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Best practices for paddy drying: case studies in Vietnam, Cambodia, Philippines, and Myanmar

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ABSTRACT

Our study made a comparative analysis of the different drying practices used in Vietnam, Cambodia, the Philippines, and Myanmar. Quantification of energy efficiency, greenhouse gas (GHG) emissions, and cost-benefits generated the implications for selecting the optimal drying practice corresponding to various techno-economic indicators, environments, scales of operations, and market demands. Using a reversible airflow flatbed dryer with a capacity of 20 tons of paddy per batch was found to be the best option in terms of cost-benefit, labor operation, and energy efficiency. On the other hand, a recirculating columnar dryer requires 15% higher energy consumption but only needs 20–50% of the floor area; while a solar bubble dryer still needs optimization in terms of reduced investment cost and labor requirement. A two-stage drying system including a fluidized-bed and ten recirculating columnar dryers is an optimal option with the lowest drying cost and labor use when aiming at an industrial capacity of greater than 200 t/day. Nevertheless, the energy consumption and GHG emission of the solar bubble dryer are lower by more than 50% than that of other practices. In addition to the comparative analysis of these techno-economic factors, this research also identified the trajectories of developing paddy drying technologies that are aligned with different postharvest systems identified as subsistence farming for own consumption, surplus farming for local markets, and surplus farming for premium and export markets. The study recommends paddy drying strategies in Southeast Asian countries that could be applied in other rice-production regions as well.

Abbreviation: GHG: greenhouse gas

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Rice; postharvest; drying; best practices; life-cycle assessment

1. Introduction

Rice is a staple food for nearly half of the world (Ricestat, 2018). Approximately 500 million tons of milled rice are produced annually around the world, of which 90% comes from Asian countries (Ricestat, 2018). Increase of quality and productivity and reduction of losses are usually the main targets of rice production research. Improper drying of wet paddy contribute about 3–5% of paddy rice losses including both of physical and quantity losses (FAO, 2013; RKB, 2016a). In tropical countries, paddy at harvest usually has moisture contents between 20–28% wet basis (MC) corresponding to wet and dry seasons. After harvesting, the paddy should be dried as soon as possible, ideally within 24 h using proper drying methods, to reduce its MC to about 14%, which is the safe MC to prevent paddy losses from respiration, germination, etc., during storage (RKB, 2016a; Tirawanichakul, Prachayawarakorn, Varanyanond, & Soponronnarit, 2004; Xiao & Gao, 2008).

Southeast Asia (SEA) contributes to about 20% of the global rice production (USDA, 2015). Many different drying technologies were developed and adapted in SEA's various regions and countries. For instance, more than 45% of the paddy in the Mekong River Delta of Vietnam (MRD) is dried by mechanical dryers as reported by Nguyen-Van-Hung, Nguyen-Le-Hung, Truong-Quang-Truong, and Phan-Hieu-Hien (2013), compared to 5–10% in Cambodia (Meas, 2012) and the Philippines (Tado et al., 2015) while just less than 5% in Myanmar (adapted from Myo, 2013; Ricestat, 2018). Paddy drying technologies with better performance than sun drying have been adapted in SEA, particularly in Vietnam, Cambodia, Myanmar, and the Philippines since the 1990s (RKB, 2016a). Currently, there are three types of dryers developed and widely used in the region: the solar bubble dryer (SBD), the flatbed dryer (FBD), the recirculating batch columnar dryer (RCD), and the two-stage drying systems (two-stage) described in RKB (2016b). The SBD was developed recently for use at both the farm and village levels

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with a capacity of 0.5–1 t/batch through a collaboration among the International Rice Research Institute (IRRI), Philippines; University of Hohenheim, Germany; and GrainPro Inc., Philippines (RKB, 2016b). An FBD normally has a capacity from 4 to 20 t/batch and is most widely used for paddy drying in SEA (Gagelonia, Bautista, Regalado, & Aldas, 2001; Meas, 2012; Nguyen-Van-Hung et al., 2013). RCD was developed and introduced more recently since 2006 and is used mostly for larger capacities, around 30 t/batch (Nguyen-Van-Hung, Duong-Thi-Hong, & Gummert, 2016). Two-stage drying systems, including fluidized-bed dryers (FLBD) and RCDs, are usually used for industrial scales with a capacity higher than 200 t/day (Nguyen-Van-Hung et al., 2013; RKB, 2016b).

Specific technologies for paddy drying are presented in many related publications. FBD use in SEA is referred to by RKB (2016a), Gummert (2013), Phan-Hieu-Hien, Truong-Vinh, and Nguyen-Quang-Loc (1995), and Tado et al. (2015). The RCD was introduced for paddy drying in some recent studies, such as Kocsis, Keppler, Herdovics, Fenyvesi, and Farkas (2011), Olaniyan and Alabi (2014), and Nguyen-Van-Hung et al. (2016). A new solar drying technology used for paddy rice was recently developed and introduced (GrainPro, 2016; RKB, 2016b). Two-stage drying of high-moisture paddy and high-temperature drying using the FLBD was reported in many studies, including on grain quality (Ibrahim, Sarker, Ab. Aziz, & Mohd Salleh, 2015; Prachayawarakorn, Poomsa-Ad, & Soponronnarit, 2005), energy savings using FLBD (Jittanit, Saeteaw, & Charoenchaisri, 2010; Thakur & Gupta, 2006), and paddy-drying strategies using FLBD (Tirawanichakul, Prachayawarakorn, Varayanond, & Soponronnarit, 2009). However, there are few publications on the best or good practices of paddy drying for a specific rice-production region or market. Good practices of paddy drying should be implemented to satisfy grain quality demand from markets, reduce drying cost, satisfy environmental requirements, and identify the proper scale of operations. These should correspond to rice production, postharvest value chain integration needs, and management capacity. To aid decision making with respect to what constitutes good practices in drying, this study did a comparative analysis of energy efficiency, greenhouse gas (GHG) emissions, and cost-benefits among the paddy-drying systems currently used in Vietnam, Cambodia, Philippines, and Myanmar, including sun drying (SunD), SBD, FBD, RCD, and two-stage.

Energy efficiency and GHG emissions of the different drying practices were analyzed based on the life cycle

assessment (LCA) approach (US-EPA, 2006). The LCA accounts for all the main components of the drying systems such as production of the machines, their maintenance, energy consumption, and postharvest losses produced by the different systems.

The aims of this study were to provide recommendations for appropriate options corresponding to various scales, environments, and market demands and to understand the development of paddy-drying technologies for sustainable rice production.

2. Methodology

We conducted the analysis on energy efficiency, GHG emissions, and costs and benefits for sun drying practice (sunD) and five drying systems:

- solar bubble dryer with a capacity of 1 t/batch (SBD-1),
- conventional flatbed dryer with a capacity of 4 t/batch (FBDc-4),
- reversible air flow flatbed dryer with a capacity of 20 t/batch (FBDc-20), and
- recirculating columnar dryer with a capacity of 30 t/batch (RCD-30),
- two-stage drying system (two-stage) used for industrial scales based on an assessment in Vietnam.

2.1. Assessment of paddy-drying systems

2.1.1. Solar bubble dryer (SBD)

Figure 1(a,b) show the schematic diagram of a SBD and the actual machine with a 1-ton capacity, respectively. It was developed by a consortium consisting of IRRI, the University of Hohenheim, and GrainPro Inc. (Azucena, 2014). This dryer has a capacity of 1 t/batch. It is composed mainly of plastic film with a transparent plastic cover on the top and a black canvas underneath. The transparent plastic allows sun radiation to pass into the drying chamber; the black plastic captures the heat generated. This heat increases the temperature of both the paddy and the air blown through the drying tunnel by one or two blowers. As the relative humidity of the drying air is reduced while being heated, the air absorbs water vapor from the wet paddy thus lowering its moisture content. Solar cell panels with a battery backup generate energy to operate the ventilators. The battery also provides power at night to keep the tunnel inflated, as drying time when using SBD usually takes more than 16 h per batch of paddy with its initial moisture content higher than 23%.

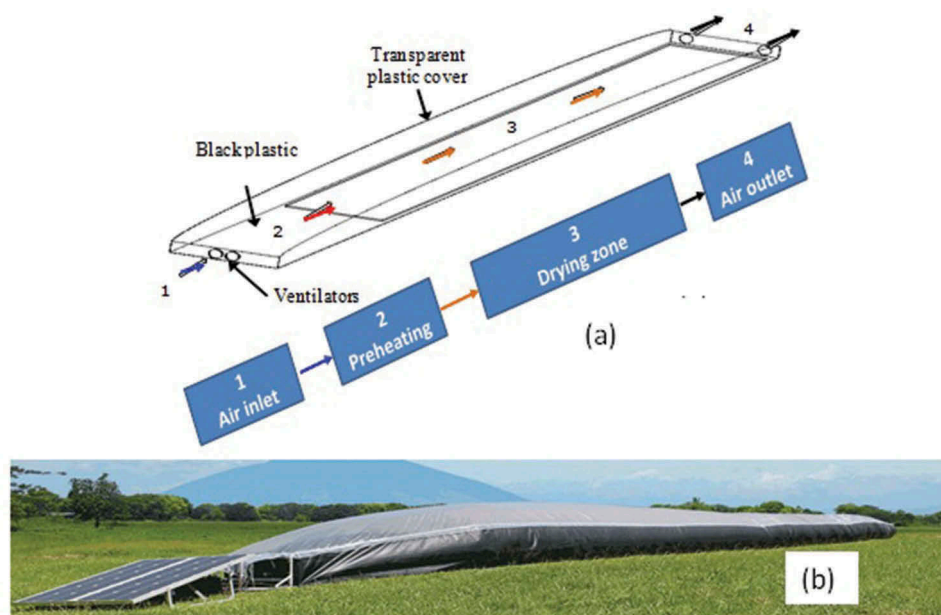


Figure 1. Solar Bubble Dryer (SBD), (a) schematic diagram and (b) photograph of the system in operation.

2.1.2. Flatbed dryer (FBD)

Figure 2(a) shows a FBD operating in the Philippines with a capacity of 4 t/batch. Nong Lam University in Ho Chi Minh City, Vietnam developed this dryer and distributed in Vietnam, Cambodia, the Philippines, and Myanmar with support from various IRRI projects (Gummert, 2013; Nguyen-Van-Hung et al., 2013). A FBD consists of three main components: blower, furnace, and drying chamber. Grain is placed in a rectangular bed on a perforated false floor. The furnace heats ambient air, which is sucked by a fan and pushed through the grain mass until it exits from the grain mass surface. The drying process continues until the grain mass is dried to the desired MC, usually 14% on average. A FBD with the drying air moving in one direction (usually upwards) is a conventional flatbed dryer (FBDc).

This dryer was improved by Nong Lam University in 2003 (Phan-Hieu-Hien, Nguyen-Van-Xuan, & Nguyen-Hung-Tam, 2003) by adding a feature that enables the drying air to move in two directions, upward and downward. This dryer is a reversible airflow flatbed dryer (FBDr). Principles of both the FBDc and FBDr are shown in Figure 2(b).

Drying material is loaded into the drying bin with a depth of 25–40 cm and 50–60 cm on a perforated floor for the FBDc and FBDr, respectively. Drying air temperatures are in the ranges of 42–45°C for grain and 40–43°C for seed production, respectively. Paddy drying processes with different flatbed dryers are reported in Nguyen-Van-Hung, Tran-Van-Tuan, and Gummert (2018). This research analyzed the FBDc (4 t/batch) and FBDr (20 t/batch).

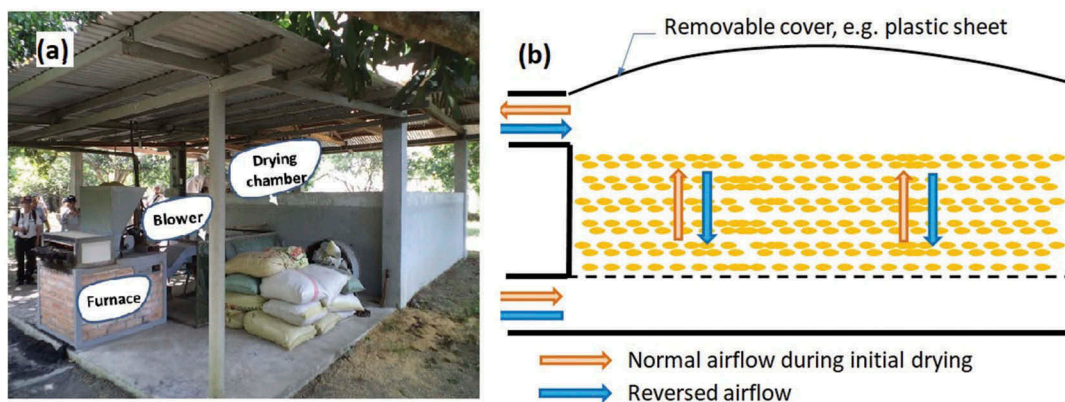


Figure 2. Flat bed dryer (FBD), (a) photograph of the system in operation and (b) principles of FBDc and FBDr.



Figure 3. Recirculating columnar dryer (RCD), (a) schematic diagram and (b) photograph of the system in operation. 1 = Feeding, 2 = Bucket elevator, 3 = Pre-cleaner, 4 = Unloading pipe, 5 = Bucket elevator, 6 = Drying tower, 7 = Controlling component, 8 = Blower, 9 = Baffle, 10 = Furnace.

2.1.3. Recirculating batch columnar dryer (RCD)

Figure 3(a,b) show, respectively, the schematic diagram and photograph of the RCD, which was introduced into SEA during the 1990s. However, the technology has been rarely used until recently when processors started buying units in Thailand and Vietnam. RCDs work effectively only when the grain MC is less than 24%; at higher MCs, there is the danger of bridge building and clogging in narrow components where the grains need to pass through, particularly in grain lots that contain impurities. Therefore, the RCD works best with clean paddy input from combine-harvesters or with paddy pre-cleaned and pre-dried with fluidized bed dryers. We analyzed only the RCD with a capacity of 30 t/batch, which is used in Vietnam where combine harvesters are used to harvest more than 90% of the paddy. Specification and performance of this RCD were

based on a design developed in collaboration between Nong Lam University and IRRI (Nguyen-Van-Hung et al., 2016; Tran-Van-Tuan et al., 2013).

2.1.4. Two-stage drying system (two-stage)

Figure 4(a,b) show the schematic diagram and a photograph of a two-stage drying system including a fluidized-bed dryer (FLBD) and RCD. The FLBD dries paddy at the first stage, usually to reduce its MC from 24 to 28% to 20 to 22%. Wet paddy passes through the drying chamber of the FLBD within 2–3 min. At the second stage, paddy is then loaded into RCDs. The FLBD works continuously while the RCD works as a batch-recirculation. In the first 30 min of RCD drying stage, paddy is being tempered by unheated air blown from the RCD's fans within 30–45 min. The paddy is then dried in the recirculating batch of RCD within

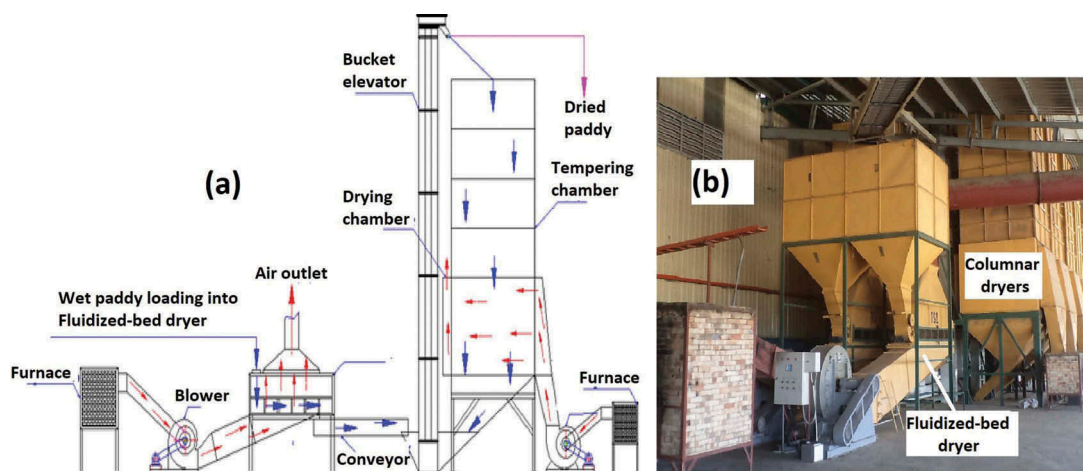


Figure 4. Two-stage drying system, (a) schematic diagram and (b) photograph of the system in operation.

6–8 h down to 14% of MC. Within this research, we collected data based on the assessments at a two-stage drying system at Vinh-Binh Rice Mill of the Loc Troi Group in Vietnam in 2013 and 2018. The FLBD has capacity 30 t/h with a drying temperature of about 60–75°C, mainly for pre-cleaning wet paddy and reducing its maximum MC by 2–3% MC. This FLBD is connected with 10 RCDs with the capacity of 30 t/batch for each unit. This practice of the two-stage drying system is now widely used in the industrial rice mills in MRD of Vietnam. Drying temperature applied in this FLBD practice (60–75°C) is lower than that (100–150°C) reported by Sarker, Ibrahim, Aziz, and Punan (2013), Jittanit et al. (2010), and Meeso, Soponronnarit, and Wetchacama (1999). Based from assessments, the reasons of this temperature difference are:

- During the dry season (Winter-Spring) in MRD, paddy harvested by combine harvesters usually has MCs lower than 24%. Applying high drying temperature in this case causes adverse effects to the head rice yield. This is also in agreement with the research of Sarker et al. (2013).
- There is a limitation of controlling drying temperature heated by rice husk furnaces to match the varying MCs of input paddy. The drying managers and operators therefore adopted the lower range of drying temperature (60–75°C) for all kinds of input paddy to prevent high levels of breaking in input paddy with low MCs.

Using the FLBD at less than 75°C of drying temperature might reduce the efficiency and effectiveness of the two-stage drying systems. Nevertheless, in actual practices in MRD, the drying time of this technology is still lower by 15–20% comparing with RCD and FBD alone.

2.2. Data collection

Data on machine production, energy consumption, and cost were based on assessments done in 2016 in Vietnam, Cambodia, Philippines, and Myanmar. Paddy losses caused by the drying systems were based on the data globally available in the RKB (2016a) and FAO (2013). Table 1 shows the input data of the drying systems obtained from our assessments. To have a valid comparison, wet paddy before drying was assumed to have 24% MC for all drying scenarios. During production or construction of the drying systems, all main material to build or produce the corresponding dryers, such as bricks, cement, steel, plastic, etc., were accounted for. These materials and equipment were assumed to have a 5-year life-span. Annual utilization of the dryers was assumed to be 60 days/year, based on the real practices in countries with similar conditions. Direct input energy was the sum of the electric power consumption for running the blower and other dryer components and the rice husks used for combustion to heat up the drying air in case of the FBD, RCD, and FLBD. Labor was also considered in the calculation and included labor

Table 1. Parameters of paddy drying (unit of cost and materials is for each ton of paddy dried).

| Items | Unit | SunD | SBD-1 | FBDC-4 | FBDr-20 | RCD-30 | Two-stage |
|--------------------------------------|-------------------|------|-------|--------|---------|--------|-----------|
| <i>Paddy and drying loss</i> | | | | | | | |
| Paddy initial MC (wet basis) | % | 24 | 24 | 24 | 24 | 24 | 24 |
| Paddy final MC | % | 14 | 14 | 14 | 14 | 14 | 14 |
| Physical grain loss in drying | % | 5 | 2 | 2 | 2 | 2 | 2 |
| <i>Capacity and scale</i> | | | | | | | |
| Capacity | t/batch | 1 | 1 | 4 | 20 | 30 | 200* |
| Land area used for drying operations | m ² /t | 40 | 28 | 12.5 | 8.0 | 6.7 | 6 |
| <i>Production materials</i> | | | | | | | |
| Brick for machine construction | kg/t | | | 1.13 | 0.98 | 0.84 | |
| Cement | kg/t | | | 0.65 | 0.31 | 0.28 | |
| Steel | kg/t | | | 0.41 | 0.31 | 1.61 | |
| Blower and DC-motor | kW | | 0.2 | 7.5 | 30 | 40 | |
| Plastic (HDPE) | kg/t | 10 | 31 | | | | |
| Solar cell | W/t | | 200 | | | | |
| Battery | Ah/t | | 70 | | | | |
| Labor for construction | days/t | | | 0.06 | 0.02 | 0.05 | |
| Total investment cost | \$US/t | 25 | 1855 | 1250 | 833 | 1317 | |
| <i>Energy consumption and labor</i> | | | | | | | |
| Electric consumption | kWh/t | | | 10.5 | 8.4 | 7.5 | 8.5 |
| Rice husk consumption | kg/t | | | 48 | 48 | 60 | 70 |
| Operating Labor | h/t | 16 | 4 | 2 | 0.4 | 0.3 | 0.05 |

Sun-D = Sun drying; SBD-1 = Solar bubble dryer 1/batch; FBDC-4 = Flatbed dryer 1 t/batch; FBDr-20 = Flatbed dryer 20 t/batch; RCD-30 = Recirculating columnar dryer 30 t/batch; Two-stage = Two-stage drying system 200 t/batch.

*The two-stage system includes a continuous FLBD 20–30 t/h and 10 RCDs with the capacity 30 t/batch. Average capacity of the system is 200 t/batch.

required for construction and operation. Drying losses were based on global data from the RKB (2016), FAO (2013), and long-term experience in paddy drying. Losses caused by drying systems were assumed to be about 1–2% and 5–10% of grain for mechanical drying and sun drying, respectively. In the LCA, each percentage point of loss is accounted for by calculating energy consumption and GHG emission generated from the manufacturing and use of inputs needed to produce the lost paddy. Within this research, we conducted the analysis with an assumption that a maximum loss of 2% was caused by mechanical drying and a minimum loss of 5% was caused by sun drying. For the two-stage drying system, we only have data on economic parameters such as capacity, investment cost, power and fuel consumption, and labor uses based on the assessments in Vietnam. Therefore, we took the two-stage system into account only when looking at the operational energy consumption and drying cost analysis.

2.3. Methodology of analysis

2.3.1. Energy efficiency and GHG emissions

Energy efficiency was calculated using total energy consumed and energy for producing the grain losses for drying 1 ton of paddy from 24 to 14% as shown in Equation 1.

$$E_e = E_c + E_l \quad (1)$$

where:

- E_e : energy efficiency, MJ/t of paddy at 14% MC;
- E_c : energy consumption for drying 1 ton of paddy, MJ/t, including electricity and fuel consumption during operation, energy used during machine production and maintenance, and labor;
- E_l : energy lost per ton of paddy, MJ/t, calculated based on the percentage of paddy loss caused by drying.

GHG emissions were calculated based on energy used in the production of the equipment, input materials, and fuel consumption during operation. Table 2 shows energy and GHG emission conversion factors of the input materials used for production of the dryer, fuel, and labor. Production of the FBD and RCD included bricks, cement, and steel for production of the furnaces, blowers, and drying chambers while production of the SBD included plastic, photovoltaic cell, inverter, and battery. Data of production, paddy, energy, and rice husk consumption were obtained from the database of Ecoinvent 3 (Ecoinvent, 2017) incorporated in the SIMAPRO software (SIMAPRO, 2017). Data for labor energy value were obtained from Ainsworth et al. (2011) and Quilty et al. (2014).

2.3.2. Calculation of drying cost

Drying cost was calculated based on the depreciation; maintenance cost; interest, energy consumption; labor for all related operations during a drying cycle including loading, unloading, and mixing of the paddy; and operating the system. For this research, costs of depreciation, interest, and maintenance of the SBD and other mechanical dryers were assumed to be the same in all countries (Vietnam, Cambodia, Philippines, and Myanmar) as shown in Table 3. Investment costs of the dryers were based on the various values in the different countries. The margins of error were in a range of from 10 to 20%. Table 4 shows the costs of labor and electric power and rice husk consumption at the research sites obtained from our assessments in 2016.

2.3.3. Comparative analysis of different drying practices

The key factors for selecting a proper mechanical dryer corresponding to a specific scale, circumstance, or rice

Table 2. Conversion factors of energy and GHG emissions.

| Parameters | Energy | | GHG emission | |
|---|-------------------|-------|--------------------------------------|-------|
| | Unit | Value | Unit | Value |
| Production of the systems ^a | | | | |
| Brick | MJ/kg | 2.69 | kgCO ₂ -eq/kg | 0.251 |
| Cement | MJ/kg | 1.61 | kgCO ₂ -eq/kg | 0.192 |
| Sand | MJ/kg | 0.186 | kgCO ₂ -eq/kg | 0.111 |
| Steel – low alloyed | MJ/kg | 21.3 | kgCO ₂ -eq/kg | 1.73 |
| Polyethylene producing net and plastic bags | MJ/kg | 78.2 | kgCO ₂ -eq/kg | 1.8 |
| Photovoltaic cell | MJ/m ² | 2880 | kgCO ₂ -eq/m ² | 175 |
| Inverter 0.5 kW | MJ/unit | 646 | kgCO ₂ -eq/unit | 44.3 |
| Battery | MJ/unit | 5260 | kgCO ₂ -eq/unit | 411 |
| Electric consumption ^a (including motor production) | MJ/kWh | 6.74 | kgCO ₂ -eq/kWh | 0.34 |
| Labor ^b | MJ/h | 0.89 | | |
| Paddy (for calculating drying loss, in dry weight basis) ^a | MJ/kg | 28 | kgCO ₂ -eq/kg | 2.05 |
| Rice husk used to generate heat for drying ^a | MJ/kg | 8.69 | kgCO ₂ -eq/kg | 1.66 |

a = adapted from the database of Ecoinvent 3 (Ecoinvent, 2017) incorporated in the SIMAPRO software (SIMAPRO, 2017); b = adapted from Ainsworth et al. (2011) and Quilty et al. (2014).

Table 3. Parameters for investment cost, maintenance, and interest of different drying practices.

| Items | Unit | SunD | SBD-1 | FBDc-4 | FBDr-20 | RCD-30 | Two-stage |
|-----------------|------------------------|------|-------|--------|---------|--------|-----------|
| Investment cost | \$US/t | 25 | 1855 | 1250 | 833 | 1317 | 1213 |
| Life span | years | - | 5 | 5 | 5 | 5 | 5 |
| Maintenance | % (of investment cost) | - | 50 | 50 | 50 | 50 | 50 |
| Interest | %/year | 12 | 12 | 12 | 12 | 12 | 12 |

Sun-D = Sun drying; SBD-1 = Solar bubble dryer 1 t/batch; FBDc-4 = Flatbed dryer 1 t/batch; FBDr-20 = Flatbed dryer 20 t/batch; RCD-30 = Recirculating columnar dryer 30 t/batch; Two-stage = Two-stage drying system 200 t/batch.

Table 4. Cost of labor and energy consumption in the countries studied.

| Component | Unit | Vietnam | Cambodia | Philippines | Myanmar |
|----------------|----------|---------|----------|-------------|---------|
| Labor | \$US/h | 1.25 | 0.88 | 0.65 | 0.46 |
| Electric power | \$US/kWh | 0.11 | 0.20 | 0.18 | 0.05 |
| Rice husk | \$US/t | 50.00 | 40.00 | 17.71 | 6.56 |

production system could be indicated by the quality of the dried grain, investment cost, drying cost, energy consumption, operating labor, land use, and the environmental footprint. We considered these factors in the study.

As the FBDc-4 currently has the broadest use for paddy drying in SEA, we considered it as the control system in the analysis. We compared these factors for FBDc-4 with those of the other mechanized drying practices (i.e. FBDr-20, RCD-30, and SBD-1) and made the analysis to identify the best practices among them.

3. Results

3.1. Energy efficiency

Table 5 shows the energy consumptions and losses of the different drying practices. SBD-1 required the lowest energy for both operation and total input at 4 and 356 MJ/t of paddy dried, respectively. The total input energy comprised 12.4% for materials for fabrication, 2.5% for labor, and the rest (85%) for paddy loss (assuming 2%/ton of dried paddy) during drying. The input energy for the SBD was lower by 54, 67, and 72% than that for SunD, FBD, and RCD, respectively. Total input and lost energy for SunD comprises 95% of the 5% paddy loss. Regarding the mechanical dryers used for community and industrial scales, including FBD,

RCD, and two-stage, they required an operational energy of from 767 to 1,093 MJ/t of paddy dried, equaling from 6.6 to 9.4 MJ/kg of water evaporated. From 90 to 95% of the operational energy came from rice husks used for heating the drying air.

3.2. GHG emissions

Table 6 shows GHG emissions from different drying practices including sun drying, SBD, FBD, and RCD. Since the SBD uses only solar energy during operation, it generated the lowest GHG emission at 44.08 kg CO₂-eq/t of paddy dried. Its emission is lower by 57, 65, and 70% than that of sun drying, FBDs, and RCD, respectively. GHG emission for sun drying was 103 kg CO₂-eq/t of paddy dried, due mainly to the high quantity and quality loss during drying. Mechanical drying practices (i.e. FBDs and RCD) generated the highest GHG emissions in the range of 125–147 kg CO₂-eq/t of paddy dried as caused by input materials for

Table 6. Indirect GHG emission from different drying systems (kg CO₂-eq/t of paddy dried).

| Components | Sun drying | SBD | FBDc-4 | FBDc-20 | RCD-30 |
|------------------------|------------|-------|--------|---------|--------|
| Brick and cement | - | - | 0.42 | 0.32 | 0.26 |
| Steel | - | - | 0.71 | 0.54 | 2.79 |
| HDPE | 0.06 | 0.19 | - | - | - |
| Battery | - | 2.28 | - | - | - |
| Photovoltaic cell | - | 0.43 | - | - | - |
| Inverter | - | 0.15 | 0.01 | - | - |
| Power consumption | - | 0.00 | 3.57 | 2.86 | 2.55 |
| Rice husks consumption | - | - | 79.80 | 79.80 | 99.75 |
| Drying loss | 102.58 | 41.03 | 41.03 | 41.03 | 41.03 |
| Total | 102.64 | 44.08 | 125.55 | 124.54 | 146.38 |

Sun-D = Sun drying; SBD-1 = Solar bubble dryer 1 t/batch; FBDc-4 = Flatbed dryer 1 t/batch; FBDr-20 = Flatbed dryer 20 t/batch; RCD-30 = Recirculating columnar dryer 30 t/batch; Two-stage = Two-stage drying system 200 t/batch.

Table 5. Energy consumption and loss of different drying practices (MJ/t).

| Energy consumption | SunD | SBD-1 | FBDc-4 | FBDr-20 | RCD-30 | Two-stage |
|--|------|-------|--------|---------|--------|-----------|
| Manufacture and maintenance | 2.6 | 48.0 | 11.8 | 9.2 | 36.5 | N/A |
| Electric consumption | - | - | 70.8 | 56.7 | 50.6 | 57.3 |
| Rice husk consumption | - | - | 710 | 710 | 888 | 1036 |
| Labor | 14.2 | 3.6 | 1.8 | 0.4 | 0.3 | 0.1 |
| Paddy loss | 760 | 304 | 304 | 304 | 304 | N/A |
| Total energy consumption for operation* | 14 | 4 | 783 | 767 | 939 | 1093 |
| Total energy input and loss ^b | 777 | 356 | 1099 | 1081 | 1279 | |

Sun-D = Sun drying; SBD-1 = Solar bubble dryer 1/t batch; FBDc-4 = Flatbed dryer 1 t/batch; FBDr-20 = Flatbed dryer 20 t/batch; RCD-30 = Recirculating columnar dryer 30 t/batch; Two-stage = Two-stage drying system 200 t/batch.

* = including power, rice husks, and labor uses

machine production and fuel and electrical power consumption during operation.

3.3. Drying costs

Figure 5 shows the component costs of drying 1 ton of paddy for different drying practices including SunD, SBD, FBD, RCD, and two-stage in Vietnam, Cambodia, Philippines, and Myanmar. The drying cost comprises the following components: (1) depreciation, maintenance, and interest for the whole system including loading and unloading; (2) labor for drying operation; (3) power and fuel consumption; and (4) labor for unloading and loading.

The highest drying cost of 25 \$US/t was for SunD in Vietnam due to labor. For the dryers, drying costs for SBD-1 were the highest, ranging from 12 to 18 \$US/t, higher by 23–34%, 43–58%, 33–49%, and 42–59% than those for FBDc-4, FBDR-20, RCD-30, and two-stage, respectively. Even though the FBDs, RCD, and two-stage had added costs for electricity and rice husk consumption, ranging from 0.7 to 4.5 \$US/t, their drying costs were still lower at from 4 to 12 \$US/t because of their much lower labor costs compared to the others. In addition, the benefit from reducing the paddy loss in mechanized drying practices can add 8–12 \$US/t of value to rice production profits. This comparison shows the effectiveness of the larger machines for bigger operations. On the other hand, the RCD and two-stage are not applicable at the farm level. We analyze this aspect in the Section 4 discussion.

We must consider that costs of labor, electric power, and rice husks very much depend on markets in the respective countries. These differences strongly affect the total drying cost and development of the mechanical dryers. Compared to Vietnam, the drying cost for Myanmar was lower as an effect of lower costs for fuel, power, and labor. The differences in labor costs in the respective countries also resulted in different best practices in terms of cost. For instance, the drying cost of SunD was the highest of the four drying systems in Vietnam and Cambodia while drying cost was still lower for SBD-1 in the Philippines and Myanmar. Lower labor costs in Myanmar and Cambodia result in lower drying costs (the case in other countries). Therefore, drying costs in Myanmar and Cambodia are lower than in other countries.

3.4. Best drying practices

Figure 6 shows the comparisons of investment cost, drying cost, energy consumption, GHG emissions, and land use for the drying systems that we studied. Figure 6 (a,b) show the cases in Vietnam and Myanmar, respectively. The results for Cambodia were very similar to Vietnam; results in the Philippines were similar to Myanmar (not shown). Particularly for the two-stage drying system, only land use, investment cost, and drying cost for the case study in Vietnam are shown in the Figure 6(a). We used the results of this comparative analysis to identify the systems that correspond best to the demands. For example, if minimizing land use is the

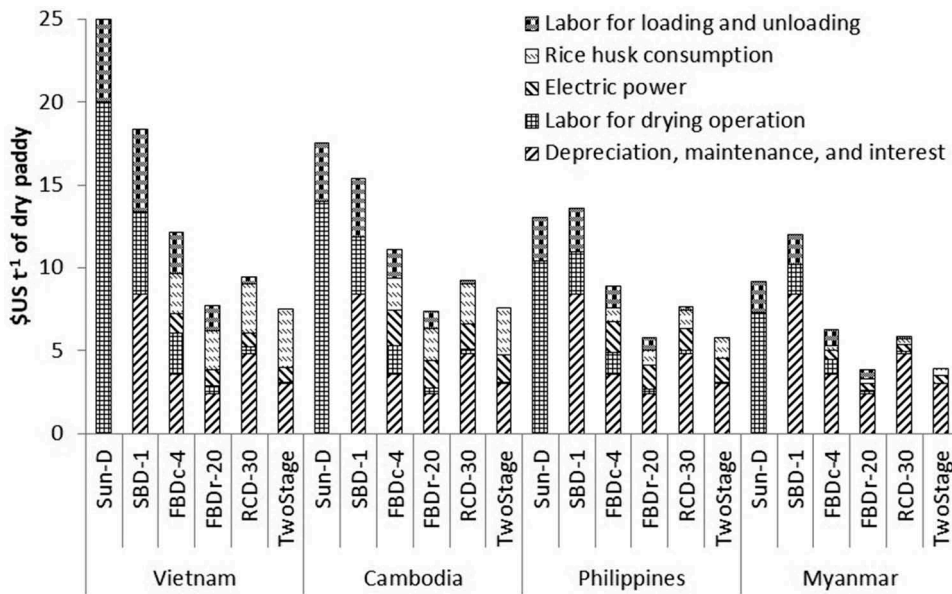


Figure 5. Drying costs of different drying systems in Vietnam, Cambodia, Philippines, and Myanmar. Sun-D = Sun drying; SBD-1 = Solar bubble dryer 1 t/batch⁻¹; FBDc-4 = Flatbed dryer 1 t/batch; FBDR-20 = Flatbed dryer 20 t/batch; RCD-30 = Recirculating columnar dryer 30 t/batch; Two-stage = Two-stage drying system 200 t/batch.

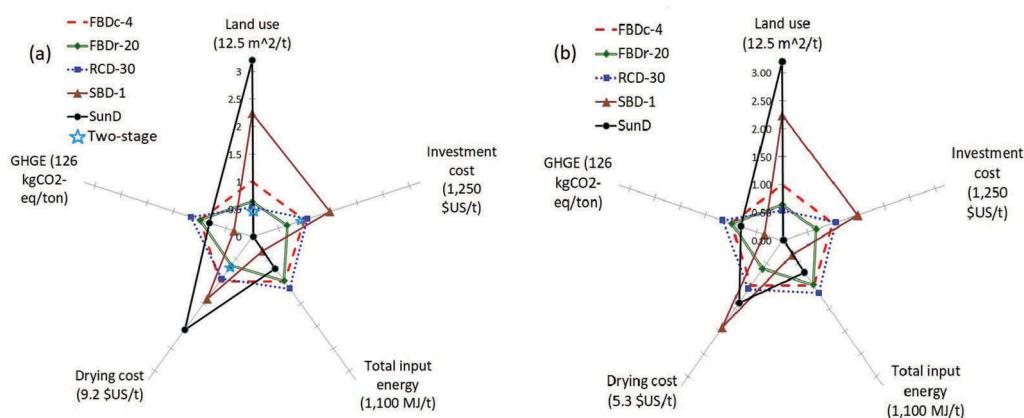


Figure 6. Techno-economic factors of different drying systems in (a) Vietnam and (b) Myanmar. Note that smaller values indicate better performance for all five parameters. Values in parentheses correspond to level 1 of the control practice of FBDC-4.

priority, then the two-stage and RCD-30 are the best solutions. On the other hand, if land use efficiency is less important, then the FBDR-20 is the best solution because of its lower labor requirements and energy consumption, which results in lowest drying and investment costs. If the investment cost and labor requirement of the SBD can be reduced to meet market preferences, then it would be the best solution since it has the lowest energy consumption.

4. Discussion

This study generated data from the drying systems and practices most widely used in the target countries. For example, we assumed that rice husks were the heat source and so these were included in the analyses. If fossil fuels such as coal, diesel, or kerosene were used instead, this could result in more than a twofold increase in energy costs and GHG emissions.

Findings of the techno-economic comparative analysis resulted in implications for both the dryer end-users and designers of these drying systems. End-users of dryers can use the findings for their best drying choice for their needs by prioritizing the indicators most important for them such as investment and drying costs. Designers can use the findings for improving their dryer designs to meet the local rice production demands and trends.

Operational energy of the mechanical dryers (i.e. FBD, RCD, and two-stage) was found to be from 6.6 to 9.4 MJ/kg of water evaporated, which was higher by from 10 to 20% than that reported by Ibrahim et al. (2015), the China Standard cited in Li, Mai, Fang, and Zhang (2014), and Jittanit et al. (2010). The differences mainly come from the calculation method. This research converted energy input based on the LCA

approach using SIMAPRO software (SIMAPRO, 2017). For instance, the energy consumption for electric power calculated in this research comprised direct energy used and input energy of manufacturing depreciation. On the other hand, that energy calculated in the other research only took the energy used value into account.

Selections of a proper drying system are usually not only based on the economic factors but may also be affected by other considerations, such as environmental and social aspects. For the environmental issues, it is obvious that the SBD is the best solution for long-term use due to its lowest energy consumption and GHG emission during the production of the dryer – and during its operation, using only solar energy with no emissions generated. For the FBDs and the RCD, the energy needed for their production and operation is almost the same. This caused the GHG emissions to be similar as well. However, based on a column design with a small-area air outlet, the RCD has an obvious advantage in terms of removing dust in the exhaust air caused during its operation, e.g. through the use of a cyclone and filtering pollution, while the FBD is designed with a large-area outlet hindering pollution treatment and increasing the treatment cost. Policy makers can get a better understanding of the different aspects of drying systems, in particular with respect to sustainable rice production and processing, for decisions on what drying systems to support.

Social issues, such as dryer management, market, and end-user requirements in terms of rice quality and labor availability, are obvious factors affecting mechanization in general and the development of mechanical dryers in particular. In addition to the factors described above included in this research, we developed an approach for identifying proper drying systems based on rice production systems as shown in Table 7. The postharvest systems

Table 7. Matching of drying systems with different capacities for rice production systems.

| Capacity (t/day) | Drying system | Postharvest Systems | | |
|---------------------|---------------|--------------------------------------|-------------------------------|--|
| | | Subsistence farming, own consumption | Surplus farming, local market | Surplus farming, premium market and export |
| Less than 2 | SBD | +++ | | |
| 4–10 | FBD | + | +++ | + |
| 11–30 | FBD and RCD | | +++ | ++ |
| Higher than 30 | RCD | | + | +++ |
| Higher than 200 | Two-stage | | | +++ |

SBD = Solar bubble dryer; FBD = Flatbed dryer; RCD = Recirculating columnar dryer; Two-stage = Two-stage drying system including fluidized-bed and recirculating columnar dryers.

of these are classified into three categories: (1) subsistence farming for home consumption, (2) surplus farming for the local market, and (3) surplus farming for premium and export markets. The dryers with a capacity of less than 2 t/day, such as SBD and FBDc-2, fit only for subsistence farming. Capacities from 4 to 10 t/day, such as FBD, best fit with surplus farming for local markets. Capacities higher than from 20 to 30 t/day, such as FBDr-20 and RCD-30, best fit with surplus farming for export markets. The two-stage drying system, which combines fluidized-bed and continuous flow columnar dryers with a capacity much higher than the batch dryers, fits best with the industrial system for the export market.

5. Conclusions

This LCA-based comparative analysis among the different drying systems used in Vietnam, Cambodia, Philippines, and Myanmar resulted in recommendations for the most appropriate options based on the indicators of energy efficiency, GHG emissions, drying costs, and market demands. Comparison of these factors resulted in the data required for selecting a proper drying system that matches the needs of a specific postharvest chain. The FBDc-20 was the best option in terms of cost-benefits, operating labor, and energy efficiency; however, it has a larger land-use footprint than the RCD and two-stage. However, for industrial-scale operations with a capacity greater than 200 t/day, the two-stage and the RCDs require 15% higher energy consumption but have from 20 to 50% lower land requirements compared to the FBDs. The investment cost and the drying cost of the SBD still need to be reduced, nevertheless, the energy consumption and GHG emissions are more than 50% lower than in the other systems. Labor requirements should be further reduced too. In addition, our research also identified potential trajectories for developing paddy drying technologies that are aligned with the types of postharvest systems of different rice cropping systems, such as subsistence farming for home consumptions, surplus farming for local markets, and surplus farming for

premium and export markets. The study resulted in recommendations for the selection of a proper drying system corresponding to specific contexts and scales in the four countries. These recommendations could be also applied in other rice production regions as well.

Nomenclature and Units

| | |
|---------------------|--|
| CO ₂ -eq | carbon dioxide equivalent |
| EF | emission factor |
| FBD | flatbed dryer |
| FBDc-4 | conventional flatbed dryer with its capacity of 4 t/batch |
| FBDr-20 | reversible airflow flatbed dryer with its capacity of 20 t/batch |
| FLBD | Fluidized-bed dryer |
| GHG | greenhouse gas |
| h | hour |
| HDPE | high-density polyethylene |
| IE | input energy |
| IRRI | International Rice Research Institute |
| kg | kilogram |
| LCA | Lifecycle assessment |
| MC | moisture content on wet basis (%) |
| MJ | Mega Joules |
| MRD | Mekong River Delta of Vietnam |
| RCD-30 | recirculating batch columnar dryer with its capacity of 30 t/batch |
| SBD-1 | solar bubble dryer with its capacity of 1 t/batch |
| SEA | Southeast Asian countries |
| SunD | sun drying |
| t | ton or mega gram |
| Two-stage | two-stage drying system |

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