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Published by the Faculty of Engineering, Khon Kaen University, Thailand

Performance and sustainability evaluation of rice husk-powered dryer under natural and forced convection mode

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Received 7 July 2023
Revised 7 September 2023
Accepted 16 October 2023

Abstract

Sun drying method has been used for drying agricultural commodities for centuries worldwide. The sun drying can be performed either by direct drying of the product under sunlight or drying using a solar collector-based dryer. However, a problem arises during the rainy season when there are lack of sunlight for proper drying. The application of biomass waste-powered dryers is a potential sustainable technology to encounter the problem. The present work aims to evaluate the performance and sustainability indicator of the rice husk-powered dryer under natural and forced convection modes while drying chili. The performance of the dryer evaluated is energy and exergy efficiency, and specific energy consumption (SEC). Meanwhile, the sustainability indicators evaluated are the waste-to-energy ratio (WER) and sustainability index (SI). The results show the performance and the sustainability indicator of the dryer are better under forced convection mode than that under natural convection mode. Overall energy and exergy efficiencies of the dryer are 3.58% and 4.93% under natural convection mode and the values are 16.85% and 16.13%, under force convection mode. Whereas, the SEC of the dryer is 26602.91 kg of rice husk/kg of water vapour for natural convection mode and 6979.89423 kg of rice husk/kg of water vapour under force convection mode. Furthermore, the sustainability of the dryer is better under force convection than under natural convection mode. WER under forced convection mode is lower than WER under natural convection mode. This gives a higher sustainability index (SI) of the dryer when operated under forced convection. The SI of the dryer ranges from 1.42 under natural convection to 1.92 under forced convection mode.

Keywords: Convection, Dryer, Forced, Natural, Sustainability

1. Introduction

Drying an agricultural commodity under sunlight is a common method used by farmers around the world. The main problem with the sun drying technique is the longer drying time. For example, it requires a week to attain a moisture content of 7.0%-7.5% of the agricultural product under adequate sunshine drying [1]. In order to shorten drying time, a solar collector-based dryer is applied. The solar collector absorbs heat from sunlight and uses it to warm up the air as a drying medium [2-4]. This technology still has problems when no sunshine is available. Another dryer that handles the lack of sunshine is a dryer with flue gas from a diesel engine as a drying medium [5]. Since the engine needs diesel fuel, the dryer lacks sustainability. Previous study revealed that the utilization of biomass as an alternative energy source could reduce energy outlay and improve economic constraints [6]. Thus, a biomass energy-based dryer is a promising drying technology for encountering those problems since Indonesia has huge biomass energy resources, approximately 33 GW [7]. Besides, the utilization of alternative biomass energy promotes a reduction in the emission of carbon dioxide and prevents a high carbon footprint process [8, 9].

The performance of a convection dryer can be affected by convection mode, i.e. natural convection mode and forced convection mode. Forced convection mode dryer has higher thermal efficiency than natural convection mode dryer. Thermal efficiency of the forced convection and natural convection of solar dryers were found to be 67.66% and 59.74%, respectively [4]. The thermal efficiency of a sliced turmeric fingers biomass powered dryer was found to be 4.35% and 4.62% for passive mode and active mode [10]. Excessive heat loss from a drying chamber in the biomass-powered dryer may be encountered by attaching thermal insulation to the drying chamber's wall [11].

Based on the first law of thermodynamics, energy analysis describes the thermal performance of the dryer. It gives only information about the type of energy and quantities of energy input and output of a process, not the quality of energy, such as losses due to irreversibility and surrounding environmental conditions [12]. Thus, exergy analysis based on the second law of thermodynamics is needed to overcome the limitations of energy analysis [13]. Exergy is defined as the maximum work that can be obtained from a system. There will be always exergy losses due to irreversibility in a process, which is equal to entropy generation [14]. Energy and exergy analysis (EEA) is helpful for better assessment of the thermodynamic performance of the dryer, designing the effective dryer, and optimising the drying process as it considers the quality and quantity of energy, losses due to irreversibility and surrounding

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doi: 10.14456/easr.2023.65

environmental conditions [15-17]. Several works on EEA of various types of dyers for drying different products have been reported so far. The EEA of microwave dryer for drying kiwi slices has been reported by Darvishi et al. [18]. The EEA of drying jackfruit skin in a solar tunnel dryer was carried out by Chowdhury et al.[19]. Meanwhile, the EEA of tomato drying in three different dryers, convective hot-air drying (HAD), a combination of hot air with microwave (MW-HAD), and combined hot air with infrared (IR-HAD) have been carried out by El-Mesery and El-Khawaga [20]. The EEA analysis revealed that the performance of forced convection was better than that of natural convection.

Terms of waste-to-energy ratio (WER) and sustainability index are commonly used to evaluate the sustainability of thermal systems. The thermodynamic performance of the dryer can be better evaluated using exergy sustainability indicators in terms of a waste-to-exergy ratio (WER) and sustainability index (SI). The indicators address the irreversibility and exergy losses in a process for a given exergy input [21].

From biomass-based dryers have been reported so far, many dryers used hot air as a drying medium. Heat from biomass combustion is used to heat the air [22]. Some dryers utilized direct flue gas from biomass combustion as a drying medium [23]. Thus, the present work performed an analysis of energy, exergy, and sustainability of the rice husk-based dryer with flue gas as a drying medium while drying chili under natural and forced convection modes.

2. Materials and methods

The flow diagram of the present work is presented in Figure 1. The work begins with experimental work followed by data analysis. The experiment was conducted at the Laboratory of Energy Conversion, Institute Sains & Teknologi AKPRIND Yogyakarta. The test was done using rice husk as an energy source while drying chili under natural and forced convection modes. Once data are obtained, energy, exergy, and sustainability analyses were performed.

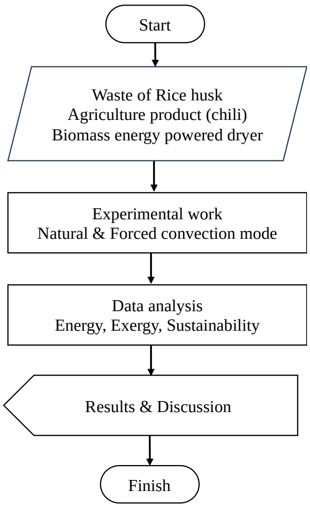

Figure 1 Flow diagram of the present work.

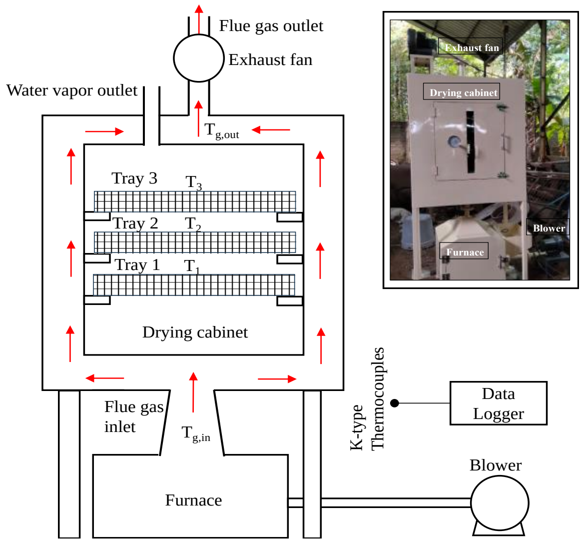

Figure 2 A photograph of a rice husk-powered dryer and schematic of the experimental set-up.

2.1 Experimental work

Figure 2 shows a photograph of a rice husk-powered dryer and a schematic of the experimental setup of the present work. The dryer has the main components of a furnace, a drying cabinet, a blower, and an exhaust fan. A sample of the agricultural commodity (i.e. 3 kg of chili) was dried in 3 trays in the drying cabinet for 2 hours. Rice husk was burnt in the furnace to generate a flue gas as a drying medium of the dryer. The combustion air in the furnace was supplied by the blower. A flue gas flew upward to the passage between the inner wall and outer wall of the drying cabinet. There was no contact between the flue gas and drying product (i.e. indirect type dryer). To operate the dryer under forced convection mode, the flue gas is induced into the passage using the exhaust fan. The temperature of the sample in each tray (T_1, T_2, T_3), the temperature of flue gas entering (Tg,in) and leaving (Tg,out) the passage, and ambient temperature (To) were measured using K-type thermocouples and logged into datalogger GraphTech240. The rice husk is sun dried to reduce its moisture content about 30%. Thus, this pre-treatment of the rice husk aims to ensure flue gas temperature which keep cabinet temperature at its setup temperature.

2.2 Data analysis

The data obtained is used to evaluate energy and exergy efficiency, specific energy consumption, and sustainability indicators (waste-to-energy ratio and sustainability index) of the dryer.

2.2.1 Energy analysis

Energy efficiency of the furnace [10]:

$$\eta_{en,f} = \frac{Q_{f,out}}{Q_{f,in}} = \frac{m_{g,}c_{p,g}\left(T_g - T_0\right)}{m_b HHV_b} \quad (1)$$

where $\eta_{en,f}$ is the energy efficiency of a furnace, $Q_{f,out}$ is the heat generated from rice husk combustion, $Q_{f,in}$ is the energy input to the furnace, m_g is the mass of flue gas, $c_{p,g}$ is the specific heat of flue gas (1.0 kJ/kg.K) [24], T_g and T_o are the flue gas temperature and the ambient temperature, m_b is the mass of rice husk, and HHV_b is the higher heating value of rice husk (13.03 MJ/kg) [7].

The energy efficiency of the drying cabinet [22, 25]:

$$\eta_{en,d} = \frac{Q_{g,used}}{Q_{g,in}} = \frac{\left(m_{s,in}c_{p,s}\Delta T_s\right) + \left(m_v h_{fg}\right)}{m_{g,,in}\, c_{p,g}\left(T_{g,in} - T_0\right)} \quad (2)$$

where $\eta_{en,d}$ is the energy efficiency of a furnace, $Q_{g,used}$ is the amount of heat used for evaporation of water vapour of the sample, $Q_{g,in}$ is the heat amount of heat flows through the passage, $m_{s,in}$ is the initial mass of the sample, $c_{p,s}$ is the specific heat of sample, ΔT_s the temperature different of the sample, m_v is the mass of water vapour evaporated, h_{fg} is the latent heat of vaporization of water (2260 kJ/kg), mg is the mass of flue gas, $T_{g,in}$ is the inlet temperature of flue gas. Assuming 0.65 volumetric efficiency of a passage, the mass of flue gas is calculated using Eq. (3). The mass of water vapour is obtained from the mass difference between the initial and final mass of the sample as given in Eq. (4).

$$\sum m_{g,in} = 0.65\rho_g A v_g \quad (3)$$

$$m_v = m_{s,in} - m_{s,out} \quad (4)$$

where ρ_g is the density of flue gas, A is the cross-sectional area of the passage, vg is the velocity of flue gas, $m_{s,out}$ is the final mass of a sample. The density of flue gas is obtained at atmospheric pressure and flue gas temperature using the graph given in www.pipeflowcalculations.com [26].

Overall energy efficiency ($\eta_{en,o}$) and specific energy consumption (SEC) are calculated using Eq. (5) and Eq. (6). SEC is the amount of energy required for evaporating 1 kg of water vapour [27-29].

$$\eta_{en,o} = \eta_{en,f}\eta_{en,d} \quad (5)$$

$$SEC = \frac{Q_{f,in}}{m_v} = \frac{m_b HHV_b}{m_v} \quad (6)$$

2.2.2 Exergy analysis

Exergy is a measure of the quality of energy based on the second law of thermodynamics. It is the available energy that can be used that provides information about available energy that can be used to optimize the drying process in the dryer [30]. Assuming a steady flow drying process, exergy per unit mass of any system is proposed by Mugi and Chandramohan [15] as

$$Ex = mc_p\left[\left(T - T_0\right) - T_0 ln\left(\frac{T}{T_0}\right)\right] \quad (7)$$

Exergy efficiency of the furnace:

$$\eta_{ex.f} = \frac{Ex_{f,out}}{Ex_{f,in}} \quad (8)$$

where $\eta_{ex.f}$ is the exergy efficiency of a furnace, $Ex_{f,in}$ and $Ex_{f,out}$ are the inflow and outflow exergy of the furnace which are calculated using Eq. (9) and Eq. (10).

Exergy inflow to a furnace represents the chemical exergy of biomass fed into the furnace which can be calculated using a simple equation proposed by Song et al.[31].

$$Ex_{f,in} = 1.047 m_b HHV_b \quad (9)$$

$$Ex_{f,out} = m_g c_{p,g}\left[\left(T_g - T_0\right) - T_0 ln\left(\frac{T_g}{T_0}\right)\right] \quad (10)$$

Exergy efficiency of the drying cabinet:
The exergy efficiency of a drying cabinet is estimated using Eq. (11) given by Akpinar [32].

$$\eta_{ex.d} = \frac{Ex_{d,out}}{Ex_{d,in}} \quad (11)$$

The inflow exergy to a drying cabinet ($Ex_{d,in}$) and outflow exergy from a drying cabinet ($Ex_{d,out}$) are determined using Eq. (12) and Eq. (13) given by Kuzgunkaya and Hepbasli [33].

$$Ex_{g,in} = m_g c_{p,g}\left[\left(T_{g,in} - T_0\right) - T_0 ln\left(\frac{T_{g,in}}{T_0}\right)\right] \quad (12)$$

$$Ex_{g,used} = m_s c_{p,s}\left[\left(T_{s,out} - T_0\right) - T_0 ln\left(\frac{T_{s,in}}{T_0}\right)\right] \quad (13)$$

where, m_g is the mass of flue gas entering the drying passage, $c_{p,g}$ is the specific heat of flue gas, $T_{g,in}$ and $T_{g,out}$ are the flue gas temperatures entering and leaving the drying cabinet, m_s is the mass of sample, $c_{p,s}$ is the specific heat of sample (1.87 kJ/kg.K), $T_{s,in}$ and $T_{s,out}$ are the initial and final temperature of the sample, and T_0 is the ambient temperature. Meanwhile, *the* overall exergy efficiency of the drying system is obtained using Eq. (14)

$$\eta_{ex,o} = \eta_{ex,f}\eta_{ex,d} \quad (14)$$

2.2.3 Sustainability analysis

The thermodynamic performance of the dryer can be also evaluated using exergy sustainability indicators in terms of waste-to-exergy ratio (WER) and sustainability index (SI) [34]. The indicators address the irreversibility and exergy losses in a process for a given exergy input [15]. The WER and SI are calculated using equations proposed by Ndukwu et al. [21].

$$WER = \frac{Ex_{loss}}{Ex_{in}} \quad (15)$$

$$SI = \frac{1}{1 - \eta_{ex}} \quad (16)$$

where exergy loss from the dryer (Ex_{loss}) is calculated using Eq. (17)

$$Ex_{f,loss} = I_f = 1.047 m_b HHV_b - m_g c_{p,g}\left[\left(T_g - T_0\right) - T_0 ln\left(\frac{T_g}{T_0}\right)\right] \quad (17)$$

3. Results and discussion

Figure 3 presents drying rate of the sample in tray 1, tray 2, dan tray 3 under natural convection and forced convection mode. The value is calculated by the mass different of the sample before and after 2 hours drying time. To prevent disturbing the drying process due to opening the cabinet's door during the process, the mass measurement of the sample is done before the and after drying. Thus, the moisture loss evolution per second cannot be presented in the present work. However, the average drying rate for 2 hours drying time can be obtained as given in Figure 3. It can be seen from the figure, the highest drying rate is obtained at tray 1 (i.e. the lowest tray) either under natural convection or forced convection. The higher the position of the tray, the lower the drying rate of the sample for both convection modes. More comprehensive discussion is given in the following section.

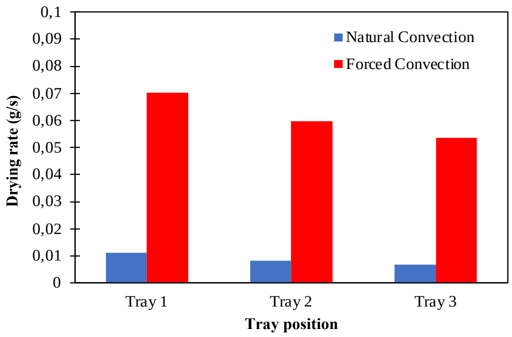

Figure 3 Drying rate

Figures 4(a) and 4(b) show the temperature of the sample in tray 1, tray 2, and tray 3 under natural convection and forced convection mode. From Figure 4(a), it can be observed a small increase in the sample's temperature under natural convection mode for 2 hours drying. The temperatures of the sample in tray 1, tray 2, and tray 3 are almost similar, indicating uniform temperature distribution in the drying cabinet. Different trends of the temperatures are observed under force convection mode. As shown in Figure 4(b), the temperatures increase significantly after 10 minutes of drying till reaching a maximum temperature of 60°C in tray 1 and a maximum temperature of 50°C in tray 3. The temperatures decrease after 90 minutes of drying. The temperature distribution in the drying cabinet is less uniform under force convection mode when compared with that under natural convection. This may be due to the turbulent effect of the flue gas flow caused by flow velocity increases from 2.5 m/s (natural convection mode) to 8 m/s (forced convection mode).

The average temperature of the sample in tray 1, tray 2, and tray 3 are given in Figure 5. It is clear that the average temperature of the sample under forced convection mode is higher than that under natural convection mode. The higher velocity of a flue gas under forced convection mode causes an increasing Reynold number of the flue gas flow. As we know, increasing Reynold number leads to enhanced convection coefficient, and in turn improves heat transfer rate from the flue gas to the sample. In other words, the drying of the sample is better under forced convection mode. From Figure 5, the natural convection shows linear trendlines between average temperature's cabinet and drying time. Average temperature of cabinet increases linearly as drying time proceeds. Meanwhile, polynomial trendlines exists between drying time and average cabinet's temperature. This indicates that cabinet's temperature reaces maximum at ¾ drying time and the temperature steps down in the following time. Thus, the mathematical model as shown in given in Figure 5 can be used to predict the average cabinet's temperature during drying process as a function of time.

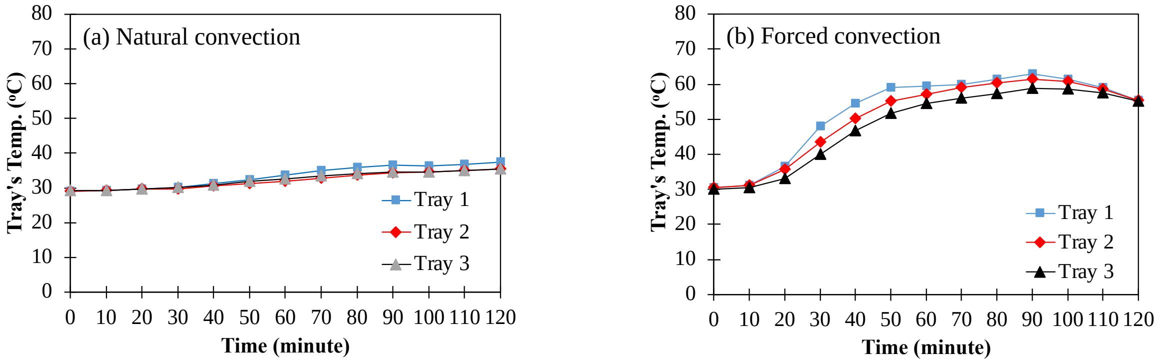

Figure 4 Temperature distribution in drying cabinet

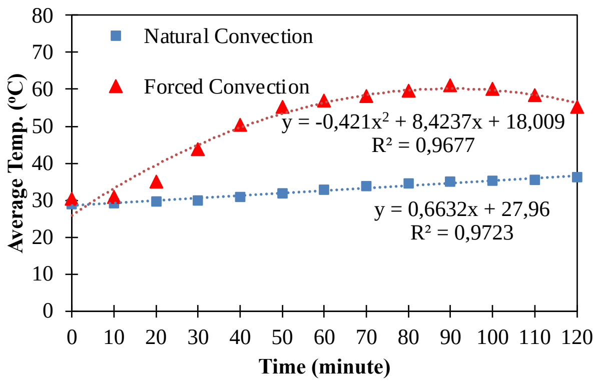

Figure 5 Average temperature of drying cabinet

Figures 6(a) and 6(b) display energy efficiency and specific energy consumption (SEC). The energy efficiency of the furnace, the drying cabinet, and the overall energy efficiency of the dryer are higher under forced convection mode. Increasing the heat transfer rate from flue gas to the drying cabinet by forced convection impacts enhancing energy utilization for drying the sample. Thus, a more effective drying process occurs in the drying cabinet. This leads to improving the energy efficiency of the drying cabinet. Since the overall efficiency of the dryer system is a function of furnace energy efficiency and drying cabinet energy efficiency, higher overall energy efficiency under forced convection mode than under natural convection mode was also observed. Overall energy efficiencies of the dryer are 3.58% under natural convection mode and 16.85% under forced convection mode. The overall energy efficiency improves about three times when flue gas velocity increases from 2.5 m/s (natural convection mode) to 8 m/s (forced convection mode). The thermal efficiency of the dryer is better under forced convection mode than under natural convection mode [4, 10]. The overall energy efficiency of the dryer lies in the drying efficiency ranges of a conventional corn dryer based on the heat exchanger pipe diameter obtained by Alit et al. [28] with values of 13.9% to 28.8%.

Increasing overall energy efficiency causes decreasing specific energy consumption of the dryer as can be seen in Figure 6(b). Since the drying process is more effective under forced convection mode than under natural one, less amount of energy source (rice husk) is required for evaporating 1 kg of water vapour during forced convection mode. The SECs of the dryer are 26602.91 kg of rice husk/kg of water vapour for natural convection mode and 6979.89423 kg of rice husk/kg of water vapour. It can be stated that the SEC reduces almost four times when the natural convection mode changes to force convection mode.

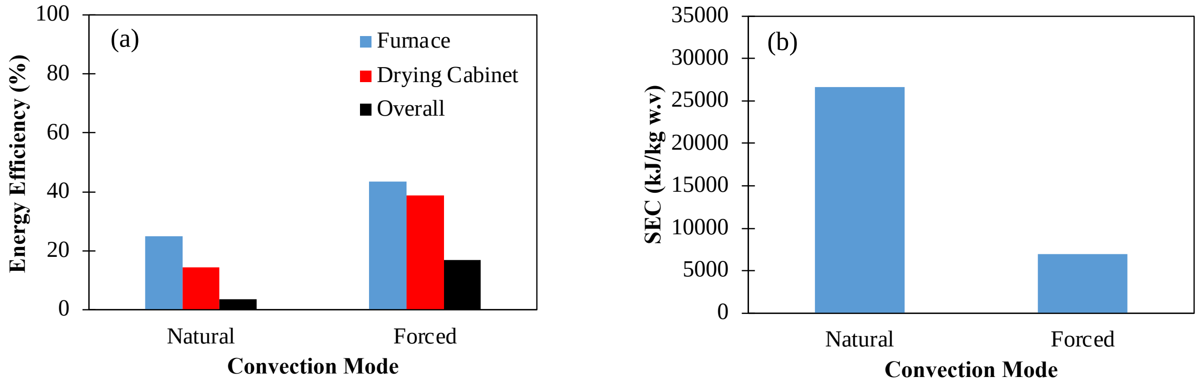

Figure 6 Energy efficiency and SEC

Figure 7(a) displays exergy efficiency and Figure 7(b) shows sustainability indicators of the dryer. Following the trend of energy efficiency, the overall exergy efficiency also moves up when the dryer is operated under forced convection mode. Useful exergy under forced convection mode is higher than that under natural convection mode. Overall exergy efficiencies of the dryer under natural convection mode and forced convection mode are 4.93% and 16.13%, respectively.

Furthermore, the sustainability of the dryer is better under forced convection than under natural convection mode. The waste-to-energy ratio (WER) is smaller under forced convection mode than that under natural convection mode. This gives a higher sustainability index (SI) of the dryer when operated under forced convection. The SI of the dryer ranges from 1.42 under natural convection to 1.92 under forced convection mode. The values obtained in the present work are lower than the values reported by Ndukwu et al. [21]. They obtained the SI ranges from 3.01 to 8.15 while investigating the sustainability indicators of a solar dryer integrated with sodium sulfate decahydrate and sodium chloride as a thermal storage medium.

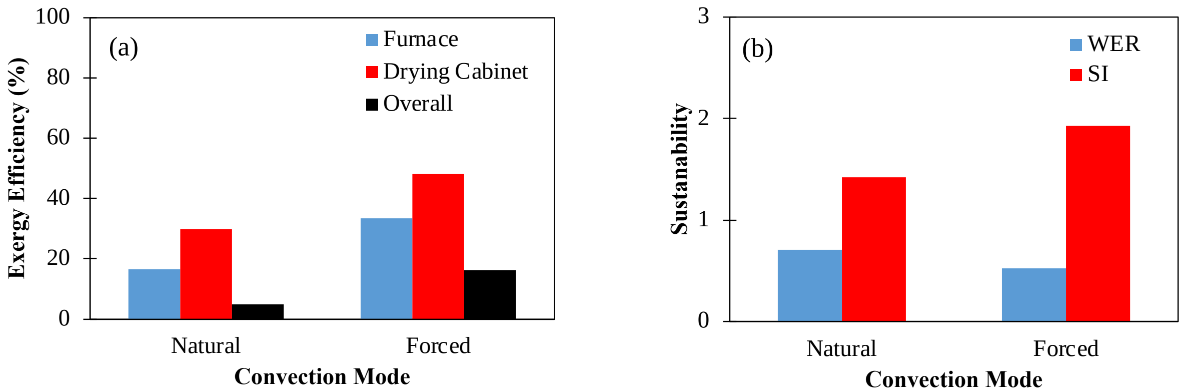

Figure 7 Exergy efficiency and sustainability indicator

4. Conclusions

The performance in terms of energy, exergy, and specific energy consumption (SEC) sustainability indicator in terms of waste to energy ratio (WER) and sustainability index (SI) of the rice husk powered dryer are investigated while drying a chili under natural and forced convection mode. It can be concluded that the energy efficiency, exergy efficiency, SEC, WER, and SI of the dryer are better under forced convection. The increasing velocity of flue gas from 2.5 m/s (natural convection mode) to 8 m/s (forced convection mode) enhances the heat transfer rate from flue gas to the sample in the drying cabinet. However, optimization of flue gas velocity under forced convection mode has to be performed in future work in order to increase the performance and sustainability of the dryer.

5. Acknowledgements

The authors would like to thank BRIN (National Research and Innovation Agency) and LPDP (Endowment Funds for Education) of the Republic of Indonesia for financial support through the scheme RIIM (Research and Innovation for Developed Indonesia) Batch II 2022 with reference number 82/II.7/HK/2022.

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