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Energy and carbon dioxide emission analysis of a batch-mode rice drying process in a rotary dryer

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Abstract: The rice drying process in a rotary dryer gives the benefit of producing uniformly dried rice in a short drying time. This work investigated a rotary dryer's efficiency and heat consumption at various temperatures (40, 50, and 60 °C) and capacities (10, 20, 30, and 40 kg). When loaded with 10 to 30 kg of rough rice and operated at 60 °C, the dryer produced dry rice with 14% w.b. moisture content for less than 3 hours. The energy efficiency and consumption were evaluated based on the experiment and theoretical analysis. According to the observation, a high temperature significantly shortened drying time. Thus, the total energy and fuel consumption decreased even at the higher capacity. The lowest carbon dioxide emission was achieved at the highest temperature and capacity.

Keywords: energy consumption; energy efficiency; fuel consumption; moisture content

Generally, a drying process uses up about 20 to 25% of the total energy required by food processing industries (Franco et al. 2020). However, energy consumption in a drying process varies with both applied drying methods and energy sources. Hence, hot-air convection dryers, microwave dryers, vacuum dryers, and infrared dryers require different quantities of energy (Motevali et al. 2011). While energy used for radiation and blower operation are the main factors for infrared drying, the power of the pump and heater are the key factors for vacuum drying operation. Consequently, the energy required for infrared and hot air becomes the major factor for a successful combined infrared and hot air drying (Onwude et al. 2019). For that reason, the selection of the drying method is one of the important considerations in the development of an energy-efficient drying process.

A previous study used several techniques to analyse the energy consumption of rice grains drying (Islam et al. 2022). Using the data collected from industrial-scale drying operation, the energy consumption of parboiled rice drying was 14.92–29.26 MJ·kg^{-1} water evaporated for 7–10 h of operation. However, the recommended operating temperatures ranged from 80–100 °C, which can be considered a high drying temperature for grain over a long period. In fact, a higher drying temperature will promote rapid moisture removal from rice grain and induce

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grain structural shock that leads to grain breakage (Utari et al. 2022). Meanwhile, an increase in drying temperature speeds up moisture reduction and thus accelerates the drying process in a pneumatic dryer (Kaensup et al. 2006). Although this dryer requires only 7.2 MJ·kg^{-1} water evaporated for drying of 250 kg·h^{-1} wet rice grains, it produced low-quality dry rice (head rice yield of 58%). Two popular drying methods to process wet rice grains are fluidised and fixed bed dryers (Das et al. 2020; Wazed et al. 2021). The drying time of fluidised bed drying can be shortened by adding spiral and cone angles on the dryer (Das et al. 2020). These additional items shortened the drying time by about 26% at 60 °C and capacity of 2.5 kg. Furthermore, the energy consumption also decreased by around 40% at 65 °C. However, scaling up is required to evaluate the rice drying process's drying time and energy consumption. Another study combined fluidised and fixed bed dryers with two stages of the rice drying process (Wazed et al. 2021). Although the drying capacities were high (1.8–3.6 t·h^{-1}), the high operating temperatures (120, 130, and 150 °C) caused low head rice yield, less than 53.43%.

A previous study claimed that the incorporation of a biomass furnace into a solar-based fluidised bed dryer demonstrates a considerably rapid drying rate and high energy efficiency, leading to low energy usage (Yahya et al. 2018). Nevertheless, the heat generated by the hybrid solar collector and biomass furnace could sustain an average drying temperature of 80.9 °C. Another report mentioned that an industrial horizontal rotary dryer consumes a closely similar amount of energy to a solar-based dryer operated by an Iranian rice processing enterprise (5.50–17.41 MJ·kg–^{1}) (Firouzi et al. 2017). That result demonstrated the superiority of rotary dryer performance, especially for a high load of rice grains. The rotary dryer allowed uniform moisture content and product quality to result from the drying chamber's rotation and mixing. Unfortunately, processing of this low initial moisture content Iranian rice (14–15% w.b.) cannot be compared to the freshly-harvested rice in Indonesia that usually has a higher moisture content, namely 24–27% w.b. in the wet season and 20–23% w.b. in the dry season (Yahya et al. 2018). Hence, it is necessary to analyse the energy consumption and provide recommendations prior to applying rotary dryers to the freshly-harvested rice grains in Indonesia and other countries with similar situations.

Alongside the calculation of energy consumption, there is rarely a discussion on the environmental impact of the drying process. This aspect becomes particularly important since the source of fossil fuel is limited and the greenhouse gas emission (GHG) effect must be kept as low as possible. Based on the Indonesian mitigation scenario, the total GHG emission is targeted to be reduced by 29 to 41% in 2030 (Wijaya et al. 2017). Before, Kaveh et al. (2020) analysed the energy requirement in correlation with GHG emissions of different drying methods for *Pistacia atlantica*. In the case of rice drying, the environmental impact analysis has been reported in the deep bed convective drying process (Beigi et al. 2021). At operational temperatures ranging from 40 to 60 °C, the calculated carbon dioxide (CO_2) emissions were 3.83–8.42 kg CO_2·kg^{-1} water evaporated. Meanwhile, the majority of research focused on carbon mitigation when applying solar as the heat source of the drying process (Hage et al. 2018; Ndukwu et al. 2020). Thus, it is critical to observe the CO_2 emissions when drying the freshly harvested rice grains using a non-conventional dryer.

The objective of this study is to evaluate the energy consumption, energy efficiency, and environmental impact of freshly harvested rice drying. This study uses a rotary dryer to assess the performance at various drying capacities, temperatures and fuels.

MATERIAL AND METHOD

Rice drying process. Freshly harvested rice was obtained from a local farmer in Mijen, Semarang, Central Java (Indonesia), with an average initial moisture content of 24.04 % (w.b.). The drying process began with setting the drying temperature to 40, 50, and 60 °C and linear air velocity to 9.5 m·s^{-1}. The capacities on the rotary drying chamber were 10–40 kg, with a rotational speed maintained at 6 rpm. Based on the assumption that rotation of the drying chamber allows the achievement of uniform grain moisture content, the moisture content was observed periodically (every 30 min) until a value of 14% w.b. was achieved with a maximum of 180 min of operation. A grain moisture meter (GMK 303-RS, G-WON Hitech, South Korea) with a resolution of ± 0.1%) was utilised to measure the grain moisture content.

Energy efficiency and consumption. The efficiency of energy utilisation in this experiment was expressed as energy efficiency (η), which can be calculated using the Equation (1):

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$$\eta = \frac{X_p \lambda}{\left[Q + P_b + P_m\right]} \quad (1)$$

where: X_p – the mass of evaporated water (kg); λ – the latent heat of vaporisation (2 400 kJ·kg^{-1}); Q – the heat consumed (kJ); P_b – the power of the blower (kJ); P_m – the power of motor (kJ).

Because the experiment employed liquefied petroleum gas (LPG) as the heat source, the specific fuel consumption of other fuels equivalent to LPG was calculated based on their calorific values. The calorific values of the calculated fuels are shown in Table 1. Furthermore, specific energy consumption (SEC) was estimated as electricity and thermal energy consumption.

Environmental evaluation. An environmental impact evaluation was performed for a rotary dryer by estimating CO_2 emission. As a comparison, this analysis also predicted the CO_2 emission if the process was conducted using other fuels, namely coal, diesel oil, and rice husk. The environmental impact of drying rice grains using rotary dryers followed steps from previous research as the amount of CO_2 emission produced ($M_{producedCO2eq.}$) (Hage et al. 2018). The impact is based on the electrical energy; E (kWh), heat consumed; H (kJ or kg fuel).

$$M_{producedCO_2} = E_{month} \times EF_{CO_2eq/1\text{kwh}} + H_{month} \times EF_{CO_2eq/fuel} \quad (2)$$

where: $EF_{CO_2eq/1\text{kWh}}$ and $EF_{CO_2eq/\text{fuel}}$ – the electricity and fuel emission factors shown in Table 2.

Table 1. Calorific values of fuels used in this study

Heat Source	Calorific value (kJ·kg^{-1})
LPG	47 300
Diesel	43 000
Coal	26 700
Rice husk	14 950

Source: Dincer et al. 2018; Steven et al. 2022

Table 2. Emission factors of several fuels used in this research

Fuels	Emission Factors
LPG	6.31×10^{-5} kg CO_2 eq·kJ^{-1}
Coal	9.97×10^{-5} kg CO_2 eq·kJ^{-1}
Diesel oil	7.41×10^{-5} kg CO_2 eq·kJ^{-1}
Rice husk	0.100 kg CO_2 eq·kg^{-1}

Source: Dones et al. 2004; Thao et al. 2011; Damayanti and Khaerunnisa 2018

RESULTS AND DISCUSSION

Moisture content. Table 3 summarises the final moisture content of rice grains after being subjected to a rotary drying process. International Rice Research Institute (IRRI) stated that the standard moisture content of rice or grains is no higher than 14% w.b. to ensure safe storage and avoid physical, enzymatic and biological deterioration (IRRI 2013.). The institute also documented that the drying process at 40 °C needs a very long drying time to achieve the acceptable moisture content of rice. Depending on the feed load, drying rice at 50 and 60 °C

Table 3. Determination of moisture content and drying time at different temperatures and capacities

Temperature (°C)	Loading (kg)	Moisture content (% w.b.)	Final product condition	Drying time (min)
40	10	15.73	not dry	180
	20	16.00	not dry	180
	30	18.60	not dry	180
	40	18.63	not dry	180
50	10	13.95	dry	120
	20	12.88	dry	180
	30	14.53	not dry	180
	40	14.67	not dry	180
60	10	12.37	dry	90
	20	13.80	dry	90
	30	14.00	dry	120
	40	12.30	dry	180

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in a rotary dryer was able to attain the standard moisture content in a period of less than 180 minutes. The findings suggest that a higher temperature is responsible for a larger energy supply and faster evaporation of free moisture at the rice husk surface for accelerated moisture removal. Accordingly, rice drying at a higher temperature requires a shorter drying time to achieve a lower grain's final moisture content. A similar phenomenon was reported for rice drying experiment using different types of dryers, such as vertical screw conveyor dryers (Utari et al. 2022), fluidised bed dryers (Chokphoemphun and Chokphoemphun 2018), and convective dryers (Beigi et al. 2021). On the contrary, the increase in rice capacity into the rotary drying chamber causes an extension of drying time due to a larger amount of moisture to be removed and less sufficient energy and physical contact between drying air and rice grains. Still, drying at 60 °C for three hours produced dry rice grains (14% w.b.) even at the highest feed load (40 kg). As a comparison, drying 20 kg of rice through a vertical screw conveyor dryer (VSC) using superficial air velocity of 9 $m \cdot s^{-1}$ at 60 °C needed 210 min to produce dry rice with 14% w.b. moisture content (Utari et al. 2022). Another reported work documented that rice drying in an air-inflated solar dyer with a 100 kg loading capacity consumed 7.5–9 h, reducing the moisture content from 22 to 14% (w.b.) (Dubey et al. 2019). Previously, a horizontal rotary dryer with a bigger loading capacity (3 t) was reported to entail 46 h for rice grain's moisture content reduction from 14.5 to 8.0% at 38–40 °C (Firouzi et al. 2017).

The analysis of variance (ANOVA) of moisture content and drying time at several drying temperatures and capacities is shown in Tables 4 and 5. From the parameter *P*-value, only the drying temperature significantly affected the final moisture content and drying time of this experiment. This work was conducted for 180 min. So, at higher capacity and drying temperature below 60 °C, the paddy rice cannot reach the targeted moisture content of 14% w.b. It means that the paddy rice cannot be fully dried. In this case, the moisture content reduction was significantly affected by the increase in temperature. The higher the temperature, the lower moisture content can be obtained.

Energy efficiency and consumption. The energy efficiency of the drying process was calculated based on the estimated drying time in Table 3. Figure 1 shows the energy efficiency of the drying process at all feed loading capacities and temperatures. This result confirmed Equation (1), which states that energy efficiency depends on the total amount of the evaporated moisture. When the drying chamber was filled with a large amount of rice grains, there was also a higher total evaporated moisture and energy utilisation. It is also shown that the energy efficiency was increased at a higher drying temperature. However, these results are still lower than the rice drying process with an electric stationary bed grain-dryer that reached an efficiency of around 40 to 70% (Wang et al. 2022).

The specific energy consumption represents the energy utilisation of this research (Figure 1B). As seen in Figure 1, the amount of energy used to remove 1 kg

Table 4. Two-way ANOVA of the moisture content at different temperatures and capacities

Source	*df*	Adj SS	Adj MS	*F*-value	*P*-value
Temperature (°C)	2	37.648	18.824	18.02	0.003*
Capacity (kg)	3	5.790	1.930	1.85	0.239
Error	6	6.268	1.045		
Total	11	49.706			

* Significant at *P*-value < 0.005; *df* – degree of freedom; Adj SS – adjusted sums of squares; Adj MS – adjusted mean squares

Table 5. Two-way ANOVA of the drying time at different temperatures and capacities

Source	*df*	Adj SS	Adj MS	*F*-value	*P*-value
Temperature (°C)	2	7 800	3 900.0	5.57	0.043
Capacity (kg)	3	3 900	1 300.0	1.86	0.238
Error	6	4 200	700.0		
Total	11	15 900			

* Significant at *P*-value < 0.005; *df* – degree of freedom; Adj SS – adjusted sums of squares; Adj MS – adjusted mean squares

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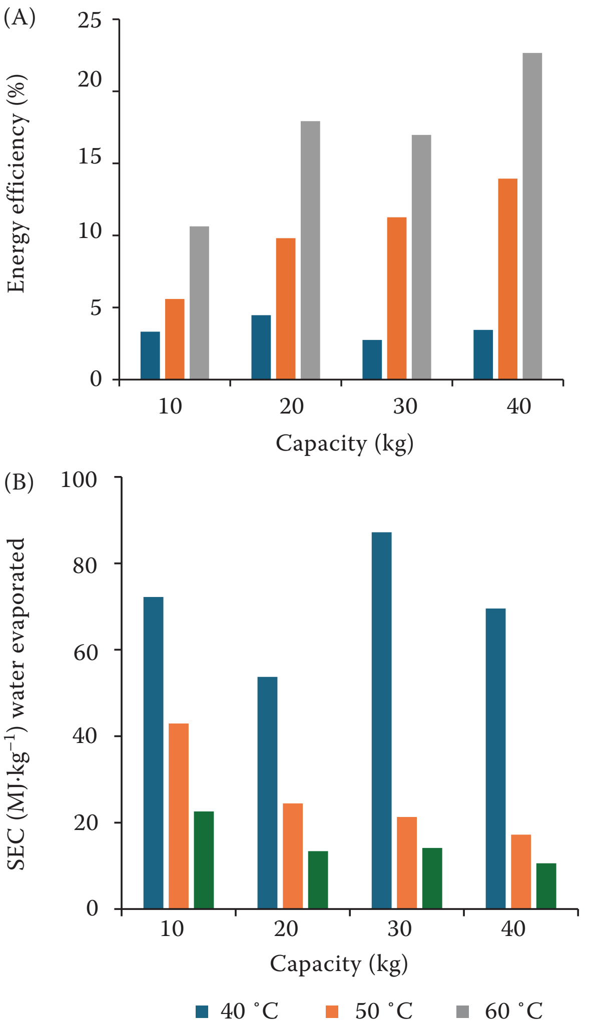

Figure 1. (A) Energy efficiency and (B) specific energy consumption (SEC) of rice drying using rotary dryer at different temperatures and capacities

water vapour ranged from 10.59 to 87.19 MJ. Indeed, this broad energy consumption range is due to the high energy consumption for the rice drying process at 40 °C with 10 and 30 kg feed capacity. Under those conditions, only a small amount of water vapour was evaporated after a prolonged drying operation that required a continuous energy supply. Surprisingly, Figure 1 also exhibits the SEC reduction due to increased capacity and temperature. According to Kaveh et al. (2020), the grain's thermal gradient was enhanced, and the moisture removal was sped up when drying was carried out at a higher temperature.

Unfortunately, the SEC of this rice drying experiment using a rotary dryer is still higher than previously reported rice drying using industrial bed dryer (IBBD) and industrial horizontal rotary dryer (IHRD) that only utilised 2.64–7.48 $MJ \cdot kg^{-1}$ water evaporated and 5.50–17.41 $MJ \cdot kg^{-1}$ water evaporated, respectively (Firouzi et al. 2017). Also, compared with rice drying using a fluidised bed dryer with an electric heater, the total energy used was only 10–23 $MJ \cdot kg^{-1}$ water evaporated (Akhtaruzzaman et al. 2022). On the other hand, Khanali et al. (2016) needed 74.73 $MJ \cdot kg^{-1}$ water evaporated for rough rice drying using a fluidised bed dryer at 60 °C employing a superficial air velocity of 2.8 $m \cdot s^{-1}$. Their observation also suggested that temperature has a more pronounced impact on the drying rate than the air velocity. As a result, a shorter drying time and lower SEC can be obtained when the drying operation is conducted at a higher temperature. In the case of rotary drum drying of green peas employing the hybrid convective-infrared heating at 40–70 °C and infrared power of 250–750 W, the SEC was much higher, which is more than 100 $MJ \cdot kg^{-1}$ water evaporated (Kaveh and Abbaspour-Gilandeh 2020). The significance of temperature and capacity variations on energy efficiency and SEC in this research is displayed in Tables 6 and 7. It is similar to the ANOVA of moisture content and drying time that showed a significant impact only from the drying temperature (*P*-value < 0.05).

Table 8 summarises the consumption of selected fuels used using the rotary dryer for the rice drying process. The drying experiment proved that the rice drying process using a rotary dryer requires the least amount of LPG. Certainly, it consumed the highest amount of rice husk. Nonetheless, the abundant availability, sustainability, and low cost of rice husk compared to other fossil fuels have placed rice husk as a good alternative. Similar to the trend of energy consumption, fuel consumption also decreased

Table 6. Two-way ANOVA of the energy efficiency at different temperatures and capacities

Source	*df*	Adj SS	Adj MS	*F*-value	*P*-value
Temperature (°C)	2	367.36	183.680	27.48	0.001*
Capacity (kg)	3	71.46	23.820	3.56	0.087
Error	6	40.11	6.685		
Total	11	478.93			

* Significant at *P*-value < 0.005; *df* – degree of freedom; Adj SS – adjusted sums of squares; Adj MS – adjusted mean squares

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Table 7. Two-way ANOVA of the drying time at different temperatures and capacities

Source	*df*	Adj SS	Adj MS	*F*-value	*P*-value
Temperature (°C)	2	6 882.3	3 441.15	36.73	<0.001*
Capacity (kg)	3	468.6	156.19	1.67	0.272
Error	6	562.2	93.69		
Total	11	7 913.0			

* Significant at *P*-value < 0.005; *df* – degree of freedom; Adj SS – adjusted sums of squares; Adj MS – adjusted mean squares

Table 8. Specific fuel consumption of rice drying using rotary dryer

Temperature (°C)	Capacity (kg)	Specific heat consumption ($MJ \cdot kg^{-1}$ water evaporated)	Specific fuel consumption ($kg \cdot kg^{-1}$ water evaporated)			
			LPG	diesel	coal	rice husk
40	10	62.77	1.33	1.46	2.35	4.20
	20	46.72	0.99	1.09	1.75	3.12
	30	75.80	1.60	1.76	2.84	5.07
	40	60.47	1.28	1.41	2.26	4.04
50	10	37.32	0.79	0.87	1.40	2.50
	20	21.27	0.45	0.49	0.80	1.42
	30	18.53	0.39	0.43	0.69	1.24
	40	14.96	0.32	0.35	0.56	1.00
60	10	19.63	0.41	0.46	0.74	1.31
	20	11.63	0.25	0.27	0.44	0.78
	30	12.29	0.26	0.29	0.46	0.82
	40	9.21	0.19	0.21	0.34	0.62

when the process was carried out under a higher capacity and temperature. The drying process at 60 °C with a 40 kg capacity of rice grains demonstrated the lowest fuel consumption, while the rotary drying process at 40 °C with a 10 kg capacity of rice grains required the highest one.

Environmental evaluation. Figure 2 depicts the CO_2 emission of rice drying with a rotary dryer using four different fuels expressed as CO_2 produced per kg water evaporated. The CO_2 emissions of this work (using LPG as the fuel) ranged between 0.87–5.96 kg $CO_2eq \cdot kg^{-1}$ water evaporated. Compared

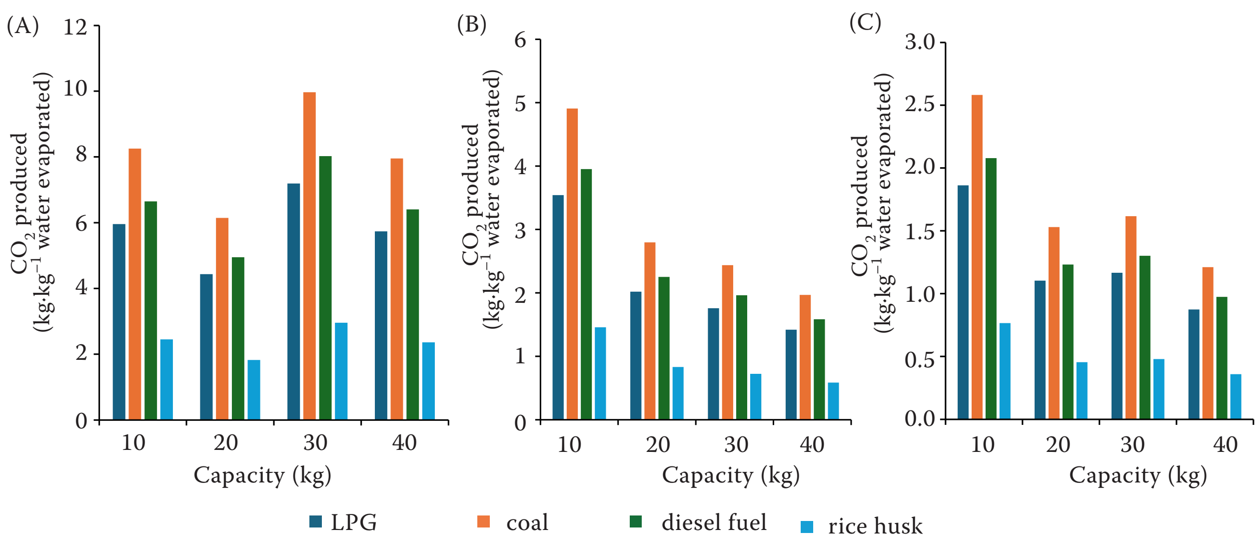

Figure 2. CO_2 emission of the experiment under different temperatures and fuels: (A) 40 °C, (B) 50 °C, and (C) 60 °C

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Table 9. ANOVA of CO_2 emission from different fuels at several temperatures and capacities

Source	*df*	Adj SS	Adj MS	*F*-value	*P*-value
Fuel	3	58.04	19.346	17.99	0.000*
Temperature (°C)	2	179.25	89.624	83.35	0.000*
Capacity (kg)	3	12.20	4.068	3.78	0.018
Error	39	41.94	1.075		
Total	47				

* Significant at *P*-value < 0.005; *df* – degree of freedom; Adj SS – adjusted sums of squares; Adj MS – adjusted mean squares

with three other fuels, coal generates the largest impact on CO_2 emission (1.21–8.25 kg CO_2eq·kg^{-1} water evaporated). A study of CO_2 mitigation of solar drying revealed tougher mitigation for coal than light diesel oil and natural gas, which indicates greater total CO_2 emission on coal consumption (Tripathy 2015). To create a more sustainable drying process, heat and electricity sources can be derived from other eco-friendly sources, such as solar, biomass, or waste heat. As seen in Figure 2, the drying process employing biomass as fuel is considered the most sustainable regarding GHG (as CO_2) emission. El Hage et al. (2018) and Ndukwu et al. (2020) reported reduced CO_2 emissions by applying solar dryers for food processing. Depending on the dryer's working capacity and life cycle, the total CO_2 reduction of the industrial-scale process can be thousands of kg per month (Hage et al. 2018; Ndukwu et al. 2020).

According to the data presented in Figure 2, regardless of the feed loading capacity, the increase in drying temperatures minimised the carbon emission of the process. Even though the increasing loading capacity and temperature led to a higher energy requirement to evaporate moisture content from rice, the shorter drying time contributes to less electricity and fuel consumption. Table 9 represents the statistical analysis of CO_2 emission of the drying process using several fuels at different temperatures and capacities. The analysis shows that CO_2 emission was significantly affected by those three factors (*P*-value < 0.005).

CONCLUSION

The effect of feed capacity and drying temperature on energy efficiency, energy consumption, and CO_2 emission have been evaluated for rice drying in a rotary dryer operated at 40, 50, and 60 °C and feed capacity of 10–40 kg. Based on the moisture removal, the increase in drying temperature led to a faster drying process and lower final moisture content. A higher loading capacity generally resulted in higher energy efficiency, with the highest value (22.66%) achieved at 60 °C and 40 kg rice grain capacity. Meanwhile, increased drying temperature and feed capacity reduced the specific energy consumption. In this work, the energy consumption and CO_2 emission ranged between 10.59–87.19 MJ·kg^{-1} water vapour and 0.87–5.96 kg CO_2eq·kg^{-1} water evaporated, respectively. The effects of drying temperature and feed capacity on the CO_2 emission were the same as the energy consumption as indicated by a lower CO_2 emission for drying at a higher temperature and feed capacity. According to the estimated results, rice husk can be more beneficial regarding fuel consumption and CO_2 emission. Finally, further study of rotary drying using rice husk or biomass is needed to evaluate the energy usage and GHG emission thoroughly.

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