carried out moisture in the air than the no dehumidification setting. There was no clear trend on the differences between the amount of water carried out during the rice drying in a fluidized bed dryer and a fixed bed dryer. The results showed that the maximum water carried out by air achieved 0.382 kg and 0.434 kg for fluidized bed and fixed bed dryers, respectively, after 60 minutes of drying, at 50°C, and ambient air dehumidification. On the other hand, the minimum water carried out of 0.131 kg and 0.113 kg for fluidized bed and fixed bed dryers were attained after 30 minutes of drying at 40°C, and without ambient air dehumidification.

3.2 Head rice yield

Table 27 illustrates the effects of dehumidification settings, air temperature, and drying duration on HRY of rough rice in the fluidized bed and the fixed bed dryers. HRY values ranged from 61.3% to 65.4% with a minimum value at 50°C without dehumidification during fixed-bed drying for 45 minutes, and the maximum value was achieved at 45°C during fluidized bed drying with dehumidification for 30 minutes. As mentioned earlier, fluidized bed drying achieved comparable HRY with fixed bed drying and did not reduce HRY. Luthra and Sadaka (2020b) reported the maximum HRY of 64.6% and 66.7% in a fluidized bed and fixed bed drying, respectively. As reported by them, the minimum values of HRY were 34.9% and 45.5% for fixed and fluidized bed conditions, respectively. Overall, this study's HRY values are in the low 60s due to the low-temperature range tested. On the other hand, Luthra and Sadaka (2020b) reported the minimum HRY achieved in their study at 60°C. Other studies confirm the trend found in this study for HRY, and they all reported a significant drop in HRY at or above 60°C drying temperature (Cnossen and Siebenmorgen, 2000; Ondier et al., 2010a; Bertotto et al., 2019). There was no drawback in using low temperatures for moisture reduction, as mentioned in the above section. The HRY at this condition was 62.5%, a decent value for the HRY. Thus, lower HRY with fluidized bed drying can be attained using lower air temperatures without compromising the high drying rate expected from the bed's fluidization.

Table 27. Effects of dehumidification settings, air temperature, and drying duration on head rice yield (%) in the fluidized bed and fixed bed dryers.

Dehumidification	Air temperature	Fluidized bed			Fixed bed		
		30 min	45 min	60 min	30 min	45 min	60 min
No	40°C	62.9 ± 0.4	62.4 ± 0.9	64.9 ± 0.3	63.3 ± 0.2	64.2 ± 0.3	64.5 ± 0.3
	45°C	63.6 ± 0.4	64.2 ± 0.8	63.2 ± 0.3	64.1 ± 0.3	64.4 ± 0.3	63.1 ± 0.3
	50°C	63.1 ± 0.1	62.3 ± 0.3	63.1 ± 0.3	62.2 ± 0.5	61.3 ± 0.4	62.0 ± 0.3
Yes	40°C	63.8 ± 0.6	64.2 ± 0.5	64.9 ± 0.2	62.3 ± 0.1	64.8 ± 0.3	63.8 ± 0.3
	45°C	65.4 ± 0.3	64.1 ± 0.3	64.3 ± 0.6	64.1 ± 0.8	61.7 ± 0.1	64.8 ± 0.3
	50°C	63.5 ± 0.2	62.3 ± 0.4	62.5 ± 0.3	63.8 ± 0.1	62.3 ± 0.7	62.8 ± 0.4

Average and standard error values are calculated for 9 readings.

Head rice yield (HRY) showed a significant difference only for the air temperature of 50^{o}C, as shown in Table 23. All other factors, i.e., bed condition, dehumidification status, drying duration, were not significant. Bed condition showing no significant difference HRY means that the fluidized bed drying of rice apprehensions of reducing HRY is not accurate, particularly under the drying temperature of 50°C. It can be postulated to the correct use of fluidized bed drying, i.e., the air temperature used should be well below 60°C as it was in this study. The air temperature in fluidized bed drying is critical, as evident from the HRY's statistical significance. With an increase in air temperature, the HRY decreased. Other than the drying temperature, the dryer design, drying duration, and ambient air relative humidity can be secondary factors to maintain the HRY of fluidized bed rice. However, the drying duration and ambient air relative humidity (dehumidification) did not statistically affect the HRY, as mentioned in Table 23. Replication did not show any statistical significance for HRY that means three replications of each experimental condition were similar in HRY.

3.3 Rice whiteness

Milled rice whiteness ranged between 35.7 and 39.1 for the FBD, whereas it ranged between 35.0 and 39.9 for the fixed bed drying, as presented in Table 28. With comparable HRY and rice whiteness achieved by fluidized bed drying, it can be an alternative to the fixed bed drying. Although the rice whiteness and HRY decreased slightly with an increase in drying air temperature, if the air temperature is at or below 50°C, the rice quality will not decrease significantly. Short drying duration should also be considered and should not be in the range of 12-24 hours to avoid a reduction in rice whiteness, as reported by Dillahunty et al. (2001). Luthra and Sadaka (2020b) conveyed the same for drying duration and air temperature used for drying.

Milled rice whiteness was analyzed to identify the significant factors that can vary the rice whiteness. Table 23 above shows that air temperature and drying duration levels were significantly different from each other. It should be mentioned that increasing air temperature decreased the average milled rice whiteness. Fluidized bed condition and dehumidified air did not decrease the rice whiteness than the fixed bed drying and non-dehumidified air. No significant difference in the replications for rice whiteness was observed. Taweerattanapanish et al. (1999) reported an acceptable range of rice whiteness for fluidized bed-dried rice. Chen et al. (2017) indicated a similar rice whiteness reduction with increasing air temperature to dry rice.

Pearson's correlation coefficient (p) was used to correlate HRY and rice whiteness at 95% confidence. Head rice yield (HRY) and rice whiteness negatively correlated (p = -0.37), which means the rough rice with high head rice yield showed lesser whiteness values. However, the lower correlation coefficient value is not considered a strong correlation. This trend was also observed by Luthra and Sadaka (2020b) as they reported the lowest value of whiteness for the sample that had the highest head rice yield for FBD conditions. It was flattering to report that the whiteness did not get compromised with increased head rice yield.

Table 28. Effects of dehumidification settings, air temperature, and drying duration on rice whiteness (dimensionless) in the fluidized bed and fixed bed dryers.

Dehumidification	Air temperature	Fluidized bed			Fixed bed		
		30 min	45 min	60 min	30 min	45 min	60 min
No	40°C	39.1 ± 0.7	39.0 ± 0.3	36.2 ± 0.3	38.0 ± 0.2	37.8 ± 0.1	36.9 ± 0.5
	45°C	39.2 ± 0.1	38.4 ± 0.6	37.7 ± 0.5	36.4 ± 0.3	36.1 ± 0.3	38.7 ± 0.2
	50°C	37.4 ± 0.4	37.8 ± 0.7	37.3 ± 0.3	37.7 ± 0.3	36.5 ± 0.4	37.5 ± 0.4
Yes	40°C	38.5 ± 0.9	38.0 ± 0.4	37.9 ± 0.2	39.9 ± 0.7	37.4 ± 0.3	37.5 ± 0.6
	45°C	35.7 ± 0.3	38.3 ± 0.4	36.6 ± 0.1	38.5 ± 0.2	39.0 ± 0.2	36.8 ± 0.5
	50°C	37.3 ± 0.2	36.1 ± 0.6	37.6 ± 0.1	36.9 ± 0.4	35.0 ± 0.3	37.3 ± 0.6

Average and standard error values are calculated for 9 readings.

3.4 Rice pasting properties

When rice starch molecules are in the vicinity of water molecules, they absorb and swell up, which increases the viscosity. Maximum viscosity, i.e., peak viscosity (PV), is attained when all the starch granules are swollen but remain intact. Thus, PV is the indicator of the product's water-binding capacity (Dang and Copeland, 2004). Peak, trough, and final viscosities were recorded in centipoises (cP), a peak time in minutes (min), and pasting temperature in degree Celsius (°C). The mean data presented below are based on 20 experiments using custom design procedures that reduced the number of runs from 108 to 20. Table 29 shows that PV was lower for all fluidized bed experiments (2712.8 cP) than the fixed bed drying experiments (2815.8 cP). However, a significant difference was not found; this could be related to the similar head rice yield of rough rice due to fixed and fluidized bed drying as mentioned above. Thus, having similar-sized rice kernels and a similar number of broken kernels are known to have similar peak viscosities, as pointed out by past studies (Mukhopadhyay and Siebenmorgen, 2017). PV with ambient air dehumidification was lower than the experiments without ambient air dehumidification (Table 29). No trend is observed for the PV due to changing drying air temperature and drying duration. Bruce et al. (2020) stated that the PV increased significantly with increasing drying temperature that contradicts this research's finding. The contradiction could be attributed to the broad temperature range (25°C to 60°C) tested by Bruce et al. (2020) as compared to the narrow temperature range (40°C to 50°C) tested in this study. No significant decrease in the PV was observed for the dried rough rice samples using fluidization, ambient air dehumidification, and the highest temperature tested. Thus, the FBD technology and the ambient air dehumidification-maintained rice's pasting quality as dried in conventional fixed-bed drying.

Moving the paddle inside the canister of RVA creates shear stress on those granules that lead to the disruption of granules. The viscosity decreases, and the thinning of paste is noticed. The minimum viscosity after the PV and before the final viscosity is referred to as the trough viscosity (TV) (Bruce et al., 2020). TV is the ability of the paste to resist breakdown (Ayo-Omogie & Ogunsakin, 2013). TV for the FBD was lower than the fixed bed, as shown in Table 29. However, the difference is not statistically significant. TV for air dehumidification, air temperature, and drying duration was not statistically significant, and the TV values for all the levels of each were similar. Thus, the TV, which indicates the sample's resistance to breakdown, does not change with the change in bed condition, air temperature, drying duration, and with or without ambient air dehumidification.

With the cooling of the paste, the granules start reassociation, and a gel is formed. The viscosity at this moment is referred to as the final viscosity (FV) (Lanning et al., 2012). The FV indicates the gel's strength formed after granules reassociation dependent on factors like protein content, amylose/amylopectin ratio, and the cooling rate (Hamaker and Griffin, 1993). The current study found that rice's final viscosity using FBD did not vary significantly from the fixed bed drying. Using the ambient air dehumidification reduced the FV of rice overall. However, statistical significance is not found. As the air temperature increased, the FV decreased, which contradicts Bruce et al. (2020). The reason could be the more extensive range of drying temperatures used by the former. Drying duration changes did not show any effect on the FV values.

It is generally the cooking time of a product and is when the PV is attained (Adebowale et al., 2005). The peak time for all experiments ranged from 5.7 to 5.8 minutes. Overall, the fluidized bed dried samples had a slightly higher peak time (cooking time) than the fixed bed dried samples. Peak time was not different for the levels of air dehumidification, air temperature, and drying duration. However, a drying temperature of 50°C and drying 60 min showed a higher peak time than the other air temperature and drying duration levels, respectively.

Pasting temperature (PT) is the temperature at which the first noticeable increase in the flour paste viscosity is attained. It indicates the water-absorbing capacity and high gelatinization tendency (Adebowale et al., 2008). It also indicates the start of the swelling of starch granules by absorbing water (Julianti et al., 2017). The food industry should have a lower PT as it is cost and energy-efficient. Fluidized bed dried samples did not show a statistical difference in PT than the fixed bed dried samples. The air dehumidification and air temperature did not increase or decrease in PT with changes in the levels. With an increase in drying duration, the PT increased.

Pearson's correlation coefficient was used to correlate HRY and viscosities at a 95% confidence. Head rice yield was positively correlated with peak (0.15) and trough viscosity (0.21). However, the correlation coefficient was not high. It means that rice having better water holding capacity and breakdown resistance showed slightly higher head rice yield. Head rice yield did not show a strong correlation with the final viscosity (0.08), peak time (0.10), and pasting temperature (-0.09).

Additionally, rice whiteness was positively correlated with PV (0.34), TV (0.37), and FV (0.32). Having high rice whiteness along with higher cooking viscosities enhances the milled rice value overall. Suwansri and Meullenet (2004) reported a positive correlation of pasting properties with rice whiteness as evaluated by the rice consumers, thus, highlighting the importance of the positive relation between rice whiteness and rice cooking quality. PV was positively correlated with TV (0.83) and FV (0.40). These trends were also reported by Sandhu and Singh (2005) for corn and by Singh et al. (2006) for rice. Pasting temperature and peak time were negatively correlated with peak and trough viscosities that agreed with Singh et al. (2006) findings. Higher peak and trough viscosity with lower pasting temperature and the peak time is ideal for any rice.

Table 29. Effects of bed conditions, dehumidification settings, air temperature, and drying duration on rice flour peak, trough, final viscosities, peak time, and pasting temperature.

Factors	Levels	Peak Viscosity (cP)*	Trough Viscosity (cP)*	Final Viscosity (cP)*	Peak Time (min)*	Pasting Temp. (°C)*
Bed Condition	**Fluidized**	2712.8 ± 219.7 [a]	1416.1 ± 89.8 [b]	3362.7 ± 253.3 [c]	5.8 ± 0.1 [d]	85.0 ± 3.2 [e]
	Fixed	2815.8 ± 198.3 [a]	1460.1 ± 20.3 [b]	3402.7 ± 249.1 [c]	5.7 ± 0.0 [d]	83.8 ± 3.6 [e]
Air dehumidification	**Yes**	2700.7 ± 216.4 [a]	1431.6 ± 103.0 [b]	3287.1 ± 254.5 [c]	5.7 ± 0.1 [d]	84.3 ± 3.9 [e]
	No	2827.9 ± 194.0 [a]	1444.6 ± 95.0 [b]	3478.3 ± 205.0 [c]	5.8 ± 0.0 [d]	84.4 ± 3.1 [e]
Air temperature (°C)	**40**	2762.2 ± 205.7 [a]	1441.7 ± 88.4 [b]	3489.2 ± 151.4 [c]	5.7 ± 0.1 [d]	85.6 ± 3.5 [e]
	45	2868.3 ± 91.8 [a]	1484.5 ± 75.7 [b]	3395.5 ± 182.3 [c]	5.7 ± 0.1 [d]	83.4 ± 3.5 [e]
	50	2687.9 ± 260.7 [a]	1400.6 ± 110.6 [b]	3293.3 ± 323.0 [c]	5.8 ± 0.0 [d]	84.2 ± 3.5 [e]
Drying duration (min)	**30**	2783.3 ± 235.3 [a]	1459.4 ± 80.8 [b]	3321.7 ± 247.3 [c]	5.7 ± 0.1 [d]	83.0 ± 3.6 [e]
	45	2761.9 ± 253.0 [a]	1433.1 ± 108.3 [b]	3326.7 ± 277.9 [c]	5.8 ± 0.0 [d]	84.1 ± 3.1 [e]
	60	2745.0 ± 154.9 [a]	1419.0 ± 111.9 [b]	3519.2 ± 175.6 [c]	5.8 ± 0.0 [d]	86.2 ± 3.2 [e]

*Average and standard deviation values. All values in the same column not having a common letter in the superscript are statistically different.

4. Conclusions

The present study evaluated the effects of ambient air dehumidification, air temperature, and drying duration on rice quality and pasting properties using fluidized bed and fixed bed drying systems. Ambient air dehumidification helped remove more moisture than that without dehumidification and did not affect the dried rice quality. Head rice yield and milled rice whiteness did not decrease significantly in fluidized bed drying of rice than the fixed bed drying.

Air temperature at or below 50°C and drying for 60 minutes were critical parameters to achieve the fluidized bed drying of rough rice. Rice pasting properties did not decrease significantly in the fluidized bed drying condition nor for the rice dried with dehumidified air than fixed bed and without dehumidification. Thus, the fluidized bed drying of rough rice and the ambient air dehumidification can be used for drying rice mainly when the ambient conditions would not allow for conventional in-bin ambient air drying. Energy consumption to dry rough rice in a fluidized bed and fixed bed need to be studied.

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Chapter 8: Impact of air dehumidification, air temperature, and drying duration on the energy and exergy efficiencies of fluidized and fixed bed systems during rough rice drying

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Abstract

Fluidized bed drying of rough rice in the U.S. has not been utilized to its full potential due to the lack of research to address quality reduction and higher energy consumption. Not much research was done to analyze the energy and exergy of the rough rice's fluidized bed drying. Thermal analysis allows utilizing the drying air's energy better and improving the drying system's thermal efficiency. Energy utilization and energy utilization ratio were calculated using the first law of thermodynamics, whereas exergy loss and exergy efficiency were determined using the second law. Drying air temperature (40°C, 45°C, 50°C), drying bed condition (fluidized and fixed), drying duration (30 min, 45 min, 60 min), and ambient air dehumidification (yes, no) were the factors of this study. Lab-scale dryer units designed by Sadaka et al. (2018) were used. Three replicates were performed to eradicate any bias or human errors. All factors did significantly affect the energy and exergy of the drying except dehumidification and replication. The minimum and maximum EU values were 0.01 kJ/s and 0.55 kJ/s for drying at fixed bed drying at 40°C for 30 min with dehumidification and at 50°C for 60 min under fluidized bed condition without dehumidification, respectively. Minimum and maximum exergy efficiency values were 13.46% and 49.14%, achieved at 45°C air temperature for fixed bed with dehumidification for 45 min duration, and fluidized bed drying using 40°C air temperature for 60 min with dehumidification, respectively. Not much difference in energy and exergy values was observed for drying with and without ambient air dehumidification. Losing energy and exergy through exit air was the primary cause of thermal inefficiency. The other thermal inefficiency source was the exergy and energy loss through the drying chamber and inlet air steel pipes. The costly solutions could be the recirculation of exit air and better insulation of the drying chamber and inlet pipes. However, using the optimum drying conditions for utilizing energy and exergy of drying air is suggested. For the current study, it was found that fluidized bed drying was better as compared to the fixed bed drying overall. At the drying process's primary stages, fluidized bed drying had higher exergy efficiency, energy utilization, and energy utilization ratio than the fixed bed drying method. 40°C air temperature using fluidized bed drying with or without ambient air dehumidification worked best as per the energy and exergy utilization in the drying system.

Keywords

Dehumidification, Energy, Exergy, Fixed bed, Fluidized bed, Rice drying.

1. Introduction

There is a lack of information about the energy and exergy of the fluidized bed drying of rice. Understanding the usefulness of the ambient air dehumidification system as studied by Luthra and Sadaka (2020b) can be better comprehended using the energy and exergy analyses. Rice drying in the U.S. is an ongoing research area to improve the drying systems for both on and off-farm rice drying. In the U.S. majority of rice is dried off-farm using cross-flow dryers. However, on-farm drying is gaining popularity amongst rice farmers due to the off-season profits. The conventional method to dry rice on-farm is ambient air-in-bin drying. This method's significant drawbacks are the slow drying rate and weather dependence, reducing rice quality and shelf life. Many drying technologies, including microwave, layer drying, and fluidized bed drying systems, have been studied in the past as alternatives to the conventional on-farm rice drying system. Fluidized bed drying in the U.S. is still not utilized at its full potential to dry rice. However, the technology has many advantages: the high drying rate and ease in handling the material to be dried (Luthra and Sadaka, 2020a).

The rice drying process's primary purpose is to reduce the moisture content to a safe storage level with minimum energy consumption. The drying process needs to be efficient as it is known to be one of the most energy-intensive processes in the industry. Having an energy-efficient drying process not only saves money but also reduces carbon emissions. Energy and exergy analyses are often utilized to understand the drying process effectiveness using a specific dryer or drying technology. Energy analysis follows the first law of thermodynamics with some limitations, like not considering its environment and energy quality degradation through dissipative processes. Also, energy analysis does not account for the irreversibility of the system's processes.

On the other hand, exergy analysis accounts for a system's total beneficial work potential (Regulagadda et al., 2010). Exergy is defined as maximum work potential that a system can attain by the matter flow, heat, or energy when at equilibrium with the environment as reference (Rossen and Scott, 2003). Exergy analysis of a drying system plays a vital role in process optimization and dryer performance improvement (Rabha et al., 2017). Exergy is also known to be the system's capacity to do practical work, whereas energy is the capacity to do work that includes energy wasted in the environment. Thus, exergy efficiency is always lower than the system's energy efficiency but follows a similar energy efficiency trend (Luthra and Sadaka, 2020a).

Not many studies to our knowledge have reported the energy and exergy of rough rice drying in a batch fluidized bed dryer. Moreover, no study reported the energy and exergy of fluidized bed drying of rough rice with ambient air dehumidification. However, some recent studies briefly mentioned energy and exergy analysis for drying agricultural commodities using a fluidized bed. Yogendrasasidhar and Setty (2018) used a heated wall batch fluidized bed dryer for Kodo millet grains and fenugreek seeds. The energy and exergy analyses were performed by changing the wall temperature, air velocity, bed height, and bed material's initial moisture content. They reported energy utilization ratio, exergy loss, and exergy efficiency of Kodo millet and Fenugreek seeds. Exergy efficiencies for Kodo millet and fenugreek seeds ranged from 40 to 72% and 40 to 75%, respectively. For both Kodo millet and fenugreek seeds, the exergy efficiencies increased with increasing wall temperature, air velocity, and drying time and decreased with increasing bed height and initial moisture content. The energy utilization ratio increased with increasing wall temperature and air velocity, and it ranged from 0.6 to 0.9 for Kodo millet and fenugreek seeds.

Ozahi and Demir (2013) developed a model to analyze the batch fluidized bed dryer's energy and exergy efficiency for corn drying and other particles using an air temperature of 50ºC. They compared the results with some past literature and found good conformity that was satisfied with an acceptable error margin of 9%. They concluded that it is important to study the system's energy and exergy to estimate optimal drying conditions in a fluidized bed. Energy and exergy analysis was used in the study by Azadbakht et al. (2017) that utilized artificial neural network modeling in fluidized bed drying of potato cubes. Inlet air temperatures of 45, 50, and 55ºC, air velocity of 0.05, 0.11, and 0.15 $m.min^{-1}$, and bed depth of 1.5, 2.2, and 3.0 cm were studied. Energy utilization, energy efficiency, utilization ratio, exergy loss, and efficiency for changes in the factors' levels were evaluated. The results showed that energy utilization, efficiency, and utilization ratio increased with increased bed depth and air velocity. Exergy loss and efficiency increased with an increase in bed depth, air velocity, and temperature.

Yahya et al. (2017) used a solar-assisted fluidized bed dryer combined with a biomass furnace to study the drying kinetics of rough rice. The air temperature used was 61°C and 78°C.

Rough rice having an initial moisture content of 20% w.b. was dried to 14% w.b. The exergy efficiency of 47.6% and 49.5% were reported for drying temperatures between 61°C and 78°C, respectively. They found lower specific energy consumption (SEC) and drying duration in the hybrid solar-biomass fluidized bed drying system compared with solar dryers. Similarly, Sarker et al. (2015) have determined the industrial fluidized bed dryer's energy and exergy performance for drying rice. The results showed that the energy utilization ratios (EUR) and exergy efficiency vary between 5.24 to 13.92 % and 46.99 to 58.14%, respectively. Exergy balance showed that 31.18 to 37.01% exergy was utilized to dry rough rice, and the remaining amount of exergy was wasted. They suggested using insulation on the dryer body and recycling the exhaust air for better exergy efficiency. Handayani et al. (2020) studied the energy and exergy analysis of celery leaves drying with the fluidized bed. They found that the increase in drying temperature increased energy utilization and energy utilization ratio and decreased the exergy efficiency. The reported energy utilization ratio was 0.0768, 0.1199, and 0.1682 for 50, 60, and 70°C, respectively. Average exergy efficiencies were 0.19, 0,16 and 0.17 for 50, 60, and 70°C, respectively. A single study that used fluidized bed drying for rough rice reported the energy and exergy analysis (Pattanayak et al., 2019). They used the drying temperature of 40 and 50°C and air velocity of 2 and 3 m/s. They found that energy utilization and energy utilization ratio decreased while exergy efficiency increased with drying time. Exergy efficiency ranged from 12.37% to 86.25%, whereas energy utilization and energy utilization ratio ranged from 55 J/s to 549 J/s and 0.087 to 0.656, respectively.

In this study, an extensive investigation to understand the rough rice fluidized bed drying was done. The study utilized energy and exergy analysis to understand the laboratory scale fluidized bed dryer's performance developed by Sadaka et al. (2018) and initially tested with rice by Luthra and Sadaka (2020b). This study used the dryer to dry rough rice, and fluidization is compared with fixed bed drying with an experimental design to study the effects of air temperature, drying duration, and ambient air dehumidification. Thus, the specific objectives were: (1) to identify the effects of bed condition, air temperature, drying duration, and ambient air dehumidification on energy utilization, energy utilization ratio, and specific energy consumption, and (2) to identify the effects of bed condition, air temperature, drying duration, and ambient air dehumidification on exergy loss and exergy efficiency during rough rice drying.

2. Materials and Methods

All the experiments in this study were performed in a laboratory in the Rice Research and Extension Center (RREC), Stuttgart, AR. The laboratory had a controlled temperature (23.5 ± 0.5°C) as obtained by the room thermostat.

2.1 Rice Samples

Rough rice samples (cv. Diamond) were obtained from a farm in Northeast Arkansas. Rough rice was first cleaned using a dockage tester (Model XT4, Carter-Day, Minneapolis, MN), and kernel physical characteristics were measured (Table 30). The rice samples were then sealed and stored in plastic bags in a cooler at 4°C until used for experiments. The rice samples required for the experiment were taken out of the cooler and left in a plastic bag at room temperature for 24 hours to restrict any dew formation on the rice surface. The rice's initial moisture content was 24.3% dry basis, measured by the standard oven method at 130°C (ASABE, 2008). 1000 rice kernel weight was determined using an automatic seed counter (Model SLY-C, Hinotek, China) and a scale (Ohaus SP-2001 Scout Pro Balance, Parsipanny, NJ). Bulk density and physical dimensions were determined using the standard method ASTM E873-82 and digital caliper (General Ultratech, Series – 147, Secaucus, NJ). Geometric mean diameter was measured using the cube root of the product of length, width, and thickness of the rice kernel (Bande et al., 2012; Sadaka et al., 2018).

Table 30. Rough rice sample characteristics (Luthra and Sadaka, 2020b, 2020c).

Parameter	Units	Rough Rice
1000 Kernel weight*	g	26.1±0.16
Bulk density*	kg/m^3	620.8±2.28
Initial Moisture content*	%, d. b.	24.3±1.1
Dimensions**		
Length	mm	8.75±0.53
Width	mm	2.40±0.14
Thickness	mm	1.14±0.14
Geometric Mean Diameter	mm	3.43±0.15

* Average of three readings, ± the standard deviations
** Average of fifty readings, ± the standard deviations

2.2 Dryer unit

The fluidized bed dryer unit used in this study was developed by Sadaka et al. (2018) and was later modified to accommodate ambient air dehumidification by Luthra and Sadaka (2020b). The dryer has five components: an air dehumidification unit, air supply unit, air heating unit, drying column and measuring systems (Figure 27). The air dehumidification unit included a laboratory-scale humidifier (AIRCARE MA1201, coverage up to 334 square meters, USA) that provided air with a mean relative humidity of 75% ± 5%. The reason to use the humidifier was to simulate the relative humidity of the ambient air in humid conditions in the Southern U.S. A duct pipe transferred the high humidity air to the 10.4 cm internal diameter metal desiccant pipe. The desiccant pipe on the top and the bottom end was connected to the duct pipe to receive the humid air and the blower, respectively. Forty-eight 50-gram silica gel packets (desiccant) tied to a rope were lowered from the top end of the desiccant pipe for ambient air dehumidification. Silica gel is a commonly used desiccant with a high absorbency rate (Ondier et al., 2011), easily regenerated (Koh, 1977), and is readily available in the market (Ondier et al., 2011). After passing through the desiccant pipe, the humid air loses some moisture, and air with 50-60% relative humidity was transferred to the blower's inlet.

A 3-kW regenerative blower (SCL k05-MS MOR, FBZ, Italy) attached with a variable frequency drive (ACS350, ABB Ltd, Switzerland) to control the airflow is part of the dryer’s air supply system. To measure the airflow, an airflow meter was used (Range: 0.0 - 1.70 m^3/min, 7510 series, KING Instrument Company, Garden Grove, CA). The air heating system consisted of a cylindrical tube furnace (Barnstead/Thermolyne Corporation type 21100 tube furnace, Dubuque, IA) that heats the 2.5 cm diameter steel pipe carrying the air. The air temperature was controlled using the thermostat on the furnace. The drying column consisted of transparent plexiglass with dimensions of 15 cm in diameter and 150 cm high. The drying column's bottom end had a distributor plate to make the airflow uniform at the drying column's inlet. Above the drying column's bottom end, a hole was drilled to attach a ball valve for easy transferring of the dried product. The top end of the drying column was left open for effortless loading of the drying product and the outlet for moisture-laden exit air. The dryer’s measuring system had sensors to measure air temperature and rice bed temperature, inlet, and exit air velocity, inlet, and exit air relative humidity, rice moisture content, and pressure drop in the bed. Thirteen J-type thermocouples were used to record bed temperature vertically as well as horizontally uniformly. Thermocouples were connected to the datalogger (OMEGA TC-08, Norwalk, CT) connected to the computer. Probe type sensor (Grain Deacon, Deacon Technologies, LLC, Prairie Grove, AR), used by Luthra et al. (2019), was installed from the open end of the drying column to record bed temperature during the drying process. Inlet and exit air relative humidity were recorded by dew-point air relative humidity meter (HI 9565, 5% to 95% Range, Hanna Instruments Ltd, Bedfordshire, England, UK). Air velocity meter (Anemometer, 80 to 5906 fpm, EXTECH, Nashua, NH) recorded the exit air velocity, and three digital manometers (Series 475, Dwyer Instruments INC, Michigan City, IN) recorded the bed pressure drop. A benchtop moisture meter (AM 5200 Grain Moisture Tester, PERTEN Instrument, Hägersten, Sweden) was used for the initial and final moisture measurement of rough rice samples.

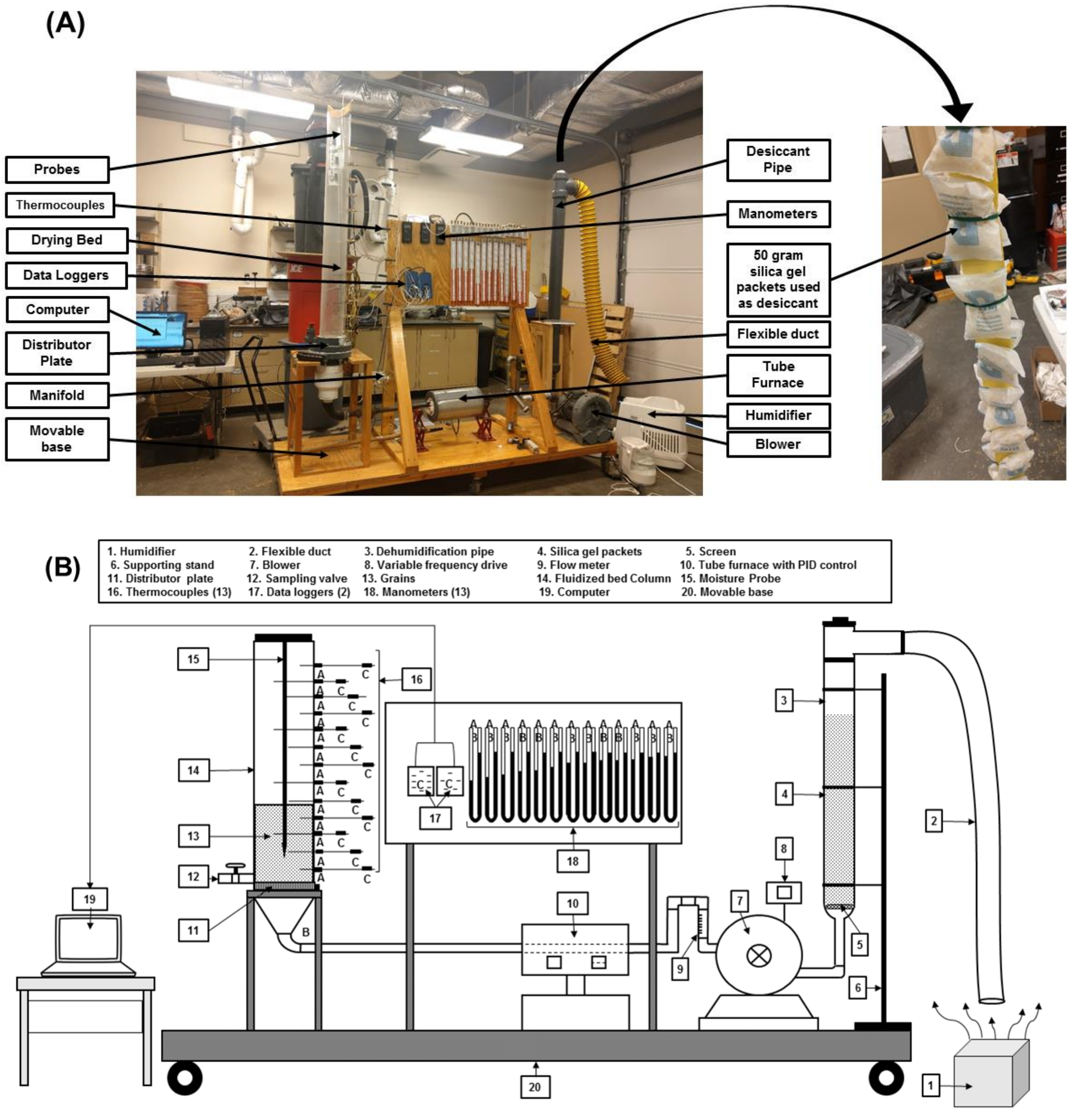

Figure 27. Drying system used in this study (A) Pictorial representation B) Schematic diagram (Luthra and Sadaka, 2020b).

2.3 Experimental Design

The experiments were designed to determine the effects of bed conditions, ambient air dehumidification, drying duration, and air temperature on the quality of rough rice and energy and exergy consumption during drying. Fixed bed drying was used as a control to compare the results of the fluidized bed. Similarly, experiments without ambient air dehumidification were used as a control for comparing results with dehumidification of ambient air. Drying air temperature ranged from 40°C to 60°C and was selected based on the results obtained by Luthra and Sadaka (2020b) that recommended drying air temperature below 60°C for rice drying. A full factorial design was used to reduce any manual or systematic bias and three replicates were used to provide more certainty to the results. In total, there were 108 experiments (Table 31). Complete randomization was done for the experiments and data were analyzed using JMP Pro 15 (SAS Institute Inc., Cary, NC). Analysis of variance was conducted to determine the statistical significance of bed condition, temperature, duration, and dehumidification, as well as the interactive effects of these. Tukey's test was used to differentiate any significant levels of the factors and their interaction.

Table 31. Experimental design.

Factors	Levels	Total number of experiments
Bed condition	Fluidized, Fixed	
Dehumidification	Yes, No	
Drying duration	30 min, 45 min, 60 min	$2 \times 2 \times 3 \times 3 \times 3 = 108$
Air temperature	40°C, 45°C, 60°C	
Replication	1, 2, 3	

2.4 Experimental Procedures

For each experiment, 4.5 kg of rough rice was brought to room temperature by keeping the refrigerated rice in the laboratory 24 hours before the experiment. The blower was turned on, and the airflow was adjusted to attain the fluidized bed (1.75±0.1 m/s) or fixed bed conditions (0.95±0.1 m/s) using the variable frequency drive attached to the blower. The furnace was powered on, and in a few minutes, the desired air temperature was attained. Fresh silica gel packets tied to the rope were installed in the desiccant pipe if the experiment required ambient air dehumidification. Silica gel packets can be regenerated but the current study avoided regeneration as to maintain the same initial condition of silica gel for each experiment. The initial weight of the silica gel packets was noted. Rough rice at room temperature was now loaded from the open end of the drying column. As soon as the rice was loaded, the experiment was initiated. A moisture content probe was installed from the open end, and the data were recorded every 10 minutes. Thermocouples recorded bed temperature every 30 seconds. Inlet and exit air temperature and relative humidity, and pressure drop readings were manually noted every 10 minutes. After the experiment ends, three 200-gram samples were collected for rice quality analysis; they were stored in a labeled plastic bag in a refrigerator. The data was saved on a computer, and the blower and furnace were shut down. The drying column was emptied and cleaned for the next experiment. If used, silica gel was pulled out, and the final weight was determined to assess the moisture adsorbed by the silica gel. The weight gain ranged from 5.5-12%, with an increasing trend for increasing experimental duration.

2.5 Dryer energy and exergy analysis

In any dryer, the energy and exergy analyses are applied to the drying chamber. Figure 28 below shows the drying chamber schematic diagram with the inlet and exit air thermodynamic properties and the nomenclature used in this section's equations. The energy and exergy analyses were done using mathematical models and equations developed by past researchers (Syahrul et al., 2002; Chowdhury et al., 2011; Karaguzel et al., 2012). For energy analysis, energy utilization

(EU) was calculated as per the first law of thermodynamics as mentioned in equation 1 (Boles and Cengel, 2014).

$$EU = m_{ia}\,(h_{ia} - h_{ea}) \qquad 1$$

where,

m_{ia} is the mass flow rate of inlet air (kg/s),

h_{ia} is the inlet air enthalpy (kJ/kg), and

h_{ea} is the exit air enthalpy (kJ/kg).

The inlet air's mass flow rate was calculated using equation 2 (Boles and Cengel, 2014).

$$m_{ia} = \rho * V * A \qquad 2$$

where,

ρ is air density (kg/m^3),

V is the air velocity of inlet air (m/s), and

A is the cross-section area of the drying chamber.

Enthalpy of inlet air was calculated using equation three below (Corzo et al., 2008).

$$h_{ia} = C_{pia} * T_{ia} + w_{ia} * h_{sat} \qquad 3$$

where,

h_{sat} is the enthalpy of saturated air (kJ/kg),

C_{pia} is the specific heat capacity of inlet air (kJ/kg*°C),

T_{ia} is the inlet air temperature (°C), and

w_{ia} is the absolute humidity of inlet air (no units).

The inlet drying air's specific heat was calculated as given below in equation 4 (Corzo et al., 2008).

$$C_{pia} = 1.004 + 1.88 * w_{ia} \qquad 4$$

The absolute humidity of the inlet air was determined using equation 5.

$$w_{ia} = 0.622 * \frac{(\mathrm{RH} * P_{sat})}{(P - P_{sat})} \qquad 5$$

where,

RH is the relative humidity of inlet air (%),

P_{sat} is the saturated vapor pressure (kPa), and

P is the atmospheric pressure (kPa).

The absolute humidity of the exit air (w_{ea}) was determined using equation 6 (Akpinar, 2004).

$$w_{ea} = w_{ia} + (\frac{m_{ea}}{m_{ia}}) \qquad 6$$

where,

m_{ea} is the mass flow rate of exit air (kg/s).

The mass transfer rate of evaporated moisture by exit air (m_{ea}) was calculated using equation 7 (Nazghelichi et al., 2010).

$$m_{ea} = \frac{(W_i - W_f)}{t} \quad 7$$

where,

W_i is the initial weight of the rice sample (kg),

W_f is the final weight of the rice sample (kg), and

t is time (s).

The energy utilization ratio (EUR) of the drying process was determined using equation 8 (Mildilli and Kucuk, 2003; Corzo et al., 2008).

$$EUR = \frac{m_{ia}(h_{ia} - h_{ea})}{m_{ia}(h_{ia} - h_{amb})} \quad 8$$

where,

h_{amb} is the enthalpy of ambient air (kJ/kg).

To understand the effectiveness of a drying system, understanding how much energy is consumed for removing per unit moisture from rice during drying is critical. The specific energy consumption (SEC) is the parameter that numerically conveys the supplied energy usage per unit of water removed from rice (Yahya et al., 2017). It is also well-defined as the ratio of the input energy to the drying system to the moisture removed from the wet agricultural commodity and is calculated as given in equation 9 (Fudholi et al., 2014; Yahya et al., 2017).

$$SEC = \frac{E_{input}}{M_w} \quad 9$$

where,

E_{input} is the total energy input to the dryer system for complete drying duration (kJ), and

M_w is the mass of water removed (kg).

The mass of water removed from the wet product is calculated as mentioned in equation 10.

$$Mw = m_p * \left(\frac{M_i - M_f}{100}\right) \quad 10$$

where,

m_p is the mass of dry matter in the product (kg),

M_i is the initial moisture content on a dry basis (%), and

M_f is the final moisture content on a dry basis (%).

The total energy input of the drying system used in this study included the energy used by a 3-kW blower and a 1-kW heater. For exergy analysis, the second law of thermodynamics was used, and input air exergy, exit air exergy, and exergy losses were determined. The past studies laid out a procedure for exergy analysis of drying chamber, the exergy values at steady-state points, and the rationale of exergy variation for the process was determined (Midilli and Kucuk, 2003; Akpinar et al., 2006; Corzo et al., 2008). The general equation (equation 11) for the steady-flow systems was used in this study (Midilli and Kucuk, 2003; Corzo et al., 2008), and the equation was derived by using the characteristics of working medium from first-law energy balance (Szargut et al., 1988). The inlet air or exit air exergy can be calculated by plugging in the inlet or exit air characteristics in equation 11 below.

$$Exergy = m * C_p \left[(T - T_{amb}) - T_{amb} * \ln\frac{T}{T_{amb}}\right] \quad 11$$

where,

m is the mass flow rate of inlet or exit air (kg/s),

C_p is the specific heat capacity of inlet or exit air (kJ/kg*°C),

T is the inlet or exit air temperature (°C), and

T_{amb} is the ambient air temperature.

Once the exergy inflow and exergy outflow are determined by equation 11, the exergy loss can be calculated by equation 12 (Midilli and Kucuk, 2003; Akpinar et al., 2006; Corzo et al., 2008).

$$Exergy\ loss = Exergy\ inflow - Exergy\ outflow \tag{12}$$

The exergy efficiency is well-defined as the ratio of net exergy used to dry the product by the inlet air exergy and can be determined using equation 13 (Midilli and Kucuk, 2003; Akpinar et al., 2006; Corzo et al., 2008).

$$Exergy\ efficiency = \frac{Exergy\ inflow - Exergy\ loss}{Exergy\ inflow} = 1 - \frac{Exergy\ loss}{Exergy\ inflow} \tag{13}$$

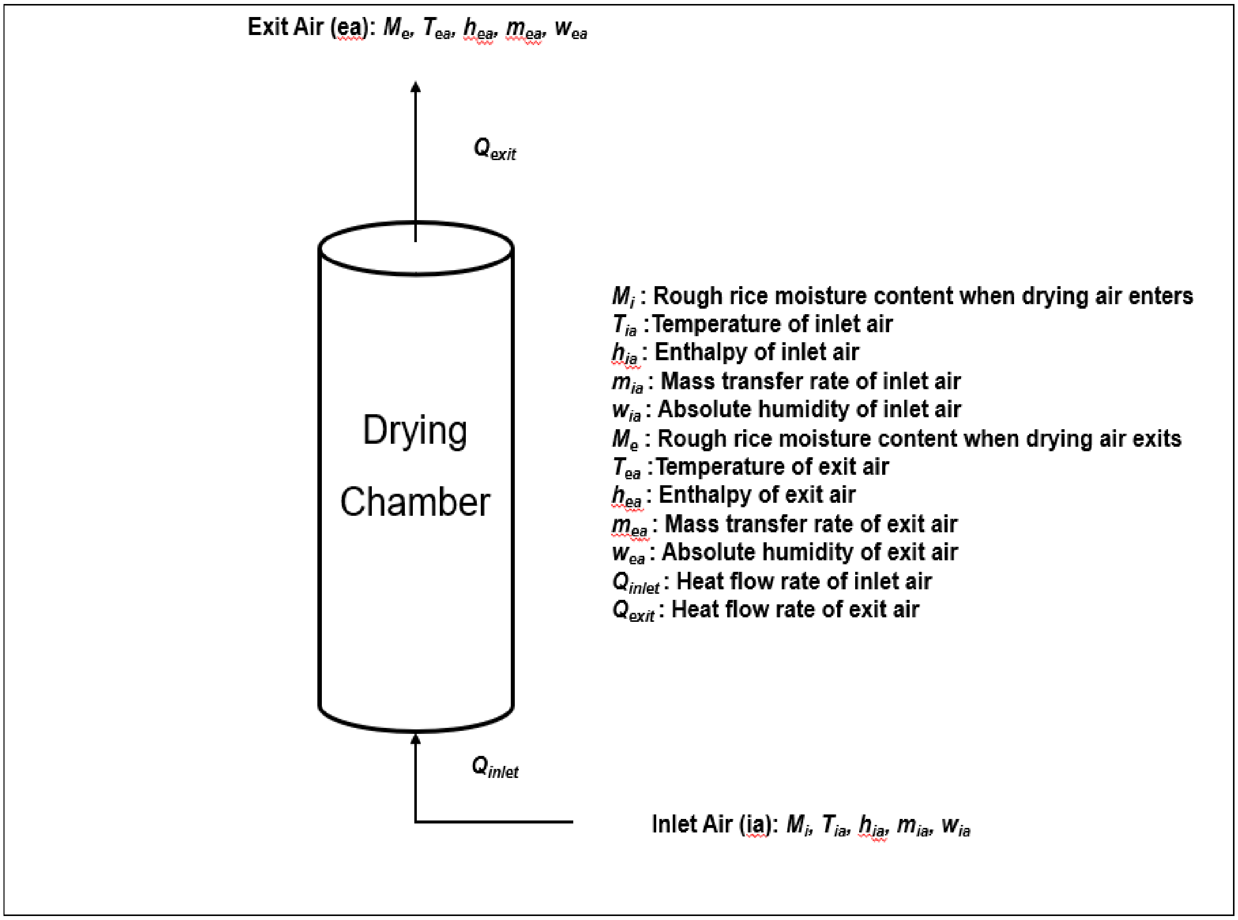

Figure 28. Schematic for drying chamber showing inlet and outlet air nomenclature.

3. Results and Discussion

3.1 Effects of bed conditions, dehumidification, air temperature and drying duration on energy utilization (EU), energy utilization ratio (EUR), and specific energy consumption (SEC)

The thermodynamics first law is employed to estimate the amounts of energy utilized and the ratio of energy utilization during the drying process. The maximum and minimum EU values were 0.55 and 0.01 kJ/s for drying at 50°C for 60 min under fluidized bed condition without dehumidification and fixed-bed drying at 40°C for 30 min with dehumidification, respectively (Figure 29). Table 32 below shows the test of significance to check the effects of bed condition, dehumidification, drying duration, air temperature, and replication on EU, EUR, and SEC. All the factors had a statistically significant effect on energy utilization and energy utilization ratio except dehumidification and replication (Table 32). With the increase in air temperature, the EU value increased significantly, as shown in figure 29 and table 32. Past studies have also reported the same trend for energy utilization for different dryers and products (Akpinar, 2004; Aghbashlo et al., 2008; Corzo et al., 2008). It can be postulated that at higher temperatures, the heat and mass transfer are more, and thus, rice absorbs more heat and releases more moisture. Overall, the fluidized bed's EU and EUR values were significantly higher than the fixed bed (Table 32). It can be due to the higher airflow in fluidized bed experiments increasing heat and mass transfer. Overall, as the drying duration increased, the EU and EUR value decreased (Table 32). Past studies also reported this trend (Aghbashlo et al., 2008; Nazghelichi et al., 2010), and the reason could be the lower moisture availability after initial drying that reduces the heat and mass transfer in rice kernels. No significant difference in three replications was found for EU and EUR values (Table 32), signifying that not much bias and errors were involved while carrying out the experiments. There was no statistical difference found for EU and EUR in dehumidified and non-dehumidified inlet air (Table 32).

Table 33 reports the SEC values for the dryer system to remove a water unit from rough rice. Table 32 showed that different bed conditions, dehumidification environment, drying duration, and air temperature significantly changed the dryer's SEC. There was no difference in the replications, as mentioned in Table 32. It is essential to mention that SEC included the energy used by the heater and blower only. Moreover, there was no heating used for fluidized bed conditions at 40°C as the temperature rose naturally due to the heat generated by the friction between the drying air and the steel pipes and fittings. The minimum and maximum SEC values of 29.0 and 142.6 MJ/kg-$_{\text{water removed}}$ were achieved at 40°C with dehumidification under the fluidized bed for 30 min of drying and fixed bed for 60 min of drying respectively (Table 33). Yahya et al. (2017) reported the average energy consumption of 17.1 MJ/kg and 14.4 MJ/kg for drying rice from 25% to 16.3% (dry basis) at 61°C and 78°C air temperature, respectively. They used solar-assisted fluidized bed drying integrated with biomass furnace, which led to lower energy consumption values than the fully electric dryer in this study. Also, the amount of rice used by Yahya et al. (2017) was almost three times (12 kg) than used in this study (4.5 kg); the more the amount of rice, the more moisture is removed per unit of energy supplied. The initial moisture content was also higher comparatively, leading to the ease of moisture removal compared to the present study. Lastly, the drying after 30 min used in the present study did not reduce much moisture as the moisture content dropped close to the safe storage level.

With the increase in drying duration, overall, the SEC values significantly increased (Table 32). This aligns with the past studies' results (Luthra and Sadaka, 2020b; Pattanayak et al., 2019; Yahya et al., 2017). With increasing duration, the available water on the rice surface gets exhausted, and thus, it takes more energy to extract the bound water. Fluidized bed conditions were significantly better than fixed bed drying in terms of energy consumption (Table 32). This can be postulated that better mixing in fluidized bed drying increased the mixing of hot air with wet rice, thus removing more moisture in the same amount of energy than the fixed bed. Ambient air dehumidification also reduced energy consumption significantly (Table 32). Dehumidification led to removing moisture from drying air, thus enhancing its capacity to remove more moisture from rice using similar energy levels compared to air without dehumidification. Increasing air temperature reduced the SEC, as shown in Table 32; this trend was also reported by past studies (Luthra and Sadaka, 2020b; Pattanayak et al., 2019; Yahya et al., 2017).

Overall, the major takeaway can be that to have better energy utilization and less energy consumption for rice drying, fluidized bed at a higher temperature, lower drying duration, and with or without ambient air dehumidification worked best. Some energy was not utilized to remove moisture, as evident from low EUR (figure 30) in fixed bed drying and fluidized bed drying for 45 and 60 min drying duration. Recycling the exhaust air that contains a significant amount of unutilized energy can be a good option for increasing EUR for rice drying in fluidized and fixed bed conditions.

Table 32. Analysis of variance for checking the statistical significance of factors with energy utilization (EU), energy utilization ratio (EUR), and specific energy consumption (SEC) as the response variable.

Factors	Levels	P-value*	Energy utilization (kJ/s)#	P-value*	Energy utilization ratio#	P-value*	Specific energy consumption (MJ/kg)#
Bed condition	Fixed	<0.0001	0.14 ± 0.01a	<0.0001	0.29 ± 0.02a	<0.0001	81.3 ± 0.97a
	Fluidized		0.32 ± 0.01b		0.38 ± 0.01b		49.1 ± 0.98b
Dehumidification	Yes	0.2123	0.23 ± 0.01c	0.1791	0.33 ± 0.02c	<0.0001	58.2 ± 0.97c
	No		0.24 ± 0.01c		0.35 ± 0.01c		72.7 ± 0.98d
Air temperature	40°C	<0.0001	0.17 ± 0.01e	0.0023	0.32 ± 0.02a	<0.0001	74.5 ± 1.19d
	45°C		0.22 ± 0.01c		0.31 ± 0.02a		65.1 ± 1.21e
	50°C		0.31 ± 0.01b		0.38 ± 0.02b		56.4 ± 1.19c
Drying duration	30 min	0.0084	0.27 ± 0.01d	0.0003	0.41 ± 0.02d	<0.0001	49.4 ± 1.19b
	45 min		0.19 ± 0.01e		0.29 ± 0.02a		66.9 ± 1.19e
	60 min		0.24 ± 0.01c		0.31 ± 0.02a		80.2 ± 1.21a
Replication	1	0.8078	0.23 ± 0.01 c	0.8895	0.34 ± 0.02c	0.1000	65.9 ± 1.22e
	2		0.24 ± 0.01 c		0.35 ± 0.02c		67.1 ± 1.19e
	3		0.23 ± 0.01 c		0.33 ± 0.02c		63.1 ± 1.19e

* p-values less than 0.05 show the factors' statistical significance at a 95% level of significance.
# Average and standard deviation values. All values in the same column not connected with the same letters are statistically different.

Table 33. Effects of dehumidification settings, air temperature, and drying duration on specific energy consumption (MJ/kg water removed) in the fluidized bed and fixed bed dryers.

Dehumidification	Air temperature	Fluidized bed			Fixed bed		
		30 min	45 min	60 min	30 min	45 min	60 min
No	40°C	33.5 ± 0.6	47.9 ± 0.9	58.1 ± 3.5	71.6 ± 2.0	122.0 ± 4.1	136.2 ± 4.3
	45°C	42.5 ± 0.3	62.9 ± 2.3	71.8 ± 0.4	66.4 ± 1.4	91.0 ± 5.3	100.0 ± 1.0
	50°C	40.2 ± 2.5	56.8 ± 0.4	68.2 ± 0.3	52.4 ± 0.7	68.4 ± 3.8	81.6 ± 0.8
Yes	40°C	29.0 ± 1.6	41.7 ± 1.7	50.0 ± 2.8	60.6 ± 0.8	86.2 ± 1.1	142.6 ± 2.5
	45°C	36.7 ± 0.8	53.0 ± 1.0	62.2 ± 2.0	49.0 ± 1.5	69.7 ± 0.8	78.8 ± 2.7
	50°C	35.4 ± 1.2	45.8 ± 0.2	56.2 ± 0.7	47.7 ± 1.5	57.6 ± 1.1	66.8 ± 0.6

Average and standard error values are calculated for 9 readings.

3.2 Effects of bed conditions, dehumidification, air temperature and drying duration on exergy loss (EL) and exergy efficiency (EE)

The minimum and maximum exergy loss values were 0.070 kJ/s and 0.236 kJ/s for fixed bed at 40°C, 60 min of drying with dehumidification, and fluidized bed at 50°C for 30 min drying duration with dehumidification, respectively. For exergy efficiency, the minimum and maximum values were 13.46% to 49.14%, achieved at 45°C air temperature, fixed bed, 45 min drying with dehumidification, and fluidized bed drying using 40°C air temperature for 60 min with dehumidification, respectively. Table 34 below shows the test of significance to check the effects of bed condition, dehumidification, drying duration, air temperature, and replication on exergy loss and exergy efficiency. All factors except dehumidification and replication did show a significant effect on exergy loss and exergy efficiency overall. Figures 31 and 32 show that with an increase in air temperature, the exergy loss increased, whereas exergy efficiency did not change much. Increasing the air temperature, increased air enthalpy, and inlet air exergy, with similar residence time at each temperature, many exergies were lost in the exit air. Past studies have reported the same trend for exergy loss with increased air temperature (Aghbashlo et al., 2008; Sarker et al., 2015).

Exergy efficiencies did not reduce much with increasing air temperature as a significant amount of exergy was lost through the exit air due to their non-utilization by the rice, but inlet air exergy also increased with an increase in air temperature. So, from equation 13, exergy efficiency did not change much with an increase in air temperature. Past studies reported that exergy efficiency increased with an increase in air temperature that contradicts the study's findings (Aghbashlo et al., 2008; Nazghelichi et al., 2010). The contradiction could be the higher air temperatures used in past studies that increased inlet air exergy more than that in the current study and thus reported an increase in exergy efficiency with increasing air temperature. Fluidized bed drying of rice had higher exergy loss and exergy efficiency than fixed bed drying. This behavior can be due to better mixing of air and rice that leads to better heat and mass transfer. An increase in drying duration did not show much quantitative difference between exergy loss and exergy efficiency. However, the values did suggest a loss in efficiency and increase in exergy loss with an increase in drying duration. Like energy utilization and energy utilization ratio, exergy loss and exergy efficiency showed that drying rice for more drying duration increased more exergy loss and less energy utilization. Not a significant difference in the three replications was found (Table 34), which means the experiments did not include much bias or errors to create a difference within replications.

Figures 31 and 32 showed that the dryer lost a large amount of exergy through the outlet or exit air and was the primary source of thermal inefficiency in the system. The other source could be the exergy and energy lost through the drying chamber and inlet air steel pipes. With recirculation of exit air and better insulation of drying chamber and inlet pies, the system's thermal inefficiencies could be reduced. However, this adds up to the dryer's initial cost; thus, using optimum drying conditions is the most critical step for utilizing energy and exergy of drying air. For the current study, it was found that fluidized bed drying was better as compared to the fixed bed drying overall. Apart from operating the fluidized bed at optimum conditions as suggested in this study and recirculation of air with better insulation to the parts where the air travels, the other suggestion could be to utilize other drying techniques with a fluidized bed, especially after the initial phase to improve the thermal efficiency in the rice drying process.

Table 34. Analysis of variance for checking the statistical significance of factors with exergy loss (EL) and exergy efficiency (EE) as the response variable.

Factors	Levels	P-value*	Exergy loss (kJ/s)#	P-value*	Exergy efficiency (%)#
Bed condition	Fixed	<0.0001	0.11 ± 0.001a	<0.0001	17.1 ± 0.4a
	Fluidized		0.16 ± 0.001b		37.7 ± 0.4b
Dehumidification	Yes	0.0881	0.14 ± 0.001c	0.1519	27.0 ± 0.4c
	No		0.14 ± 0.001c		27.8 ± 0.4d
Air temperature	40°C	<0.0001	0.08 ± 0.001e	0.0203	28.4 ± 0.5d
	45°C		0.13 ± 0.001d		26.5 ± 0.5ce
	50°C		0.18 ± 0.001f		27.4 ± 0.5cd
Drying duration	30 min	0.0002	0.14 ± 0.001c	<0.0001	26.0 ± 0.4e
	45 min		0.13 ± 0.001d		27.0 ± 0.4c
	60 min		0.13 ± 0.001d		29.3 ± 0.4f
Replication	1	0.1842	0.13 ± 0.001 d	0.0906	27.9 ± 0.5d
	2		0.13 ± 0.001 d		26.6 ± 0.5ce
	3		0.13 ± 0.001 d		27.8 ± 0.5d

* p-values less than 0.05 show the factors' statistical significance at a 95% level of significance.
# Average and standard deviation values. All values in the same column not connected with the same letters are statistically different.

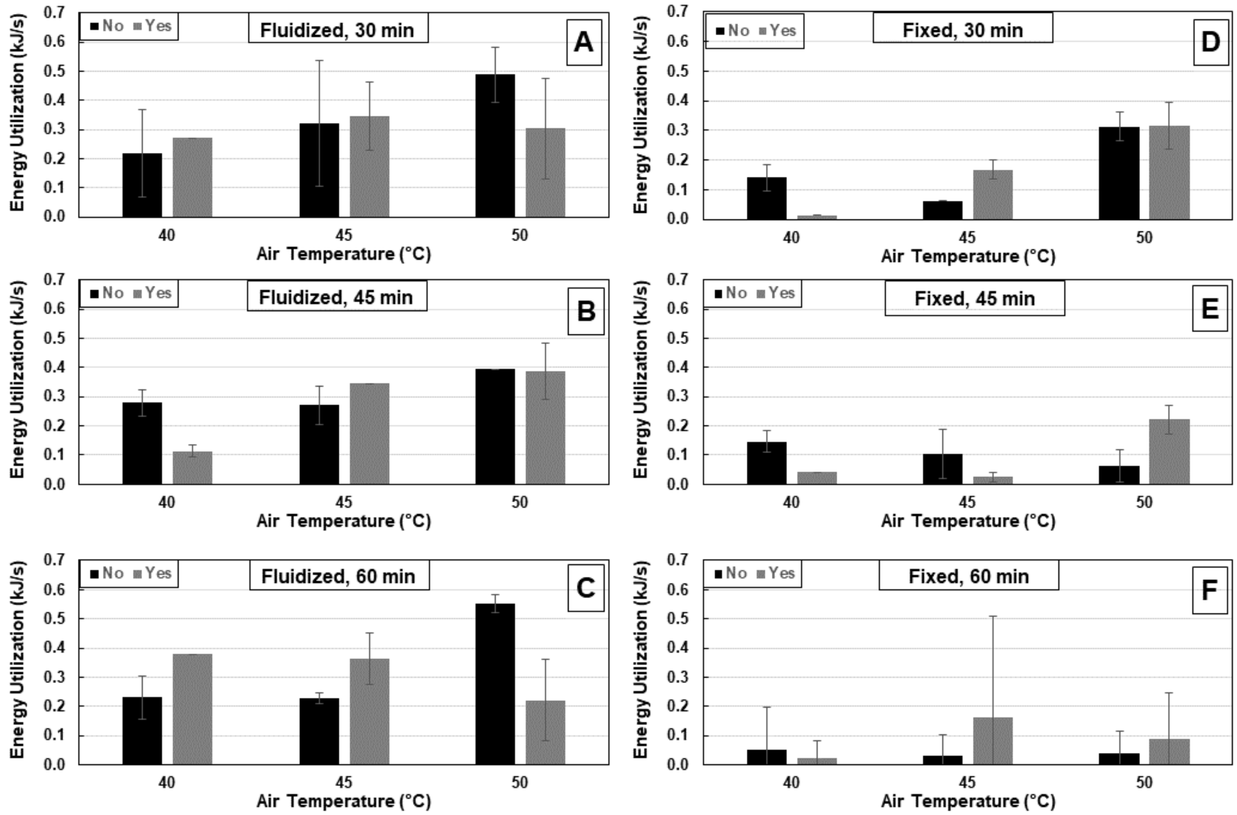

Figure 29. Energy utilization for experiments at different drying temperature and dehumidification conditions for(A) fluidized bed and 30 min duration, (B) fluidized bed and 45 min duration, (C) fluidized bed and 60 min duration, (D) fixed bed and 30 min duration, (E) fixed bed and 45 min duration, and, (F) fixed bed and 60 min duration. Mean values with error bars were found for three replications.

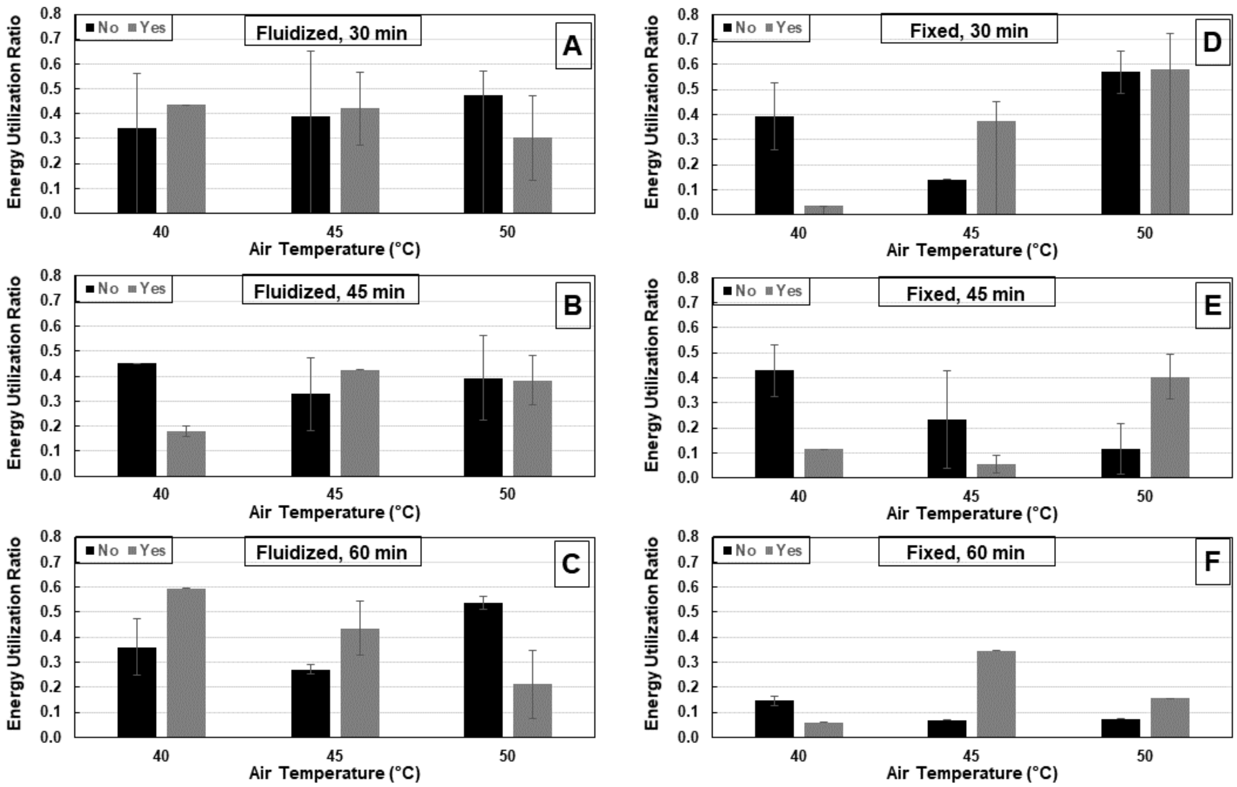

Figure 30. Energy utilization ratio for experiments at different drying temperature and dehumidification conditions for(A) fluidized bed and 30 min duration, (B) fluidized bed and 45 min duration, (C) fluidized bed and 60 min duration, (D) fixed bed and 30 min duration, (E) fixed bed and 45 min duration, and, (F) fixed bed and 60 min duration. Mean values with error bars were found for three replications.

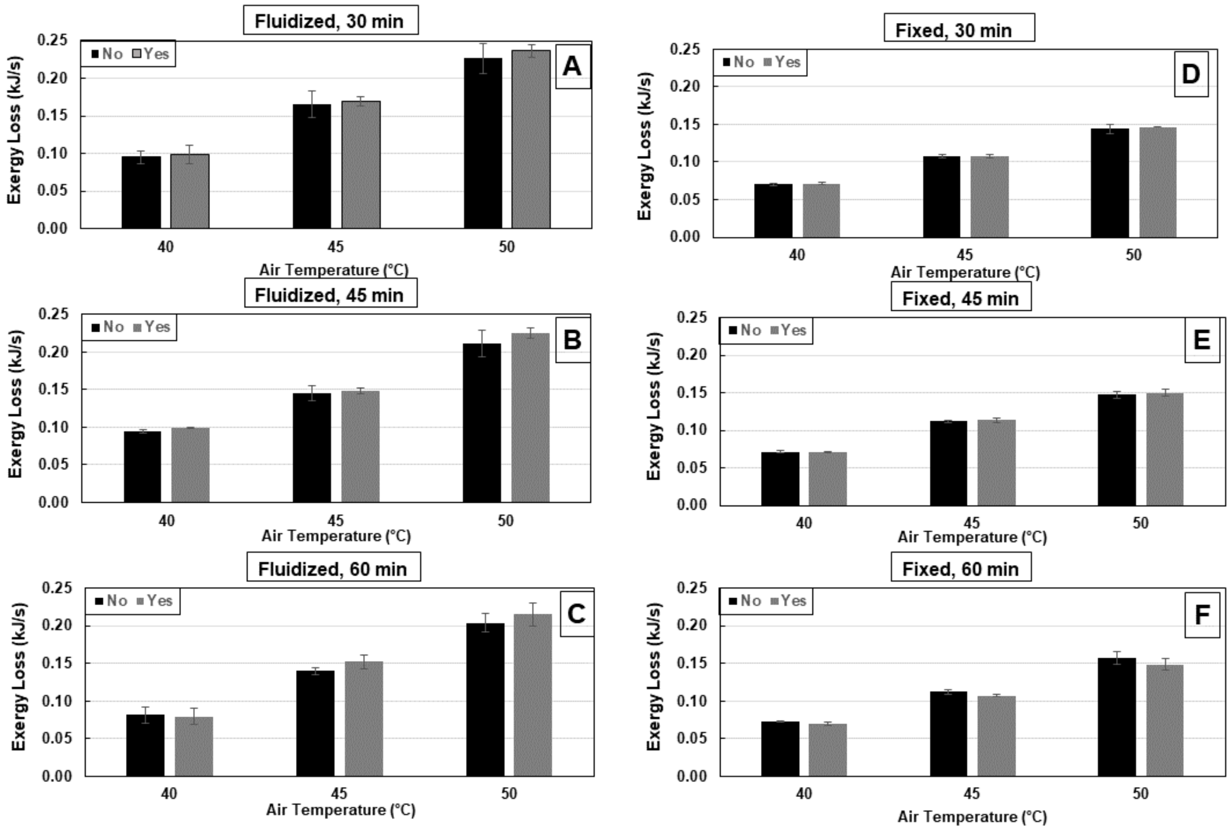

Figure 31. Exergy loss for experiments at different drying temperature and dehumidification conditions for(A) fluidized bed and 30 min duration, (B) fluidized bed and 45 min duration, (C) fluidized bed and 60 min duration, (D) fixed bed and 30 min duration, (E) fixed bed and 45 min duration, and, (F) fixed bed and 60 min duration. Mean values with error bars were found for three replications.

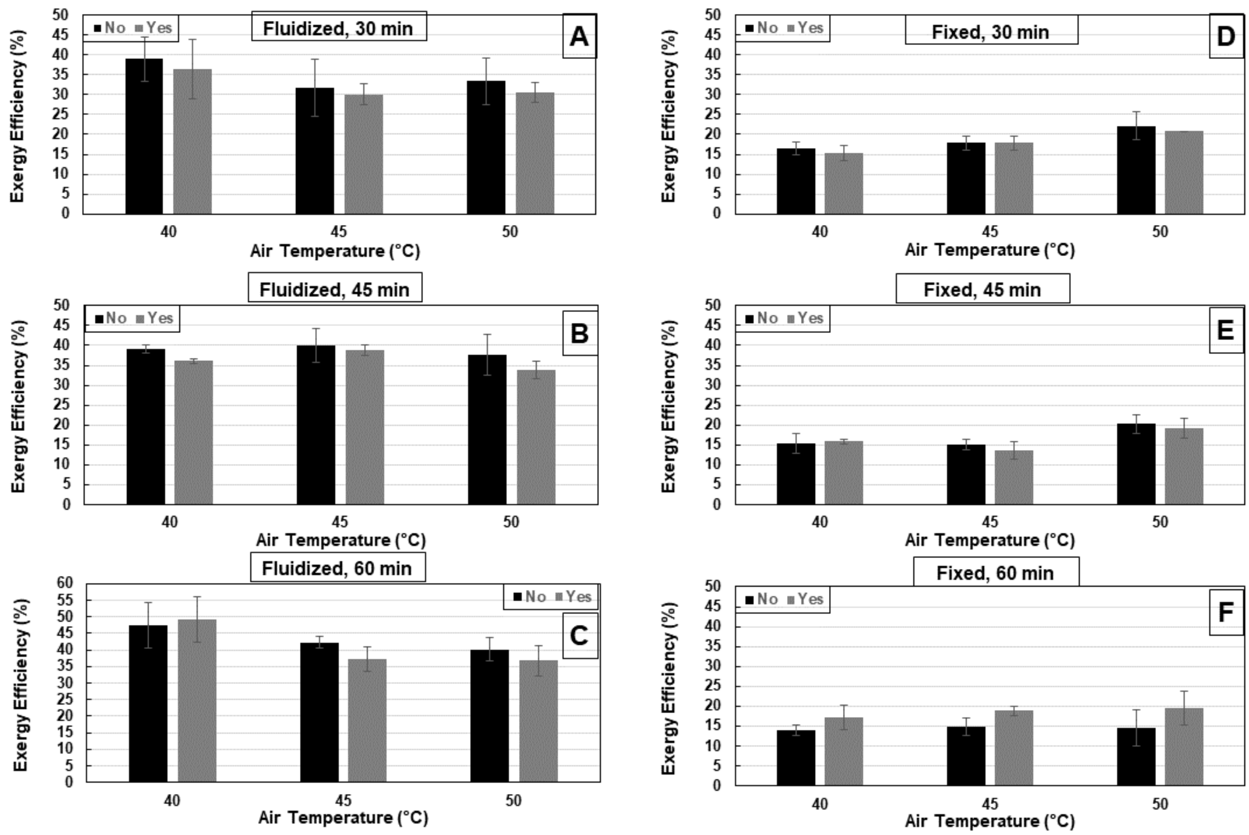

Figure 32. Exergy efficiency for experiments at different drying temperature and dehumidification conditions for(A) fluidized bed and 30 min duration, (B) fluidized bed and 45 min duration, (C) fluidized bed and 60 min duration, (D) fixed bed and 30 min duration, (E) fixed bed and 45 min duration, and, (F) fixed bed and 60 min duration. Mean values with error bars were found for three replications.

4. Conclusions

One hundred eight experiments were done for energy and exergy analyses of fluidized and fixed bed drying of rough rice along with the ambient air dehumidification system. Energy utilization and energy utilization ratio were calculated using the first law of thermodynamics, whereas exergy loss and exergy efficiency were determined using the second law. Drying air temperature (40°C, 45°C, 50°C), drying bed condition (fluidized and fixed), drying duration (30 min, 45 min, 60 min), and ambient air dehumidification (yes, no) were the factors that were tested to check their significance on energy and exergy of the drying system. Lab-scale dryer units designed by Sadaka et al. (2018) were used for testing with rough rice. The minimum and maximum EU values were 0.01 kJ/s and 0.55 kJ/s for drying at fixed-bed drying at 40°C for 30 min with dehumidification and 50°C for 60 min under fluidized bed condition without dehumidification, respectively. All factors did significantly affect the energy and exergy of the drying except dehumidification and replication. With an increase in air temperature, energy utilization increased significantly. Fluidized bed drying showed better energy utilization and energy utilization ratio. The best energy utilization was reported for rice drying fluidized bed at a higher temperature, lower drying duration, and with or without ambient air dehumidification. The minimum and maximum exergy loss values were 0.070 kJ/s and 0.236 kJ/s for fixed bed at 40°C, 60 min of drying with dehumidification, and fluidized bed at 50°C for 30 min drying duration with dehumidification, respectively. For exergy efficiency, the minimum and maximum values were 13.46% to 49.14%, achieved at 45°C air temperature, fixed bed, 45 min drying with dehumidification, and fluidized bed drying using 40°C air temperature for 60 min with dehumidification, respectively. The exergy loss increased with an increase in air temperature, whereas exergy efficiency did not change much in fluid and fixed bed drying. Not much difference was observed for drying with and without ambient air dehumidification.

The dryer lost a large amount of exergy through the outlet or exit air and was the primary cause of thermal inefficiency. The other thermal inefficiency source was the exergy and energy loss through the drying chamber and inlet air steel pipes. With recirculation of exit air and better insulation of the drying chamber and inlet pipes, the system's thermal inefficiencies could be reduced. However, this led to adding the cost of the system. Thus, the study suggested using the optimum drying conditions for utilizing energy and exergy of drying air. For the current study, it was found that fluidized bed drying was better than the fixed bed drying overall. At the initial stages of the drying process, fluidized bed drying had higher exergy efficiency, energy utilization, and energy utilization ratio than the fixed bed drying method. Furthermore, 40°C air temperature using fluidized bed drying with or without ambient air dehumidification worked best per the energy and exergy utilization in the drying system.

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Chapter 9: Modeling of the rice drying process in a custom-made lab-scale fluidized bed dryer.

Contributing Authors: Kaushik Luthra and Sammy Sadaka

Abstract

There are numerous well-developed empirical models for rice drying, but none have been fitted to check their relevance with ambient air dehumidification of rough rice and fluidized bed drying systems. Consequently, the goals of this research were (1) to determine the best-fit model or models for rough rice dehydration in a fluidized bed dryer system using ambient air or dehumidified air, and (2) to assess the effective moisture diffusivity and the activation energy of rough rice drying. Nine mathematical models were selected and fitted to the experimental data of rough rice fluidized bed drying at 40°C, 45°C, and 50°C using ambient air or partially dehumidified air. Ambient air dehumidification was introduced as a novel technology to partially dehumidify humid ambient air to maintain the drying process running mainly in damp conditions. Nonlinear regression analysis instituted that Verma et al. model and Modified Henderson and Pabis model were the two best models for describing fluidized bed drying characteristics of rough rice with and without dehumidification conditions. The goodness of fit was determined using coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2), with values for the two best models ranging from 0.9760 to 0.9996, 0.0000 to 0.0022, and 0.0040 to 0.0180, respectively. Verma et al. model was the best fit of 66.67% of the studied cases. Modified Henderson and Pabis model was the best fit for 33.33% of the studied cases. The results revealed that the evaluated adequate moisture diffusivity increased with the drying air temperature and ambient air dehumidification. It varied from 2.19×10^{-9} to 2.44×10^{-9} m^2/s with R^2 higher than 0.9556. The activation energy under the dehumidification conditions (13.720 kJ/mol) was lower than the activation energy under the non-dehumidification conditions (19.756 kJ/mol). Pre-exponential factor values were 4.908×10^{-7} and 4.940×10^{-6} with and without dehumidification, respectively.

Keywords

Air dehumidification, Fluidized bed dryer, Mathematical modeling, Model fitting, Rice drying.

1. Introduction

Drying is a complex practice as it involves heat and mass transfers. There are three mechanisms of drying in a food particle: (1) surface diffusion or liquid diffusion on pore surfaces, (2) liquid or vapor diffusion due to the moisture concentration differences, and (3) capillary action in granular and porous food due to surface forces (Erbay and Icier, 2010). The drying occurs at a constant rate and subsequent falling rate periods until an equilibrium is reached for hygroscopic materials. However, for most of the grains like rice that contain high moisture content, drying takes place in the second falling rate period, and no constant rate period is observed (Erbay and Icier, 2010). During the second falling rate period, the dominant diffusion mechanism is vapor diffusion due to moisture concentration differences.

Modeling the drying process can help understand the process better and lead to process design, optimization, energy and exergy analysis, and process automation and control (Erbay and Icier, 2010). Grain drying models are used as tools to explain the drying phenomenon using mathematical equations. Thus, model development aims to find these mathematical equations for characterizing the system of interest (Gunhan et al., 2005). To understand rice drying, the change in moisture content and then the rice kernel's temperature needs to be tracked throughout the drying process, i.e., the purpose of any rice drying model. In general, there are two types of models in research, i.e., empirical and theoretical models. Empirical models are the one that is developed by fitting the experimental data to have a mathematical equation (Chen and Wu, 2000). Empirical models in rice drying are used for developing the kinetic models that target the drying kinetics of the rice kernel. Kinetic models are mostly exponential decay models such as the Newton model, Henderson model, Page model, Pabis model, two-term exponential model, and approximate diffusion model (Proctor, 1994). On the other hand, theoretical models are developed using heat and mass transfer equations (Wu et al., 2004).

The fluidized bed drying (FBD) technique has been in practice for almost three decades to dry rough rice (Tirawanichakul et al., 2004; Karbassi and Mehdizadeh, 2008; Tuyen et al., 2009). The main advantage of fluidized bed drying with rice is the increase in drying rate and the reduction of rice spoilage after harvest. Conversely, the major disadvantage is the low dried rice quality (Kassem et al., 2011). The published modeling work is different from each other by bed configuration (geometry, with or without in-bed heater) and operating parameters (environmental conditions, initial moisture level, differences in rice variety, and physical forms).

Soponronnarit and Prachayawarakorn (1994) investigated the fluidized bed rice dying to determine the optimum strategy for the best effects on rice quality, drying capacity, and energy consumption. Heat and mass transfer equations were considered along with empirical models like Page and Henderson to determine rice's moisture content at a specific time. A finite difference method was used to find the solutions to the equations. Ramesh and Rao (1996) used a vibro fluidized bed dryer to examine the effect of fluidized bed drying of rice at air temperature between 160°C to 240°C and fitted Page equation experimental data. The discoloration of rice was noticed at around 240°C air temperature, and it was found that the Page equation did fit well. Izadifar and Mowla (2003) developed a mathematical model to simulate the rice drying process in a continuous cross-flow fluidized bed dryer. The model used the momentum, mass, and energy balance equations for each dryer element and rice properties. The model was solved for the moisture content of rice as output while taking operating conditions as input. They tested air temperature between 50 to 60°C and feed rate of 1000 kg/h. Experimental data was used to validate the proposed model, and model predictions showed good agreement with the experimental results. Thakur and Gupta (2006) dried high moisture content rice in stationary and fluidized beds using the rest period. They used a single-term diffusion model to fit the first, rest, and second drying period experimental data. The nonlinear regression method was used, and diffusion coefficients were evaluated. The rest period of 75 min and 90 min at a moisture ratio of around 0.715 were best for both fluidized and stationary bed. Fluidization reduced energy consumption with no decrease in head rice yield. Tirawanichakul et al. (2004) determined the effect of fluidized bed on drying of long grain rice with varied air temperature (40-150°C) and rice initial moisture content (25.0 to 32.5% d.b.). The mathematical model using thin-layer drying equations was developed, and the prediction of the drying process was made. The simulation results concluded that the long grain rice fluidized bed drying under a high initial moisture content and drying air temperature over 100°C was recommended. Bizmark et al. (2010) developed a continuous plug flow fluidized bed sequential model for rough rice drying. The study included initial moisture content, airflow, and particle flow rate as variables. Their model found moisture content with up to 4.5% inaccuracy, which makes this model unreliable as even the slightest inaccuracies can lead to unreliable predictions of moisture content. Khanali et al. (2012) did experiments on a custom-made fluidized bed dryer for drying rice to evaluate the effects of air temperature, air velocity, and solids holdup on the drying rate. They modeled and fitted their experimental data with several well-known empirical and semi-empirical grain drying models. They found that the increase in air temperature and air velocity increased the drying rate, while the increase in the solids holdup decreased the drying rate. Their results revealed that the Midilli et al. model to be the best model for describing the drying kinetics of rice drying in the fluidized bed dryer. Khanali et al. (2014) used a plug flow fluidized bed dryer to dry solids and determine outlet gas humidity and temperatures. This model was extended to determine the dynamic mass and energy transfers between solids and gas phases. They investigated rough rice drying under dynamic conditions to validate the model results. A sound agreement between simulated and measured results was found. Luthra et al. (2021) introduced ambient air dehumidification in a fluidized bed to continuously dry rough rice even under mist ambient air. They found that the MC decreased with an increase in air temperature. Head rice yield did not reduce with fluidization and ambient air dehumidification compared to the control fixed bed drying. Their results also revealed the same for the rice pasting quality. Their results also revealed the importance of developing the best fit model of drying rough rice under dehumidification conditions.

No published research, to our knowledge, did the modeling of fluidized bed drying of rough rice utilizing ambient air dehumidification. Therefore, the objectives of this study were:

(1) To determine the best fit kinetic model of rough rice fluidized bed drying and evaluate the effects of air temperature and ambient air dehumidification on the model constants, and

(2) To determine the effective moisture diffusivity and the activation energy of rough rice drying with dehumidification and without dehumidification of ambient air.

2. Materials and Methods

A custom-made lab-scale fluidized bed dryer developed by Sadaka et al. (2018) and then developed by Luthra and Sadaka (2020a) was used in this study. All laboratory experiments were performed at the Rice Research and Extension Center (RREC) in Stuttgart, AR. The following sections elucidate the materials and methods used in the present study.

2.1 Rice Samples

Rough rice (cv. Diamond) was used in this study and obtained from a Northeast Arkansas farm. Processing rough rice includes cleaning with a dockage tester (Model XT4, Carter-Day, Minneapolis, MN) and homogenization to have a representative sampling during the experiments. Rough rice physical characteristics were determined, as shown in Table 35 below. 1000-kernels sample was obtained using an automatic seed counter (Model SLY-C, Hinotek, China) to determine rough rice weight using a scale (Ohaus SP-2001 Scout Pro Balance, Parsipanny, NJ). The standard oven method (ASABE, 2008) was used to determine the rough rice's initial moisture content. Bulk density was obtained using the standard method ASTM E873-82. Length, width, and thickness were calculated using the digital caliper (General Ultratech, Series – 147, Secaucus, NJ). For the geometric mean diameter, the cube root of the product of all three dimensions was done (Bande et al., 2012; Sadaka et al., 2018). The rough rice samples were then stored in a clean box at 4°C in a cooler and taken out 24 hours before experiments to attain ambient temperature.

Table 35. Rough rice sample characteristics (Luthra and Sadaka, 2020b, 2020c).

Parameter	Units	Rough Rice
1000 Kernel weight*	g	26.1±0.16
Bulk density*	kg/m^3	620.8±2.28
Initial Moisture content*	%, d. b.	24.3±1.1
Dimensions**		
Length	mm	8.75±0.53
Width	mm	2.40±0.14
Thickness	mm	1.14±0.14
Geometric Mean Diameter	mm	3.43±0.15

* Average of three readings, ± the standard deviations
** Average of fifty readings, ± the standard deviations

2.2 Drying unit

The grain drying unit developed by Sadaka et al. (2018) was used in the present study. The dryer system was used as a fluidized bed dryer. The dryer consisted of five parts: ambient air dehumidification system, air-supply system, air-heating system, drying column, and measuring systems. The ambient air dehumidification system consisted of a desiccant pipe that holds forty-eight 50-gram silica gel packets tied to a rope, and the rope was hung inside the desiccant pipe from the top end. The desiccant pipe's internal diameter is 10.4 cm, with the top-end joined to a duct pipe that sucks the humid air (70-80% RH) out of an industrial humidifier (AIRCARE MA1201, coverage up to 334 square meters, USA). The relative humidity range was selected to be practical with the farmers' real relative humidity experiences during summer months in Arkansas. Relative humidity of more than 80% was not achievable due to the laboratory size.

The air supply system consists of a 3-kW regenerative blower (SCL k05-MS MOR, FBZ, Italy) that takes the air coming from the desiccant pipe. The airflow is controlled using a variable frequency drive (ACS350, ABB Ltd, Switzerland) with an airflow meter (Range: 0.0 - 1.70 m^3/min, 7510 series, KING Instrument Company, Garden Grove, CA) attached in line. In the air-heating system, a 2.5 cm diameter steel pipe carrying the air is heated by a tube furnace (Barnstead/Thermolyne Corporation type 21100 tube furnace, Dubuque, IA). The desired air temperature is attained by setting the furnace at the required steady-state temperature. The drying column is made up of plexiglass and is 150 cm long and 15 cm in diameter. A ball valve is installed above the distributor plate to take the samples and clean the drying column. The measuring system includes sensors to measure the grain and air temperature, pressure drop, air relative humidity, grain moisture content, and air velocity. 13 J-type thermocouples inserted horizontally in the drying column spaced 10 cm apart are used to measure air temperature along the length of the column. The data loggers (OMEGA TC-08, Norwalk, CT) were connected to the thermocouples connected to a PC. Probe-type sensors (Grain Deacon, Deacon Technologies, LLC, Prairie Grove, AR), as used by Luthra et al. (2019), recorded the rice moisture content to create a moisture content profile for the experimental duration.

A relative humidity dew point meter (HI 9565, 5% to 95% Range, Hanna Instruments Ltd, Bedfordshire, England, UK) was used to record the inlet and exit air relative humidity. A velocity meter (Anemometer, 80 to 5906 fpm, EXTECH, Nashua, NH) was used to record the exit air velocity. The pressure drop system consisted of three digital manometers (Series 475, Dwyer Instruments INC, Michigan City, IN). The moisture content of rough rice samples (initial and final) was measured using a moisture meter (AM 5200 Grain Moisture Tester, PERTEN Instrument, Hägersten, Sweden). For more details about the drying unit, refer to Sadaka et al. (2018).

2.3 Experimental Design

Eighteen experiments were done in total. The factors included in this study also listed in Table 36 were: dehumidification of ambient air (yes or no), air temperature (40°C, 45°C, and 50°C), and replication (1, 2, and 3). All the experiments were performed for fluidized bed conditions and 60 min of experimental duration. Ambient air without any dehumidification was used as the control for the dehumidification factor. The moisture content of rice was used as the response variable in the study.

Table 36. Experimental design.

Factors	Levels	Total number of experiments
Dehumidification	Yes, No	
Air temperature	40°C, 45°C, 50°C	2×3×3 = 18
Replication	1, 2, 3	

2.4 Experimental Procedures

Rough rice samples were kept in room conditions for 24 hours before the experiments. The blower was turned on, and the airflow was adjusted to attain the fluidized bed condition (1.75±0.1 m/s). The furnace was turned on, and the air temperature was set to the desired level. Silica gel packets tied on a plastic rope were weighed and installed in the desiccant pipe for air dehumidification experiments. 4.5 kg of rough rice was dumped in the drying column. The air temperature reached the desired level. Continuous temperature readings were recorded with a frequency of 30 seconds. Moisture content was measured every 10 minutes using the probes inserted in the rice sample from the drying column's open end. After the experiment's end, three samples were obtained from the ball valve for further rice quality processing. The drying column was then emptied and cleaned. Silica gel packets were weighed and kept in a conventional oven at 120°C for 24 hours for regeneration.

2.5 Mathematical Models

Some of the conventional empirical mathematical models were used to predict rough rice's drying behavior using the custom-made fluidized bed dryer in the current study. Nine models are given in Table 37 to find the best fit for this study's experimental data. The dimensionless moisture ratio, MR calculated for modeling purposes, was calculated using the following equation 1.

$$MR = \left(\frac{M_t - M_e}{M_i - M_e}\right) \tag{1}$$

where

M_t = instantaneous moisture content (at time t) in % (d.b.),

M_i = initial moisture content in % (d.b.), and

M_e = equilibrium moisture content in % (d.b.).

Equilibrium moisture content is calculated using equation 2, as mentioned below (Atthajariyakul and Leephakpreeda, 2006 as cited by Khanali et al., 2012).

$$Me = \left(\frac{\ln(1-RH)}{-4.723*10^{-6}(1.8*T+491.7)}\right)^{1/2.386} \quad (2)$$

where

M_e = equilibrium moisture content in % (d.b.),

T = air temperature in °C, and

RH = air relative humidity in decimals.

Table 37. Conventional empirical drying kinetic grain models are used to predict rice moisture content during drying.

Model	Equation	Reference
Lewis	MR = exp(-kt)	Lewis (1921)
Henderson and Pabis	MR = A exp(−kt)	Henderson and Pabis (1969)
Logarithmic	MR = A exp(−kt) + B	Chandra and Singh (1995)
Two-term	MR = A exp($-k_1$t) + B exp($-k_2$t)	Henderson (1974)
Modified Henderson and Pabis	MR = A exp($-k_1$t) + B exp($-k_2$t) + C exp($-k_3$t)	Karathanos (1999)
Verma et al.	MR = A exp($-k_1$t) + (1-A) exp($-k_2$t)	Verma et al. (1985)
Page	MR = exp ($-kt^n$)	Page (1949)
Midilli et al.	MR = A exp($-kt^n$) + Bt	Midilli et al. (2002)
Wang and Singh	MR = 1 + At + Bt^2	Wang and Singh (1978)

MR is the moisture ratio (dimensionless), t is time (s), and A, B, C, x, y, k_1, k_2, k_3, and n are equation coefficients.

2.5 Statistical Analysis

Nonlinear regression was used to determine the model coefficients for each empirical model listed in Table 37. The solver add-in in Microsoft Excel software (Microsoft Corporation, Redmond, Wash.) was used for the analysis. The coefficient of determination (R^2), the root means square error (RMSE), and the chi-square ($\chi 2$) were calculated to determine the model accuracy. R^2 measures the proportion of variability between predicted data points relative to experimental data. The higher the R^2, the best fit the model (Jamali et al., 2006). RMSE and $\chi 2$ were calculated to determine the prediction error by the model. Low values of RMSE and χ^2 are desired by the models (Chen and Jayas, 1998; Chapra and Canale, 2010). RMSE and $\chi 2$ were calculated, as mentioned in equations 3 and 4, respectively.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(M_E^i - M_P^i)^2}{N}} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(M_E^i - M_P^i)^2}{N-P} \tag{4}$$

where

M_E = experimental MR,

M_P = predicted MR,

N = number of experimental data points, and

P = number of parameters in the model.

2.6 Effective Diffusivity (D_{ef}) and Activation Energy (E_a)

Moisture movement from the inside of the rice kernel to the surface during drying is a complex process. It involves molecular diffusion, capillary flow, Knudsen flow, and surface diffusion (Khanali et al., 2016). The overall moisture transport rate of grain kernels in dryers is defined by effective diffusivity (D_{ef}) instead of quantifying individual moisture diffusivity rates for each diffusion type (Khanali et al., 2016). Effective diffusivity is the function of kernel structure, moisture content, and temperature of drying. The accurate values of effective diffusivity for a particular product helps design effective and efficient processing unit operations, including drying (Mujumdar, 2006).

Few assumptions that were considered in this study are as follows: (1) rice kernels are considered as spherical geometry (Khanali et al., 2012), (2) the shape of all rice kernels is uniform and remain constant during the whole drying process, (3) drying of all kernels in the dryer is uniform, and (4) Moisture diffuses radially from the particle's interior to its surface, where it evaporates.

In this analysis, effective diffusivity was calculated using equation 5, i.e., the Fick's law equation that is often used to explain solid diffusion for spherical particles with pure radial and constant diffusion. This equation is apt to characterize any biological material's drying behavior in a falling-rate period (Madhiyanon et al., 2009). Various researchers used an analytical solution to Fick's law equation 5 as mentioned below (equation 6) to measure various materials' effective diffusivity (Yogendrasasidhar and Setty, 2019; Hu et al., 2017; Khanali et al., 2016). Equation 6 is the simplified version of the analytical solution of equation 5, as found by Crank (1975).

$$\frac{\partial M}{\partial t} = D_{ef} * \left[\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}\right] \tag{5}$$

where

M = moisture content of rice (%, d.b.),

D_{ef} = effective diffusivity (m^2/s),

r = radial coordinate (m), and

t = drying time (sec).

$$MR = \frac{6}{\pi^2} exp\left[-\pi^2 * \frac{D_{ef} * t}{r^2}\right] \tag{6}$$

where

D_{ef} = the effective diffusivity (m^2/s),

t = drying time (sec), and

r = the geometric mean radius of the rice kernel (m).

The natural logarithm of both sides of equation 6 was taken to yield equation 7 to determine the effective diffusivity

$$ln\, MR = ln\left(\frac{6}{\pi^2}\right) - \left(\pi^2 \, * \frac{D_{ef} * t}{r^2}\right) \tag{7}$$

The slope of equation 7 expressing a relationship between ln MR and time is determined (equation 8), and effective diffusivity is then calculated by equation 8.

$$Slope = \left(\pi^2 \, * \frac{D_{ef}}{r^2}\right) \tag{8}$$

The activation energy (E_a) in the drying process is minor energy needed to make the process possible. In other words, activation energy signifies the ease of water molecules to diffuse out of the solid. The activation energy can be calculated using the Arrhenius correlation equation (equation 9) to emphasize any dryer's drying kinetics. It also tells about the dependency of effective diffusivity on temperature.

$$D_{ef} = D_o * \, exp\left[-\frac{E_a}{R * T_{abs}}\right] \tag{9}$$

where

D_o = pre-exponential factor (m^2/s),

E_a = activation energy of diffusion (J/mol),

R = universal gas constant (8.314 J/mol-K), and

T_{abs} = absolute rice temperature (K).

The above exponential form of the Arrhenius equation (equation 9) is changed to a linear form considering both sides' natural logarithm, logarithmic form, as shown in equation 10.

$$\ln D_{ef} = \ln D_o - \frac{E_a}{R * T_{abs}} \tag{10}$$

The activation energy can be calculated from the slope of the relationship between ln D_{ef} versus $1/T_{abs}$, i.e., E_a/R.

3. Results and Discussion

3.1 Effects of temperature and dehumidification on moisture ratio

Figure 33 shows the effects of air temperature and drying duration on the moisture ratio under the studied cases of dehumidification conditions (with and without dehumidification) and air temperature (40ºC, 45ºC, and 50ºC). It should be mentioned that each moisture ratio level is the mean of the three moisture ratios resulted from the experimental replicates. The drying curve with an increase in temperature and drying duration shows a reduction in moisture ratio. It can be postulated to the higher energy corresponding to the higher air temperature, leading to more moisture removal from the rice kernel. Additionally, air dehumidification shows a slightly lower moisture ratio as compared with no dehumidification. The lower air relative humidity conforming to the dehumidification status resulted in higher moisture removal. For instance, at the air temperature of 40ºC, 45ºC, and 50ºC and the drying duration of 60 minutes, the moisture ratio reached 0.655, 0.649, and 0.629 (dimensionless), respectively, under no dehumidification condition. On the other hand, at the same air temperature levels and with air dehumidification, the moisture ratio reached 0.639, 0.633, and 0.620 (dimensionless).

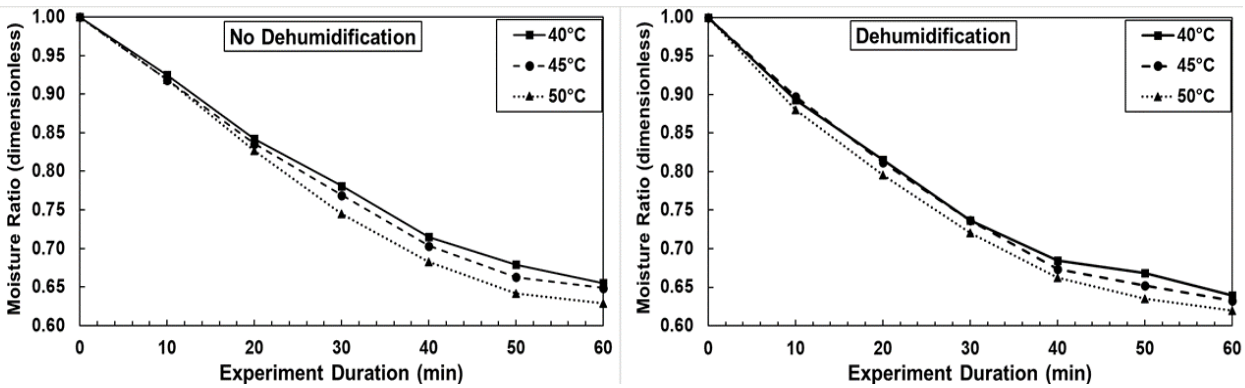

Figure 33. Drying curves (moisture ratio vs. experiment duration) for fluidized bed drying at 40°C, 45°C, and 50°C with and without ambient air dehumidification. All three replications were averaged for each level of temperature, respectively.

3.2 Determination of the best-fit models

Nine mathematical models were analyzed using a nonlinear regression model fitting for the experimental moisture ratio data under the two studied dehumidification conditions (with and without dehumidification). The analysis results are listed in Tables 38 and 39 below for air dehumidification and no dehumidification conditions. Each model was fitted separately for each drying temperature, i.e., 40°C, 45°C, 50°C, and air dehumidification condition (no and yes). The results presented are for fluidized bed drying of rough rice for 60 minutes of drying duration. The best fit model out of the nine models was selected based on the highest R^2, the lowest RMSE, and the lowest χ^2.

Table 38. Model goodness of fit results for fluidized bed experiments with air dehumidification at drying temperatures of 40°C, 45°C, and 50°C.

Model	Temp. (°C)	Model Constants (X 10^4)	R^2	RMSE	χ2
Lewis	40	k = 1.4521	0.9724	0.0252	0.0007
	45	k = 1.4724	0.9634	0.0282	0.0009
	50	k = 1.5744	0.9649	0.0302	0.0011
Henderson and Pabis	40	k = 1.4522, A = 9999.9998	0.9724	0.0252	0.0009
	45	k = 1.3598, A = 9741.3127	0.9613	0.0250	0.0009
	50	k = 1.4321, A = 9676.7742	0.9622	0.0255	0.0009
Logarithmic	40	k = 4.5876, A = 4602.2491, B = 5419.7748	0.9970	0.0068	0.0001
	45	k = 4.9410, A = 4548.3167, B = 5509.4323	0.9943	0.0095	0.0002
	50	k = 5.2214, A = 4603.0334, B = 5419.9905	0.9980	0.0059	0.0001
Two term	40	k1 = 9.0730, k2 = 0.7494, A = 1937.5973, B = 8103.6984	0.9953	0.0086	0.0002
	45	k1 = 3.4523, k2 = -1.0951, A = 7226.6869, B = 2838.8761	0.9963	0.0078	0.0001
	50	k1 = 2.8326, k2 = -2.5063, A = 8779.5852, B = 1223.1302	0.9994	0.0032	0.0001
Mod. Henderson and Pabis	40	k1=3.3422, k2= -0.5548, k3=-9.1451, A=6556.4224, B=3443.2873, C= 5.7877	0.9973	0.0065	0.0003
	45	k1=1.0478, k2=-0.0949, k3=-5.6000, A=18404.0621, B=-8787.5612, C=385.0034	0.9992	0.0036	0.0001
	50	k1 =2.6791, k2=-1.7360, k3=-4.0761, A=8887.3434, B=797.1431, C=314.1208	0.9995	0.0029	0.0001
Verma et al.	40	k1 = 2.7906, k2 = -1.6264, A = 8131.3551	0.9974	0.0064	0.0001
	45	k1 = 1.9890, k2 = -7.1449, A = 9890.0333	0.9989	0.0042	0.0001
	50	k1 = 2.5478, k2 = -3.5516, A = 9310.1414	0.9995	0.0029	0.0001
Page	40	k = 10.9117, n = 7426.6854	0.9920	0.0112	0.0002
	45	k = 11.2982, n = 7399.2718	0.9847	0.0157	0.0003
	50	k = 15.4722, n = 7080.7061	0.9911	0.0124	0.0002
Midilli et al.	40	k = 10.9141, n = 7436.5230, A = 8126.2285, B = 0.5081	0.9252	0.1008	0.0237
	45	k = 11.0378, n = 7761.4327, A = 10110.1927, B = 0.2547	0.9874	0.0142	0.0005
	50	k = 15.4276, n = 7015.8259, A = 9983.5505, B = -0.0467	0.9903	0.0129	0.0004
Wang and Singh	40	A = -1.9061, B = 0.0002	0.9966	0.0073	0.0001
	45	A = -2.0015, B = -0.0002	0.9979	0.0066	0.0001
	50	A = -2.0425, B = 0.0002	0.9994	0.0034	0.0001

The results revealed that R^2 ranged between 0.9252 and 0.9995 for the nine models under air dehumidification (Table 38). The three best models for all experiments at 40°C, 45°C, and 50°C temperature levels were Modified Henderson and Pabis, Verma et al., and Modified Henderson and Pabis, respectively. Khanali et al. (2012) reported Midilli et al. model to be the best for describing fluidized bed drying of rough rice, which did not agree with the drying results with air dehumidification in the present study.

Table 39. Model goodness of fit results for fluidized bed experiments with no air dehumidification at drying temperatures of 40°C, 45°C, and 50°C.

Model	Temp. (°C)	Model Constants (X 10^4)	R^2	RMSE	χ^2
Lewis	40	k = 1.4903	0.9720	0.0250	0.0007
	45	k = 1.2072	0.9710	0.0200	0.0005
	50	k = 1.5493	0.9780	0.0230	0.0006
Henderson and Pabis	40	k = 1.3904, A = 9770.2307	0.9699	0.0224	0.0007
	45	k = 1.1596, A = 9886.8303	0.9710	0.0190	0.0005
	50	k = 1.4634, A = 9802.9173	0.9760	0.0210	0.0010
Logarithmic	40	k = 4.5811, A = 4757.4338, B = 5300.8026	0.9965	0.0076	0.0001
	45	k = 2.5516, A = 5601.9729, B = 4395.6300	0.9760	0.0180	0.0005
	50	k = 0.1838, A = 0.2083, B = 7651.8142	0.9530	0.1340	0.0314
Two term	40	k_1 = 3.3434, k_2 = -0.9305, A = 7131.4446, B = 2925.4829	0.9977	0.0062	0.0001
	45	k_1 = 2.2264, k_2 = -0.2936, A = 6757.7749, B = 3335.4382	0.9760	0.0180	0.0007
	50	k_1 = 1.8794, k_2 = -9.5700, A = 9983.8118, B = 34.8114	0.9990	0.0010	0.0000
Mod. Henderson and Pabis	40	k_1=1.7724, k_2= -2.5422, k_3= -5.3626, A=10430.6556, B=-837.4324, C= 420.6964	0.9996	0.0026	0.0001
	45	k_1=2.2573, k_2= -0.2426, k_3=2.1107, A=7477.9776, B=3423.8661, C=-908.1850	0.9760	0.0180	0.0022
	50	k_1 =1.6552, k_2=-1.6783, k_3=-16.2507, A=7236.7196, B=2813.6761, C=2.1975	0.9989	0.0044	0.0001
Verma et al.	40	k_1 = 1.9659, k_2 = -6.6024, A = 9865.9010	0.9995	0.0029	0.0001
	45	k_1 = 1.5066, k_2 = -15.3403, A = 9997.3203	0.9970	0.0024	0.0000
	50	k_1 = 1.8635, k_2 = -9.6220, A = 9966.4116	0.9990	0.0010	0.0000
Page	40	k = 9.3547, n = 7655.7479	0.9886	0.0138	0.0003
	45	k = 3.5332, n = 8633.9164	0.9760	0.0180	0.0004
	50	k = 4.3515, n = 8612.3412	0.9870	0.0152	0.0003
Midilli et al.	40	k = 0.0010, n = 0.0010, A = 9746.5699, B = -1.0840	0.9410	0.0320	0.0024
	45	k = 4.0469, n = 8423.1404, A = 10021.9578, B = -0.0320	0.9760	0.0180	0.0007
	50	k = 3.4473, n = 9416.4546, A = 10130.6961, B = 0.4135	0.9921	0.0120	0.0003
Wang and Singh	40	A = -1.7250, B = 0.00019	0.9960	0.0090	0.0001
	45	A = -1.2900, B = 0.00100	0.9740	0.0190	0.0005
	50	A = -1.7423, B = 0.00019	0.9963	0.0089	0.0001

On the other hand, under the no dehumidification conditions, the R^2 ranged between 0.9410 and 0.9996, for the tested models (Table 39). The best model for the 40°C temperature level was Modified Henderson and Pabis, whereas Verma et al. was the best for 45°C, and 50°C. Accordingly, Verma et al. model was the best fit for 4 studied cases out of the six conditions, representing 66.67% of the best fit cases. On the other hand, Modified Henderson and Pabis model was the best fit for the 2 cases, representing 33.33% of the studied cases.

3.3 Effects of temperature and dehumidification on effective moisture diffusivity and activation energy

The effective moisture diffusivity (D_{ef}) and the R^2 for all air temperatures with and without dehumidification were presented in table 40. The D_{ef} values ranged between 2.19×10^{-9} and 2.44×10^{-9} m^2/s, and R^2 values were above 0.9556. A couple of vibrant trends are clear from table 40; firstly, there is an increase in the D_{ef} values with an increase in air temperature, and secondly, experiment with dehumidification had higher D_{ef} values than ones without dehumidification. This can be postulated to the increase in the dehumidified input air's drying capacity (Sadaka and Atungulu, 2018). Also, the D_{ef} increase is the significance of increased drying rate; as the air temperature increased, the air temperature's drying potential or water holding capacity increases. Similar findings were reported by Khanali et al. (2016).

The D_{ef} values for hygroscopic agricultural commodities ranged within 10^{-8} to 10^{-12} m^2/s (Gazor and Mohsenimanesh, 2010; Khanali et al., 2016). The diffusivity values reported for fluidized bed drying of rough rice in table 40 were within this range. The reported values of D_{ef} in the current study were higher than the past studies on rough rice. Khanali et al. (2016) mentioned the range of 4.78×10^{-11} to 1.36×10^{-10} m^2/s for fluidized bed drying of rough rice, and Steffe and Singh (1982) found the range to be 4.7×10^{-12} to 6.0×10^{-11} m^2/s for fixed-bed drying of rough rice.

Table 40. Mean effective moisture diffusivity for different experiments.

Dehumidification	Air temperature	D_{ef} (m^2/s)	R^2
No	40°C	2.19×10^{-9}	0.9845
	45°C	2.26×10^{-9}	0.9785
	50°C	2.43×10^{-9}	0.9741
Yes	40°C	2.24×10^{-9}	0.9584
	45°C	2.34×10^{-9}	0.9593
	50°C	2.44×10^{-9}	0.9556

The activation energy (E_a) and pre-exponential factor (D_o) using the Arrhenius equation were reported for fluidized bed drying of rough rice with and without dehumidification levels (Table 41). All the temperature levels were combined for the calculation of E_a for each level of dehumidification. The E_a for dehumidification experiments (13.720 kJ/mol) was lower than the experiments without dehumidification (19.756 kJ/mol). Having lower relative humidity of the dehumidified air had led to a higher moisture gradient development between the air and the rice surface. Thus, the water molecules' minimum energy to break the intermolecular forces to evaporate was lower in dehumidified air. R^2 values were 0.9999 and 0.9877, and pre-exponential factor values were 4.908×10^{-7} and 4.940×10^{-6} with and without dehumidification, respectively (Table 41). Sadaka and Atungulu (2018) reported that the drying activation energy value reached 9.4 kJ/mol under isothermal drying conditions while drying grain sorghum. Khanali et al. (2016) reported the range of activation energy of 36.59 to 44.31 kJ/mol, and in general, the agricultural commodities have the E_a values of 12.7 to 110 kJ/mol (Gazor and Mohsenimanesh, 2010). Thus, this study's E_a values were towards the lower end of this range, as reported by Gazor and Mohsenimanesh (2010).

Table 41. Pre-exponential factor (Do) and activation energy (Ea) calculated using the Arrhenius equation for all three temperature levels combined.

Dehumidification	Do (m^2/s)	Ea (kJ/mol)	R^2
No	4.940 × 10-6	19.756	0.9877
Yes	4.908 × 10-7	13.720	0.9999

4. Conclusions

Nine mathematical models were fitted for the experimental data obtained from the testing of a custom-made fluidized bed dryer. Rough rice was tested with drying at temperatures of 40°C, 45°C, and 50°C. Ambient air dehumidification was a novel factor in the study that supposedly can help farmers reduce ambient air humidity to achieve continuous drying. The model fitting for experiments with dehumidification and without it was compared. Nonlinear regression analysis was used and found that Verma et al. and Modified Henderson and Pabis were the two best models for describing fluidized bed drying characteristics of rough rice both with and without dehumidification. Coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square ($\chi 2$) values were used to demonstrate the goodness of fit. Verma et al. model was the best fit model for 4 cases out of the six studied cases representing 66.67% of the studied cases. On the other hand, the modified Henderson and Pabis model was the best fit model for the remaining 33.33% of the studied cases. Moisture diffusivity was defined using an Arrhenius equation. Moisture diffusivity differed between 2.19×10^{-9} to 2.44×10^{-9} m^2/s with R^2 more than 0.9556 as the drying air temperature and ambient air dehumidification increased. Experiments with dehumidification had lower activation energy (13.720 kJ/mol) than experiments without dehumidification (19.756 kJ/mol). Without and with air dehumidification, the pre-exponential factor values were 4.940×10^{-6} and 4.908×10^{-7}, respectively.

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Chapter 10: Conclusions

This study aimed to develop a new drying air dehumidification approach that would allow for continuous on-farm in-bin drying even in humid environments. Also, investigating the effectiveness of fluidized bed drying of rice was the other goal of this study. As a result, a custom-made fluidized bed dryer was created by installing a dehumidification unit holding silica gel, which was employed as a desiccant in the current investigation. The experiment design was a complete randomized design. The effects of ambient air dehumidification, air temperature, and drying duration on rice quality and pasting qualities were investigated using the fluidized bed and fixed bed drying systems.

The results indicated that head rice yield and rice whiteness did not differ substantially between the fluidized bed and fixed bed drying. However, rice whitening was shown to be adversely linked with head rice yield. Rough rice moisture removal was enhanced by ambient air dehumidification, which may be used in humid environments and had no effect on the quality of the dried rice. The idea of getting excellent quality rice dried in a fluidized bed system over a fixed bed system was further supported by pasting characteristics. The air temperature had to be below 50°C and the drying time had to be 60 minutes to accomplish fluidized bed drying of rough rice.

The energy utilization grew dramatically as the ambient temperature rose. The energy utilization and energy utilization ratio of fluidized bed drying were both higher. Rice drying using the fluidized bed with a higher temperature, shorter drying time, and with or without ambient air dehumidification had the highest energy usage. Exergy loss increased as air temperature rose, while exergy efficiency in fluid and fixed bed drying remained reasonably constant. When drying with and without ambient air dehumidification, there was little change. Fluidized bed drying demonstrated greater exergy efficiency, energy utilization, and energy utilization ratio than fixed bed drying in the early phases of the drying process. According to the energy and exergy consumption in the drying system, 40°C air temperature employing fluidized bed drying with or without ambient air dehumidification performed well. The dryer was the principal source of thermal inefficiency since it wasted much energy through the outlet or exit air. The exergy and energy loss via the drying chamber and inlet air steel pipes was the second cause of thermal inefficiency. The system's thermal inefficiencies might be minimized by recirculating exit air and better insulation of the drying chamber and intake pipes. However, this will increase the system's cost.

The model fitting for tests with and without dehumidification was examined. Verma et al. and Modified Henderson and Pabis were determined to be the two best models for characterizing fluidized bed drying characteristics of rough rice with and without dehumidification using nonlinear regression analysis. The quality of fit was demonstrated using the coefficient of determination (R^2), root means square error (RMSE), and reduced chi-square (2) values. The Verma et al. model was the best fit model for four of the six instances investigated, accounting for 66.67 percent of the total instances. The modified Henderson and Pabis model, on the other hand, was the best fit model for the remaining 33.33 percent. An Arrhenius equation was used to calculate moisture diffusivity. As the drying air temperature and ambient air dehumidification rose, moisture diffusivity varied from $2.19*10^{-9}$ to $2.44*10^{-9}$ m^2/s, with R^2 greater than 0.9556. In addition, dehumidification trials exhibited lower activation energy (13.720 kJ/mol) than non-dehumidification trials (19.756 kJ/mol). The pre-exponential factor values were $4.940*10^{-6}$ and $4.908*10^{-7}$, respectively, without and with air dehumidification.

Overall, the research showed that using dehumidified air in a fluidized bed drying system may dehydrate rough rice without affecting its quality. The device effectively dehumidified ambient air with silica gel, allowing continuous ambient air in-bin on-farm drying of rough rice. Fluidized bed drying of rice did not reduce the dried rice physical quality compared to fixed bed drying. To effectively utilize fluidized bed drying of rice, it is suggested to use air temperature of 50°C and below and drying duration of fewer than 60 minutes. Future work needs to establish the results found in this study for the farm and industrial-scale setup.