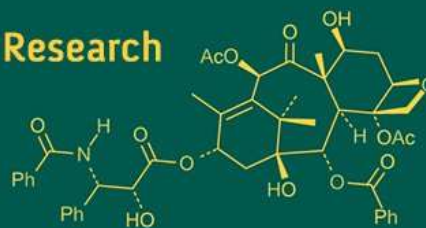
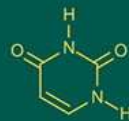
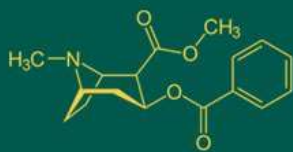


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Design, development and testing of a vibro-fluidized bed paddy dryer

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Abstract

A laboratory model vibro-fluidized bed dryer of 50 kg capacity was fabricated for drying paddy. The dryer was tested to compare the performance of drying paddy in static as well as vibratory bed. Mixing index of grain was studied with mixing time during vibration of drying bed. Paddy was conditioned to initial moisture content of 32% (w.b.) and drying experiments were conducted for 20 kg paddy with 10 cm bed thickness at 40 °C in both static and vibratory mode of operation. Drying was continued for a total period of 3 h and samples were drawn at regular intervals of 30 minutes for moisture content measurement. The drying curves, dryer performance parameters and milling quality were determined to compare the static and vibratory bed drying. The mixing index was observed to be more than 0.99 after 30 min of operation and there was no significant difference of coloured grain proportions with mixing time indicating that proper mixing occurred within 30 min of operation of the dryer. It took 120 and 180 min to dry paddy from an initial average moisture content of 48 to 14% (d.b.) when the dryer was operated in vibratory and static mode, respectively. It was observed that both drying time and vibration had significant effect ($p < 0.05$) on moisture content of sample during drying. The drying rate was found to be more in vibratory bed than static bed and drying took place under falling rate period in both the modes of operation. The specific energy consumption were 1.0 and 0.79 kWh/kg water whereas, drying efficiency were 69.8 and 87.8% for static and vibratory mode of drying, respectively. Head rice yield of paddy dried in vibratory mode was 1.3% more than dried in static mode due to uniform drying. From the above study, it was concluded that vibro-fluidised bed dryer could be used for drying paddy efficiently at farm level with less drying time, lower energy consumption and higher head rice yield.

Keywords: Vibro-fluidized bed dryer, paddy, drying efficiency, drying time, head rice yield

Introduction

Drying is one of the most important processes involved in the post-harvest handling and processing of rice (Olaniyan and Alabi, 2014) [9]. It is considered as one of the important stages because it affects almost all other stages, and loss due to drying stage is rather at the high level. Drying minimizes post-harvest losses in rice, enhances safe storage, improves milling quality; facilitate efficient transportation, distribution, further process and utilization. Delay in drying, incomplete drying or ineffective drying reduce grain quality of paddy and results in qualitative and quantitative loss (Reddy *et al.*, 2018; Madhava *et al.*, 2019) [11, 8]. Drying is also an important operation in parboiling process in which moisture content of steamed paddy is reduced from 32-33% to 14%.

Paddy is dried conventionally under sun, in solar dryer (Shanmugam *et al.*, 2014) [14], inclined bed dryer (Sarkar *et al.*, 2012) [13], LSU dryer (Lilhare *et al.*, 2012) [7], fluidised bed dryer (Suherman *et al.*, 2017) [16], and spouted bed dryer (Puspasari *et al.*, 2014) [10]. Though mechanical flat-bed dryers, bin dryers and LSU dryers are commonly used commercially, these take long drying time and uneven drying. To avoid non-uniformity in drying, reduce residence time and removal of moisture from high moisture content paddy by application of high temperature, pressure fluidized bed dryers were introduced for paddy. In fluidized bed dryers, grains are dried in a state of fluidization by blowing strong heated air current through the products. Fluidized bed dryers are used extensively for drying of wet particulate and granular materials such as agricultural products, foods, chemicals, and pharmaceuticals. Vibro-Fluidized Bed Dryer (VFBD) was introduced with better heat and mass transfer, shorter drying time and low energy consumption.

Mechanical agitation in vibro-fluidized bed dryer instead of the fluidized or spouted bed increases the heat and mass transfer coefficients. It reduces the minimum fluidization velocity and can even reduce the pressure drop. The direct contact between particles and air/gas is possible in vibro-fluidized dryer as compared to conventional dryers. Vibro-Fluidized Bed Dryers (VFBDs) have many advantages, such as: better mixing, reduction of air flow requirements, and smaller pressure drops, in addition to the ability to fluidize cohesive and viscous materials. The volume of dead regions as well as channeling and bubble formation may also be reduced.

Soponronnarit *et al.* (1998) ^[15] designed, constructed and tested a prototype of vibro-fluidized bed dryer with a capacity of 2.5-5.0 t/h and reported that paddy drying with the vibro-fluidization technique consumed specific primary energy 7% less as compared to the fluidized bed drying without vibration. Han *et al.* (1991) ^[5] reported appropriate operating conditions of paddy drying using fluidization technique to obtain good paddy quality and recommended that vibration intensity and amplitude should be in range of 1.0-3.3 and 5-10 mm, respectively. Different workers have worked on drying of food product (Rysin and Ginzburg, 1992) ^[12], muskmelon seeds (Gulzar *et al.*, 2017) ^[4], tea (Akhtaruzzaman *et al.*, 2013) ^[1] and mint leaves (Ardestani *et al.*, 2015) ^[2] in vibro-fluidization technique and suggested suitable operating conditions of vibration intensity, amplitude, bed characteristics, heat transfer, minimum fluidization velocity and different time-temperature profiles. So, a laboratory mode VFBD has been designed, fabricated and tested for drying of paddy in the present study. As fluidized bed dryers are suitable for high moisture paddy, the developed dryer can also be used for drying of parboiled paddy at lesser time and lower energy consumption.

Materials and Methods

Design of vibro-fluidised bed dryer

The design calculations of the vibro-fluidized bed paddy dryer were done based on the following assumptions.

Assumptions for design of the dryer

Amount of paddy to be dried per batch	50 kg
Initial MC	32% (w.b.)
Final MC	34% (w.b.)
Drying time	3h
Ambient air temperature	30 °C
Ambient air RH	60%
Drying air RH	35%
Drying air temperature	40 °C
Exhaust air temperature	33 °C
Grain outlet temperature	33 °C
Bulk density of paddy	600 kg/m ³
Grain bed depth	20 cm

Calculation of rate of moisture removal from the product during drying

Bone dry of paddy to be dried = amount of paddy to be dried x (100-Initial MC (wb))/100 = 50 x (100-32)/100 = 34 kg

Amount of moisture present initially = 50-34 = 16 kg

Amount of moisture removed from paddy during drying = Bone dry weight (Initial MC (db)-Final MC (db)) = 34 x {(32/(100-32))-(14/(100-14))} = 10.46 kg

Moisture removed per hour = Amount of moisture removed/drying time = 10.46/3 = 3.48 kg/h

Calculation of the heat requirement for drying and air requirement

Sensible heat gain of paddy = paddy bone dry weight x specific heat x (Grain temp-Amb. temp) = 34 x 11.676 x (33-30) = 170.952 kJ

Sensible heat gain by water = Amount of water present x Specific heat of water (Grain temp-Amb. temp) = 16 x 4.19 x (33-30) = 201.12 kJ

Latent heat requirement = Amount of water removed x latent heat of vaporization = 10.46 x 2501.4 = 26177.4 kJ

Total heat requirement = 26549.47 kJ

Heat requirement assuming 10% loss = 26549/0.9 = 29499.4 kJ

Rate of heat transfer = Total heat requirement/Drying time = 29499.4/3 = 9833 kJ/h = 9.83 MJ/h

Drying air requirement = 9833/(1.04 x (40-33) x 3600) = 0.377 kg/s

Volume of air requirement = 0.377 x Humid volume = 0.0317 x 0.918 = 0.346 m³/s

Calculation of blower power requirement

Volume of paddy to be dried = Weight/Bulk density = 50/600 = 0.0833 m³

Floor area requirement = Volume/Grain bed depth = 0.0833/0.2 = 0.4166 m²

Assuming 50% perforations, area through which air passes = 0.4166 x 0.5 = 0.2083 m²

Air flow rate per unit area = Volumetric air flow rate x 60/Area of air flow = 0.346 x 60/0.2083 = 99.7 m³/m²min = 1.66 m³/m²s

If pressure drop is 8.13 cm water column for 30.48 cm grain bed depth, pressure drop for 20 cm grain bed depth = 8.13 x 20/30.48 = 5.33 cm = 0.0533 m water column

Pressure drop in air column = 0.0533 x 1000 x 0.918 = 48.98 m air column

Assuming 20% pressure loss in the duct, total pressure drop = 48.98 x 1.2 = 58.7 m

Power requirement of blower = Air column height x air flow rate x 9.81/746 = 58.7 x 0.377 x 9.81/746 = 0.29 hp

Assuming mechanical efficiency of motor to be 0.9, the motive power requirement is 0.32 hp. So a 0.5 hp motor is chosen for the blower.

Calculation of dryer dimension

The height of paddy grain in drying chamber is 0.2m. By providing 0.1 m clearance above the sample in the drying bed, height of drying chamber is 0.3 m = 30 cm

Providing height of plenum chamber as 0.8 m, height of the dryer is 1.1 m which is comfortable loading height by a person.

The floor area was calculated as 0.4166m². Assuming length to width ratio of drying chamber to be 2:1, the width of drying chamber = $100 \times \sqrt{\frac{0.4166}{2}} = 45 \text{ cm}$

Length of drying chamber = 90 cm

So, the dimension of drying chamber is 0.9 m x 0.45 m x 0.3 m

Providing space of 10 cm on both sides of the drying chamber, length and width of plenum is 110 cm and 65 cm, respectively.

So the dimension of drying chamber with plenum is = 1.1 m x 0.65 m x 1.1 m

Calculation of vibrating motor power

The mass of paddy is 50 kg. Assuming empty mass of

drying chamber to be oscillated is 10 kg, total mass of drying chamber with paddy is 60 kg.

If the rpm of vibrating motor is reduced from 1440 rpm to 205 rpm, the vibration frequency is 3.4 revolutions per second.

Eccentricity of the vibrating shaft is 0.0125 m and co-efficient of friction to be 0.4

So torque = $T = 60 \times 9.81 \times 0.4 \times 0.0125 = 2.94 \text{ Nm}$

Power required = $2 \times \eta \times N \times T = 62.8 \text{ W}$

If total resistance factor due to friction in moving part and secondary resistances is assumed to be 3, power requirement is 188.5 W.

Assuming mechanical efficiency of motor and transmission efficiency to be 0.9 and 0.8, then motive power requirement is 262 W. So a 0.5hp motor is chosen for vibration of the drying bed.

Abstract of design results

Moisture to be removed	10.46 kg
Moisture removed rate	3.49 kg/h
Volume of grain bed	0.0833 m ³
Dimension of drying chamber	0.9 m x 0.45 m x 0.3 m
Dimension of drying chamber with plenum	1.1 m x 0.65 m x 1.1 m
Heat requirement	14 MJ/h
Electrical heater power	3.9 kW
Vol air required	1250 m ³ /h
Blower power requirement	0.5 hp
Vibrating motor power requirement	0.5 hp

Development of laboratory model Vibro fluidized bed paddy dryer

Basing on the design data, a laboratory model vibro-fluidized bed paddy dryer of 50 kg holding capacity was fabricated in the workshop of College of Agricultural Engineering and Technology, Bhubaneswar (Fig. 1). The dryer was fabricated in order to run it in batch mode with mechanical vibration of the drying bed. The dryer consisted of different components i.e. drying chamber, plenum chamber, vibration system, air heating unit, blower with pipes.

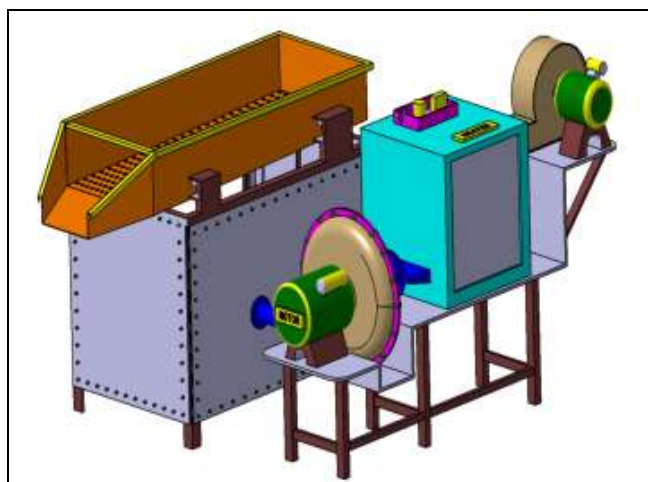


Fig 1: Developed Vibro-fluidized bed paddy dryer

Principle of Operation

Paddy is loaded into the drying chamber up to the required height. Supplementary blower feeds ambient air to the air heating unit. The air is heated in the air heating unit by electrical heaters. The heated drying air from the air heating unit is blown to the drying chamber through the plenum

chamber. The motor of the vibration system provides vibration to the drying chamber. Vibration of drying bed facilitates uniform drying by mixing of grain mass during drying. The solid modeling.

Testing of the dryer

Determination of mixing index in vibrating drying bed

Vibration of grain bed leads to uniform drying due to intimate mixing of grain during drying. So, mixing index of grain during vibration of drying bed was studied. About 6 kg of paddy was taken and mixed well with red colour. The coloured paddy was first loaded to the bottom layer of the drying chamber. Then 14 kg uncoloured paddy was loaded above it. Then the motor of the vibration system was switched on to vibrate the drying bed. Representative samples were collected from different layers (top, middle and bottom) of the drying bed at regular interval of 30 min. The coloured and uncoloured grain were separated and counted to determine the proportion of coloured grain in the sample. The mixing index at different time of mixing was determined from the initial variance, variance at any given time and final variance approached after a long time.

$$\text{Mixing index} = \frac{s_0^2 - s^2}{s_0^2 - s_\infty^2}$$

$$S_0^2 = p \times (1-p)$$

$$\text{Variance} = \frac{\sum(x-\bar{x})^2}{(n-1)}$$

p = Proportion coloured grain mixed = 0.3

Drying experiment

Sample preparation

Paddy (Novin variety) sample used for the drying experiment was purchased from OUAT Central Farm. The paddy was first cleaned to remove the unwanted foreign materials. The initial moisture content of the grain was measured by digital moisture meter and hot air oven method. After determination of initial moisture content, calculated amount of water was sprayed on the paddy and mixed well to obtain the desired initial moisture level of 32% (w.b.) which was the moisture content of parboiled paddy. The sample was then heaped, covered with tarpaulin sheet and kept for 16-24 hours for moisture equilibration.

Drying

The drying experiments were conducted with 10 cm grain bed depth at temperatures 40°C in both static (without vibration) and vibration mode of drying bed. Before starting the experiment, the electrical connections were checked carefully and the dryer was started 30 min before the experiment in order to attain desired drying air temperature and steady state condition. After stabilization of the whole system, 20 kg of conditioned paddy samples were loaded manually into the drying chamber up to 10 cm depth. Paddy samples were drawn by a sample collector at regular intervals of 30 minutes for moisture content measurement in triplicate. The temperature and relative humidity of ambient, drying and exhaust air were measured during the drying process using digital temperature and RH recorder and data logger. The air velocity was also measured using a hot wire anemometer.

The electrical energy consumed by blower, air heating unit and vibrating motor during the drying process was measured by an energy meter. The plot of moisture content vs drying time and drying rate vs moisture content were plotted for both static and vibration mode of operation to analyze the drying behavior. The moisture ratio and drying time data were fitted to the exponential model to determine the drying constant. The samples after drying were kept as such for 12 h for moisture equilibration and the samples were used for milling study.

$$\text{Drying rate} = \left(\frac{\%M.C.(d.b.)}{h} \right)$$

$$= \frac{\text{Moisture content (d.b.) at } t + dt - \text{Moisture content (d.b.) at time } t}{\text{Time interval } dt}$$

Dryer performance factor

The dryer performance parameters such as effective heat efficiency, heat utilization factor, specific energy

$$\text{Heat Utilization Factor (HUF)} = \frac{\text{Air temperature decrease during drying}}{\text{Air temperature increase due}} \text{ heating of air}$$

$$= \frac{\text{Temperature of drying air} - \text{Temperature of exhaust air}}{\text{Temperature of drying air} - \text{Temperature of ambient air}}$$

Drying efficiency

Dryer efficiency was defined as the ratio effective energy utilized during drying to the total energy supplied to the system. It was calculated using following formulae.

$$\text{Drying efficiency, \%} = \frac{\text{Water removed} \times \text{latent heat of evaporation}}{\text{Total energy consumption}} \times 100$$

$$\text{Milling Recovery, \%} = \frac{\text{Weight of milled rice (head rice \& broken rice) obtained}}{\text{Weight of dried paddy sample taken for Milling}} \times 100$$

The rice samples obtained by milling were graded manually to separate head rice (at least 75% of their original length) and broken kernels to determine head rice yield. It is defined as the ratio of the mass of head rice to the mass of paddy taken for milling (Ibrahim, 2014) [6].

$$\text{Head rice yield, \%} = \frac{\text{Weight of head rice}}{\text{Weight of paddy sample taken for milling}} \times 100$$

Results and Discussion

Effect of vibration of drying bed on mixing index

The proportion of coloured grain in the samples collected from top, middle and bottom layer at different time interval is shown in Fig. 2. The mixing index for different mixing time is given in Table 1. There was no significant difference of coloured grain proportions of 30, 60 and 90 min mixing time indicating that proper mixing occurred within 30 min of operation of the dryer. The mixing index was observed to be more than 0.99 after 30 min of operation. However, proportion of coloured grain varied significantly among different layers. Higher proportion of coloured paddy was

consumption and drying efficiency were calculated for comparison between static and vibration mode of drying.

Effective heat efficiency (EHE)

The effective heat efficiency considers the sensible heat in drying air as being the effective heat for drying which is calculated as follows (Chakravarty, 1994) [3].

The effective heat efficiency of a grain dryer is

$$\text{Effective heat efficiency (EHE)} = \frac{\text{Air temperature decrease during drying}}{\text{Maximum possible decrease } \epsilon \text{ drying}}$$

$$= \frac{\text{Temperature of drying air} - \text{Temperature of exhaust air}}{\text{Temperature of drying air} - \text{Wet bulb temperature}}$$

Heat Utilization Factor

It is the ratio of temperature decrease due to cooling of the air during drying and the temperature increase due to heating of air.

Milling quality

The milling quality of dried paddy was determined for comparison between static and vibration mode of drying. Approximately 125 g of paddy sample was taken for dehulling in a Satake testing rubber roll sheller followed by polishing using a Satake testing rice polisher. The weight of the rice sample obtained was taken to determine the milling recovery which is the ratio of weight of milled rice to the total amount of paddy taken (Ibrahim, 2014) [6].

found in the bottom layer as coloured grains were initially loaded to the bottom layer of the dryer followed by loading uncoloured grain on it.

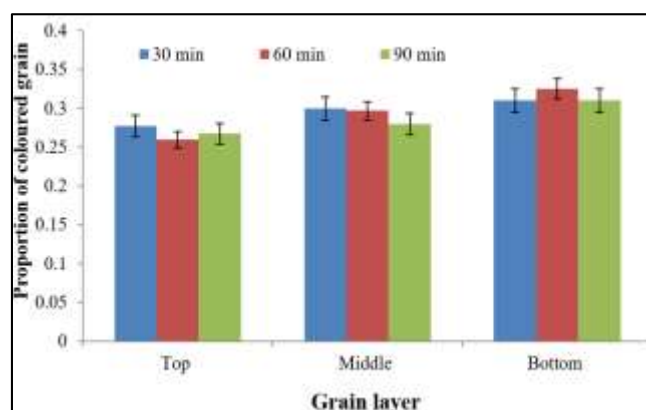


Fig 2: Variation of mixing time on proportion of coloured grains in different layers

Table 1: Effect of mixing time on mixing index

Mixing time	Proportion of coloured grains			Variance	Mixing index
	Top layer	Middle layer	Bottom layer		
30 min	0.277	0.300	0.310	0.000282	0.998661
60 min	0.260	0.297	0.325	0.001063	0.994942
90 min	0.267	0.280	0.310	0.00048	0.997718

Effect of vibration on drying characteristics

Moisture content reduction with drying time

The change in moisture content of paddy dried at 40 °C in vibro-fluidised bed dryer operated in static and vibratory mode of operation is shown in Fig. 3. Moisture removal was observed to be faster when drying bed was vibrated mechanically as indicated by the steepness of the curve. It took 120 and 180 min to dry paddy from an initial average moisture content of 48 to 14% (d.b.) when the dryer was operated in vibratory and static mode, respectively. The lower drying time in vibration mode was due to mixing of grain samples during drying and exposure of all surfaces to the drying air. It was observed that both drying time and vibration had significant effect ($p < 0.05$) on moisture content of sample during drying. However, there was no significant difference in moisture content of paddy up to 30 min of drying between both the modes of operation owing to the high initial moisture content of the samples. The moisture ratio varied exponentially with drying time having coefficient of regression value of 0.98 (Fig. 4). So, the exponential model described well the variation of moisture content data with drying time.

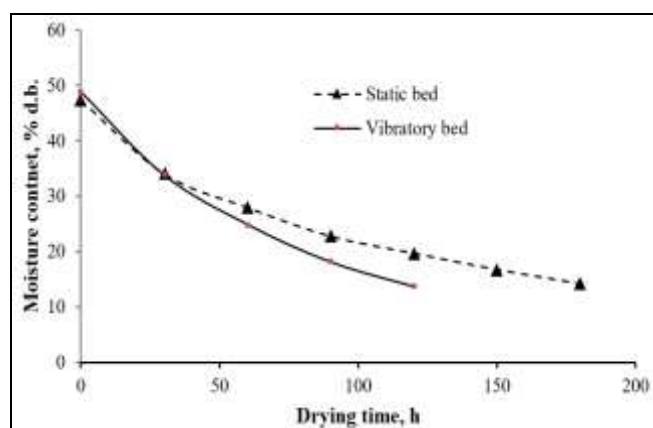


Fig 3: Variation of moisture content with drying time during static and vibratory mode of drying

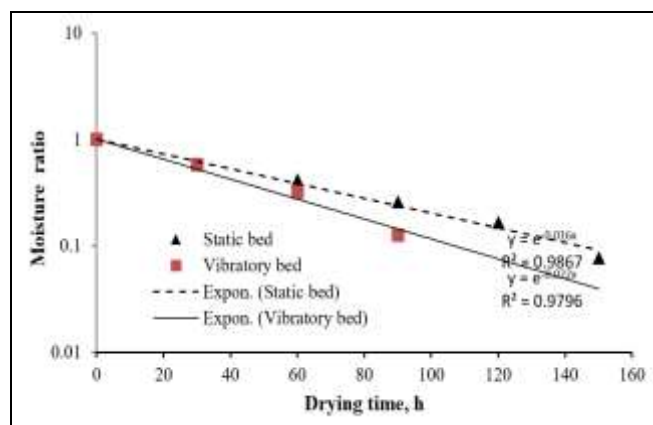


Fig 4: Variation of moisture ratio with drying time during static and vibratory mode of drying

Effect on drying rate

The drying rate was found to be more in vibratory mode of operation of the dryer (Fig. 5). The drying took place under falling rate period in both the drying modes of with and without vibration (static bed). A prominent second falling rate period was observed in static bed drying which might be due to bottom dried layer. As grain samples got mixed

during drying in vibratory mode, drying rate was still higher at the later part of drying. The initial drying rate were found to be 30.1 and 26.67% m.c.(d.b.)/h in vibratory and static bed drying modes, respectively.

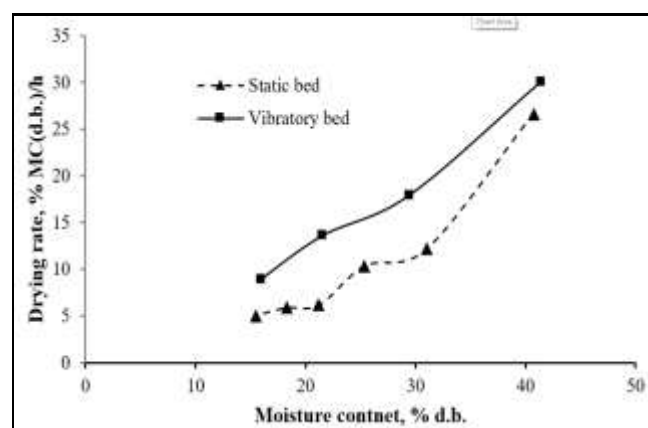


Fig 5: Variation of drying rate with moisture content during static and vibratory mode of drying

Temperature and RH of exhaust air during drying on vibratory bed

The temperature and relative humidity profile of the exhaust air and effective heat efficiency during vibratory bed drying is shown in Fig. 6. The relative humidity increased and temperature decreased slightly during initial period of drying due to rapid drying of high moisture paddy at the beginning (Appendix D). Then the relative humidity decreased and temperature increased as the drying proceeded. It was observed from Fig. 4.6, that exhaust air temperature approached drying air temperature after 120 min in vibratory mode of drying indicating completion of drying as the dried sample attained the equilibrium moisture content.

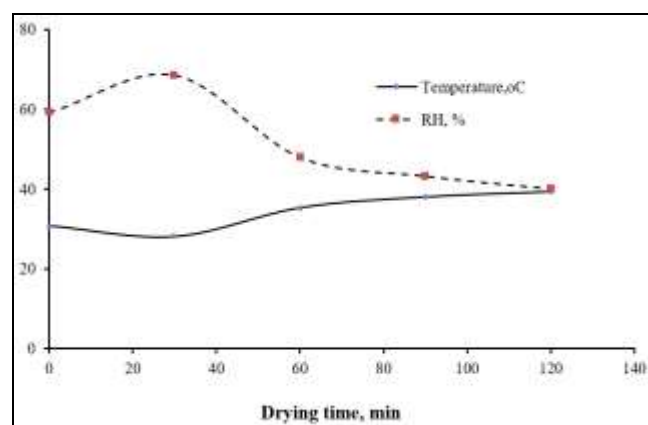


Fig 6: Change in temperature and relative humidity of exhaust air during vibratory bed drying

Performance of the dryer

Effective heat efficiency and heat utilization factor in vibratory bed drying

The effective heat efficiency increased initially to 0.86 due to higher drying rate which decreased to 0.05 at the final stage of drying (Fig. 7). Heat utilization factor followed a similar trend which increased from an initial value of 1.02 to 1.32 after 30 min and decreased subsequently to 0.08 after 120 min.

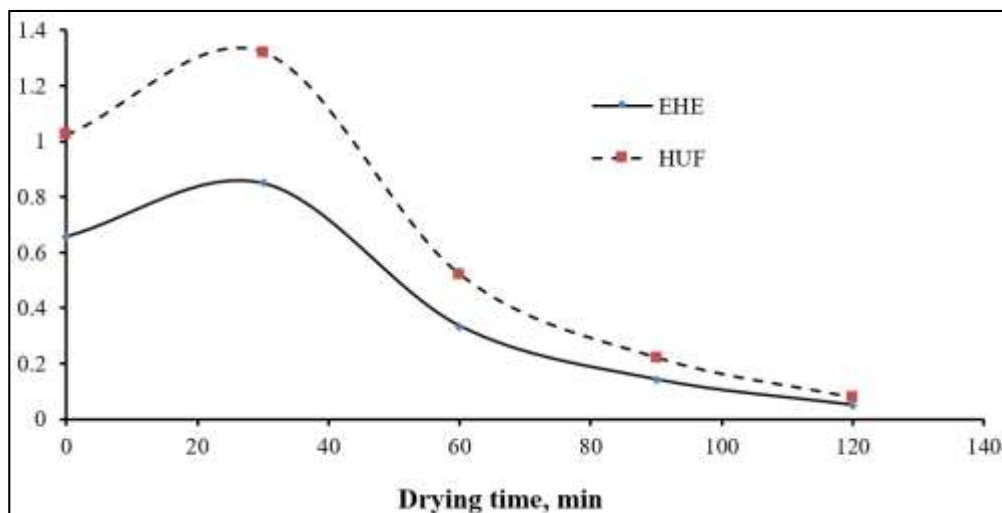


Fig 7: Change in effective heat utilization (EHE) and heat utilization factor (HUF) during vibratory bed drying

Specific energy consumption and drying efficiency

The drying rate constant were found to be 0.96 and 1.32 h^{-1} for dryer operation in static and vibratory bed drying. Vibration accelerated the drying rate by proper mixing and exposing all surface to drying air. The specific energy consumption were 1.0 and 0.79 kWh/kg water whereas, drying efficiency were 69.8 and 87.8% for static and vibratory mode of drying, respectively (Table 2). The lower specific energy consumption and higher drying efficiency in vibratory bed drying were due to lower drying time.

Effect of vibration of drying bed on milling quality

Milling recovery and head rice yield (HRY) are the important criteria in assessing the quality of the paddy, which is greatly influenced by drying. The milling yield were 66.8 and 66.2% whereas, head rice yield were 61.1 and 62.4% for paddy dried in static and vibratory mode of operation, respectively. The higher head rice yield in vibratory mode was probably due to uniform drying of sample because of mixing during drying.

Table 2: Comparison of dryer performance factors for static and vibratory bed drying in the vibro-fluidized bed dryer

	Static bed	Vibratory bed
Sample dried, kg	20	20
Grain bed depth, cm	10	10
Ambient temperature, °C	30	31
Ambient RH, %	42	57
Drying air temperature, °C	40	40
Drying air RH, %	24	35
Wet bulb temperature, °C	22	26
Air velocity, m/s	0.6	0.6
Drying time, h	3	2
Drying rate constant, h^{-1}	0.96	1.32
Moisture removed, kg	4.50	4.78
Average moisture extraction rate, kg/h	1.5	2.39
Total energy consumption, kWh	4.5	3.8
SEC, kWh/kg water	1.0	0.79
Drying efficiency, %	69.8	87.8
Milling yield, %	66.8	66.2
Head rice yield, %	61.1	62.4

Conclusion

The mixing index was observed to be more than 0.99 after 30 min of operation. There was no significant difference of coloured grain proportions of 30, 60 and 90 min mixing

time indicating that proper mixing occurred within 30 min of operation of the dryer. It took 120 and 180 min to dry paddy from an initial average moisture content of 48 to 14% (d.b.) when the dryer was operated in vibratory and static mode, respectively. It was observed that both drying time and vibration had significant effect ($p < 0.05$) on moisture content of sample during drying. The specific energy consumption were 1.0 and 0.79 kWh/kg water whereas, drying efficiency were 69.8 and 87.8% for static and vibratory mode of drying, respectively. The milling yields were 66.8 and 66.2% whereas, head rice yield were 61.1 and 62.4% for paddy dried in static and vibratory mode of operation, respectively. From the above study, it was concluded that vibro-fluidized bed dryer could be used for drying paddy efficiently at farm level with less drying time, lower energy consumption and higher head rice yield.

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