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Original Research Article

Performance Evaluation of Modified STR Dryer for Drying of Paddy in Process of Reducing Post-Harvest Losses

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Drying, STR dryer, field, paddy, moisture, air velocity

A B S T R A C T

Drying of grains after harvest is one of the important unit operation for reducing loss and storing for longer period for the purpose of seed consumption and marketing. High moisture causes the development of insects and molds that are harmful to the grain. It is necessary to adapt technology for drying paddy at small and marginal farmers' level as an alternative to traditional sun drying. In this study technical and financial performance was evaluated using a low cost modified STR dryer which has a capacity of 500 kg per batch. Four different air velocities such as 1.5, 2.0, 2.5 and 3.0 m/s were used for drying with temperature of 50 °C. The air temperature and moisture content inside grain bin was recorded using probe thermo cum moisture meter. The results showed that the temperature and moisture distributions in STR dryer were quite uniform. Duration of drying of paddy from 24.78 % to 8.5 % moisture content (w.b.) was 3.5–7 h depending upon the source of energy used. The operating cost of drying was found Rs 1.23 per kg with electric based blower. At all the air velocities, the lowest value of lightness was observed at air velocity of 3.0 m/s and the highest values were recorded at air velocity 2.0 m/s. The benefit-cost ratio and payback period were found 1.9 and 0.28 yr for diesel engine operated STR dryer from the experiments at field level. This dryer is considered to be a one of the alternative effective drying technologies.

Introduction

Drying is the process of removing moisture from a porous media by evaporation, in which hot air is passed through a thin layer of the material until equilibrium moisture content (EMC) achieved. Moisture removal from an agricultural product depends on drying air temperature, velocity, relative humidity, variety and maturity. Hence, various isolated and combined methods are involved in moisture removal from a grain Couto, 2002). India is the second largest rice producer in the world. Rice provides more calories per hectare than any other cereal crops. Its nutritional value is high among cereals and grains. Though the protein content of rice is less than that of wheat, the protein digestibility and biological value of rice protein are the highest among wheat and other cereals. Paddy is harvested in moisture range between 16 to 28% w.b. dependent on harvest method, variety and location. Paddy has a high respiration rate and is susceptible to attacks by micro-organisms, insects and other pests at harvesting time. High moisture promotes the development of insects and molds that are harmful to the grain. If the moisture content of paddy is inappropriate for storage, it will be exposed to fungal diseases and chemical reactions and damaged after paddy husking (Mehdizadeh and Zomorodian, 2012). High moisture in grain also lowers the germination rate of paddy. Therefore, drying of paddy is critical to prevent insect infestation and quality deterioration of rice grain and seed. Drying of paddy is a major problem in Bihar due to rain season (June - August) and short day and foggy weather (November –January). Improper or delayed drying leads to loss in grain quality, at post-harvest level. To reduce post-harvest losses especially in drying operation and increasing quality of storage paddy, it is necessary to adapt drying technologies for paddy at small scale traders and farmers' level (Bala *et al.,* 2010).

The STR dryer was modified after testing and the modified version was tested again in Kharif season 2017. From the lab test and economic analysis, it was found that STR dryer was better than open field sun drying.

Therefore, it is necessary to test this modified version at the field level to investigate technical performance and cross-check the economic parameters. The specific objectives of the research are to study spatial distribution of drying air temperature and velocity in STR dryer, and also to investigate the technical and financial performance of STR dryer at field level of Bihar.

Materials and Methods

Sample preparation

Rajendra sweta variety of paddy was procured from directorate of seed and farm, BAU, Sabour, Bhagalpur in the state of Bihar (India) for this study. A randomly selected sample was, then cleaned to remove any impurities followed by mechanical grading to achieve quality paddy.

Initial Moisture Content

Hot air oven method was used to determine the initial moisture content of the selected paddy. A pre weighed paddy sample of 15 g was kept in a pre-dried and weighed moisture box in oven at 80ºC for 24 hours (Ranganna, 2002). The dried samples were cooled in desiccators to room temperature and then weighed using electronic balance and moisture content (w.b.) of sample which was expressed as g water/g dry matter was used for calculations.

STR Dryer

The STR dryer consists of inner bin, outer bin, hot air pipe, blower (fan) with 1 hp motor and stove (chula). The dryer is modified with attaching 1 hp motor, provision of gate valve for ambient air entry and 15° slope at bottom for easy discharge of dried grains. The diameter of outer bin is adjustable to hold desired volume of paddy sample. The dryer is made of two perforated concentric cylinders with grains inside the annular space. Hot air allows to pass from top to bottom through the inner prepared cylinder bin grains inside the annular space. An axial flow blower is used to suck the hot air from the stove (Chula) through iron pipe and force the air radially through perforated bins (Fig. 1 and 2). Locally available rice husk briquette is used as fuel in a portable locally made stove.

Dryer installation procedure

The STR dryer was installed and tested at department of Agricultural Engineering, Bihar Agricultural University, Sabour for paddy. At first, surface must be levelled where dryer to be installed. Once dryer installed on level surface, 500 kg of paddy was filled in annular space. The axial flow blower was set up on the top of the inner bin of the dryer and a polythene cover was used to protect hot air leaking from the paddy of the dryer using bricks. A stove (chula) was placed in one side of the grain bin and firing was done using rice husk briquette. Then the hot air supply pipe was fixed with stove at one end and drying chamber with other end.

Parameters observation during drying

Moisture content and temperature were measured from nine locations inside the bin during the operation. Among the nine locations namely T_1…..T_9 and M_1……M_9 respectively. Moisture content at M_1 and M_2 maintaining 45 and 55 cm from centre of inner bin; M_3, M_4, M_5 maintaining 65, 50, 35; M_6, M_7, M_8 and M_9 maintaining a distance of 65, 50, 35 and 65 cm distance from centre line of inner bin during drying operation. The experimental runs of vertical drying were conducted at initial moisture content of 21.5, 22.5, 23.10 and 24.78 % (w.b) with four air velocities (1.5, 2.0, 2.5 and 3.0 m/s). The moisture content was measured using probe sensor digital moisture meter at a time interval of 10 min during first hour of drying, 30 min for second hour and 60 min for third hour till the end of drying. Drying was terminated when the grains reached at Equilibrium moisture content.

Colour measurement

Colour is important to consumer as a mean of identification, as a method of judging quality and for its basic esthetic value and food is no exemption. The overall objective of colour to the food is to make it appealing and recognizable. The most common technique to assess the colour is colorimeter. There are several colour scales used in a Hunter Lab Colorimeter such as L^* a^* and b^* which represented the surface colour. The colour values are obtained as L^* is the lightness coefficient, ranging from 0 (black) to 100 (white), a^* is purple-red (positive a^* value) and blue-green (negative a^* value). a* and b^*, that represents yellow (positive b^* value) or blue (negative b^* value) colour (McGuire, 1992).

Colour of the dried paddy was measured using a Hunter Lab Colorimeter. A cylindrical glass sample cup (6.35 cm dia. x 4 cm deep) was placed at the light port (3.175 cm dia). Each sample was measured for colour values three times.

The instrument was initially calibrated with a black as well as with standard white plate. From these values chroma (C) was calculated according to following relation as suggested by (Pomeranz and Meloan, 1971)

$$h^0 = \arctan (b^*/a^*)$$

$$C = \sqrt{(a^*)^2 + (b^*)^2}$$

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

Where,

$$\Delta L^* = L^* - L^*_{st}$$

$$\Delta a^* = a^* - a^*_{st}$$

$$\Delta b^* = b^* - b^*_{st}$$

Where, st subscript represents L*, a* and b* values of a standard rice.

Energy Consumption

In order to mathematically express Qt as a function of MC and T for the different types of rice, Qt, MC and T data were used to statistically determine the constants of the relationship given by Truong *et al.*, (2005):

$$Q_t = A_1 + B_1.T + (A_2 + B_2.T)\exp(-A_3.MC) \quad (1)$$

Qt data was used to develop an equation that predicts the theoretical energy required per unit mass dry matter of rice (QTrice) to dry rice from a given MCi to a MCf when drying at a given T, similar in approach to Tsami *et al.*, (1990). To calculate QTrice, an integration of Eq. (1) was performed:

$$Q_{T_{rice}} = \int_{MC_i}^{MC_f} Q_t dMC \quad (2)$$

Where, QTrice is the energy required to dry rice from MCi to MCf per unit dry mass of rice at a given T. Thus, T was considered constant throughout the integration.

Substituting Eq. (1) into Eq. (2) and integrating

$$Q_{T_{rice}} = \int_{MC_i}^{MC_f} (A_1 + B_1.T + (A_2 + B_2.T)\exp(-A_3.MC))dMC = \quad (3)$$

$$= A_1[MC_f - MC_i] + B_1.T.[MC_f - MC_i] + \frac{(A_2 + B_2.T)}{-A_3}(\exp(-A_3.MC_f) - \exp(-A_3.MC_i))$$

By using Eq. (3), expressions for each type of rice were obtained, whereby energy requirements for drying a unit mass of rice dry matter were obtained for given MCi, MCf and T inputs. The value of QTrice (J/kg dry matter rice) is negative but the absolute value was reported.

To express the energy requirements to dry rice from an MCi to MCf on a per unit mass of water removed, QTrice from Eq. (3) was divided by Δmevap the mass of water removed in the drying process per unit rice dry matter, which can be expressed as:

$$\Delta m_{evap} = MC_i - MC_f \quad (4)$$

It is emphasized that QTrice can thus be expressed as drying energy required per unit mass of rice dry matter, Eq. (3), or energy per unit mass of water removed by dividing Eq. (3) by Δmevap(Eq.4).

Results and Discussion

Performance of dryer

The field performance of modified STR dryer was satisfactory in terms of drying capacity, drying efficiency and milling recovery of dried paddy. Paddy was dried unit it reaches the equilibrium moisture content when no more change in moisture content during drying was observed. The moisture content versus drying time for paddy at selected air velocity is shown in fig 4. It is apparent that moisture content decreases continuously with drying time. The moisture content after 50 min of drying at air velocity of 1.5, 2.0, 2.5 and 3.0 m/s was 11.67, 10.79, 9.76 and 8.31 % (wb) and after 107 min it was found to be 10.09, 9.37, 8.55 and 7.89 % (wb) respectively. The drying times to reach the equilibrium moisture content for paddy were 390, 250 and 210 min at 1.5, 2.0, 2.5 and 3.0 m/s respectively.

As indicated in the curves (fig4), there was no constant rate period in drying of paddy. All the drying process occurred in the falling rate period, starting from the initial moisture content of paddy (24.75%, 22.50%, 21.50%, 23.10% wb) to final moisture content (8.5%, 9.0%, 8.75%, and 8.5%) wet basis. Diamante and Munro (1993) studied that in the falling rate period the material surface is no longer saturated with water and drying rate is controlled by diffusion of moisture from the interior of solid to the surface.

The temperature sensors were set at the different distance from the centre line of the inner bin from where hot air was entering into grain pile. Temperature was varied initially among the horizontal locations because distances from the center of the inner bin were different. The temperature profile proved that the drying air uniformly distributed inside the dryer (Fig. 4). Table 2 shows that maximum temperature at T_1 (51 ºC) and minimum temperature was at T_3 (38 ºC) for air velocity of 1.5 m/s. Similarly maximum at T_1 (52 ºC) and lowest at T8 (42 ºC) for air velocity of 2.0 m/s; maximum at T_1 (55 ºC) and lowest at T_7 (40 ºC) for air velocity of 2.5 m/s; maximum at T_1 (57ºC) and lowest at T_8 (46ºC) for air velocity of 3.0 m/s. After certain time, temperature distribution of all horizontal sensors location became almost same.

The drying temperature increased rapidly within two hours and then increasing rate was nearly steady or slowed down till the completion of drying. It proves that hot air temperature uniformly distributed to all over the drying section of the dryer. Moisture content measured from same points were also recorded. Rapid moisture removal was observed at M_1 (18.10%), M_6 (17.25%), M_6 (17.51%) and M_5 (17.08%) for air velocity of 1.5, 2.0, 2.5 and 3.0 m/s respectively. From fig (5) it was observed that drying rate was maximum at air velocity of 3.0 m/s and lowest was observed at 1.5 m/s.

However, variations of the temperature over the time depend on the efficiency of steady fuel supply for producing same hot air temperature which needs to be taken care of. The drying time varied with the variation of grain size. In first treatment, the drying time is lower than that of other treatments because of bold grain size. The spore space is much higher in bold grain compared to other medium grains. Drying air can easily pass through the big spore space from inner part to outer part of grain bin which directly affect temperature distribution and drying time. The grain was dried uniformly and reached same and desired moisture level in all part of the dryer in 3.5 to 7.5 hours depending on the initial moisture content of paddy and air velocity. Similar results have been reported for paddy seed drying in hybrid dryer (Hossain *et al.,* 2012). The paddy was dried from 24.78% to 8.5%; 22.5 to 9%; 21.5 to 8.75 and 23.10 to 8.5 at air velocity of 1.5, 2.0, 2.5 and 3.0 m/s within the range of 3.5 to 7.5 hrs, respectively (Table 1).

Color Analysis

The average measured color indices of the fresh paddy were 60.12, -7.28 and 14.71 for *L**, *a** and *b**, respectively. Color change conditions and the effects of the various air velocity, and *L*a*b** values showed that the color changing characteristics at higher air velocity were more than on lowest air velocity. As a result, the changing of color values at 3.0 m/s was more than other velocity and temperatures (Fig 6) because, with increasing air velocity, the husk surface of paddy became darker and the variations of the sample color increased after drying process. The average values of *L**, *a** and *b** were obtained in the drying process at three iterations. The *L** values of paddy during the drying process decreased with increase in drying time.

Brightness change of the dried samples can be taken as a measurement of browning (Lee and Coates, 1999). Values of *a** and *b** increased with increase in drying time (Fig 6), so that these results were similar to those reported by Shafafi Zenozian *et al.,* (2008).

Table.1 Test result of modified STR dryer at four different air velocity

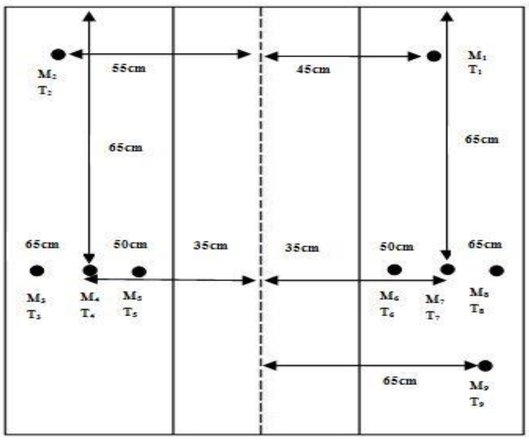
Particulars	Air velocity			
	1.5 m/s	**2.0 m/s**	**2.5 m/s**	**3.0 m/s**
Loading Date	15/10/2017	22/10/2017	29/10/2017	03/11/2017
Unloading Date	15/10/2016	22/10/2017	29/10/2017	03/11/2017
Capacity(kg)	500	450	475	490
Initial MC (%, wb)	24.75	22.50	21.50	23.10
Final MC (%, wb)	8.5	9.0	8.75	8.50
Fan speed (rPM)	950	1050	1200	1400
Energy Consumption (kWh)	18	12.5	8.5	9
Drying Time (min)	7.5	6.5	4.17	3.5

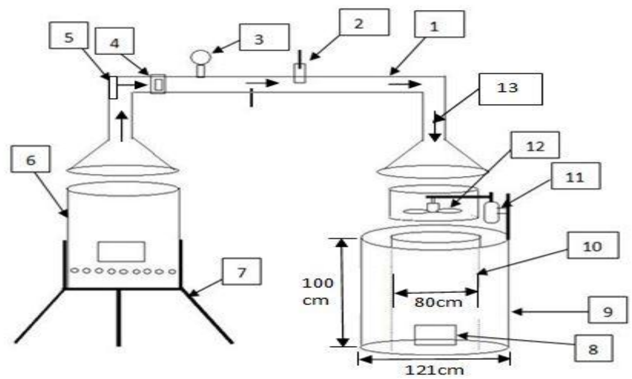
Table.2 Temperature and Moisture content during drying after one hour

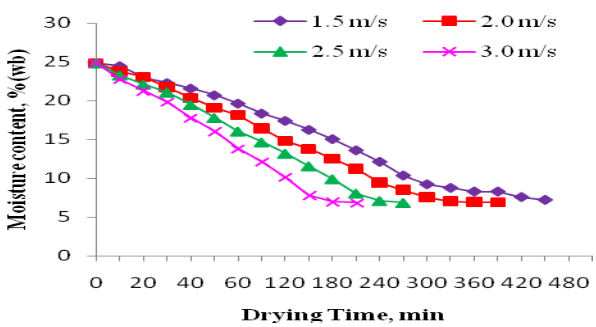
Point	Air velocity							
	1.5 m/s		**2.0 m/s**		**2.5 m/s**		**3.0 m/s**	
	T(°C)	**M(%,wb)**	**T(°C)**	**M(%,wb)**	**T(°C)**	**M(%,wb)**	**T(°C)**	**M(%,wb)**
T_1M_1	51.0	18.10	52.0	17.38	55.0	17.72	57.0	17.63
T_2M_2	46.0	18.13	50.0	18.32	51.0	17.91	53.0	17.81
T_3M_3	38.0	18.81	46.0	18.81	48.0	18.31	51.0	17.31
T_4M_4	40.0	18.14	48.0	18.06	46.0	18.21	49.0	17.14
T_5M_5	44.0	18.31	49.0	17.32	43.0	17.81	48.0	17.08
T_6M_6	47.0	18.19	48.0	17.25	41.0	17.51	49.0	17.28
T_7M_7	44.0	18.31	46.0	18.21	40.0	18.23	47.0	17.47
T_8M_8	40.0	18.64	42.0	18.37	43.0	17.76	46.0	17.51
T_9M_9	39.0	18.72	43.0	18.16	45.0	17.81	48.0	17.25

Fig.1 Photographic view of modified STR dryer

Fig.2 Temperature & Moisture measured at different locations of the dryer Fig.3 Schematic diagram 1. Hollow pipe; 2. Digital temperature sensor; 3. Pressure gauge; 4. Digital anemometer; 5. Gate valve; 6. Stove; 7. Tripod stand; 8. Discharge gate; 9. Outer cylindrical bin; 10. Perforated inner cylindrical bin; 11. Motor 12. Fan and 13. Hot air







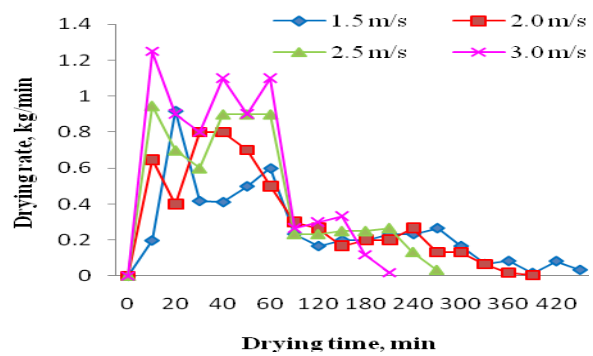
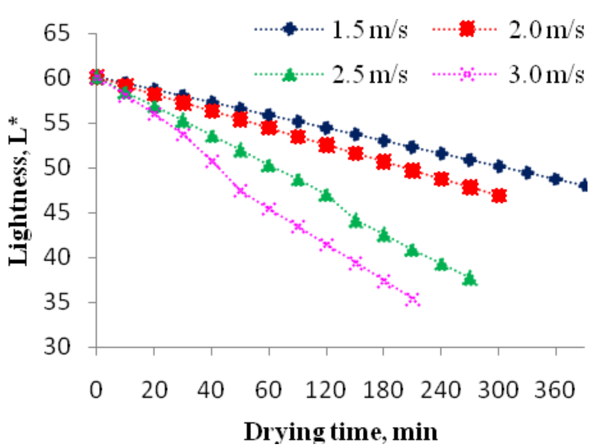


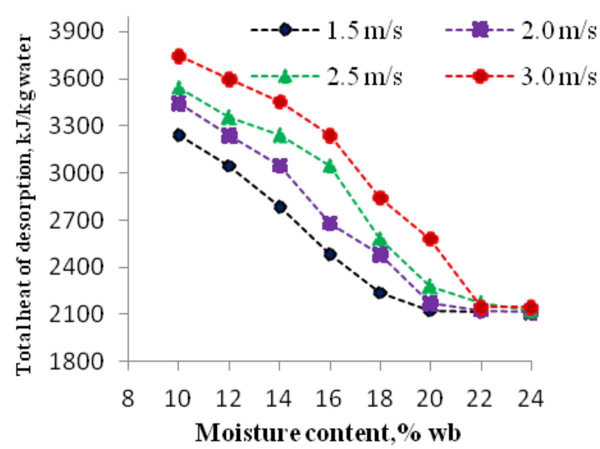
Fig.4 Effect of air velocity on drying curve at different air velocity

Fig.5 Effect of air velocity on drying rate at different air velocity

Fig.6 Variation in lightness with drying time at different air velocity for paddy

Fig.7 Total heat of desorption (Qt) at moisture content (24.78% wb) rice at different air velocity





At all air velocities, the lowest *L*a*b** values corresponded to air velocity of 3.0 m/s and the highest values were recorded at air velocity 2.0 m/s with air temperature of 50°C. This nonlinearity in color feature changes may be due the distortion resistance of the paddy crust at the early period of moisture decline. In other words, at the initial stages of drying, free water was removed from capillary tubes without causing a significant variation in the color of the paddy. After this stage, the color features gradually changed. One of the other reasons of the paddy color changes was pigment degradation of paddy. This result is similar to that of Wan *et al.,* (2011) and Golpour *et al.,* (2015) for paddy.

Energy required during drying

Based on Eq. (3), mathematical expressions that predict the energy required to dry rice from an MCi to a desired MCf (QTrice) at a given drying T were developed. Eq. (3) can be adjusted to predict energy requirements to dry rice from an MCi to an MCf on a per unit mass of water removed basis by dividing by the mass of water removed (Eq. (4)). Fig. 7 shows the variation of QTrice (drying energy required per unit mass wet rice and per unit dry matter) with MCi for paddy at 60°C. QTrice per unit mass wet rice was obtained by dividing QTrice (Eq. (3)) by the amount of wet rice corresponding to a unit mass dry matter at the MCi. The trends indicated in Fig. 7 are practically linear. An explanation for this would be that the linear terms of the equations as shown, representing the energy required to vaporize free water, are considerably greater than the exponential terms and therefore, the linear terms contribute considerably more to QTrice. Nevertheless, in order to obtain accurate theoretical energy requirements, including both terms in the equation is necessary because as MC decreases. For instance, the exponential term is 4.2% of the QTrice value when drying from 24.75, 22.5, 21.5, and 23% to 8.5, 9.0, 8.75, and 8.5% (w.b)

A conventional way of quantifying drying energy requirements in the grains industry is to express energy requirements on a per unit mass of water removed. Fig. 7 shows the energy required to dry rice from an MCi to a desired MCf of 8.5%, 9.0% 8.75% and 8.5% on a per unit mass of water removed at 60°C. QTrice decreased exponentially as MCi increases, when expressed on a per unit mass of water removed. In addition, QTrice increases as MCf decreases. Both of these observations reflect the increasing importance of Qn at the lower MC levels. Therefore, the energy required to remove a unit mass of water from rice should not be considered constant across MCi. QTrice decreases exponentially as MCi increases for the different rice types, when expressed on a per unit mass of water removed.

The effect of air velocity on energy requirements to dry rice from MCi to EMC is shown in Fig7. The energy required to dry rice from MCi to EMC decreases as drying air velocity increases. For instance, the energy required to dry rice from 24.75 to 8.5% at 1.5m/s was of 2,517 kJ/kg water removed, at 2.0m/s was of 2,482 kJ/kg water removed at 2.5m/s was of 2398kJ/kg and at 3.0m/s was of 2,417 kJ/kg water removed (Fig. 7). These results were inlined with similar report of Alam *et al.,* (2016) for paddy.

Economic analysis

The fabrication cost of STR dryer (Electric operated) was Rs.35000/- with economic service life 10 years. Economic analysis for STR dryer in field level showed that the operating cost of paddy dryer was found Rs

0.98 per kg whereas in traditional sun drying methods the operating cost was Rs 1.13 per kg. The benefit cost ratio (BCR) was 1.9. The payback period of the dryer was 0.28 year. Payback period of STR dryer was less than one year which was very encouraging for farmers in rural area of Bihar. It is evident from the economic analysis that STR dryer is economically viable in terms of technical and financial analysis and suitable for Bangladesh conditions. It would be more economical, if the dryer could be used for other crops such as maize and paddy seeds.

Temperature distribution and moisture removal rate of STR dryer were uniform throughout the dryer. Half ton (500 kg) paddy could be dried in 3.5 to 7 hours depending on initial moisture content. Drying cost was 1.13 kg with pay-back period of less than a year.

Therefore, it can be an effective means of drying paddy in the farmers and traders' level of Bihar. During field experiment, it was found that the farmers and small traders are very interested to use STR dryer in rainy season and cloudy weather because STR dryer can be used for drying paddy in their limited space in every households.

The energy required to remove a unit mass of water when drying from a given MCi to a desired MCf decreased exponentially as MCi increased at a given T. These equations provide a more accurate estimate of the energy required to dry rice than the approach of simply using the latent heat of vaporization when assessing energy efficiency of a drying process. At all air velocities, the lowest value of lightness was observed at air velocity of 3.0 m/s and the highest values were recorded at air velocity 2.0 m/s with air temperature of 50°C. The benefit-cost ratio and payback period were found 1.9 and 0.38 yr for electric operated STR dryer from the experiments at field level.

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