Drying kinetics of dried *injera (dirkosh)* using a mixed-mode solar dryer

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Drying kinetics of dried injera (dirkosh) using a mixed-mode solar dryer

Senay Teshome Sileshi¹², Abdulkadir Aman Hassen¹ and Kamil Dino Adem¹*

Abstract: Injera is a staple food for Ethiopians both in the country and abroad. Injera has high nutritional value as it is reach in fibre and other nutrients most importantly it is gluten free. Dried injera (dirkosh) is mostly preserved using open sun drying. But there is no study conducted to improve the drying process and evaluate dried injera (dirkosh) for its drying kinetics and performance of the solar dryer. This is the first attempt to formulate the drying kinetics of dried injera. Thus, a mixed mode natural convection solar dryer was designed, manufactured and tested using injera (dirkosh) in Addis Ababa, Ethiopia. The test result indicated that the drying efficiency and overall drying rate were 17.7% and 3.69 × 10⁻⁵ kg/s, respectively. The moisture content of injera was reduced from 65.5% to 12% in wet basis in 4 h in the solar dryer. Statistical analyses of the result have shown that Midilli and Verma as a best fit models with the highest value of the correlation coefficient (R²) and the lowest values of reduced chi-square (χ²) and root mean square error (RMSE). Finally, it was concluded that solar drying of injera could be a feasible method for preserving and maintaining the quality of dried injera (dirkosh) with a minimum cost.

Subjects: Renewable Energy; Clean Technologies; Renewable Energy

Keywords: solar drier; mixed-mode solar dryer; injera; drying kinetics

ABOUT THE AUTHOR

As a group we are currently working on a solar dryer and its use for developing countries such as Ethiopia. The main driver for this specific project is Senay Teshome Sileshi who has conducted extensive test on a solar dryer. The second author, Dr Abdulkadir Aman Hassen who is the chair of Thermal & Energy Conversion brought his valuable experience from previous research on solar baking of injera. The third author, Dr Kamil Dino Adem who has written a review article on injera baking technologies supplemented the team to effectively conduct and report the results of the aforementioned project. The first author is from Dire Dawa Institute of Technology and the second and third authors are from Addis Ababa Institute of Technology.

PUBLIC INTEREST STATEMENT

Injera is a circular pancake with soft spongy like structure with 2-4mm thickness and a diameter of 58 cm in size. A mixed-mode solar dryer is used to dry injera (dirkosh). The solar dryer has two parts the solar collector and drying chamber. The solar collector absorbs solar radiation to heat the incoming air which moves towards the drying chamber. The drying chamber receives heated air and direct sun light to dry injera placed in the drying chamber shelves. The use of such kind of solar dryer will benefits both in terms of financial savings and reduction in greenhouse gas (GHG). In addition, crop-based food drying could have relevance even to the most advanced countries in the west. This study has been conducted to understand the behavior of injera drying.
1. Introduction
The staple Ethiopian fermented bread injera is made from teff (Eragrostis tef) (Baye, 2014). Teff is a cereal crop, which is produced in Ethiopian highlands for thousands of years and it is Ethiopia’s indigenous grain. Injera is a circular pancake with soft-spongy like structure and 2–4 mm thickness and around 58 cm diameter in size (Adem & Ambie, 2017). About two-third of Ethiopian diet consists of injera and its nutritional value is high, as it is rich in fibre, amino acids, calcium, iron and most importantly it is gluten-free (Zewdu, 2012). Injera together with ‘wot’ (sauce) is a food eaten by Ethiopians and Eritreans and some areas of Somalia and Sudan (Adem & Ambie, 2017; Tesfay et al., 2014).

Dehumidification of food using heat as driving force is called food drying process. Food drying helps to preserve and extend shelf-life of food. Additionally, it decreases the weight and volume of product and reduces the space and storage requirements. Since ancient time, open sun drying is a common practice to store and preserve food and different agricultural products especially in developing countries, as it is the cheapest method. Similarly in Ethiopia, injera is dried for household consumption and for commercial purpose by using open sun drying and it is called dirkosh. Furthermore, injera is dried to avoid mould spoilage and in times of food scarcity (Zewdu, 2012). Dirkosh can be prepared by simply spreading injera out on apparel mat. But this technique suffers from many drawbacks, for example it is labour intensive, demands large area and susceptible for attack by insects and fungus which leads to poor quality and contamination. In addition, some commercial enterprises prepare dirkosh using electric oven and this dirkosh preparation method requires additional financial capacity to procure electric oven dryer and to pay for electric bill. Consequently, poor quality of dirkosh and inefficient injera drying practise is common in Ethiopia.

In food drying operation, implementation of mathematical modelling to describe the drying kinetics of the product is essential (Kaleta et al., 2013). Thin layer drying is a process of food drying using thin or single layer of product (Midilli et al., 2002) and drying kinetics of different food products are described effectively using thin layer drying models (Onwude et al., 2016). A number of researchers developed solar dryers to evaluate the drying kinetics of different foods and performance of solar dryers. The products or foods to be dried mainly categorized in to fruits, vegetables, grains, medical and aromatic plants and others (Erbay & Icier, 2009). In their studies, the proposed thin-layer drying model, type of product tested and the type of dryer used for experiment were reported in detail. For example, Verma et al. for parsley and Modified Page (I) for both mint and basil using open sun drying (Akpinar, 2006), diffusion model for apricots and figs, modified Henderson and Pabis model for apricot (NaHSO3-Sulphured), grape, and plum and Verma et al. for peach using open sun drying (Toğrul & Pehlivan, 2004), Midilli et al. model for grain-crain (CC), fever (FV), and bitter (BT) leaves using open sun drying (Sobukola et al., 2007), Midilli and Logarithmic model for cassava slices using mixed-mode natural convection solar dryer (Dairo et al., 2015), Logarithmic model for shelled and unshelled pistachio using forced solar dryer and two term model using cabinet type natural convection solar dryer (Midilli & Kucuk, 2003), Logarithmic model for stone apple slices using forced convection dryer (Rayaguru & Routray, 2012), Midilli-Kuck model for potato slices using forced convective dryer (Naderinezhad et al., 2016), two term model and Page model for sliced black turmeric (curcuma caesia) using mixed-mode forced convection solar dryer with energy storage and open sun drying (Lakshmi et al., 2018), Page model for tomato (Lycoperson esculentum) drying using a solar swivel dryer forced type (Ahkijani et al., 2016), Midilli and Kucuk model for mint and Page and modified Page model for thymus using an indirect-mode forced convection solar dryer (El-Sebaii & Shalaby, 2013), Logarithmic model for ber (zizyphus mauritiana) using combined hybrid PVT solar dryer (Poonia et al., 2018), Midilli et al., Page and Weibull models for persimmon slices (Diospyros kaki L.) using electrical cabinet dryer (Doymaz, 2012), Logarithmic model for white mulberry using electrical cabinet dryer (Doymaz, 2004), Midilli model for West Indian Lemongrass (Cymbopogan citratus) leaves using electric dryer (Mujaffar & John, 2018).

Drying is an energy intensive process. Use of solar energy technologies in recent years is rapidly gaining acceptance as an energy saving measure in different application area where thermal
energy is required, because it is abundant, inexhaustible and non-polluting (Ekechukwu & Norton, 1999; Lingayat et al., 2017). Drying performance of a solar drying system is highly dependent on the climate conditions of the given geographical location (Royen et al., 2020). The weather condition of Ethiopia with diverse climate and thirteen months of sunshine with relatively longer sunshine hours per day will have a positive impact on using solar energy for drying application. The non-uniformity of final moisture content of dried product at different tray position is commonly encountered in multi-tray dryers. This is due to the same air passes through different trays and results in differences in drying air temperature through the drying unit (Mathioulakis et al., 1998).

The key to the successful operation of multi-tray solar cabinet dryer is uniform airflow distribution over the trays through guidance of drying air inside the drying unit (Margaris & Ghiaus, 2006; Mathioulakis et al., 1998; Misha et al., 2013).

Experiments were conducted to evaluate the performance of the solar collector and drying performance of solar dryers. Forson et al. (2007) developed a natural convection mixed-mode solar dryer and conducted test on cassava, the full loaded drying efficiency recorded was 12.3%. Similarly, Abubakar et al. (2018) tested yam slices in a natural convection solar dryer without thermal storage and obtained collector efficiency and drying efficiency of 40.10% and 24.2%, respectively. Lingayat et al. (2017) evaluated an indirect type natural convection solar dryer and reported an average collector efficiency of 31.5% and drying efficiency of 22.38%. The performance of indirect solar dryer was evaluated by Madhlopa et al. (2002) and the result of collector efficiency ranges between 17.0% and 21.3%. Musembia et al. (2016) evaluated indirect passive updraft solar dryer and the result indicated that the overall dryer efficiency of 17.8% and drying rate of 2.237 × 10^{-5} kg/s. The performance of indirect type solar dryer was evaluated in which case the mass of pear was reduced from 0.997 kg to 0.135 kg in 24 hours with drying efficiency of 11.1% (Essalhi et al., 2017). Wang et al. (2018) evaluated an indirect forced convection solar dryer with auxiliary heating device and the result indicated an average collector efficiency in range of 52.3%–53.6% and average dryer efficiency in range 30.9%–33.8%.

However, to the best of our knowledge, drying kinetics of injera under mixed mode solar drying has not been reported. Furthermore, there is limited or no study in the literature about the design of mixed-mode natural convection solar injera dryer specifically for mitigation of non-homogeneity in drying air over drying trays except multi-chimney mixed mode solar crop dryer (Abubakar et al., 2018). Therefore, in this study, we investigated the drying kinetics of injera using existing drying kinetics models and design a mixed-mode solar dryer specifically for injera drying with the ability of distributing drying air uniformly over drying trays in the climatic condition of Addis Ababa, Ethiopia.

2. Materials and methods

2.1. Fundamental design conditions, assumptions and constraints

2.1.1. Design assumptions and conditions

To carry out sizing of the solar injera dryer, the design conditions applicable to the geographical location of Addis Ababa, Ethiopia located at 9.02 latitude and 38.42 longitude were considered. Data regarding the loading quantity per batch with the climatic condition, property of injera and other design parameters, which were used in sizing the mixed mode solar dryer, were listed in the Table 1.

2.1.2. Design constraints

According to different authors, the design constraints, which can be applied to mixed mode natural convection solar dryer includes the following:

(i) The optimum collector tilt (β_col) for maximum collection of incident solar radiation for all year round operation of a collector is to be taken as the latitude of the site (Duffie & Beckman, 2013). But to avoid the accumulation of rain water on the collector during rainy period collector tilt of 13° was used.
Table 1. Design conditions and assumptions used in sizing the solar dryer

| No. | Parameter                                                                 | Value | Reference                                                                 |
|-----|---------------------------------------------------------------------------|-------|---------------------------------------------------------------------------|
| 1   | Ambient air temperature, $T_a$ [°C]                                       | 25    | (EMA, Ethiopian Meterological Agency, 2021)                               |
| 2   | Ambient relative humidity, $\text{RH}_a$ [%]                              | 72    | (EMA, Ethiopian Meterological Agency, 2021)                               |
| 3   | Maximum allowable drying air temperature, $T_{d,max}$ [°C]                | 50    | (Augustus Leon et al., 2002)                                              |
| 4   | Drying time (sunshine hours 8 h) $t_d$ [hrs]                             | 16    |                                                                          |
| 5   | Incident solar radiation $h_i$ [W/m²]                                     | 390   | (Amibe & Tiruneh, 2011)                                                   |
| 6   | Wind speed, $u_a$ [m/s]                                                  | 0.5   | (EMA, Ethiopian Meterological Agency, 2021)                               |
| 7   | Drying efficiency, $\eta_d$ [%]                                          | 21    | (Forson et al., 2007; Madhlopa et al., 2002)                               |
| 8   | Vertical distance between two adjacent trays, $d$ [m]                    | 0.3   | (Abubakar et al., 2018)                                                   |
| 9   | The ratio of drying chambers floor area to the collector                  | 0.75  | surface area ($\frac{A_f}{A_c}$)                                          | (Abubakar et al., 2018) |
| 10  | Food                                                                      | injera|                                                                          |
| 11  | Design drying period                                                     | July  |                                                                          |
| 12  | Mass of single injera $m_i$ [g]                                          | 310   |                                                                          |
| 13  | Design initial mass of the injera to be dried per batch, $m_i$ [kg/batch] | 10    |                                                                          |
| 14  | Average thickness of injera $t_i$ [mm]                                    | 4     |                                                                          |
| 15  | Diameter of injera $D_i$ [m]                                              | 0.52  |                                                                          |
| 16  | Design initial moisture content of injera, $M_i$ [%] wet basis            | 58    |                                                                          |
| 17  | Design final moisture content of injera, $M_f$ [%] wet basis              | 12    |                                                                          |
| 18  | Length to width ratio of solar collector ($\frac{L}{W}$)                  | 2     | (Pawar et al., 1994)                                                      |
| 19  | Collector depth [m]                                                      | 0.1   | (Macedo & Altermani, 1978)                                                |

(ii) Drying bed thickness ($h_i$) for natural air circulation through a dryer was recommended to be $h_i \leq 0.2$ m (Forson et al., 1996).

(iii) For optimum performance of the solar collector, the length to width ratio ($\frac{L}{W}$) is in the range of 1.5–2.5 as reported in (Pawar et al., 1994).

(iv) For total pressure between 0.8 and 2.5 Pa across the dryer, the corresponding maximum height of the hot air column, $H$, is recommended to be between 2 and 6 m (Forson et al., 2007).

(v) To account for heat losses through the roof and wall of the solar dryer, 12% of the heat required was assumed to be lost as heat losses to the surrounding.

(vi) Since bound water is to be evaporated from the product to be dried, the value of latent heat of evaporation ($L_v$) was increased by a factor of 15% (Bena & Fuller, 2002).

2.2. Description of the solar dryer

In the design results of the modified mixed mode solar injera dryer, it is important to point out that because of constructional difficulties some of the dimensions may be changed slightly within the design constraint to allow for ease of assembly. The dryer was constructed using locally available materials. Figure 1 (a), (b) and (c), shows the front, side and back view of the modified mixed mode solar injera dryer, respectively. The modified mixed mode solar injera dryer contains two parts, the collector and drying chamber. The collector, with a dimension of $1 \text{ m} \times 2 \text{ m} \times 0.1 \text{ m}$ was tilted at an angle $13^\circ$ to the horizontal. Its sides and bottom were built using plywood. The top of the collector was covered with 5-mm-thick transparent glass.
The absorber was constructed using galvanized sheet metal and painted with black. Its bottom side is filled with 50 mm sawdust as insulation and between the absorber and the sawdust there is an air gap of 10 mm, which can further help to reduce the bottom heat loss. The front and rear sides of the collector were open to help circulate the air through the dryer. The collector front is covered using galvanized wire mesh to protect the dryer from insect and other contaminant objects.

In the construction of the dryer, an allowance of 0.3 m was made for the height of collector inlet above the ground level to allow air to flow naturally through it (Forson et al., 2007). Inside of the drying chamber, there are three parts. The first is a plenum chamber with a depth of 0.3 m from the base of drying chamber and 1 m wide, which helps to stabilize the pressure and velocity of the air coming from the collector. The second part is a novel vertical air distribution channel, which is constructed from galvanized steel painted black. This part helps to regulate and maintains uniform distribution of velocity, temperature and other flow parameters over the trays of drying chamber. The third part of the drying chamber is a set of four injera storage tray, which were evenly placed within the drying chamber, and the dimension of these trays is 1 m × 1.1 m. The position of the first tray is 0.2 m above the plenum and between each tray 0.3 m space was provided and above the top tray 0.8 m space is provided resulting drying chamber total height of 2.2 m. The trays were made of galvanized wire mesh and supported by two wooden frames mounted on the drying chamber walls at the right and left side as shown in Figure 2 (b).

2.3. Experimental test procedure
Experiment was performed during the month of August 27 and 28, 2020 in Mechanical Engineering workshop, Addis Ababa Institute of Technology, Addis Ababa University. The chosen month was a month with relatively low solar incidence and it represents the worst-case drying situation. Figure 2 (a) and (b) shows the experimental setup of open sun and modified mixed mode dryer, respectively.

The Injera used in this experiment was purchased from the local market with approximate weight of 2.26 kg. Before starting the drying experiment, the injera was weighed and divided in 1.13 kg and sliced into rectangular shape (manually) having a length and width of around 50 × 40 mm. To compare the performance of the modified mixed mode solar dryer with the traditional
open sun drying, open sun drying test was carried by spreading injera on a plastic sheet placed on the ground near the modified mixed mode dryer by considering the shading effect.

The initial and final moisture content of fresh and dried injera samples were determined as per American society for testing and methods (ASTM, American Society for Testing and Materials, 2014). The experiment was performed from morning 09:30 am to 14:00 pm. However, to achieve the steady state condition inside the dryer, measurements were started after 1 hr and each drying trays of the modified mixed mode dryer were loaded with 280 g of injera.

To measure the moisture content of injera, samples were taken from six selected locations with approximate total weight of 128 g from each tray of the modified mixed mode solar dryer and open sun drying. The samples from both drying systems were thoroughly mixed and weighed in 30 min interval and placed back to both drying systems in the shortest time possible until no further weight loss of injera was observed. The weight of the sample was measured by using Explorer Pre weighing balance with accuracy of ± 0.001 g located near both drying systems. The measurement of moisture content was not performed during the night. The moisture content was determined in terms of both wet and dry basis and the moisture ratio of injera was fitted to the thin layer drying models to find the best model that describes injera drying.

Six temperature sensors were used to measure the temperature of the air every 5 minutes by fixing them at collector inlet, collector outlet and above drying trays and the collected data were transferred to a PC through a LabVIEW 2017 Data Acquisition system (DAQ).

The temperatures at various positions of the dryer were measured with K-type thermocouples (accuracy ± 0.2°C). The air velocity was measured by using Extech's 4-in-1 Model 45,170, which contain an anemometer on it with a resolution and accuracy of 0.1 m/s and ± 0.03 m/s respectively.
3. Mathematical modelling of injera drying

3.1. Modelling of semi-theoretical thin-layer drying of injera

Mathematical modelling is used widely and effectively in many researches and out of many mathematical models, thin-layer drying models have been widely used for food drying (Erbay & Icier, 2009). Among different thin-layer drying models, eight models were considered in this study and listed in Table 2 where \( a, n, c, \) and \( b \) are model coefficients, \( t \) is time, \( s, k \) is the drying rate constant, \( s^{-1} \) and \( MR \) is moisture ratio.

Using the experimental data, moisture ratio (MR) is calculated by Equation 1 (Ertekin & Yaldiz, 2004; Midilli et al., 2002; Olurin et al., 2012; Poonia et al., 2018; Rayaguru & Routray, 2012).

\[
MR = \frac{M_t}{M_o}
\]

Where:

\( M_t \) is the moisture content (g water/ g dry solid) at any time \( t \),

\( M_o \) is the initial moisture content (g water/ g dry solid).

The initial moisture content, the final moisture content, and moisture content at any time \( t \) were computed using Equation 2–4, respectively.

\[
M_o = \frac{m_i - m_d}{m_i}
\]

\[
M_f = \frac{m_f - m_d}{m_f}
\]

\[
M_t = \frac{m_t - m_d}{m_t}
\]

where:

\( m_i = initial \ mass \ of \ injera(g) \)

| No. | Thin-layer model      | Equation                                                                 | Reference                              |
|-----|-----------------------|--------------------------------------------------------------------------|----------------------------------------|
| 1   | Two-term exponential  | \( MR = a_s \exp(-k_s t) + (1 - a_s) \exp(-k_a t) \)                       | Sharaf-Eldeen et al., 1980             |
| 2   | Henderson and Pabis   | \( MR = a_s \exp(-k_s t) \)                                              | Henderson & Pabis, 1961                |
| 3   | Lewis                 | \( MR = \exp(-k_s t) \)                                                  | Lewis, 1921                            |
| 4   | Page                  | \( MR = \exp(-k_s t^n) \)                                                | Page, 1949                            |
| 5   | Modified page-I       | \( MR = \exp(-k_s t^n) \)                                                | Overhults et al., 1973                |
| 6   | Logarithmic           | \( MR = a_s \exp(-k_s t) + c \)                                          | Yagcioglu et al., 1999                |
| 7   | Verma                 | \( MR = a_s \exp(-k_s t^n) + (1 - a_s) \exp(-b_s t) \)                   | Verma et al., 1985                    |
| 8   | Midilli               | \( MR = a_s \exp(-k_s t^n) + bt \)                                       | Midilli et al., 2002                   |
\[ m_f = \text{final mass of injera (g)} \]
\[ m_d = \text{dry mass of injera (g)} \]
\[ m_t = \text{mass of injera at time (g)} \]

Amount of moisture to be removed from injera, \( m_w \), to bring it to the desired final moisture was estimated from Equation 5 (Abubakar et al., 2018).

\[ m_w = \frac{m_t(M_o - M_f)}{100 - M_f} \tag{5} \]

The experimental moisture ratio result against drying time was fitted to the thin-layer drying models to select the best model, which can describe the thin-layer drying curve of injera. The regression analysis was performed using Excel-solver tool in Microsoft office 2016 software. To estimate the goodness of the fit for selected thin layer drying models, three comparison criteria were used. These are, root mean square error (RMSE) and reduced chi-square \( \chi^2 \) based on their lower values and coefficient of determination \( R^2 \) based on its higher value. Several authors used these criteria to select the best thin-layer drying model. The value of RMSE, \( \chi^2 \) and \( R^2 \) were obtained using Equation 6–8.

\[ \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (\text{MR}_{\text{pre, } i} - \text{MR}_{\text{exp, } i})^2}{N}} \tag{6} \]

\[ \chi^2 = \frac{\sum_{i=1}^{N} (\text{MR}_{\text{exp, } i} - \text{MR}_{\text{pre, } i})^2}{N - n} \tag{7} \]

\[ R^2 = 1 - \frac{\sum_{i=1}^{N} (\text{MR}_{\text{exp, } i} - \text{MR}_{\text{pre, } i})^2}{\sum_{i=1}^{N} (\text{MR}_{\text{exp, } i} - \text{MR}_{\text{pre, } i})^2} \tag{8} \]

Where:

\( \text{MR}_{\text{exp, } i} \) is the \( i \)-th experimental moisture ratio
\( \text{MR}_{\text{pre, } i} \) is the \( i \)-th predicted moisture ratio
\( N \) is the number of observations
\( n \) is the number of model constants

### 3.2. Performance evaluation

#### 3.2.1. Moisture content

The moisture content is a measure of wetness or dryness of material. It can be calculated on either a wet or dry basis. The wet basis moisture content, \( M_{wb} \), is the ratio of mass of water in a sample to the wet mass of the sample whereas on the dry basis moisture content, \( M_{db} \), is the ratio of the mass of water in a sample to the mass of the dry matter (Lingayat et al., 2017). Equation 9 and 10 can be used to compute the above two moisture contents.
\[ M_{wb} = \frac{m_{ws} - m_d}{m_{ws}} \]  

\[ M_{db} = \frac{m_{ws} - m_d}{m_d} \]  

Where:

\[ m_{ws} = \text{mass of wet sample. (kg)} \]

\[ m_d = \text{dry mass of injera. (kg)} \]

3.2.2. Average drying rate

Average drying rate, \( M_{dr} \), is determined from the moisture content difference between two consecutive drying time and time interval using Equation 11 (Mercer, 2007):

\[ M_{dr} = \frac{M_{t+dt} - M_t}{t_d} \]  

Where:

\[ M_t = \text{moisture content at time } t \text{ (g water/g dry solid)}, \]

\[ M_{t+dt} = \text{moisture content at } t + dt \text{ (g water/g dry solid), and} \]

\[ t_d = \text{drying time (hr)} \]

3.2.3. Drying (or system) efficiency

The system efficiency \( (\eta_d) \) of a solar dryer is a measure of how effectively the input energy, solar radiation, of the drying system is used in drying the product. The normalized drying efficiency \( (\eta_n) \) can be calculated by dividing the drying efficiency by the total weight of the product and it is used to compare the drying efficiency of the system with other dryers. For natural convection solar dryers, the drying efficiency and the normalized drying efficiency can be calculated using Equation 12 and 13, respectively (Augustus et al., 2002),

\[ \eta_d = \frac{m_w L_v}{I \Delta T} \]  

\[ \eta_n = \frac{\eta_d}{m_i} \]  

Where

\[ m_w = \text{Mass of evaporated water, (kg)} \]

\[ m_i = \text{Initial mass of injera, (kg)} \]

\[ L_v = \text{Latent heat of vaporisation of water at exit air temperature (J/kg)}, \]

\[ I = \text{Hourly average solar radiation on the aperture surface (W/ m^2)}, \]
\[ A_r = \text{Aperture area or total energy collection surface area of the dryer (m}^2). \]

4. Results and discussion

The temperature over the drying tray shows a uniform distribution throughout the testing period Figure 3. The collector outlet temperature was above 10°C from the ambient over the entire testing hour. This drying air temperature is sufficient for drying application as previously reported (Augustus et al., 2002). The temperature variation between drying trays was observed to be around 2°C. This uniform temperature distribution over drying trays shows that, the entire injera were equally exposed to warm air and this could be due to the vertical air distribution channel. It was also observed that the drying air temperature difference between the collector outlet and drying trays was higher (9°C) in the first two hours and this difference decreases (3°C) towards the end. This trend is related to the decreases in moisture content of injera through the drying process.

The drying efficiency and normalized drying efficiency of the modified mixed mode dryer were calculated using Equation 12 and 13. The drying efficiency and normalized drying efficiency of the dryer were found to be 17.7% and 0.156%/kg. Madhlopa and Ngwalo (2007) indicated that a typical value of drying efficiency for a natural convection solar dryer is in the range from 10% to 15%. The result of drying efficiency obtained in this work is comparable with the result reported as 17.8% by Musembia et al. (2016) and lower than Wang et al. (2018) who obtained an average dryer efficiency in the range from 30.9% to 33.8%. However, the result obtained in this work is higher than the reported values which is in the range from 10.61% to 15.4% (Dejchanchaiwong et al., 2016; Erick César et al., 2020; Essalhi et al., 2017).

The injera was dried as a thin or single layer in modified mixed mode dryer and open sun drying. Figure 4 shows the drying curves of injera under modified mixed mode solar dryer and open sun dryer. It was plotted by using the moisture content versus drying time. The average initial moisture content of fresh injera was 1.9 g water/g dry solid. The injera dried in modified mixed mode dryer took about 4 sunshine hours while in open sun drying it took over 5 sunshine hours in two days to reach the final moisture content of 0.14 g water/g dry solid. Differences in the drying time of injera could be due to the drying air temperature difference between the modified mixed mode dryer and open sun dryer. Because the higher temperature results higher moisture transfer rate (Darıcı & Sen, 2015). The energy for drying injera in modified mixed mode solar dryer was obtained from the solar collector and incident solar radiation transmitted from the top transparent cover. Also, the vertical
air distribution channel surface absorbs the incident solar radiation since it is painted black and helps to increase the temperature inside the dryer.

Whereas, in open sun drying it is only from incident solar radiation and some amount this energy will be lost to the environment. The decrease in drying time with higher drying temperature have been observed in drying apple (Kaleta et al., 2013; Royen et al., 2020), stone apple (Rayaguru & Routray, 2012), potato (Kavak et al., 2003), pumpkin (Guiné et al., 2011), pumpkin (C. moschata) (Seremet et al., 2016). This indicates that using mixed mode solar dryers will help to reduce the drying time of injera when compared to the traditional open sun drying.

The drying rate was calculated using Equation 11 and drying rate curve of injera drying in modified mixed mode solar dryer and open sun dryer is shown in Figures 5 and 6, respectively. At the beginning, the drying rate increased in both drying systems up to moisture content of 1.7029 and 1.5056 g water/g dry solid. The maximum drying rate was observed to be 0.0163 and 0.0136 (g water/g dry solid)/min for modified mixed mode solar dryer and open sun dryer,
respectively. This stage can be identified as adjustment period and the temperature of injera is lower than the drying air temperature. At this period, mass transfer was dominated by vaporization of unbound moisture. The injera dried in both drying systems did not show a constant rate drying period under the experimental drying condition employed.

Since both systems were operated in low temperature, the rate of heat input was low and this could extend the initial adjustment period to the critical moisture content and possible results the absence of constant rate drying period (Rao et al., 2005). The absence of constant rate drying period was also observed in other studies for fish under open sun drying (Jain & Pathare, 2007), potato under forced convection drying (Kavak et al., 2003), apple slice under convective dryer (Rayaguru & Routray, 2012; Royen et al., 2020) and pumpkin under convective dryer (Guiné et al., 2011).

Once the temperature of injera reaches the drying air temperature at maximum drying rate, the drying rate decreased with moisture content and falling rate drying period started. In falling rate drying period, capillary forces provide the driving force for moving water through the pores to the porous surface of injera. Higher drying temperature in modified mixed mode dryer resulted the higher drying rate when compared with the open sun drying. Similar effect and trends were found in drying rate (Seremet et al. 2016; Akpinar, 2006; Falade & Solademi, 2010; Therdthai & Zhou, 2009).

In this section, moisture ratio calculated from Equation 1 using the moisture content of injera during drying were fitted to the eight drying models in Table 2. Table 3 show the statistical regression results of the different models used, including the drying model coefficients and the comparison criteria used to evaluate goodness of fit, \( R^2 \), \( \chi^2 \) and RMSE, of injera. From the eight tested thin-layer drying models, Midilli and Verma model were found to be the best model to describe the drying curve of injera with the high \( R^2 \) value and the lowest \( \chi^2 \) and RMSE as shown in Table 3. On the other hand, the Modified Page-I and Lewis models were found to be worst models based on their lowest \( R^2 \) value and high \( \chi^2 \) and RMSE values.

Figures 7 and 8 show the comparison between the experimental and predicted moisture ratio (evaluated using Midilli and Verma model) values of injera drying using modified mixed mode solar dryer. The predicted data generally lined around the straight line which showed the suitability of Midilli and Verma model in describing drying kinetics (behaviour) of injera under the experimental drying condition employed. A number of researchers found these models as a best fit model.
| Model name               | Statistical parameters result | Model constants |
|-------------------------|-------------------------------|-----------------|
|                         | chi-square ($\chi^2$)        | k   | n   | a   | c   | b   |
| Page                    | RMSE $R^2$                    | 0.000689 | 0.023748 | 0.994588 | 0.017450 | 1.323229 |
| Modified Page-I         | RMSE $R^2$                    | 0.003213 | 0.051275 | 0.974771 | 0.041087 | 0.205538 |
| Henderson and Pabis     | RMSE $R^2$                    | 0.002333 | 0.04369  | 0.981683 | 0.009031 | 1.071481 |
| Lewis                   | RMSE $R^2$                    | 0.002892 | 0.051275 | 0.974771 | 0.008445 |
| Two-Term Exponential    | RMSE $R^2$                    | 0.000602 | 0.022188 | 0.995276 | 0.012710 | 1.916618 |
| Logarithmic             | RMSE $R^2$                    | 0.001764 | 0.035822 | 0.987686 | 0.007169 | 1.159470 | -0.11077 |
| * Verma                 | RMSE $R^2$                    | 0.000666 | 0.022004 | 0.995354 | 0.010310 | 1.226448 | 0.910688 |
| * Midilli               | RMSE $R^2$                    | 0.000568 | 0.021555 | 0.995542 | 0.001381 | 1.385755 | 1.007506 | 0.000111 |

*These models were found to be the best model to describe the drying curve of injera.
5. Conclusion
A modified mixed mode solar injera dryer integrated with vertical air distribution channel and 2 m² collector area with drying chamber surface area of 1.5 m² and 2.2 m height was designed and manufactured for drying 10 kg of injera and tested under the meteorological conditions of Addis Ababa, Ethiopia during the days of August 27 and 28, 2020.
From the drying rate and drying curve of injera it was possible to conclude that drying of injera took place in the falling rate drying period and drying injera in modified mixed mode solar dryer results significant reductions in drying time when compared to the traditional open sun drying. The results obtained from fitting the experimental data to 8-layer thin kinetic models tested allowed to determine that the models that best characterize the drying kinetics for injera under the experimental condition are Midilli and Verma.

The experimental result of the modified mixed mode solar dryer showed that uniform distribution of drying air temperature throughout the drying trays due to the vertical air distribution channel. In the drying chamber, sufficient amount of drying air temperature was observed over the entire testing period.

Finally, it is concluded that solar drying of injera is a feasible method for preserving and maintaining the quality of dried injera (dirkosh) with a minimum cost. Researchers in solar drying area could use the results of this research to explore further on drying kinetics of injera drying.

This attempt to characterize the drying behaviour of dried injera (dirkosh) will be used by other researchers as input towards improving the quality of injera. In addition, this research will shed light for advancement of solar drying of crop-based food products both in the developing and developed countries.

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