Exergy and Economic Analysis of Modified Mixed Mode Solar *Injera* Dryer

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Abstract. In Ethiopia *injera* is consumed by most of the population. However, the application of solar dryers in drying *injera* is not a common practice. The aim of this study is to evaluate the performance of a modified mixed mode solar *injera* dryer which integrates a vertical air distribution channel using energy and exergy analysis and to determine the economic significance. The overall drying efficiency of the modified dryer in drying *injera* was found to be 10% and it takes around 4 h to reduce the moisture content to 0.14 g water/g solids. In drying *injera*, an even temperature distribution of drying air was observed over the drying trays with 2 °C temperature difference. The embodied energy of the modified dryer was obtained to be 765.46 kWh. The overall exergy efficiency of the modified dryer was found to be 13.2% and the result indicated that the exergy efficiency has an inverse relation with exergy loss. The exergy losses of the bottom and top trays were found to have very similar values and the exergy losses were observed to have monotonic relation with exergy inflow and an inverse relation with moisture content. From the economic analysis the saving per day of the modified dryer turns out to be 111.48 ETB/day and the cumulative present worth of the annual savings by using the modified dryer was found as 154,459 ETB with payback period of 104 drying days. This solar *injera* dryer will be a cost-effective choice for mass producers of dried *injera*.

Keywords: Mixed mode dryer · *Injera* drying · Exergy analysis · Economic analysis · Embodied energy

1 Introduction

The most important food in Ethiopian is *injera. Injera* is a fermented bread which is prepared from teff (*Eragrostistef*) [1]. *Injera* is rich in fiber and it is free from gluten [2]. Traditionally, *injera* is stored and preserved most of the time using open sun drying. Open sun drying is a traditional method and it suffers from may drawbacks like, prolonged drying, susceptibility to infestation and uncontrolled drying. This results deterioration in the quality of drying food [3]. Food preservation is possible by

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implementing appropriate drying technology. Conventional dryers uses substantial amount of energy that leads to an adverse environment impact due to greenhouse gas emission and increases the cost of dried product [4]. To overcame this problem, application of solar energy is an alternative approach for drying food, as it is abundant, renewable, inexpensive and environmentally friendly [5]. Solar food dryer helps to prevent the microbial growth and by lowering the moisture content it improvs shelf-life of food [6, 7].

For low temperature drying, mixed mode solar dryers were very efficient and found to retain the quality of dried food products [6, 8]. Mixed mode solar drying system comprises a flat plate solar collector and drying chamber. In this system, the transmitted solar radiation from a transparent cover is converted into heat through both components and utilized in the drying chamber to extract the moisture contained in the food [4].

Ethiopia is one of the countries with diverse climate condition and it is favorable for solar drying application due to availability of sufficient sunshine [9]. Solar dryers could be an effective solution to improve the economic benefit of the society by improving value-added food products locally. Since, solar dried food product are considered as branded product, the profit is certainly higher than traditionally dried food products [10–12]. Also, applying this technology will present good employment opportunity, create income generating system and helps in enhancing the nutritional standards and foreign exchange opportunity of the country [9].

The aim of design and optimization of drying system is to maximize the moisture loss of the dried product with minimum energy consumption. Consequently, quality and quantity of energy consumed during food drying process have to be evaluated to measure overall thermal performance of drying system [13]. Energy analysis of solar dryer using first law of thermodynamics helps to identify the type and amount of energy which flows through the drying system, but not the quality and losses due to irreversibility of energy [7]. Exergy analysis of solar dryer based on second law of thermodynamics will overcome the constraints of energy analysis [14]. Using energy and exergy analysis will give a clear idea about the performance of a dryer and helps to optimize the drying process [15].

Prakash et al. [16] conducted environomical analysis with energy and exergy analysis to evaluate modified greenhouse dryer operating in active and passive modes. The payback period was found to be 1.89 and 1.11 years and the embodied energy was found to be 628.73 kWh and 480.277 kWh. The exergy efficiency was in the range 30% to 78% and 29% to 86% for active and passive modes, respectively. Fudholi et al. [17] performed energy and exergy analyses on an indirect solar dryer operating in a forced mode and the experimental result showed a drying and exergy efficiency of 13% and 57%, respectively. Also, the specific energy consumption (SEC) was observed to be 5.26 kWh/kg with maximum exergy loss of 238.4 W.

Celma and Cuadros [18] applied energy and exergy to evaluate a passive natural convection solar dryer. It was observed that the exergetic efficiency decreases as drying chamber inlet temperature increases. Fudholi et al. [19] tested indirect type active solar seaweed dryer and the result indicated a drying efficiency of 27% and exergy efficiency of 30%.The improvement potential and SEC of the solar drying were found to be 247 W and 2.62 kWh/kg, respectively. Akpinar et al. [20] performed energy and exergy analyses using a cyclone dryer and the result showed exergy loss in a range from 0 to 1796 J/s. Also, it was observed that the exergy loss took place mainly in the first tray.

Even though, there are several studies on solar dryers for drying different food products [5, 21–28]. Also, few studies have been reported in improving the uneven distribution of drying air through drying chamber of mixed mode dryers [24, 29–31]. None of the published papers addressed *injera* drying using a modified mixed mode solar dryer with a comprehensive long term economic and exergy analysis. Therefore, the purpose of this study was to design and perform energy and exergy analysis with economic analysis of a modified mixed mode solar *injera* dryer with a vertical air distribution channel integrated into a drying chamber.

2 Material and Methods

2.1 Experimental Setup

The modified dryer contains, flat plate collector and drying chamber and it is constructed using locally accessible material (Fig. 1). The flat plate solar collector (1 m 2 m) with air depth of 0.1 m and tilted at an angle of 13° from horizontal was constructed. The slop of the flat plate collector was taken as the latitude of the site for optimum year-round incident solar radiation collection [32]. But to prevent accumulation of rain water during rainy season, the collector tilt was modified. The collector top was covered with 5 mm transparent window glass. The absorber was black painted galvanized sheet metal and between the absorber and plywood bottom cover there is heat insulation with 10 mm air gap and 50 mm sawdust. The drying chamber with 2.2 m height and 1.5 m depth holds three parts, a plenum chamber, vertical air distribution channel and four drying trays. The vertical air distribution channel was constructed from black painted galvanized sheet metal and it is a unique feature integrated into the drying chamber to facilitate uniform air distribution throughout the drying chamber trays. The roof of the drying chamber was covered using corrugated polycarbonate sheet which helps to transmit solar radiation to the drying chamber.

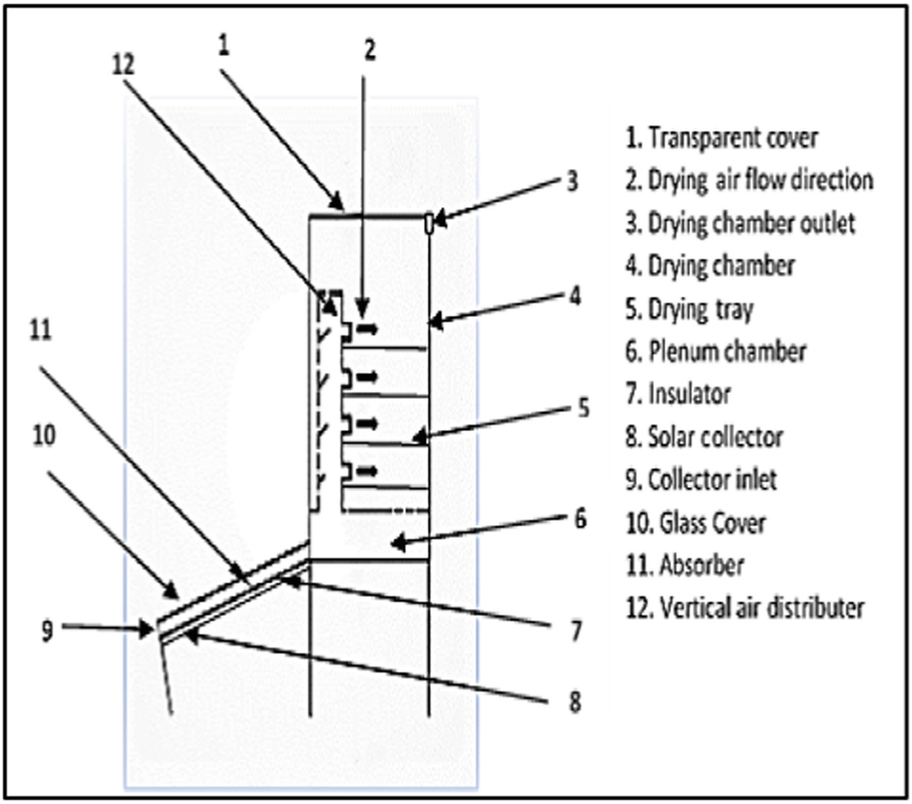

Fig. 1. Schematic view of modified mixed mode natural convection solar *injera* dryer

2.2 Experimental Procedure

To perform the experiment a month of August was chosen to represent an environment with low solar radiation. This condition will help to evaluate the performance of the dryer in a worst-case scenario and ensures the ability of the dryer to operate all year round. The experiment was conducted from 09:30 am till 14:30 pm. Before starting the experiment, the dryer was run for an hour to attain steady state condition through the modified dryer (Fig. 2 (a) and (b)).

To measure the temperature distribution at different locations K-type thermocouples were installed with an accuracy of ±0.2 °C at six locations and readings were taken every 5 min [33] using LabVIEW 2017 Data Acquisition system (DAQ) which is connected to a PC and the data was interpreted using Excel 2017. To measure the air velocity an anemometer integrated in (Extech's Model 45170) was used with ±0.03 m/s accuracy.

Injera with an approximate weight of 1.13 kg was purchased from local *injera* providers and used the same day for the experiment after sliced manually in rectangular shape (50 × 40 mm) [34]. The moisture content of *injera* before drying was determined following the recommendation by ASTM 2014 [35] and it was found to be 1.9 g water/g solids after drying *injera* in an oven for 24 h at 105 °C. To determine the weight change of *injera* through the experiment samples with approximate weight of 128 g were collected in 30 min interval from the drying trays and weight measurement was performed by using an electric balance (Ohaus Explorer) with ±0.001 g accuracy until desired final moisture content was achieved [33].

Fig. 2. Photographic view of the experimental setup

2.3 Energy Analysis of Modified Solar Dryer

Energy analysis of the designed solar *injera* dryer is evaluated using different methods implemented by different authors [23, 36–39] and these parameters were evaluated using the equations below.

$$SEC = \frac{E_t}{M_w} \tag{1}$$

$$SMER = \frac{1}{SEC} \tag{2}$$

$$\eta_d = \frac{M_w L_v}{E_t} \tag{3}$$

Where, M_w is the amount of moisture removed from *injera* and can be calculated from Eq. 4 [40].

$$m_w = \frac{M_w(M_i - M_f)}{100 - M_f} \tag{4}$$

Daily thermal output (E_d) of the modified *injera* dryer is calculated using Eq. 5 and to account for the energy required to increase the sensible heat of *injera* by 15% and by 10% for heat loses from different parts of the dryer. The annual thermal output of the dryer per batch of dried *injera* (E_{an}) is calculated using the daily thermal output and the total sunshine days per year of the specific location and it is given by Eq. 6 [41].

$$E_d = \frac{M_w \times L_v}{3.6 \times 10^6} \tag{5}$$

$$E_{an} = E_d \times N_d \tag{6}$$

The sunshine days (N_d) in a year and the drying days (N_b) per batch were taken as 212 days [42] and 2 days/batch, respectively. The energy payback time of the dryer is estimated using Eq. 7 [43].

$$\text{EPBT} = \frac{EE}{E_{an}} \tag{7}$$

Finally, the embodied energy of various materials used in fabrication of the dryer were calculated and presented in Table 1.

Table 1. The embodied energy of dryer

S. no.	Material	Embodied energy coefficient (kWh/kg)	Quantity (kg)	Total embodied energy (kWh)	Ref
1	GI sheet	9.67	17.75	171.59	[44]
2	Paint (solvent based)	27.25	5.00	136.25	
3	Plywood	2.88	80.95	233.86	
4	Timber	0.55	31.80	17.67	
5	Polycarbonate	10.19	3.69	37.66	
6	Glass sheet	4.41	25.00	110.42	
7	Steel wire mesh tray	9.66	1.50	14.50	
8	Fittings				
	Hinges	55.28	0.20	11.06	
	Handle	55.28	0.10	5.52	
	Steel common nails	9.67	1.50	14.51	
	Door lock	55.28	0.02	1.38	
9	Sawdust	0.55	19.90	11.06	[45]
	Total			**765.46 kWh**	

2.4 Exergy Analysis

The exergy equation for steady state system based on second law of thermodynamics is shown in Eq. 8 [46].

$$E_x = \dot{m}_{da} \times C_{pda}\left[(T - T_{amb}) - T_{amb} \times \left(\ln \frac{T}{T_{amb}}\right)\right] \quad (8)$$

The exergy inflow to the drying chamber of the modified dryer comprises the drying air flowing from the collector and the incident radiation passing through the top transparent cover of the drying chamber and it is calculated using Eq. 9 and 10 [39, 47, 48].

$$E_{x,dc_{in}} = E_{x,T1_{in}} = \dot{m}_{da} \times C_{pda}\left[\left(T_{dc,in} - T_{amb}\right) - T_{amb} \times \left(\ln \frac{T_{dc,in}}{T_{amb}}\right)\right] \quad (9)$$

$$E_{x,dc,rad_{in}} = I \times \tau \times \alpha \times A_d\left(1 - \frac{T_{amb}}{T_{sky}}\right) \quad (10)$$

Where, T_{sky} is taken as $\frac{3}{4}T_s$, which results T_{sky} to be 4,077 °C and T_s is the black body temperature of the sun [39, 48].

The exergy outflow and losses from drying tray one and drying chamber is calculated using Eq. 11–14, respectively [49].

$$E_{x,T1_{out}} = \dot{m}_{da} \times C_{pda}\left[\left(T_{T1,out} - T_{amb}\right) - T_{amb} \times \left(\ln \frac{T_{T1,out}}{T_{amb}}\right)\right] \quad (11)$$

$$E_{x,dc_{out}} = \dot{m}_{da} \times C_{pda}\left[\left(T_{dc,out} - T_{amb}\right) - T_{amb} \times \left(\ln \frac{T_{dc,out}}{T_{amb}}\right)\right] \quad (12)$$

$$E_{x,T1_{loss}} = E_{x,T1_{in}} - E_{x,T1_{out}} \quad (13)$$

$$E_{x,dc_{loss}} = E_{x,dc_{in}} - E_{x,dc_{out}} \quad (14)$$

Exergy efficiency for drying tray one and drying chamber is calculated using Eq. 15 [20].

$$\eta_{E_x} = 1 - \frac{E_{x,loss}}{E_{x,dc_{in}}} \quad (15)$$

The optimum improvement of exergy efficiency is achieved when the exergy loss from the modified mixed mode solar *injera* dryer is reduced. This improvement potential (*IP*) of the *injera* dryer is given by Eq. 16 [37].

$$IP = (1 - \eta_{E_x})E_{x,loss} \quad (16)$$

2.5 Economic Analysis

Economic analysis of the modified dryer is evaluated using, the annualized cost analysis, life cycle analysis and payback period [50]. The annualized cost of *injera* drying is evaluated by Eq. 17 [51].

$$C_a = C_{ac} + C_m - V_a + C_{rf} + C_{re} \tag{17}$$

The annualized capital cost (C_{ac}) and salvage value (V_a) of the *injera* dryer are calculated using Eq. 18 and 19, respectively [52].

$$C_{ac} = C_{cc} \times F_c \tag{18}$$

$$V_a = V \times F_s \tag{19}$$

where, F_c and F_s are defined by Eq. 20 and 21, respectively [52].

$$F_c = \frac{d \times (1+d)^n}{(1+d)^n - 1} \tag{20}$$

$$F_s = \frac{d}{(1+d)^n - 1} \tag{21}$$

The cost of *injera* drying (C_s) per kilogram of dried *injera* and amount of *injera* dried (M_y) per year using the modified dryer are evaluated by Eq. 22 and 23, respectively [50].

$$C_s = \frac{C_a}{M_y} \tag{22}$$

$$M_y = \frac{M_d * N_d}{N_b} \tag{23}$$

For an electric *injera* dryer, which can dry the same amount of *injera* by substituting the modified dryer, the annual running fuel cost (C_{rf}) can be evaluated by using the equation below [50].

$$C_{rf} = \frac{M_y\left[\left(\frac{M_c}{100}\right) \times L_v \times C_e\right]}{\eta_e \times 3600} \tag{24}$$

Where, M_c is the moisture content of *injera* in dry basis and evaluated using Eq. 25 [5].

$$M_c = \left(\frac{M_f - M_d}{M_d}\right) \times 100 \tag{25}$$

In the life cycle savings method, the savings per *injera* drying days in the base year and the present worth of the annual savings over the life time of the modified dryer will be evaluated.

The cost of fresh *injera* per kilogram of dried *injera* is evaluated by Eq. 26 [50].

$$C_{dp} = C_{fp} \times \left(\frac{M_f}{M_d}\right) \tag{26}$$

The expense required in drying 1 kg of *injera* (C_{ds}) is evaluated for the solar *injera* dryer and electric *injera* dryer by adding the fresh *injera* cost (C_{dp}) with the cost of *injera* drying (C_s) [50].

$$C_{ds} = C_{dp} + C_s \tag{27}$$

By drying *injera* using modified dryer, the saving per kilogram (S_{kg}) in the base year can be evaluated by Eq. 28 [50].

$$S_{kg} = C_b - C_{ds} \tag{28}$$

The savings due to *injera* drying using the modified dryer per batch (S_b) and also per day (S_d) in the base year can be calculated using Eq. 29 and 30, respectively [50].

$$S_b = S_{kg} \times M_d \tag{29}$$

$$S_d = \frac{S_b}{N_b} \tag{30}$$

The annual savings (S_j) and the present worth (P_j) of *injera* drying using the modified mixed mode solar dryer in the j^{th} year can be found by using Eq. 31 and 32 [50].

$$S_j = S_d \times N_d \times (1+i)^{j-1} \tag{31}$$

$$P_j = F_{pj} \times S_j \tag{32}$$

$$F_{pj} = \frac{1}{(1+d)^j} \tag{33}$$

Finally, the payback period (N) is evaluated by the equation below [53].

$$N = \frac{\ln\left(1 - \left(\frac{C_{cc}}{S_1}\right) \times (d-i)\right)}{\ln\left(\frac{1+i}{1+d}\right)} \tag{34}$$

3 Result and Discussion

3.1 Performance of Modified Dryer

The drying air temperature distribution through the dryer is shown in Fig. 3. During the experiment the average ambient temperature was recorded as 21 °C with solar radiation of 402 W/m^2. From the result it can be observed that the drying air temperature from the collector outlet was more than the ambient throughout the experimental period. This indicates that the dryer can provide sufficient amount of temperature for drying *injera* over the entire drying hour [33].

The extent of temperature variation between drying trays were found to be insignificant and it was within a narrow range of about 2 °C (Fig. 3). This uniform temperature distribution over the modified dryer could be the result of the air distribution channel and this indicates the use of this configuration will increase the efficiency of solar dryers.

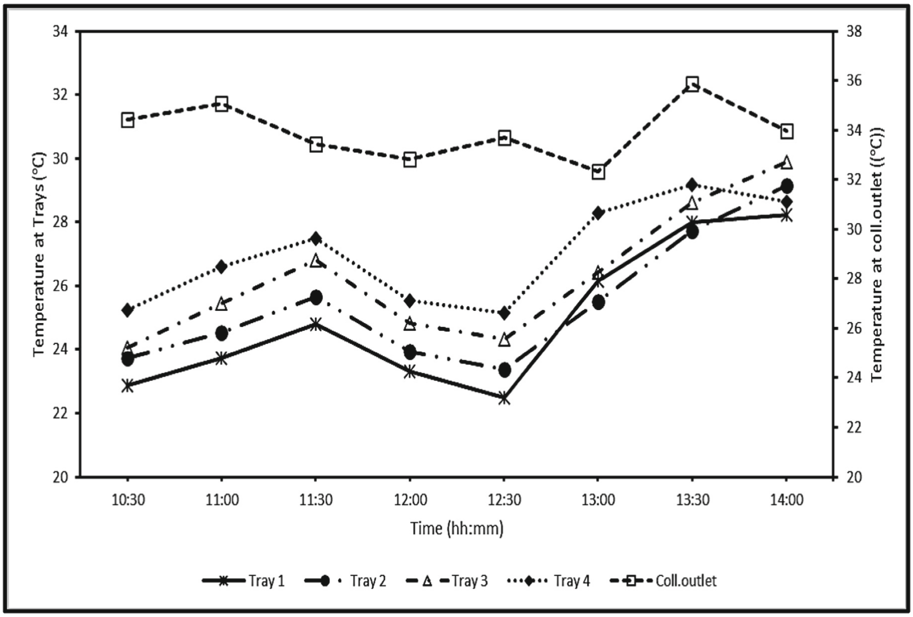

Fig. 3. Temperature variation at tray 1, 2, 3, 4 and collector outlet with drying time

The change in moisture content of injera over the experiment is shown in Fig. 4. The result indicates that to dry injera to a moisture content of 0.14 g water/g solids using the modified dryer, it takes around 4 h and the moisture content of injera was observed to decrease as drying time advances.

It was noted that the drying chamber temperature was affected as the moisture content of *injera* decreases since at the final stages of the experiment it starts to increase.

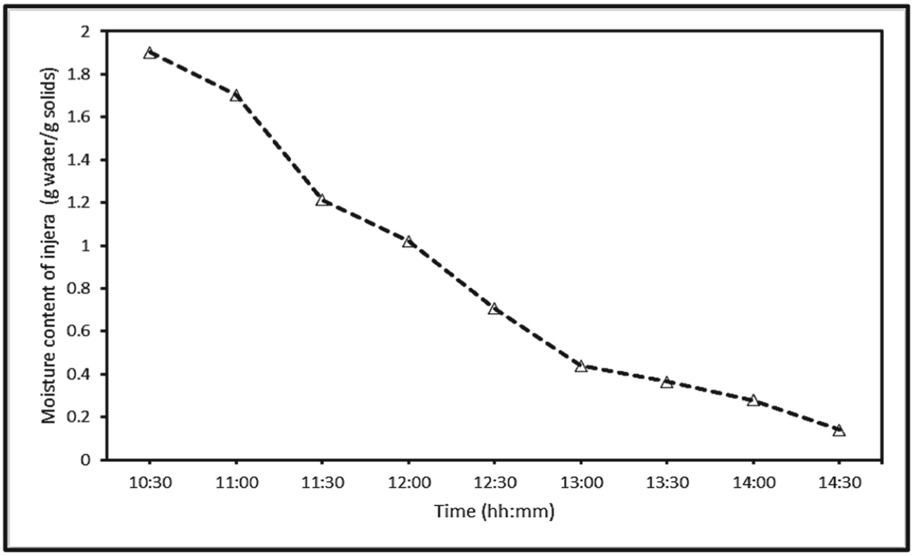

Fig. 4. The change in moisture content of *injera* with respect to drying time

3.2 Energy Performance of the Solar Dryer

The change in useful energy gain from the solar collector and the solar radiation on the collector is shown in Fig. 5. It can be seen from this result that the energy gain of the drying air from the collector increases as solar radiation decreases. The average value of energy gain from the collector was 2.1 kJ/s at corresponding solar radiation of 402 W/m^2.

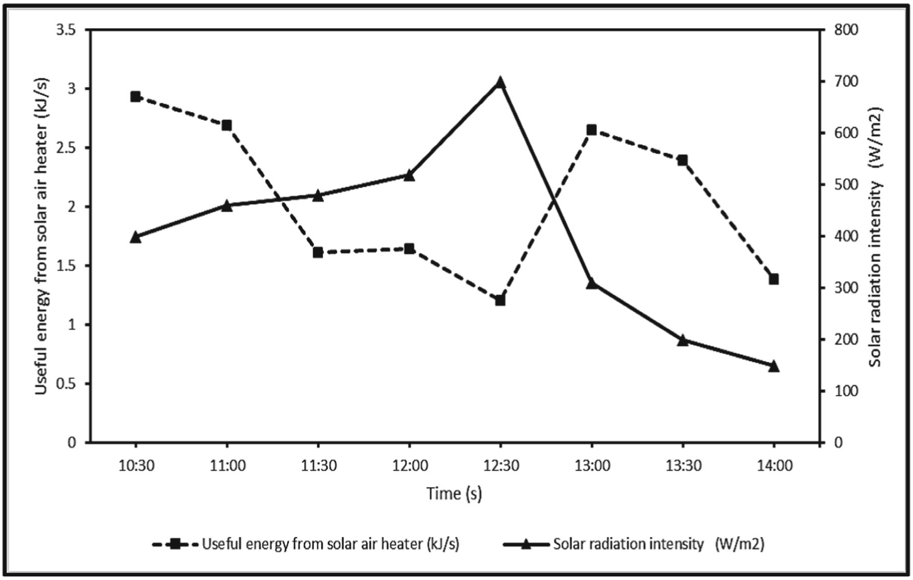

Fig. 5. Change in useful energy and solar radiation as a function of drying time

To evaluate the overall performance of the modified dryer the selected parameters with their computed results are presented in Table 2. Madhlopa and Ngwalo [54] specified a drying efficiency between 10 to 15% for natural convection dryers and the result from our study lies in this range. However, if the dryer was loaded to the design capacity, the results of this parameters could change particularly the specific energy consumption would decrease, while the drying efficiency increases.

Table 2. Performance parameters of the dryer

Parameters and performance	Unit	Value
Daily thermal output	kWh	4.01
Specific energy consumption	kWh/kg	6.9
Specific moisture extraction rate	kg/kWh	0.14
Drying efficiency	%	10%

3.3 Embodied Energy

The embodied energy of the materials used in the manufacturing the modified mixed mode solar dryer is shown in Table 1 and the percentage share is shown in Fig. 6. The percentage share of plywood was found to be the highest compared to the other materials used. The total embodied energy in the modified dryer was computed to be 766 kWh (Table 1) and the energy payback time (*EPBT*) was found to be 1.8 years. The result of the energy payback time could be considered as very low, when compared to [36, 55] reported values of 4.36 and 3.53 years.

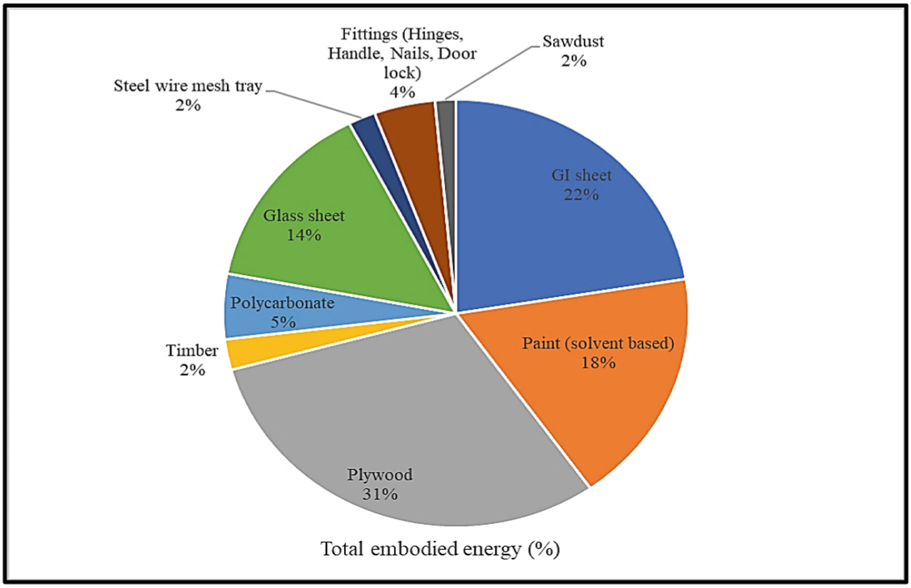

Fig. 6. Percentage embodied energy of the dryer

3.4 Exergy Analysis Result of the Modified Dryer

Figure 7 shows the exergy band diagram of the dryer which is obtained from the exergy analysis.

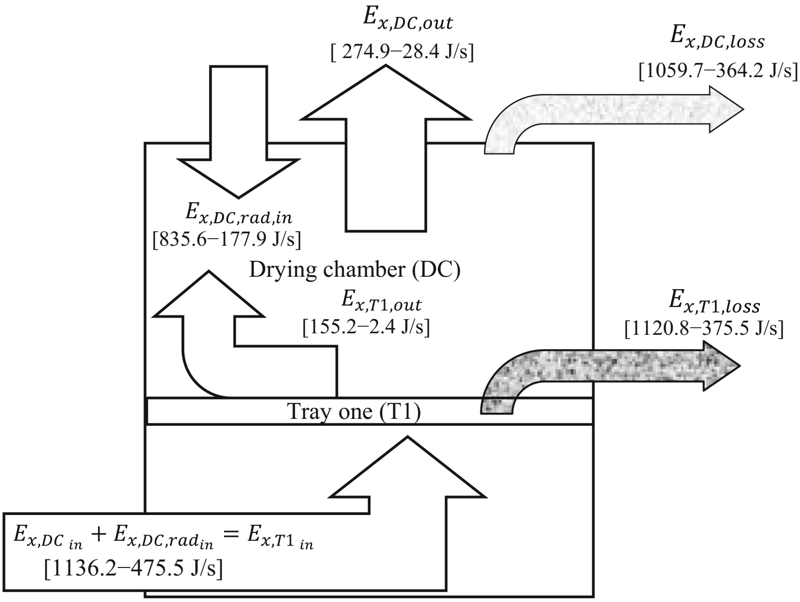

Fig. 7. Exergy band diagram of the modified dryer

The exergy in, out and loss during the drying experiment are shown in Fig. 8 and Fig. 9 for drying chamber and drying tray one, respectively. The exergy in and out from drying chamber and drying tray one varies between 1136.2 to 475.5 J/s and 274.9 to 28.4 J/s and 1136.2 to 475.5 J/s and 155.2 to 2.4 J/s, respectively. The change in exergy flowing in and out over the experimental period can be explained by the variation in solar radiation [46]. Similarly, exergy loss from drying chamber and drying tray one varies between 1059.7 to 364.2 J/s and 1120.8 to 375.5 J/s, respectively. Also, the change in exergy loss can further be related to the change in moisture content of injera over the drying experiment [20]. The exergy loss from drying chamber and drying tray one was observed to be almost identical. This can indicate that the energy utilized by the dried *injera* located at different trays was equivalent. Since the exergy losses of the drying chamber were equal to exergy losses from drying tray four.

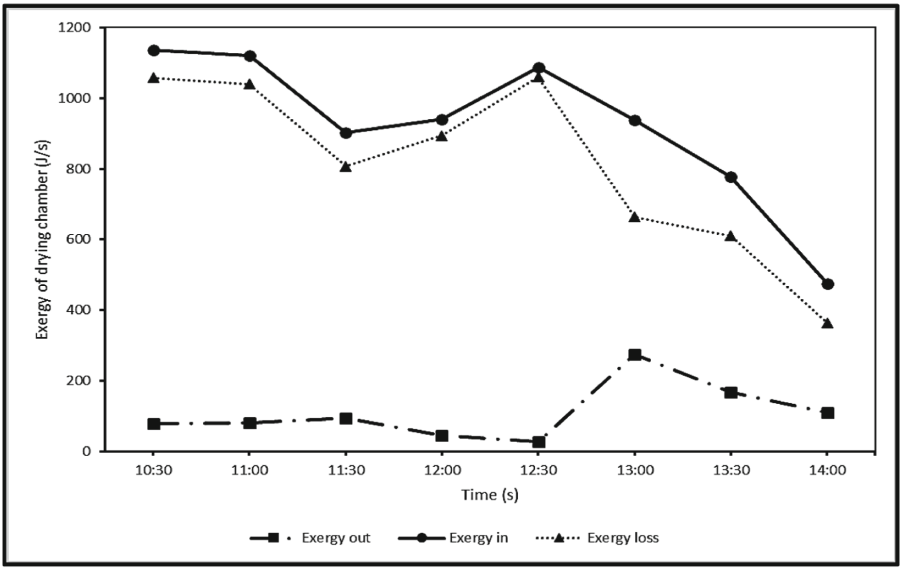

Fig. 8. Exergy in, exergy out and exergy loss with drying time for drying chamber

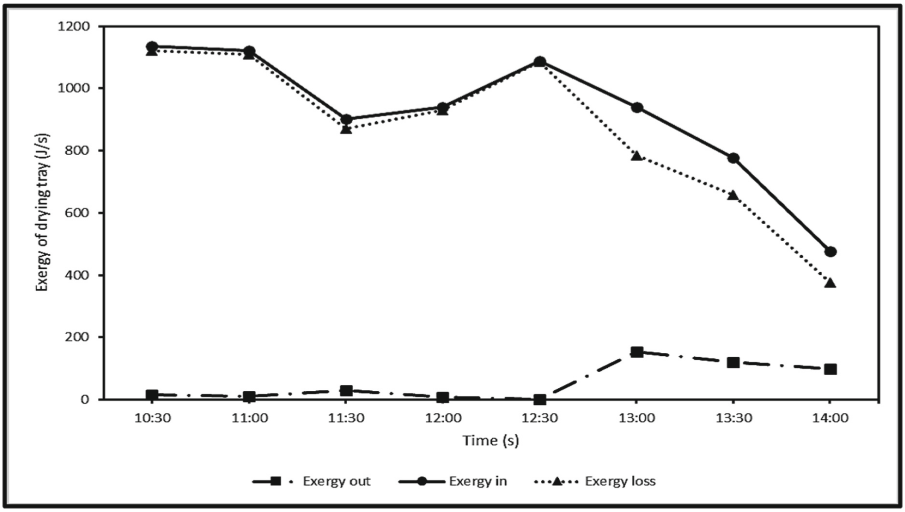

Fig. 9. Exergy in, exergy out and exergy loss with drying time for drying tray one (T1)

The change in exergy efficiency with respect to exergy loss for drying tray one is shown in Fig. 10. The exergy efficiency for drying tray one ranges from 0.22% to 21.1%. The exergy efficiency was found to be lower and steady for about the first two hours of the drying process and then it starts to increase when the exergy loss starts to decrease. The higher exergy loss and lower exergy efficiency indicates that the energy contained in the drying air was utilized effectively in drying *injera*. The exergy loss was observed to decline when the moisture content of *injera* decrease as the drying process advances (Fig. 11) and similar pattern was observed in Akpinar et al. [20].

Similar pattern was also observed with the drying chamber exergy efficiency and loss. The exergy efficiency of the drying chamber was obtained to vary from 2.6% to 29.3%. The value of improvement potential was calculated to be in the range from 278.8 J/s to 1032 J/s. It was noted that as drying time progresses the exergy efficiency rises and improvement potential declines. Similar pattern was reported by Lakshmi et al. [39] between the exergy efficiency and improvement potential.

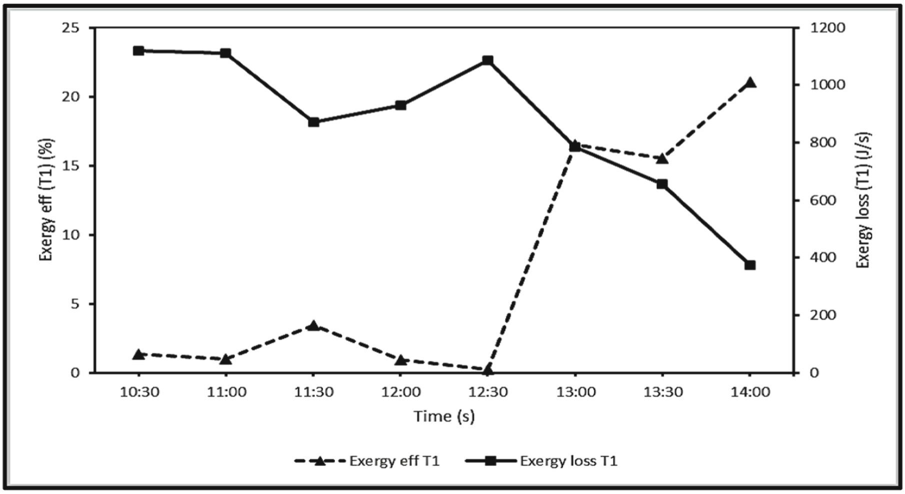

Fig. 10. Exergy loss and exergy efficiency for drying tray one (T1)

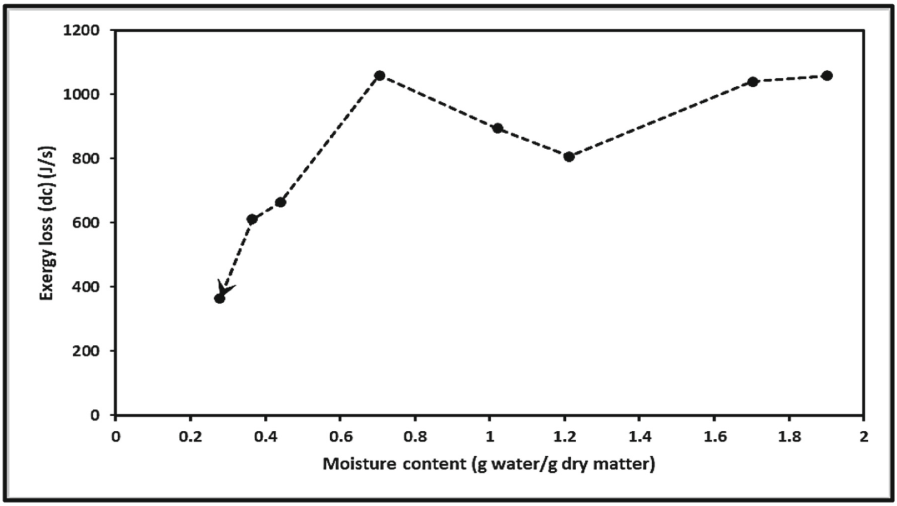

Fig. 11. Variation in exergy loss with moisture content for injera drying

3.5 Annualized Cost

To perfume the economic analysis different assumptions were implemented. The values of C_m and V were considered to be 10% of the C_{ac} and the interest rate was considered as the sum of the inflation rate and real interest rate [12, 50]. Also, additional parameters which were used in the analysis are presented in Table 3 and this parameter values are considered based on the economic condition in Ethiopia.

The annual drying capacity of a single modified solar *injera* dryer was evaluated and found to be 509 kg of *injera*. The annualized cost was evaluated for drying *injera* using the modified solar dryer and electric dryer and it was found to be 2,466 ETB and 3,403 ETB, respectively.

Similarity the cost of drying one kilogram of *injera* was evaluated for both drying methods and the result shows that drying *injera* using the modified dryer will cost 4.8 ETB while using electric dryers will cost 6.7 ETB. The result indicates that using modified solar dryer will reduce the cost of *injera* drying by 2 ETB per kilogram of dried *injera*.

Table 3. Parameters used in the economic analysis of the modified dryer

Parameters	Values
Capital cost for single modified dryer	10,000 ETB
Inflation rate	11%
Real interest rate	7%
Interest rate	18%
Life span of the modified dryer	10 years
The average domestic cost of electricity	0.77 ETB/kWh
Cost of fresh *injera* (for one kilogram)	21 ETB/kg
Capital cost for single electric dryer	12,500 ETB
Efficiency of the electric dryer	0.75%
Selling price of dried *injera*	95 ETB/kg

US$1 = ETB 40

3.6 Life Cycle Savings

In this part the savings by drying *injera* in this proposed modified dryer is evaluated by comparing it with the cost of commercially available dried *injera* which is available in the market and considered as a branded dried *injera*. The saving by using the proposed modified dryer for drying *injera* was found to be 111.48 ETB in a single drying day. Other results related to life cycle savings analysis are presented in Table 4. It was noted from this result that an annual saving present worth of 154,459 ETB over the lifespan of the modified dryer. This result can imply that by investing 10,000 ETB on this proposed modified dryer today, a user can save 154,459 ETB today.

3.7 Payback Period

The payback period was evaluated and the time needed to cover the initial investment by the savings from using the modified dryer was determined to be 0.49 years or 104 drying days. This result can indicate that the dryer will operate without any cost for around 9.5 years. This can be explained by the materials used in the fabrication of the dryer which were locally accessible and inexpensive. In addition, the dryer was construct by locally available skilled workers with minimum cost.

Table 4. Results of the life cycle saving analysis for the modified dryer over the lifespan of ten years

Year	Annualized cost (ETB)	Annual savings (ETB)	Present worth of annual saving (ETB)	Present worth of cumulative saving (ETB)
1	2,466.00	23,633.76	20,028.61	20,028.61
2	2,466.00	26,233.47	18,840.47	38,869.08
3	2,466.00	29,119.16	17,722.82	56,591.90
4	2,466.00	32,322.26	16,671.46	73,263.36
5	2,466.00	35,877.71	15,682.48	88,945.84
6	2,466.00	39,824.26	14,752.16	103,698.00
7	2,466.00	44,204.93	13,877.03	117,575.04
8	2,466.00	49,067.47	13,053.82	130,628.86
9	2,466.00	54,464.89	12,279.44	142,908.30
10	2,466.00	60,456.03	11,551.00	154,459.30

4 Conclusion

The performance of the modified dryer was evaluated based on the energy and exergy analysis and finally the economic analysis of the proposed dryer was performed. The temperature over *injera* drying trays was observed to have an even distribution. To dry *injera* to the final moisture content of 0.14 g water/g solid it took around 4 h. The SEC and drying efficiency of the modified dryer were 6.9 kWh/kg and 10%. The total embodied energy and the energy payback time of the modified dryer was computed to be 766 kWh and 1.8 years, respectively.

From the exergy analysis it was observed that the exergy losses of the modified dryer decrease as the drying process progress and as the moisture content of *injera* reduces. Also, the exergy losses of the bottom and top *injera* drying trays were found to be very similar and this indicated that *injera* dried at different levels of drying trays were exposed to uniform drying energy. The value of exergy efficiency was observed to ranges from 2.6% to 29.3% and it increase as the value of exergy loss decreases.

The economic analysis of the modified dryer indicated that the cost of drying *injera* using electric dryer will cost 40% more when compared with the proposed modified dryer. The cumulative present worth of the modified dryer was evaluated to be 154,459 ETB with a very low payback time of 104 drying days.

Finally, the result indicates that *injera* drying using the modified dryer will benefit users by reducing the drying time because of the higher temperature in the drying chamber and will improve the quality of dried *injera*. Evaluating a dryer using energy, exergy and economic analysis will give significant insight about the system.

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