Development of an inflatable solar dryer for improved postharvest handling of paddy rice in humid climates

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Abstract: Rice is the staple food for more than three billion people worldwide. Although considerable progress has been made with respect to improved breeds and production practices, losses during postharvest handling remain considerable. Drying and storage of paddy are two key stages where management can be improved. For rice, grain moisture content of 14% prevents microbiological activity, while a level of about 12% minimizes quality losses over prolonged storage periods. Due to the need for simple and economical technologies, an inflatable solar dryer (ISD) was developed based on adaptations of the Hohenheim-type solar tunnel dryer. To form a drying tunnel, transparent polyethylene (PE) film attaches by zipper to a reinforced black polyvinyl chloride (PVC) film. To reduce heat loss, a flexible multilayer floor was used along the drying area. The tunnel does not need a substructure as it is stabilized adequately from pressure created by two axial flow ventilators. During experiments, paddy was spread on the floor and mixed with a special roller bar. The ISD has been evaluated for paddy in the Philippines during both rainy and dry seasons and was subsequently optimized. Sun drying and shade drying were carried out in parallel for comparison and product was evaluated for moisture content and quality in terms of milling recovery and head rice yield. Moisture content was reduced from 23% to 14% within 26-52 h of continuous operation during the rainy season and 16% to 14% within 4-26 h of drying during the dry season. In both seasons, the final moisture content of 12% was reached after prolonged drying periods. Quality was not found to be affected with respect to drying treatment. The ISD showed advantages over sun drying, despite longer drying periods.

Keywords: paddy rice, postharvest handling, solar dryer, mobile dryer, collapsible dryer, Philippines
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1 Introduction

Over three billion people consume rice worldwide. Global rice production, and specifically rice production in the Philippines, have shown stable increments to 16 million tons and 418 thousand tons, respectively, over the past decade[1,2]. Despite the steady increase in rice production, local demand is not met in the Philippines, where considerable amounts are imported from Vietnam (82%) and Thailand (17%)[2]. In the 1960s, the

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Philippine government showed interest in increasing the domestic rice supply and implemented actions in terms of pricing policies and subsidy programs mostly via irrigation technologies, introduction of high-yielding varieties, improved fertilizers, and increased access to agricultural credits[3-7]. Since then, research and extension services have been promoted by public and private institutions to provide efficient postharvest strategies via mechanization in harvesting, drying, storing and milling. In the late 1970s, rice production was affected by the land reform and small-scale farms were reestablished. During the 1980s, farmer cooperatives were promoted, but this policy unfortunately subsided[8]. In the 1990s, intensified projects in postharvest management were funded to reduce postharvest deterioration of product quality, since reported losses can be as high as 35%[9-12].

Among the postharvest operations, drying and storage are key processes to improve yield in rice production. The importance of moisture content reduction is a decrease in water activity to secure levels which consequently prevent microbiological growth[10,13-15]. When not properly executed, drying can negatively affect the grain quality during storage or further processing. A general recommendation for safe storage of paddy rice is a moisture content of 14%[16-19] and a reduction to about 12% moisture content is advisable for airtight storage to minimize losses of quality during longer periods and to avoid negative effects such as reduction of germination capacity[20,21].

Small-scale producers in the Philippines mostly perform open sun drying twice a year after the harvest, corresponding to the dry season (January-June) and rainy season (July-December)[22]. Freshly harvested rice is spread and periodically mixed with a wooden rake, until it is dried. With exposure to open areas, major limitations are encountered during the different harvest seasons, for example in the dry season: over-drying, animals feeding on the grains, spillage and non-uniform drying. Whereas in the rainy season the expected problems are: delays in the drying process, incomplete drying, yellowing, fungal propagation and mycotoxin contamination[16,23,24].

Currently, farmers, small handlers and millers trade paddy directly after harvesting to avoid product losses. However, the fresh paddy market offers low farm gate prices to the producers[25,26]. Thus, the use of solar dryers emerges as a promising alternative for small farmers due to low energy consumption as well as realistic investment and operating costs compared to commercial dryers that use petrol fuels for heating the air[27]. In the 1980s, solar drying of paddy was tested in a solar tunnel dryer with an integrated solar air collector. The results were promising, although operators faced difficulties in mixing the grains for quick and uniform drying[28,29]. Various initiatives followed, which provided alternative drying practices, but in most of the cases energy consumption and loading capacity limited the adoption of those technologies[30-32]. Therefore, the objective of this research was to develop a solar dryer for drying paddy under tropical weather conditions and to evaluate its performance in direct comparison to sun and shade drying in terms of operating conditions and product drying as well as final quality, including milling recovery and head rice yield.

2 Material and methods

2.1 Design of the inflatable solar dryer

The inflatable solar dryer (ISD) was developed within the framework of a cooperation project between the Institute of Agricultural Engineering in the Tropics and Subtropics of the University of Hohenheim, the International Rice Research Institute (IRRI) and the GrainPro Philippines Inc. The design was based on the Hohenheim-type solar tunnel dryer that has been developed over the last three decades and commercialized after a series of improvements and adaptations for different climate zones[33-39]. In contrast to the Hohenheim-type dryer, which consists of an elevated metal platform covered by a tented transparent plastic film, the ISD is a collapsible design as shown in Figure 1.

The dryer is made of a 150 μm UV-stabilized transparent polyethylene (PE) film and connected by a zipper to a reinforced black polyvinyl chloride (PVC) film of 0.52 mm (Figure 2). A heavy duty zipper is aligned and stitched along the edges of both plastic films.

The whole unit is directly laid on the ground. The tunnel does not require a support structure and is stabilized adequately by air pressure from inflation. Two 220 V AC axial flow ventilators blow air into the tunnel which is exhausted through two vents on the opposite side. To use the black floor as efficient absorber for solar pre-heating of the drying air, a variable length of the tunnel is left bare after the inlet. In this study, 1.5 m and 3.0 m length of pre-heating area have been tested.

Figure 1 Images showing external (left) and internal (right) views of the inflatable solar dryer

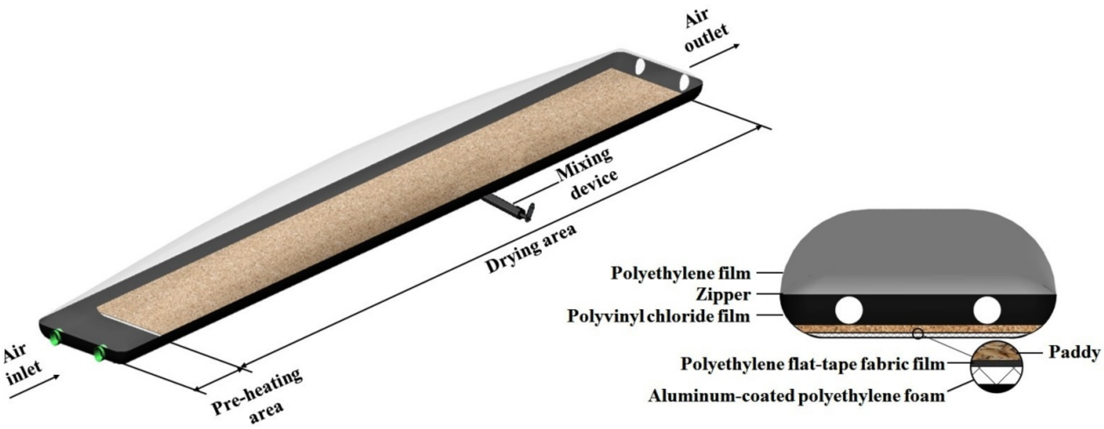


Figure 2 Isometric view (left) and cross section (right) of the inflatable solar dryer (ISD)

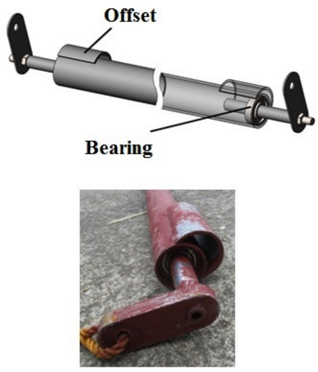
Table 1 shows the design parameters such as total length of the dryer, length of pre-heating area, ventilator size and loading capacity which have been adjusted in the wet season based on the experience gained in the dry season. To reduce heat losses, a flexible multilayer design was used for the floor along the drying area, instead of a rigid platform. The outer layer is formed by a length of reinforced black PVC film, followed by 10 mm of aluminum-coated PE foam and finally covered by a black 356 μm PE-flat-tape fabric (Figure 2). The fresh paddy was spread out with a height of 40 mm. For mixing the grains, which is essential to prevent over-heating of the top-layer exposed to the sun, a special roller bar was developed. The roller bar was made from a 3 m long iron pipe of 47.7 mm diameter with bearings at both ends to which towing ropes were attached. For mixing, two persons pull the roller bar below the flexible floor along the drying tunnel as is shown in Figure 3.

Table 1 Design parameters of the inflatable solar dryer

Design parameter	2012 Rainy season	2013 Dry season
Length of tunnel/m	15	25
Length of pre-heating area/m	1.5	3.0
Width of tunnel/m	2	2
Drying area/m^2	27	44
Capacity (fresh)/kg	600	1000
Specific capacity per drying area/kg·m^{-2}	22.2	22.7
Diameter of ventilators/mm	200	300
Power of ventilators (220V AC)/W	2×60	2×144
Air flow rate/m^3·h^{-1}	670	1390
Specific air flow rate per dryer area/m^3·h^{-1}·m^{-2}	0.045	0.036
Specific air flow rate per kg dried paddy /m^3·(h·kg)$^{-1}$	0.896	0.719

The grain on the floor is agitated by the lifting impetus of the roller bar passing below, which allows the paddy to be mixed without interrupting the drying process. To enhance the mixing effect, pieces of 50 mm half-pipe were welded as offsets at both ends of the roller bar to cause an oscillating movement when rotating.

a. Two persons pulling the roller bar below the flexible floor



b. Roller bar with bearing and welded half-pipe for oscillation

Figure 3 Roller bar as mixing device

2.2 Drying experiments

The ISD was operated at IRRI located in Laguna province in the Philippines (14°11'N, 121°15'E, 21 m a.s.l.). Drying of three batches of paddy was done for two main seasons: during the rainy season (November 2012) and the dry season (April 2013). Weather data were obtained from the climate station at IRRI as shown in Figure 4, where the period of the experiments is indicated by the shaded area. As visible in Figure 4, precipitation events are relatively short and intensive in both seasons. The rainy season showed 14 days with rainfall events amounting to 83 mm against 35 mm of cumulative rainfall over 3 days during the dry season. In general, more than 6 h of sunshine were experienced for most of the days in the rainy season and more than 9 h of sunshine for the dry season. Average relative humidity values were 5 to 10 times higher in the rainy season than in the dry season and average ambient temperature was about 28°C in both seasons.

The ISD was placed on a concrete tract at the IRRI experimental station in Los Baños. Mixed variety (rainy season) and the cultivar PSB Rc18 (dry season) were used for the trials. Each experimental trial started on the morning after the day of harvest. Initial moisture content (wet basis) was found to be 23% during rainy season and 16% during the dry season. Ventilators were allowed to operate during the whole time of each experimental trial, also at nighttime, to keep the tunnel inflated. The paddy was mixed with the roller bar at a regular interval of 1 h during daylight hours.

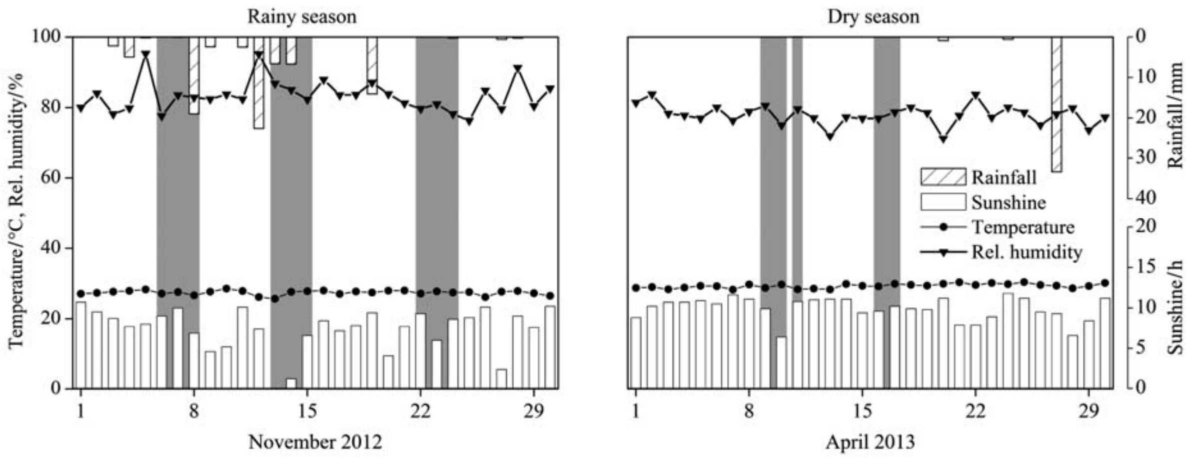


Figure 4 Daily average temperature and relative humidity for drying experiments in the rainy season (left) and the dry season (right) together with the daily rainfall and sunshine hours recorded at IRRI experiment station in Laguna Province, Philippines; shaded area indicates time period of drying experiments

As a reference method, sun drying was carried out using 250 kg of paddy per batch as it is frequently done by farmers. The sample was spread out with a bulk height of 40 mm on a black PVC film next to the inflatable solar dryer. The grains were mixed by manual raking at the same mixing interval of the ISD. During the night or when it was raining, the paddy was protected by covering it with the excess of the plastic film as is shown in Figure 5. A reference sample for each experimental trial was dried in the shade for comparison with the ISD and sun drying samples in terms of grain quality. For shade drying, 5 kg of paddy was placed in a single layer inside a laboratory room at an average temperature of 28°C and relative humidity of 81% in the rainy season and 30°C and 57% in the dry season.

Figure 5 Sun drying (left) and paddy covered to protect from sudden rainfall (right)

2.3 Instrumentation of drying experiments

Ambient weather conditions were measured at an unshaded location near the dryer: solar radiation was measured by a pyranometer (CM11, Kipp & Zonen, Netherlands), temperature and humidity were measured with a self-logging capacitive humidity sensor (OM-EL-USB-2, Omega, USA). Surface temperature of the preheating area and grain temperature were measured with thermocouples (Type K, RS components, UK) at fixed points inside the ISD as shown in Figure 6. Self-logging sensors for measuring temperature and relative humidity of the drying air have been placed above the paddy bulk at the same position as the thermocouples.

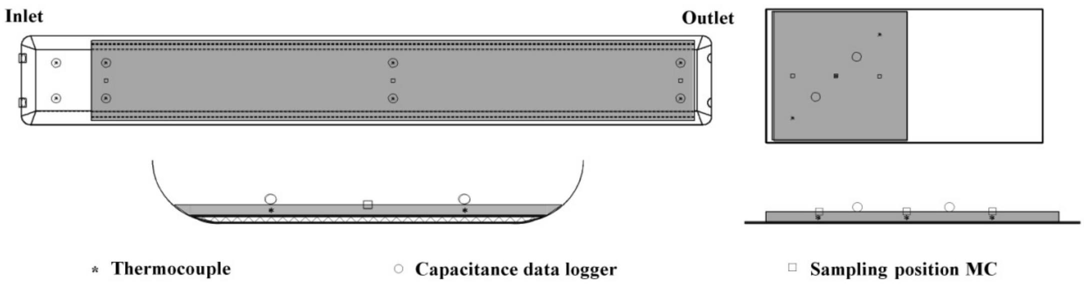


Figure 6 Position of measuring devices top view and cross section view of the inflatable solar dryer (ISD) (left) and of the sun drying platform (right)

Velocity of the drying air was measured at the outlet vents with a hot-wire anemometer (HHF42, Omega, Taiwan). Analogous to the ISD, three measurement points for grain temperature and two temperature/humidity loggers have been installed for sun drying. Samples of paddy for moisture and quality analysis have been taken from the same place as the measurement points.

Pyranometer and thermocouples were connected to a data logger (34970A, Agilent, USA). Data was logged at 5-min intervals and merged with the data from the climate loggers after each drying experiment. Specific humidity x was calculated as:

$$x = 0.622 \cdot \frac{\varphi \cdot p_S}{p - \varphi \cdot p_S} \tag{1}$$

where, φ is the relative humidity, %; p is the ambient pressure, Pa; p_S is the saturation vapor pressure, Pa, which was calculated by the Magnus formula[40]:

$$p_S = 611.21 \cdot \exp\left(\frac{17.123 \cdot T}{234.95 + T}\right) \tag{2}$$

where, T is the temperature of air in Celsius, °C. To analyze condensation phenomena, dew point temperature T_{DP} has been calculated as[41]:

$$T_{DP} = 6.54 + 14.526 \cdot \alpha + 0.7389 \cdot \alpha^2 + 0.09486 \cdot \alpha^3 + 0.4569(\varphi \cdot p_S)^{0.1984} \tag{3}$$

where,

$$\alpha = \ln(\varphi \cdot p_S) \tag{4}$$

2.4 Moisture content analysis

To establish drying curves, paddy samples were collected from the experimental trials every hour during daytime. For moisture content analysis, about 10 g of paddy was weighed by an electronic balance of ±0.001 g accuracy (PS-20, Voltcraft, Germany). The samples were put into plastic bags and sealed for transport to the laboratory.

Gravimetric method was conducted according to AOAC methods using a ventilated oven (ESP-400 Series, BLUE M, USA) at 130°C for 16 h[42,43]. Moisture content (MC, wet basis) was computed as:

$$MC = \frac{m_i - m_{DM}}{m_i} \cdot 100\% \tag{5}$$

where, m_i is the initial mass of the sample before oven-drying, g; m_{DM} is the mass of dry matter, g.

2.5 Grain quality analysis

Milling quality of the paddy after ISD, sun and shade drying was assessed by determining milling recovery and head rice yield, as these are the main criteria considered for grain quality[16,44-46]. Before milling, the MC of the paddy samples was equilibrated to about 14% by two weeks storage. Foreign material (straw, insects, etc.) was removed from the paddy by a pneumatic rice cleaning machine. A total of 250 g of cleaned paddy, weighed by a precision balance, was de-hulled by a rubber roll husker (Satake Engineering, Japan). The obtained brown rice was polished by a horizontal abrasive whitener (Satake Engineering, Japan) to remove the bran. Milling recovery yield (Y_{MR}) was calculated as:

$$Y_{MR} = \frac{m_{milled}}{m_{paddy}} \times 100\% \tag{6}$$

where, m_{milled} is the mass of milled rice, g; m_{paddy} is the mass of paddy rice before milling, g.

Milled rice was graded by a rotating indented cylinder (Satake Engineering, Japan) and head rice yield (Y_{HR}) was calculated as:

$$Y_{HR} = \frac{m_{head}}{m_{paddy}} \times 100\% \tag{7}$$

where, m_{head} is the mass of the head rice fraction determined by milled kernels that have a length greater than 75% of the unmilled kernel, g.

2.6 Statistical analysis

The statistical software package SAS 9.2 version was used for conducting analysis of variance (ANOVA). Comparisons of means were performed by Duncan's Multiple Range Test for milling recovery and head rice yield. p values less than 0.05 were considered significant.

3 Results and discussion

3.1 Solar radiation, temperature and relative humidity

Solar radiation as well as ambient temperature and temperature rise inside the ISD are shown in Figure 7 for exemplarily 24 h cycles during the rainy and dry seasons. The solar radiation varied due to short periods of cloudiness, reaching a maximum solar radiation around noon of 990 W/m^2 during the rainy season and 1100 W/m^2 during the dry season. The sum of daily solar radiation ranged from 1.48 kWh/m^2 to 4.24 kW·h/m^2 during the experiments in the rainy season and from 3.48 kW·h/m^2 to 5.15 kW·h/m^2 in the dry season.

Ambient air temperature varied between 25°C and 37°C in the rainy season and between 27°C and 40°C during the dry season. Figure 7 also shows the temperature rise above ambient temperature at the end of the collector area and at the end of the drying area. During the rainy season, maximum temperature rise was 13°C and 18°C at the end of the collector and drying area, respectively, whereas during the dry season the temperature rise was between 15°C and 23°C, respectively.

Figure 8 shows the air temperature profile inside the ISD, data is shown for selected experimental trials during favorable and adverse weather conditions in the rainy and dry seasons. Generally, a gradual temperature rise was observed in the direction of airflow. Moreover, the crop absorbed solar radiation during day time and release the heat gain accordingly while being mixed. Drying air temperature was higher in the dry season than in the rainy season, reaching maximum values of 72°C and 60°C, respectively. After sunset, the temperature inside the ISD dropped gradually and eventually approached ambient temperature.

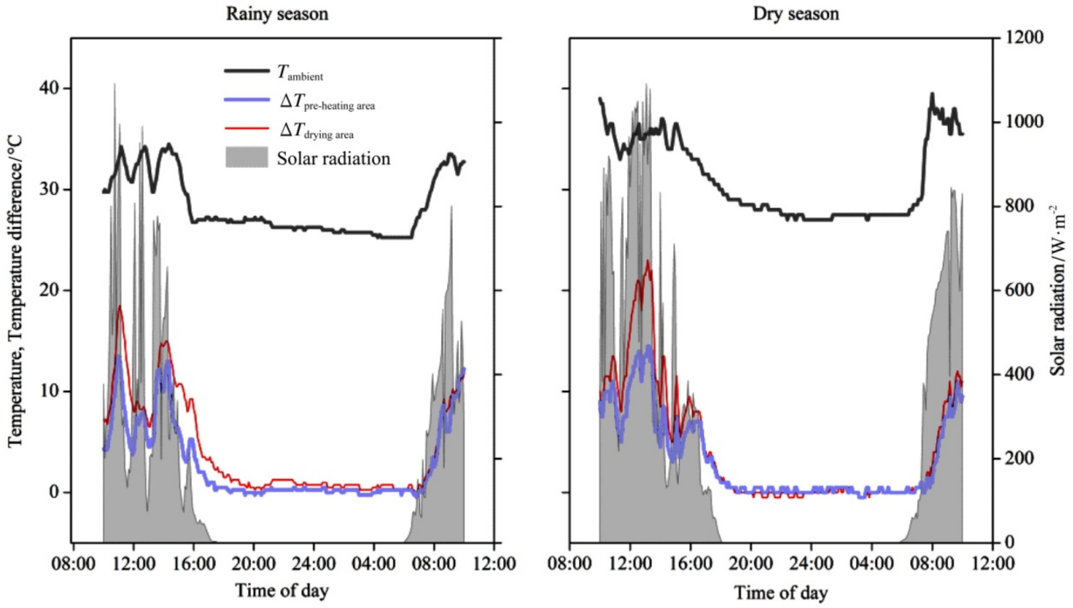


Figure 7 Solar radiation, ambient temperature and temperature rise at the end of the collector area and at the end of the drying area of the inflatable solar dryer (ISD) during the rainy season (left) and the dry season (right)

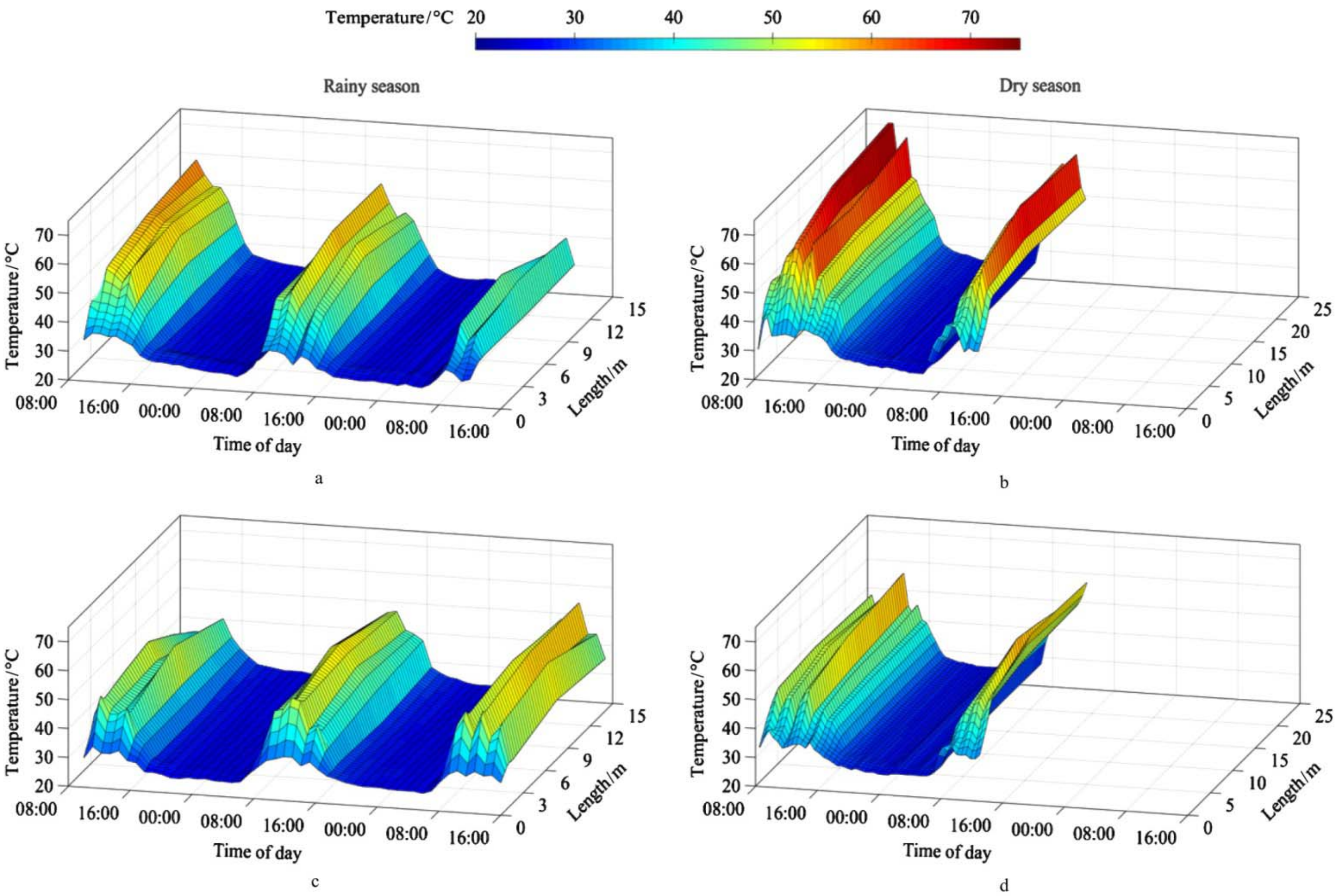


Figure 8 Temperature profile along the inflatable solar dryer ISD during the rainy season (left) and dry season (right), under a-b favorable and c-d adverse weather conditions

Figure 9 shows examples of temperature, relative humidity and specific humidity of drying air along the ISD at noon during the rainy and the dry seasons. Temperature sharply increased after passing the pre-heating area and reached 43°C in the rainy season and 53°C in the dry season. Further temperature rise in the dryer was moderate, mainly because of evaporative cooling caused by drying of the paddy and also because of increased convective losses due to a higher temperature difference to ambient air. As a result of a combined effect of solar heating and water uptake, relative humidity during the rainy season was reduced from 50% to 20% over the first 3 m of the dryer, then rose to 30% from the middle due to water evaporation from the crop and kept this value towards the outlet on the first day. The second drying day also showed a similar pattern. However, the lowest relative humidity was observed at the middle of the dryer and then increased to 40% near the outlet as the crop progressively dried from the inlet to the outlet. In the final stage of the drying process, a stable relative humidity of about 45% was observed along the dryer. In the dry season, relative humidity was reduced to 20% and remained constant along the remaining length of the dryer. Water uptake by the air was indicated by the change in specific humidity along the dryer between 0.019 kg/kg and 0.040 kg/kg during the rainy season and 0.019 kg/kg to 0.026 kg/kg in the dry season.

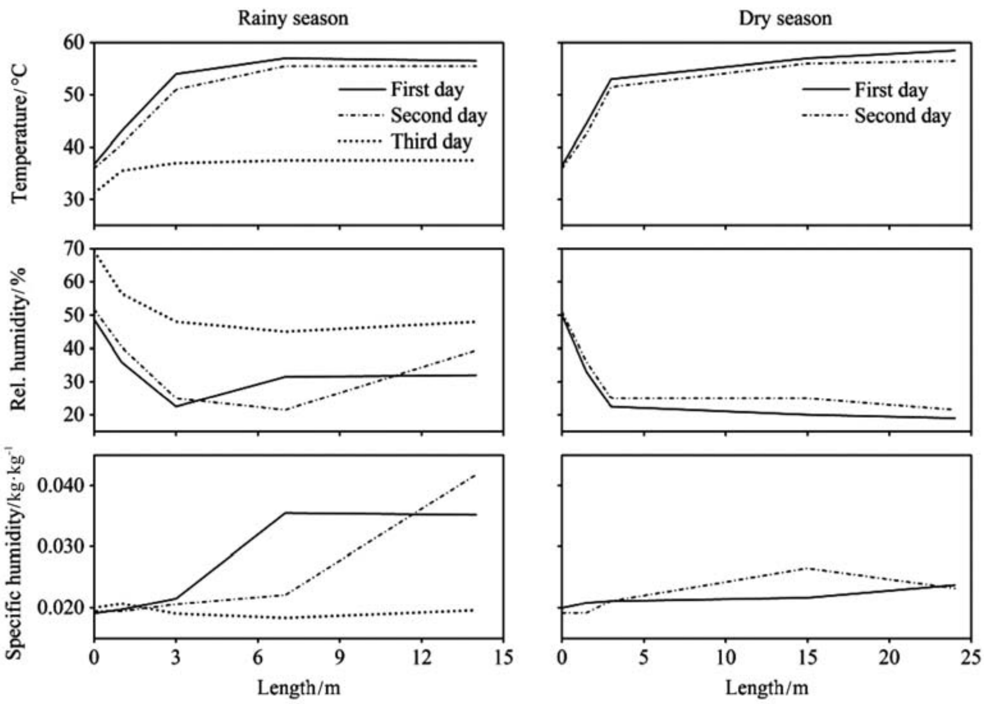


Figure 9 Temperature, relative humidity and specific humidity along the inflatable solar dryer (ISD) at noon during the rainy season (left) and the dry season (right)

3.2 Grain temperature

Paddy was heated by solar radiation but cooled via moisture evaporation as drying air took up water vapor[47]. Figure 10 shows the grain temperature for ISD and sun drying for favorable and adverse weather conditions during the rainy and dry seasons. The y-intercept indicates the maximum grain temperature, whereas the x-intercept indicates the total drying time during the drying runs.

The area below the curves indicated accumulated temperature-hours. A maximum grain temperature of 45°C was reached under most weather conditions, despite air temperatures of 50°C-70°C observed in the ISD (Figure 8). This effect is due to the constant airflow and grain mixing. However, a maximum temperature of 50°C was only reached for a very short time under adverse weather during the rainy season. Therefore, quality losses of paddy might be expected by temperature-time effects since drying temperatures higher than 50°C have been found to compromise grain quality in many studies[25,48,49]. It can also be observed in Figure 10 that drying time in the rainy season was longer compared to the dry season experiments, thus drying in the ISD becomes a challenge under adverse weather conditions. Nevertheless, the target MC of 14% was reached in the ISD, whereas it was not possible for the sun drying method where MC was still at 17% when the drying experiment was terminated.

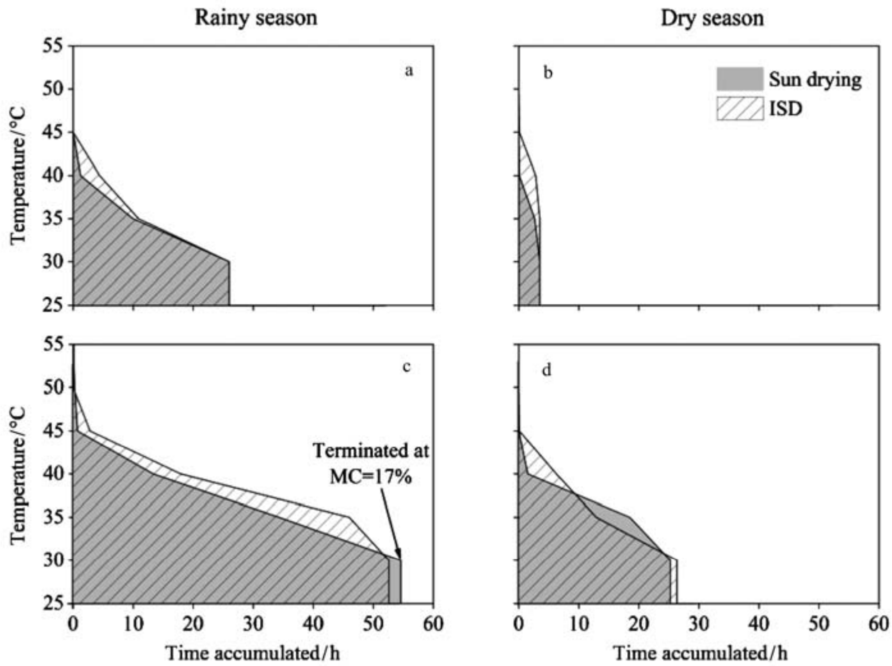


Figure 10 Accumulated grain-temperature-hours for drying to a target MC of 14% in the ISD and sun drying during the rainy season (left) and the dry season (right), under favorable (a, b) and adverse (c, d) weather conditions

3.3 Condensation phenomena

Condensation was encountered on the floor of the ISD in some batches during the rainy season experiments as shown in Figure 11. Condensation occurred when the temperature of paddy or surfaces of the dryer fell below dew point temperature of the drying air[50]. Figure 12 shows that grain temperatures in the ISD were higher in the top layer (T_{top}) than in the bottom layer (T_{bottom}) during the daytime. This is because the top layer of paddy is exposed to solar radiation and the temperature is increased by heat absorption. The bottom layer is gradually heated from above by heat conduction, which is low in grain bulks, as well as by heat convection via air flow and diffusion through the pore spaces. During the night, the temperature gradient is close to zero.

Figure 11 Condensation along the drying area ISD during the rainy season experiments (paddy is moved aside to show the wet areas)

The top layer cools down, mainly by long-wave radiation to the sky, and the heat flow is reverted from top-down to bottom-up. By considering the difference between grain temperatures at the top and bottom of the bulk layer, respective to the dew point temperature of the drying air (T_{DP}), negative values occur for the bottom layer between 8:00 and 12:00 ($\Delta T_{bottom\text{-}DP}$), i.e. condensation occurs as indicated by red lines in Figure 12.

The drying process is accelerated by the onset of solar heating and the dew point temperature is increased by water uptake of the drying air. When the hot and humid air reaches the still cold bottom layer, condensation occurs. To prevent this, higher mixing frequency should be applied after sunrise in order to transport the heated top layer of paddy to the bottom. During the dry season, dew point temperature was always below the grain temperature for both top and the bottom positions in the bulk layer and condensation was not observed.

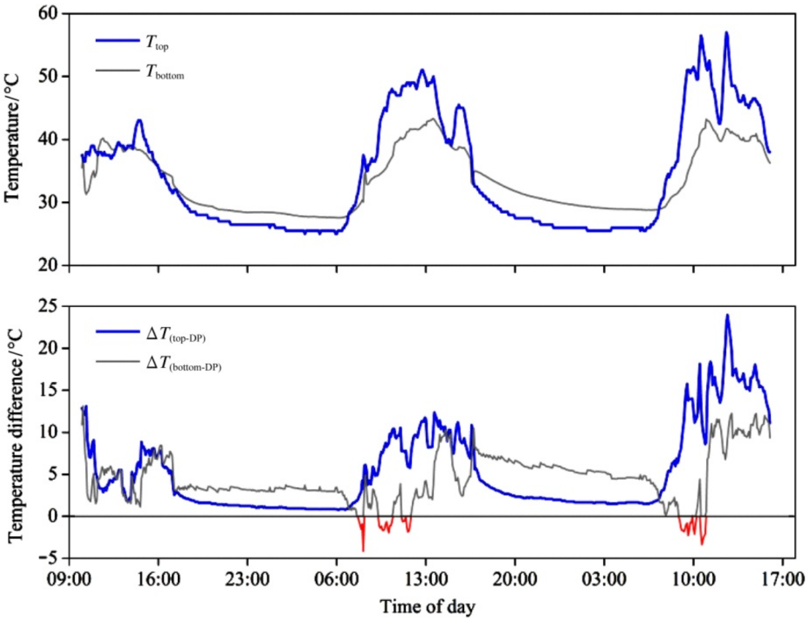


Figure 12 Course of the temperature at the top (T_{top}) and bottom (T_{bottom}) layer of the paddy bulk (top) and temperature difference between the top layer-dew point ($\Delta T_{top\text{-}DP}$) and bottom layer-dew point ($\Delta T_{bottom\text{-}DP}$) during the rainy season (bottom), negative values are marked red as condensation is to be expected

3.4 Drying behavior

MC of paddy during ISD and sun drying are shown in Figure 13. Upper and lower limits of MC for conventional and airtight storage (14 and 12%, respectively) are indicated by the shaded area. During the rainy season, paddy with an initial MC of 19% dried to the target of 14% within 2 days (10:00 until 12:00 following day). A similar drying behavior was observed in the Hohenheim-type solar tunnel dryer[29]. By continuing drying in the afternoon, the lower target MC of 12% could nearly be reached for both drying methods. However, considerable remoistening occurred in the ISD during the following night due to precipitation (19 mm) while the ventilators were working continuously to inflate the tunnel. MC of 12% was reached for the sun drying during a third day, but MC of only 13% was achieved in the ISD. During the dry season, the initial MC of the paddy was 16%. Drying to the upper target MC of 14% took 3 h in the ISD. For sun drying, the lower target MC of 12% was reached in the afternoon when the ISD reached a MC value of 12.5%. In the ISD, 20 h more were required to reach 12%.

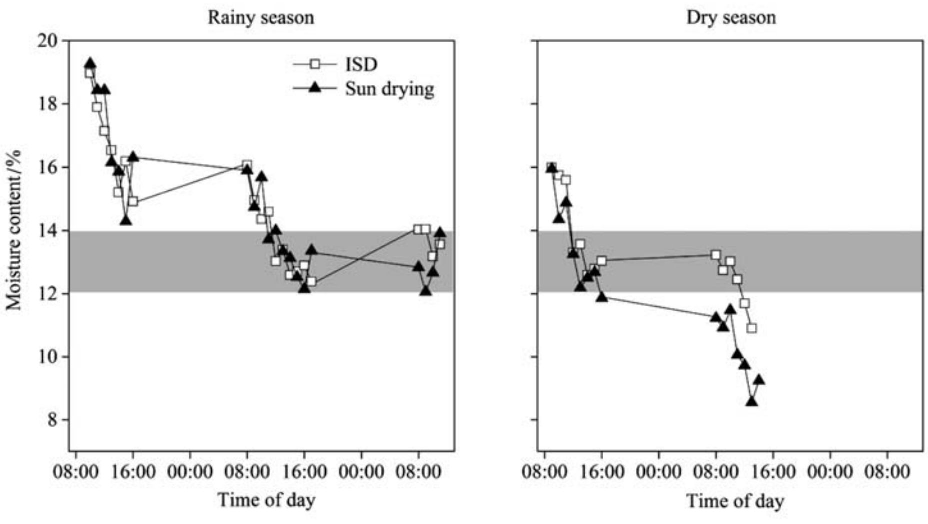


Figure 13 Moisture content of paddy in the inflatable solar dryer (ISD) and sun drying during the rainy season (left) and the dry season (right)

The lowest MC values during the experiments in the dry season were 11% and 8.6% for the ISD and sun drying, respectively. Similar behavior was documented in previous studies on solar tunnel dryers where increased temperature and decreased relative humidity of the drying air showed accelerating effects on the drying rate of the product[33,37,51,52]. However, Djokoto et al.[29] reported that the target MC of 14% was unable to be reached in the rainy season when using the Hohenheim-type solar tunnel dryer.

3.5 Product quality

Results of grain quality are shown in Table 2 for samples obtained from the drying during the rainy and dry seasons. Milling recovery reached values around 68% and was neither affected by season, nor by drying method. Gagelonia et al.[53] reported similar results of Y_{MR} when using a flatbed dryer in the Philippines.

Table 2 Milling recovery (Y_{MR}) and head rice yield (Y_{HR}) after drying in the inflatable solar dryer (ISD), sun drying and shade drying

Drying method	Rainy season		Dry season	
	Y_{MR}/%	Y_{HR}/%	Y_{MR}/%	Y_{HR}/%
ISD	67.30 ± 0.58^{a}	53.68 ± 1.53^{ab}	68.26 ± 2.41^{a}	45.41 ± 2.29^{a}
Sun drying	67.45 ± 0.20^{a}	50.93 ± 1.27^{b}	68.51 ± 4.69^{a}	44.18 ± 2.61^{a}
Shade drying	68.23 ± 1.68^{a}	57.66 ± 1.18^{a}	68.05 ± 1.66^{a}	46.52 ± 3.20^{a}

Note: Means within a column with different letter are significantly different at $p<0.05$.

Head rice yield reached 57.7% after shade drying in the rainy season, but only 46.5% during the dry season. This difference might be attributed to the different varieties, growing and harvesting conditions. Although considerable over-drying occurred in ISD and sun drying during the dry season, no significant differences in head rice yield were found. These results for the dry season are in agreement with Meas et al.[54]. Moreover, temperatures inside the solar dryer or ambient temperature for the sun drying practices, fluctuated and showed mostly a sinusoidal pattern which allows: i) gradual temperature rise, ii) short exposure to elevated temperatures, iii) internal moisture movement toward the surface slowly and iv) a reduction of the moisture gradient inside the grain due to the intermittent drying. Therefore, grain stresses were reduced[55-58]. During the rainy season, head rice yield was not significantly lower after ISD drying than after shade drying, whereas it was lower for sun drying, reaching only 50.9%. Zhou et al.[59] and Zhao and Fitzgerald[60] reported higher values of head rice yield in the dry season than in the wet season. This can be explained by the lower MC (<11%) that was achieved during the dry season experiments, even though the samples were equilibrated to MC of 14%.

Martinez[61] investigated the influence of final MC and drying temperature (30°C-90°C in 10°C increments) on head rice yield. Temperatures of up to 40°C were not found to affect head rice yield, even when drying to a MC of 9%. At a drying temperature of 50°C and MC of 9%, head rice yield was reduced from 60% to 30%. The moderate quality losses in the present experiments are probably explained by the short exposure time to temperatures above 45°C (Figure 10).

4 Conclusions

Drying of paddy rice is problematic in monsoon regions such as the Philippines, where rainfall events can occur even during the dry season. Sun drying poses a high risk for spoilage, when the time is too short to pile and cover the paddy in case of sudden rainfall. This problem may be solved with the inflatable solar dryer, as the water-proof structure protects the paddy even under heavy rainfall. The dryer is easy to transport and can be installed at a new location within 30 min. The simple design is easy to operate and maintain as it is made of plastic material and has few moving parts. On the basis of the successful development of the inflatable solar dryer, a commercial version is available from GrainPro, Inc. under the label Solar Bubble Dryer™[62].

The experiments presented have shown that a batch of 1000 kg of paddy can be easily dried to a target MC of 14% within the first day during the dry season, achieving a high quality in terms of head rice yield. However, a second day of drying is often necessary during the rainy season. As the ventilators have to be operated also during the night to inflate the structure, efforts should be made to finish drying within the first drying day. Therefore, drying should start as early as possible in the morning to make maximal use of solar radiation. Further research should focus on integrating a photovoltaic power supply for the ventilators to allow off-grid operation as well as further optimization via simulation models.

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