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Theoretical modeling to analyze the energy and exergy efficiencies of double air-pass solar tunnel dryer with recycled organic waste material

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Abstract. In this study, the effect of recycled organic waste thermal insulation materials and insulation thickness on a double air pass solar tunnel dryer performance for the charcoal briquette drying process was investigated based on the heat transfer model, that was computed with Python code. The result reveals that, an average temperature of bagasse insulated a double air pass solar tunnel dryer was higher than wood, paper, corn cop, and sawdust insulation by 17.5%, 12%, 8.3%, and 6%, and higher than rock wool, mineral wool, and glass fiber by 3.01%, 4%, and 25.41%, respectively. The energy and exergy efficiency were considerably enhanced with bagasse insulation, comparatively. Thus, the assimilation of recycled organic waste thermal insulation materials enhances the evaporation rate besides reducing energy and exergy losses to the ambient while concomitantly minimizing costs and environmental impacts.

Introduction

In recent years solar energy-driven technologies have been widely used in power generation for industrial processes, household appliances, and commercial centers and in thermal energy extraction for air, water, and process heating, drying, and cooling applications. Conventionally, solar drying and air heating systems are the most economically viable ways of solar energy conversion [1]. The significant problem encountered in solar thermal technologies is energy and exergy loss to the ambient through the bottom and edge wall [2]. This phenomenon indicates that the overall thermal and exergetic efficiency of solar thermal systems is considerably affected by heat loss [3]. Solar air heaters were analyzed in terms of exergy loss to the environment due to absorber plate temperature and the result showed that at a higher absorber plate temperature, there was an increment in the exergy and thermal energy loss [4]. In solar air heaters with double glazing, the exergy and heat loss increased as the heater surface area and absorber plate temperature increased [5].

The onion drying system was analyzed using a mathematical model in terms of exergy loss and the result indicates that the rate of exergy loss reached 28.6% of the incoming exergy in the drying chamber at a velocity and temperature of 2 m/s and 80 ºC [6]. The exergy destruction of a hybrid-solar drying system for the rosemary drying process was investigated experimentally and the authors documented that the rate of exergy loss varied from 0.009 to 0.028 KW with a variation in air velocity from 1 to 2 m/s and temperature from 40 to 70 ºC [7]. A solar tunnel drying system was investigated experimentally for the drying presses of orange peels and the result revealed that the average exergy loss reached 57.99% in the dryer at higher solar radiation [8]. This indicates that exergy and thermal loss increased with the increment of solar intensity. Recently, different

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research has been conducted to address and improve the effect of thermal insulation materials on the heat resistance capacity in solar thermal and building technologies [9]. The performance of building elements with and without insulation material was investigated experimentally and the authors documented that using insulation materials reduces the indoor air temperature by 8 ºC [10].

Besides thermos-physical properties, insulation thickness was one of the major factors that altered the performance of solar thermal systems. The effect of insulation thickness on collector efficiency of solar flat plate collectors was analyzed by ANSYS FLUENT and the result showed that the collector efficiency for 50 mm insulation thickness was higher than 35 and 25 mm by 10% and 18%, respectively [11]. The energy-saving capacity of salinity gradient solar ponds with different insulation thicknesses was analyzed using mathematical modeling and the authors reported that the energy-saving enhanced by 36.7% to 55.2% for the optimum thickness of 62 to 122 mm, respectively compared to those without insulation [12]. The energetic performance of solar water heating systems using flat plate collectors with different insulation thicknesses was analyzed by developing the thermal model and the result indicates that the energy efficiency was enhanced by 3.66% as the insulation thickness increased from 20 to 40 mm [13]. The effect of insulation thickness on energy-saving capacity and cost of the building was analyzed and the authors reported that the selection of proper insulation thickness enhances the average annual energy saving by 33.5% and the total energy saving cost by 4.4 to 53.5 \$/(m^2year) through the reduction energy loss factor [14].

The literature mentioned above indicates the energy efficiency, exergy efficiency, and moisture removal rate are reduced in the solar drying technologies due to the heat and exergy loss to the environment through the thermal insulation thickness [15]. Recently, recycled organic waste thermal insulation materials have promising alternatives to organic (synthetic) thermal insulation materials from the perspective of environment and sustainable development [16]. Additionally, recycled organic waste materials are widely available and economically beneficial over organic synthetic thermal insulation materials. Accordingly, this work intends to study the effect of recycled organic waste thermal insulation materials and thickness on the energy, exergy, and evaporation rate performance of a double air pass solar tunnel drying system for the drying of charcoal briquette, to reduce thermal energy loss to the ambient and environmental impacts of thermal insulation materials during the production process. Integrating recycled organic waste insulation material could reduce the material and manufacturing costs. Heat and exergy loss reduction performance and drying rate enhancement by developing heat transfer models, and the solution was computed by using Python code.

Material and methods

Dryer dimensions

This study will be investigated based on the hourly ambient parameters data of the Jimma zone, Oromia region, Ethiopia (7º40'0" N, 36º50'0'E). The hourly ambient conditions vary from 06:00 a.m. to 17:00 for 11 sunshine hours of the day. The effect of recycled organic waste thermal insulation materials and thickness were computed by developing mass and heat transfer models using the principle of exergy, mass, and energy balance. Throughout the heating and drying process, the mass flow rate of the air stream was considered constant at 0.018 and 0.035 Kg/s, at a constant velocity of 2 m/s, respectively. The influence of recycled organic waste thermal insulation materials on the energy outcomes, exergy extraction, and evaporation rate of a double air pass solar tunnel drying system (DAPSTDS) was studied by using five different materials, namely bagasse, paper, corn cop, wood, and sawdust as well as their respective thermophysical properties are listed in **Table 1.** The variation of thermal efficiency, exergy efficiency, and evaporation rate from the surface of a drying product in a DAPSTDS with the change of insulation was investigated by considering three different dimensions 0.05, 0.25, and 0.5 m.

Table 1: *The recycled organic waste, and the inorganic insulation material.*

Material		Density $(\mathbf{Kg/m^3})$	Specific heat $(\mathbf{J/Kgk})$	Thermal conductivity $(\mathbf{W/Km})$	Emissivity
Recycled organic waste	Bagasse	120	460	0.041	0.88
	Paper	800	1340	0.093	0.93
	Corn cop	282.38	1500	0.16	0.9
	Wood	920	1670	0.4	0.9
	Saw-Dust	415	900	0.062	0.75
Insulating material	Glass Fiber	1857	800	0.36	0.75
	Mineral Wool	200	850	0.046	0.94
	Rock Wool	200	1030	0.043	0.05

The schematic diagram of a double air pass solar tunnel drying system with the drying product and the main components is displayed in **Figure 1.** The drying system is divided into two main chambers. The heating chamber where the air stream enters through the inlet is heated by an absorber plate and the fraction of solar radiation scattered inside the chamber then flows to the next chamber. The drying chamber is where the air stream gains thermal energy from the absorber plate through convection for the second time and simultaneously, the moisture is removed from the surface of the charcoal briquette, and finally, the moist air is discharged to the ambient through, the outlet. The overall dimensions of the drying system are listed in **Table 2**.

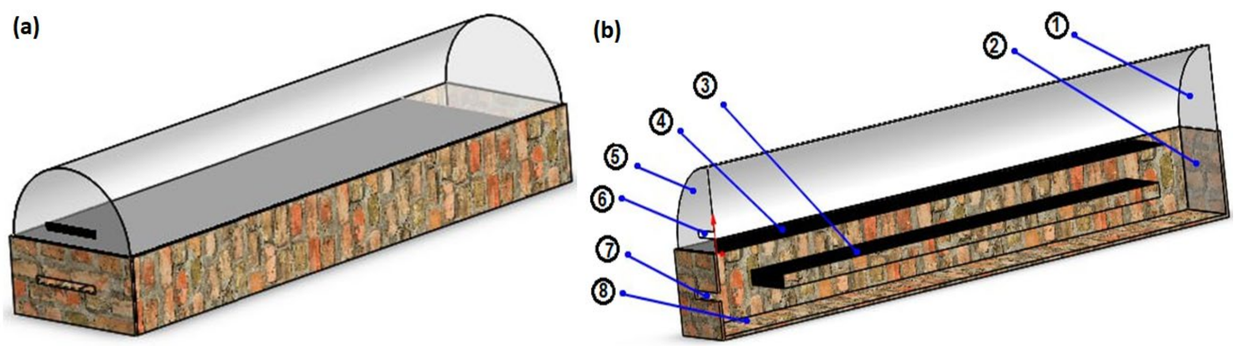

Figure 1: *Schematic diagram of a double air pass solar tunnel dryer: (1) heating chamber, (2) drying chamber, (3) charcoal briquette (drying product), (4) absorber plate, (5) cover, (6) inlet, (7) outlet, and (8) floor.*

Table 2: *The Dimension Specification of DAPSTDS.*

Parameters	Dimensions					
	Wet Base			Dry Base		
Mass of briquette	30 Kg			30 Kg		
Initial moisture content	0.5%			100%		
Final moisture content	0.1%			11.111%		
Moisture to be removed	0.4%			88.889		
Mass to be removed	12 Kg			26.667 Kg		
Parameters	Components				Chambers	
	Cover	Plate	Briquette	Floor	Heating	Drying
Length, (m)	2.4	2.25	1.6	2.4	2.4	2.4
Width, (m)	1.885	1.2	0.75	1.2	1.2	1.2
Thickness, (m)	0.0002	0.0004	0.125	0.2	0.6	0.6
Area, (m^2)	4.5	2.574	1.2	2.86	0.5652	0.72

Theoretical modeling

Modelling of the dryer

The thermal energy transfer modeling was developed by applying energy balance on the rate of thermal energy exchange between the dryer components (absorber plate, cover, and floor), Charcoal Briquette, and the air stream in both chambers, based on the schematic diagram shown in **Figure 2.** The analysis was performed using the COMSOL Multiphysics 5.2a software.

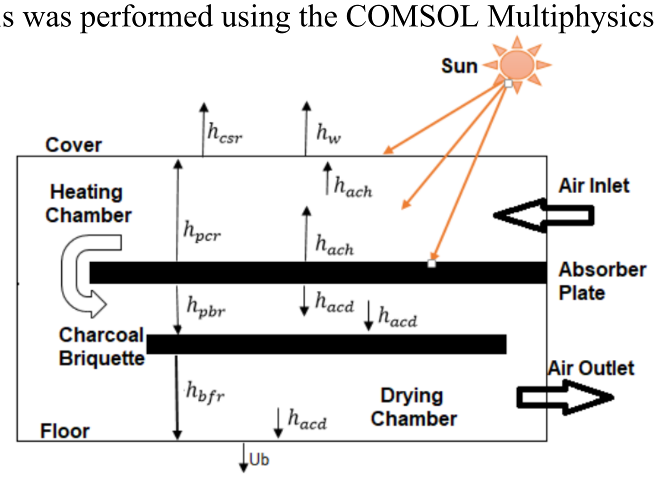

Figure 2: *Schematic diagram of heat energy interaction inside the drying system.*

Thermal efficiency

Energy is the ability to do work and exergy is the capacity for work extraction, which can be determined from the initial and final temperature with the corresponding time [17].

The rate of input energy ($\dot{Q}_{in}$) is computed as:

$$\dot{Q}_{in} = [A_{pr} I] \tag{1}$$

The amount of useful energy outcome ($\dot{Q}_u$) is evaluated as:

$$\dot{Q}_u = [\dot{m}_a C_{pa}(T_{ao} - T_{ai})] \tag{2}$$

The amount of heat energy loss ($\dot{Q}_{loss}$) is calculated as:

$$\dot{Q}_{loss} = [A_f U_b (T_{ad} - T_{ai})] \tag{3}$$

The thermal efficiency (η_{th}) is determined as:

$$\eta_{th} = \left[\frac{\dot{Q}_u}{\dot{Q}_{in}}\right] \tag{4}$$

Exergy efficiency

The rate of input exergy ($\dot{Ex}_{in}$) is computed as,

$$\dot{Ex}_{in} = \left[A_{pr} I \left\{1 - \left(\left(\frac{4}{3}\right) * \left(\frac{T_{am}}{T_{sun}}\right)\right) + \left(\left(\frac{1}{3}\right) * \left(\frac{T_{am}}{T_{sun}}\right)^4\right)\right\}\right] \tag{5}$$

The amount of exergy outcome ($\dot{Ex}_u$) at a given time is computed as:

$$\dot{Ex}_u = \left[\dot{m}_a C_{pa} \left\{(T_{ao} - T_{am}) - \left(T_{am} Log\left(\frac{T_{am}}{T_{sun}}\right)\right)\right\}\right] \tag{6}$$

The exergy efficiency (η_{ex}) is expressed by:

$$\eta_{ex} = \left[\frac{\dot{Ex}_u}{\dot{Ex}_{in}}\right] \tag{7}$$

Results and discussion

The energy outcomes, exergy extraction, and evaporation rate of the drying systems mainly depend on the ambient conditions. Thus, the mathematical model simulation was computed based on the hourly ambient parameters data of Jimma zone, Ethiopia available on 16^{th}, March, 2023, the maximum solar intensity, temperature, and wind speed were 1051 W/m^2, 28 ºC, and 1.61 m/s, respectively.

Air temperature at outlet

The effect of recycled organic waste thermal insulation materials on the temperature was analyzed by applying equations. The hourly variation in the temperature of the drying system under recycled organic waste thermal insulation materials was illustrated in **Figures 3(a-b)**. The average temperature achieved from the analysis in the drying and heating chamber from 09.00 AM to 17:00 PM was 52.2 (40 ºC), 48 (38.4 ºC), 46.5 (37.9 ºC), 44.1 (37.3 ºC), and 41.1ºC (36.3ºC) for bagasse, sawdust, corn cop, paper, and wood, respectively. The lower temperature difference was found in the morning which increased with an increment of solar insolation, then it reached the pick-point in the afternoon at higher insolation, and after that, it declined concerning the amount of solar irradiance.

The average temperature in the dryer with bagasse insulation was higher than wood, paper, corn cop, and sawdust insulation by 17.5%, 12%, 8.3%, and 6%, respectively. This shows that integrating bagasse insulation with a double-air pass solar tunnel drying system could play a role in enhancing the temperature in the heating and drying chamber during the sunshine period than other recycled organic waste insulation materials.

The comparison results of recycled organic waste material (bagasse) with inorganic materials (glass fiber, mineral wool, and rock wool) are illustrated in **Figures 3(c-d)** for similar insulation thickness. The result rivals that the average temperature from 09.00 am to 17:00 was 52.2 (40 ºC), 50.63 (39.4 ºC), 50.2 (39.3 ºC), and 39 (35.6 ºC), for bagasse, rock wool, mineral wool, and glass fiber in descending order, respectively. This indicates that the average temperature in the drying system with bagasse insulation was found higher compared to rock wool, mineral wool, and glass fiber by 3.01%, 4%, and 25.41%, respectively. This occurrence was due to bagasse having a better combination of thermos-physical properties compared to rock wool, mineral wool, and glass fiber [18]. Therefore, integrating customized recycled organic waste thermal insulation materials with a solar drying system enhances the temperature.

Materials Research Proceedings 43 (2024) 368-376 https://doi.org/10.21741/9781644903216-48

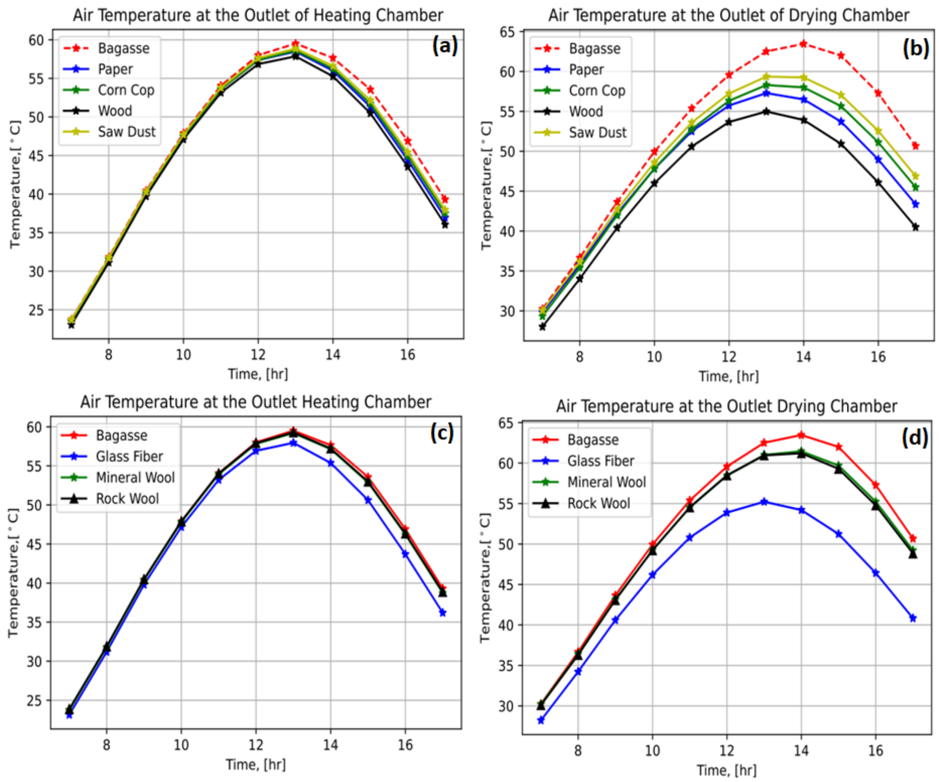

Figure 3: *(a-b) Temperature in the heating and drying chamber for recycled organic waste, and (c-d) Inorganic (synthetic) thermal insulation materials.*

Energy efficiency

The hourly variation of thermal efficiency in the drying system insulated with recycled organic waste thermal insulation material was displayed in **Figure 4(a)**, and the drying system insulated with inorganic thermal insulation materials was presented in **Figure 4(b)**. The result shows that the average thermal efficiency from 07:00 a.m. to 17:00 was 40.8%, 36.93%, 35.24%, 33.93%, and 30.24%for bagasse, sawdust, corn cop, paper, and wood, respectively, and for mineral wool, rock wool, and glass fiber was 39.1%, 38.76%, and 30.65%, respectively. The minimum thermal efficiency was observed at noon, where the solar insolation and the heat loss reached maximum. This phenomenon indicates that the change in thermal efficiency is due to the variation in heat loss caused by solar radiation variation with time. The result indicates that higher thermal efficiency was achieved in a drying system with bagasse than other recycled organic waste and inorganic thermal insulation materials. Because comparatively lower heat loss and higher temperature differences during the daytime were achieved in bagasse-insulated drying systems [19].

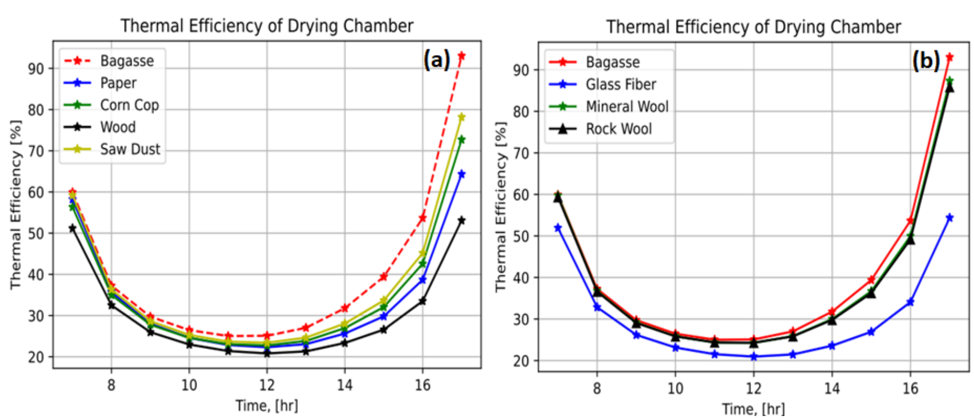

Figure 4: *Thermal efficiency of the drying system with (a) recycled organic waste and (b) standard thermal insulation materials.*

Exergy efficiency

The exergetic performance of the drying system integrated with recycled organic waste thermal insulation materials and for comparison with commonly used thermal insulation materials. **Figure 5(a)** and **Figure 5(b)** shows the hourly variation of the exergetic efficiency of the drying system under recycled organic waste thermal insulation material and inorganic thermal insulation materials. The average exergy efficiency from 07:00 a.m. and 17:00 was 45%, 36.76%, 33.71%, 31.35%, and 25.47% for bagasse, sawdust, corn cop, paper, and wood, respectively.

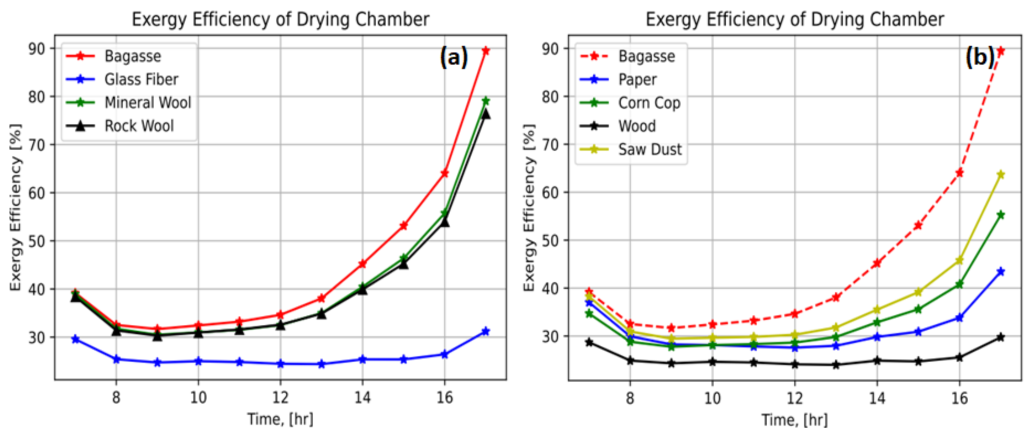

Figure 5: *Exergetic efficiency of the drying system with (a) recycled organic waste and (b) standard thermal insulation materials.*

The average exergy efficiency of mineral wool, rock wool, and glass fiber was 41.17%, 40.53%, and 26.08%, respectively. The useful work extraction efficiency fluctuation was considerably influenced by the input ambient condition variation during the drying period.

Comparatively, at a constant insulation thickness and emissivity of charcoal briquette, the exergetic efficiency of the dryer was higher with bagasse insulation than other recycled organic waste and inorganic thermal insulation materials. Thus, a double air pass solar tunnel drying system with bagasse insulation has a better useful work extraction capacity than other recycled organic waste standard insulation materials, because of their lower heat loss and higher temperature difference.

Energy and exergy efficiency on insulation thickness

Figures 6(a)-(b) shows the effect of insulation thickness on a double air pass solar tunnel drying system thermal efficiency and exergy efficiency investigated. The hourly average thermal efficiency was 38.5%, 40.8%, and 40.31%, and the hourly average exergy efficiency was 40.5%, 45%, and 43.88% for insulation thickness of 0.05, 0.25, and 0.5 m, respectively. The thermal and exergy efficiency enhanced until the thickness reached 0.25m due to the increment of temperature, then reduced as the thickness increased further because temperature also decreased. Thus, the maximum thermal and exergy efficiency was found when the thickness was 0.25 m.

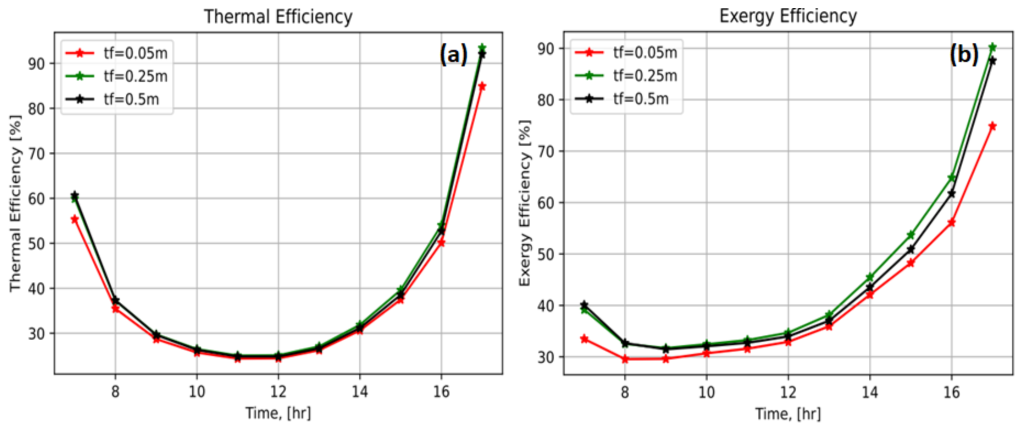

***Figure 6:** (a) Thermal efficiency and (b) exergy efficiency of drying system for different insulation thickness.*

Conclusion

This study presents the numerical analysis of the effect of recycled organic waste thermal insulation materials and thickness on the energetic, exergetic, and evaporation rate performance of a double air pass solar tunnel drying system in terms of heat loss and environmental impact reduction for the drying process of biomass charcoal briquette. A comparative analysis of the recycled organic waste materials with commercially available thermal insulation materials and between different insulation thicknesses was investigated in terms of heat and exergy loss reduction performance and drying rate enhancement by developing mass and heat transfer models, and the solution was computed by establishing the Python code.

Comparatively, a higher temperature, thermal efficiency, and exergy efficiency were obtained in the drying system insulated with bagasse material than other recycled organic waste materials, and the most commonly used thermal insulation. Comparatively, a higher temperature, thermal efficiency, exergy efficiency, and moisture evaporation rate of the charcoal briquette were achieved at an optimum thermal insulation thickness of 0.25 m.

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