Performance Comparisons of Solar Mixed and Indirect Dryers for Maize Grain Drying

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Abstract. This paper presents the design, construction and performance evaluation of mixed (SCMD) and indirect (SCID) -mode solar cabinet dryers for drying of maize grain with varieties of BH-540 and BH-660. The performances of the solar dryers were tested with three levels of sample loading, 21.74 kg/m^2 (thick layer), 16.3 kg/m^2 (medium layer), and 10.87 kg/m^2 (thin layer). In both dryers, the air was heated in the solar collector and passed naturally through a grain bed. For SCMD, the drying cabinet absorbs solar energy directly through the transparent roof. The solar irradiance, temperature and relative humidity distribution for ambient and in different parts of the dryer, and moisture loss of the grain at each try have been recorded. The result revealed that, a temperature raise of 15 °C was found in both dryers with respect to the ambient air. The required drying time was varied depending on the amount of sample loaded. About 32 h was required in thin layer compared to 53 h in thick layers drying process to reduce the moisture content of the grain to its safe storage value of 13% (w,b). The drying rate, collector efficiency and overall system efficiency were varied from 0.41–0.56, kg/h, 44.4–57.2%, and 24.0–32%, for SCID and from 0.47–0.58, kg/h, 44.4–57.2%, and 24.6–33%, for SCMD respectively. Statistically, no significant difference has observed on drying rate and overall dryer efficiency between SCMD and SCID.

Keywords: Drying rate · Dryer efficiency · Solar dryers

1 Introduction

In developing countries, the majority of the population is engaged in farming active ties. Almost 80% of the total food products is cultivated by small farmers [1]. In many rural locations of these countries, grid-connected electricity and supplies of other non-renewable sources of energy are unavailable, unreliable or, too expensive. Hence, open sun drying is the only means to dry crops before harvesting. However, for large-scale production the limitations of open-air drying are well known. Among these are high labor costs, large area requirement, and lack of ability to control the drying process, possible degradation due to biochemical or microbiological reactions, insect infestation, and so on. The drying time required for a given commodity can be quite long and

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resulted in post-harvest losses of up to 30% [2]. The advancement of open sun drying is solar drying, which is drying of food products using solar energy. Solar energy is the primary source of all renewable energy resources. It has enormous potential to meet growing energy requirements of the increasing population of the developing world. Its virtually inexhaustible supply with global distribution and environmentally safe nature make solar energy a very attractive prospect worldwide [3].

In the solar drying process, food products are dried in an enclosed unit to keep them safe from damage from birds, insects, microorganism, pilferage, and unexpected rainfall. Moreover, solar drying of agricultural products in enclosed structures by forced convection is an attractive way of reducing post-harvest losses and low quality of dried products associated with traditional open sun-drying methods [4]. Hence, the introduction of solar dryers in developing countries can reduce crop losses and improve the quality of the dried product significantly when compared to the traditional methods of drying, such as sun or shade drying [5]. Crop grain post-harvest loss in Ethiopia is estimated as high as 10% to 30% [6–8].

Different types of solar dryers have been developed and tested for the efficient utilization of solar energy around the world [9–12]. The literature survey indicates that out of several dryer designs developed and studied, the indirect and mixed mode solar dryers have received the maximum attention of researchers in mathematical modeling and thermal performance evaluation [2]. But, limited work is available in open literature on performance comparisons of those dryers. Simate et al. [13] had developed a lab scale mixed and indirect natural convection dryers using wood for the construction of the dryer chamber part. The authors have reported higher drying rate for mixed mode than indirect type. Singh [3] had also compared the performance of solar mixed and indirect dryer under forced condition by varying the flow rate of the inlet air. The author reported that, higher drying rate and dryer effectiveness for solar mixed type than indirect. From literature, performance of solar dryers may vary depend on the type of construction materials, their working conditions, weather conditions, and so on. So, the main aim of this study was to test the performance of solar mixed and indirect cabinet dryers for drying of freshly harvested maize grain in Amhara Region, Ethiopia, to reduce the large percentage of post-harvest loss of maize grain in the country.

2 Materials and Methods

Freshly harvested maize grains (Zea Mays) with varieties of BH-540 and BH-660 obtained from farmers in the villages of Merawi district, Birakat were used in this study. It was harvested at a moisture content of 22–25% (w.b).

2.1 Experimental Set up and Description

Solar cabinet mixed dryer (SCMD) and solar cabinet indirect dryer (SCID) were used for drying of freshly harvested maize grain. The dryers were constructed from locally available materials by following rules of thumb [14]. The design specification is presented in Table 1. Both dryers' constructions are almost identical with a difference in drying chamber top cover arrangement. Both dryers consist of a solar air heating

Table 1. Design specifications of solar cabinet indirect and mixed- mode dryers

Parameter	Mixed-mode	Indirect-mode
Mode of heating	Mixed	Indirect
Loading provision	Sliding tray	Sliding tray
Number of trays	6	6
Air outlet provision	Chimney at the top	Chimney at the top
Air circulation	Natural (0.085 m/s)	Natural (0.0085 m/s)
Collector area	3.8.0 m^2	3.8.0 m^2
Drying capacity	150 kg	150 kg
Collector slope	15°	15°
Thinness of plastic sheet	4 mm	4 mm
Drying chamber size	2.0 * 0.6 * 1.5 m, its top part is transparent/glass	2.0 * 0.6 * 1.5 m, its top part is opaque/metal sheet
Size of trays	1.9 * 0.36 * 0.02 m	1.9 * 0.36 * 0.02 m
Chimney with constant cross section	Bottom and top each 0.3 * 0.3 * 0.3 m, Height 1.5 m	Bottom and top each 0.3 * 0.3 * 0.3 m, Height 1.5 m

collector system, drying chamber with a chimney and supporting stand (Fig. 1). The Solar collector was constructed using a galvanized iron sheet at the bottom acting as an absorber and transparent covering (glazing) at its top. The galvanized iron sheet was painted matt black and used as an absorber for maximum absorption of solar heat energy. The drying chamber consists of six trays arranged in parallel fashion and

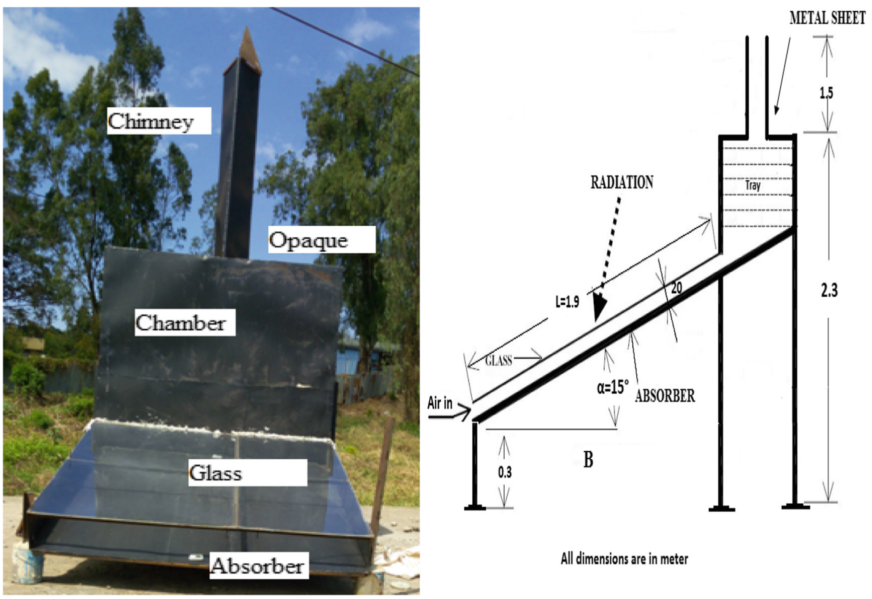

Fig. 1. Schematic diagram of solar cabinet indirect dryer, SCID

chimney located at the center of the chamber. The drying cabinet alongside the structural support of the dryer was built from a galvanized iron sheet which could withstand the unfavorable weather condition. Chimney is used to generate buoyant force on the air, thereby increasing the rate of air flow through the dryer. The chamber and the chimney were fabricated from galvanized iron sheet material. But for SCMD type the top part of the chamber replaced by transparent glass. Galvanized iron wire mesh was used to construct the trays. Both dryers consisted of an inclined flat-plate solar air collector with air flowing between plate and glass cover (Fig. 1) with an average air flow rate of 0.085 m/s. There was pre-heating of inlet air by the solar collector. In a mixed type of solar dryer, grain is dried on a perforated surface and is subjected to direct radiation on its top surface through the transparent drying chamber cover, and hot air current passing through the grain bed from a solar collector. The grain is, therefore, dried by a combination of both direct radiation with conduction of heat from the top layer grains to the bottom ones and the convection of hot air from the solar air heater entering the bottom layers and moving to the top ones. In indirect-mode dryer on the other hand, grain is dried by hot air alone from a solar collector (Fig. 2).

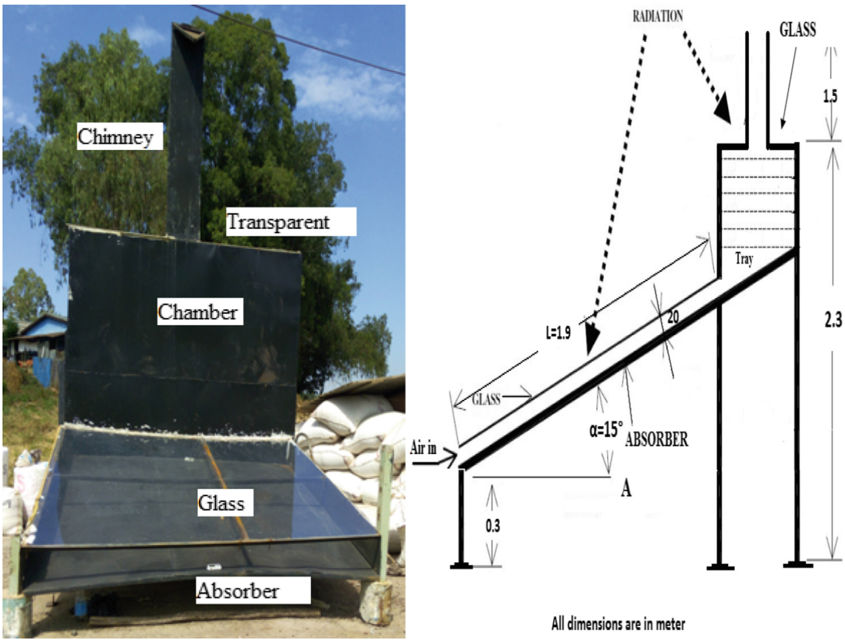

Fig. 2. Schematic diagram of solar cabinet mixed dryer, SCMD

2.2 Experimental Procedures

All the experiments were carried out in an open space on an elevated surface with location of 11° 35′ 37.10″ N Latitude and 37° 23′ 26.77″ E Longitude. Both dryers were installed in north, south direction in order to attain the maximum intensity of solar radiation. Freshly harvested maize grain was uniformly placed over each mesh tray inside the drying chamber. Samples were loaded at three different amounts, 21.74 kg/m^2 (thick layer), 16.3 kg/m^2 (medium), and 10.87 kg/m^2 (thin layer) which mean total sample load of 150 kg, 100 kg and 75 kg, respectively in each cabinet dryer. Drying experiments were started at 9:00 AM and continued till 5:00 PM according to the weather condition of the study area, Bahir Dar city. Grain maize sample was loaded in the dryers during night time and the drying was continued until the desired moisture content of 13% (wet basis) was reached. The moisture content of the grain was periodically measured with an interval of 3 h using moisture meter (JOHN DEERE, MOISTURE CHEK PLUS^{TM}, SW08120, and USA). Temperature and relative humidity of ambient air and drying air inside the solar dryers were periodically measured by the Hobo ware data logger (UX 100-011 Temp/RH, Onset HOBO Data Loggers). Each record was taken inside the solar cabinet dryers along the number of trays in loaded or unloaded conditions. Anemometer (CFM/CMM Thermo-Anemometer, model -PMA90, PYLE, and accuracy ± 3%) and Lux meter (Dr Meter Digital Illuminance Meter, model- LX1330B, and accuracy ± 3%) were used to hourly measure the inlet wind speed to solar cabinet dryers and global solar radiation on the ground, respectively. Temperature and relative humidity from the solar collector inlet & outlet, as well as temperature and relative humidity of ambient air temperature were measured from 9:00AM to 05:00PM. A similar standard was followed by Nabnean et al. [15].

2.3 Performance Evaluation of Solar Dryers

According to Augustus Leon *et al.* [9], physical features of the dryer, thermal performance, quality of dried product, and cost of dryer & payback period are parameters generally used for the evaluation of performance of solar dryers. For this study the comparisons of mixed and indirect type solar cabinet dryers were done by their moisture removal and thermal analysis, which are the basic standard procedure for evaluating solar dryer performance [16]. The performances of these systems were evaluated using moisture loss, drying rate, and the system drying efficiency. The drying system was evaluated using the solar collector efficiency, drying rate, percentage moisture loss, and drying efficiency of the dryer. The system performance and the drying characteristics of maize such as moisture content, drying rate, and efficiency were calculated using the following equations.

Moisture Content: The moisture content of maize grain was measured within two hours interval of drying using moisture meter.

Drying Rate (DR) is expressed as the quantity of moisture removed from the food item over the drying time [16]

$$DR = \frac{M_w}{t_d} \tag{1}$$

Where M_w is mass of water evaporated (kg) and t_d is drying time per day, (h).

Solar Collector Efficiency

The efficiency of a solar collector is the ratio of heat gained by the air leaving the collector to the incident solar energy over a particular time period [17]. The steady state thermal efficiency of a solar collector is given by Hottel-Whillier-Bliss equation [11].

$$\eta_c = \frac{m_a C_p (T_o - T_a)}{A_c I_T} \tag{2}$$

Where η_c is collector efficiency, %, m_a is the air mass flow rate (kg/s), C_p is specific heat capacity of air, (kJ/kgK), T_o is the temperature of the outgoing air from the collector, (^{0}C), T_a is ambient air temperature (^{0}C), A_c is a collector surface area (m^2), and I_T is incident solar radiation on the tilt surface (W/m^2).

Dryer Efficiency

Thermal performance or drying rates of the products are the key factors used for the evaluation of the solar drying system efficiency [16]. For natural convection solar dryer, the system efficiency can be expressed as given by [13].

$$\eta_{dryer} = \frac{M_W L_V}{I_T A_C t_d} \tag{3}$$

Where η_{dryer} is the dryer efficiency, and L_V is latent heat of vaporization of water, (kJ/kg).

2.4 Experimental Design

The effects of sample load variation, 150, 100, and 75 kg and solar cabinet dryer type (SCMD and SCID) on the performance of the dryers, were analyzed using R (version 3.3.2, 2016) software T-test at 95% confidence interval. Each experiment was done in triplicate.

3 Results and Discussion

Startup procedures: The dryers were operated at the unloaded condition to equilibrate the atmospheric condition inside the drying chamber. The results for the temperature and relative humidity distribution for ambient and within the dryers are presented in Figs. 3 and 4.

The ambient temperature was quite low, varying from a minimum of 24 °C to a maximum of 31 °C. This is followed by the average temperature of the dyers which ranges from a minimum of 25 °C to a maximum of 41 °C in SCID and a minimum of 25 °C to a maximum of 42 °C in SCMD. Similarly, the average relative humidity of ambient air was varying from 29–45%, whereas in dryers varying from 23–44% and 21–44% in SCID and SCMD, respectively. The average radiation was also ranged from 571–1133 W/m^2 during the test period. As it can be seen, the air temperature and solar

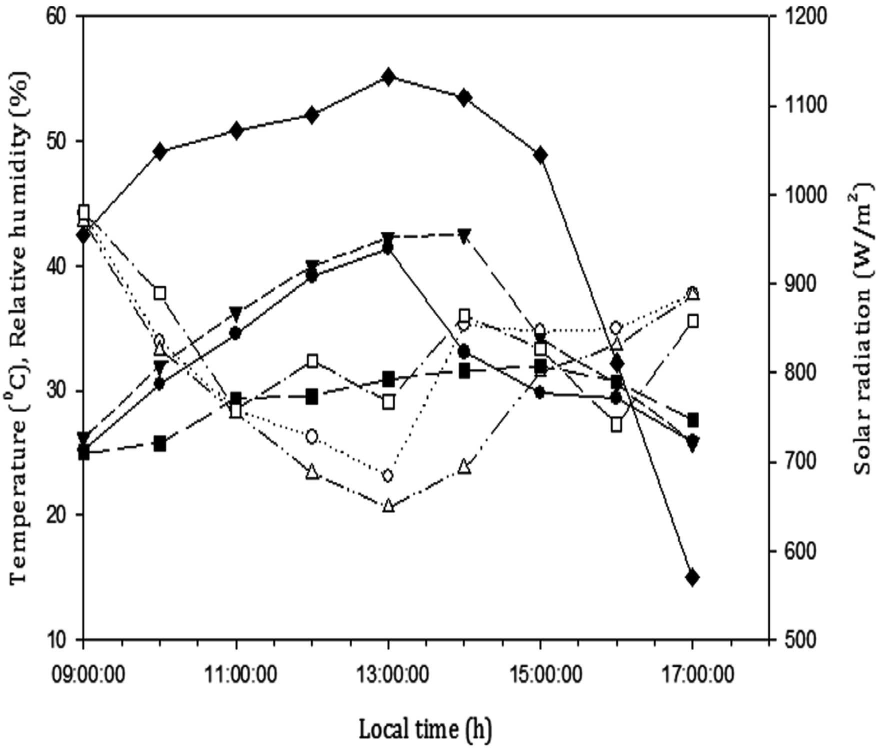

Fig. 3. Average radiation, temperature and relative humidity distribution for the month December, 2016. Temperature distribution; (●) inside SCID, (▼) inside SCMD, & (■) for ambient & relative humidity distribution; (o) inside SCID, (Δ) inside SCMD & (□) for ambient and (♦) solar radiation

radiation increase with hourly sunshine and reaches their pick value of 310C and 1133 W/m^2, respectively from 11:00 AM to 1:00 PM; whereas, relative humidity was reached the lower curves during this pick time. Thus, drying air temperature inside the dryers was higher than ambient air temperature and relative humidity was lower than the ambient relative humidity in most daily hours of the experiment. This shows that the dryer can perform better than the open sun drying. Warm air can hold more moisture than cold air, so the amount required depends on the temperature to which it is heated in the collector as well as the amount held (absolute humidity) when it entered the collector. The way in which the moisture absorption capability of air is affected by its initial humidity and by the temperature to which it is subsequently heated. Increasing the temperature of the drying air will increase the drying rate in two ways. First, this increases the ability of drying air to hold moisture. Secondly, the heated air will heat the product, increasing its vapor pressure. This will drive the moisture to the surface faster [9].

The hourly variation of the drying air temperature and relative humidity along the number of the trays inside SCID and SCMD chamber are shown in Fig. 4. There is a

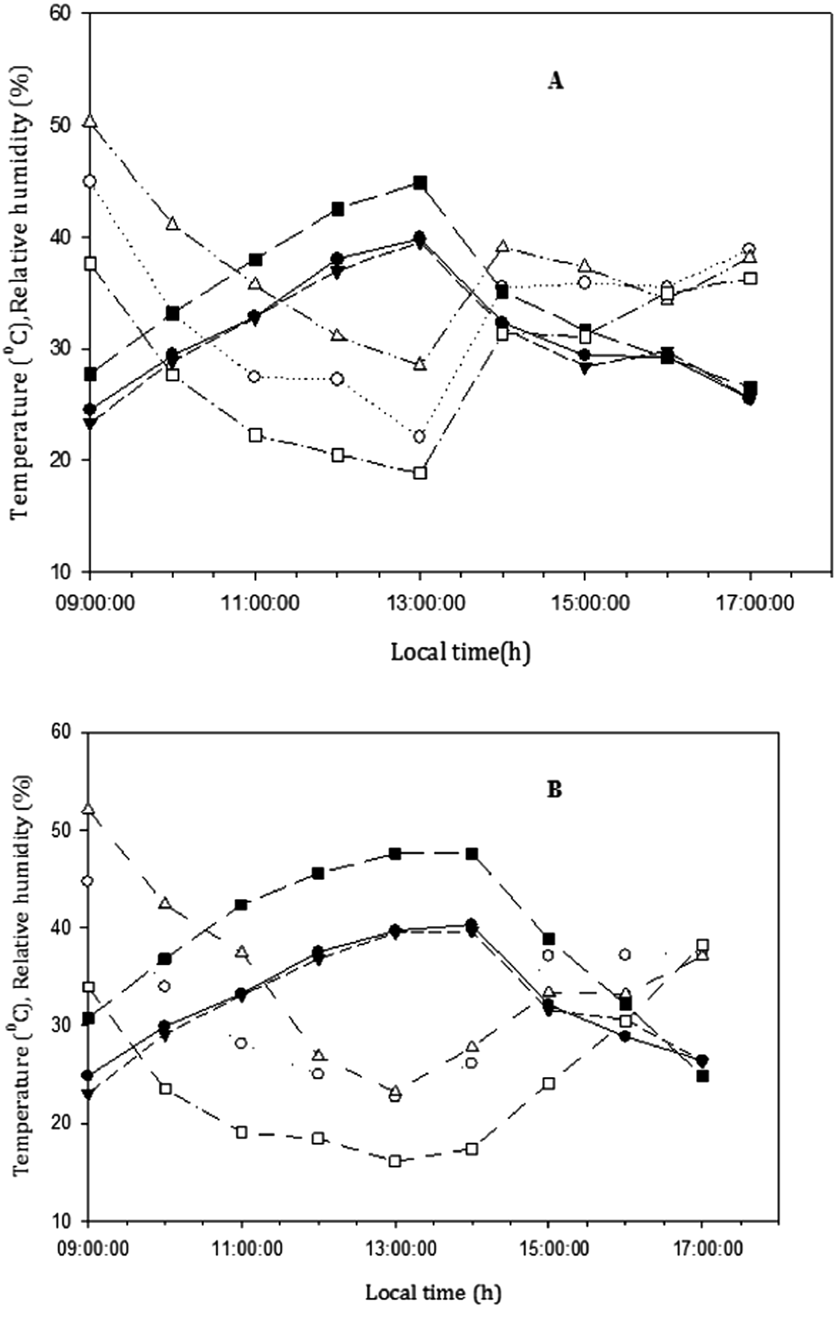

Fig. 4. Average distribution along the number of trays: Temperature (●) tray 1, (▼) tray 3, & (■) tray 6, and relative humidity (o) tray 1, (Δ) tray 3 & (□) tray 6 (A) SICD; (B) SMCD

difference in temperature and relative humidity distribution along the number of trays which is from bottom to top. Higher temperature 48 °C and 45 °C in SCMD and SCID, respectively, and lower relative humidity 16% and 19%, in SCMD and SCID, respectively were recorded at the top tray. Simate *et al.* [13] has reported also the same for mixed type, but lowest temperature for the indirect type at top tray. The authors were using wood for the construction of the indirect dryer chamber and top parts; consequently, the temperature at the top was reduced due to evaporative cooling effect. But, in this study the top part of SCID was metal sheet which has higher thermal conductivity than wood. In SCMD this higher temperature is expected since its top part is transparent. In addition, in SCID top tray temperature was higher, due to the longer time overhead of sun rays at most day time and high thermal conductivity of metal sheet. Daily, higher temperature in the dryer was maintained little bit for a longer time (beyond 15:00) in SCMD than SCID (up to 14:00); this happens due to additional heat supply for SCMD at its top part. However, the average temperature in both dryers was the same.

Lower values of relative humidity were observed at the top tray in both dryers. Relative humidity of drying air is also crucial to the drying process. The ability of air to hold more moisture can be increased by either dehumidifying or heating the air (decreasing its relative humidity or increasing its moisture holding capacity) before it enters the drying chamber or by heating it and thus increasing its evaporative capacity.

Moisture Content and Drying Rate: Figure 5A and B shows the drying curves for freshly harvested maize grain in SCMD and SCID for the drying of both varieties under different sample loading conditions. Generally, an initial moisture content of maize, which varying from 25–33% (db) was dried to the final moisture content of 13.4–15.23% (db) in all conditions. Thus, both dryers have a performance to reduce the moisture content of the grain to the safe storage value which is 15% (db) [6]. As indicated in Fig. 5, the time required to reduce the grain initial moisture content to the safe storage moisture was varying depending on the initial moisture content of the grain, daily solar intensity, and the amount of sample loaded in the dryer. Longer drying time is required for thicker sample load (150 kg) than thin and medium layer (Fig. 5). For example, the desired moisture content of 15% (db) can be reached within 32 h of drying in a thin layer (75 kg) drying, while it takes 53 h of drying in thicker sample load (150 kg) (Fig. 5). Thus, short drying time is required for the thin layer drying process.

Both SCMD and SCID have nearly the same drying rate (Fig. 5) and statistically insignificant difference has been observed. Simate *et al.* [13] has been reported higher drying rate for mixed type than indirect. However, there is a difference in the construction material which is the author was using wood to construct the chamber of the dryers. Under thin layer drying, the drying curves of SCMD have lower value than SCID; because, solar rays lie on the top part of SCMD can pass to the next bottom trays and heat up the grains. However, in thick layer drying conditions, both SCMD and SCID have almost equal drying rate for the whole range of hourly sunshine. This could be due to the increment of the thickness of the sample bed from 3 cm (thin) to 6 cm (thick). Thus, the overhead sun radiation at the top of SCMD can dry only the grain which located at the top and couldn't pass to the lower part of SCMD under this natural

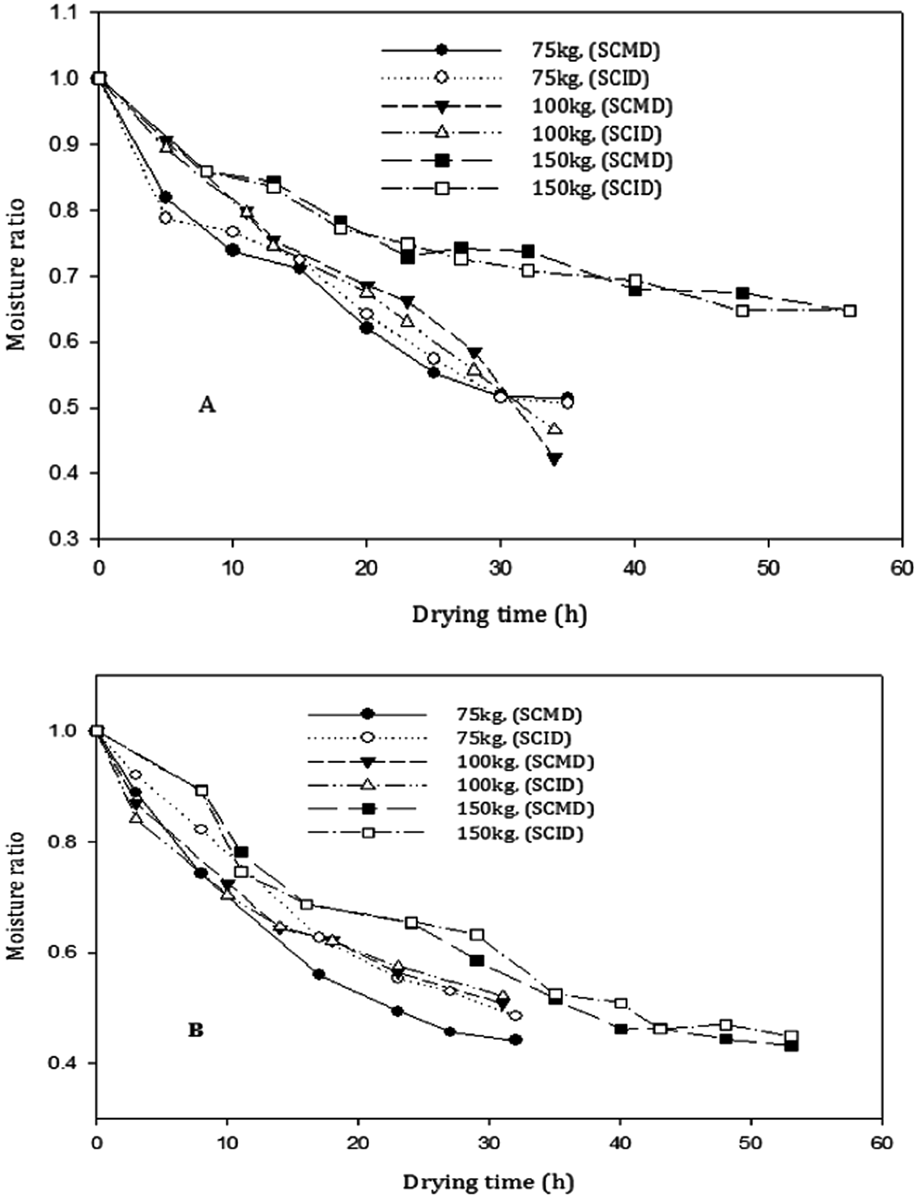

Fig. 5. Variation of moisture loss for different sample load of maize grain; A - BH- 540 variety and B - BH-660 variety

convection system. The other reason could be the flow direction of the air that is from bottom to top; hence lower moisture content was recorded only at the top tray.

All drying rate curves have first and second falling rate periods which are common in all grain drying process [18]. The result also shows that, drying rate of maize was higher at the first falling rate period when compared than the second falling rate. The drying rate was found to decrease with increase in drying time. Drying rate was higher during the initial stages of drying and becomes very low in the later stages; because at the first stage, free water of the grain is evaporated without any restrictions.

Figure 6 shows the drying curve for freshly harvested maize grain in SCID and SCMD for varieties of BH-660 under thin and thick layer conditions at different location of the dryers. Since there is a temperature and relative humidity difference along the number of trays, moisture removal was also varied. As it can be seen in Fig. 6, both in SCMD high moisture removal or lower moisture content of the grain were observed at the top tray both in thin and thick layer sample loading. This is because of presence of higher temperature and lower relative humidity at top tray (Fig. 4). Where as in SCID, lower moisture of the grain was observed at top tray for thin layer and at the bottom for the thick layer drying process. On the other hand, the low moisture removal rate was observed at the center (tray 3) in both thin and thick layers drying. When hot drying air flows from bottom to top, it picks up grain moisture in vapor form. Consecutively, the relative humidity of the air increases (Fig. 4) from bottom onwards. At the center (tray 3), the air becomes saturated and its vapor carrying capacity becomes reduced. Hence, lower moisture removal rate or high moisture content of grain was observed weather in thick or thin layer drying process at the center (tray 3).

The drying rate, overall system efficiency, and moisture removal (db) were varied depending on dryer type and amount of sample loaded. The drying rate, collector efficiency and overall system efficiency for drying of freshly harvested maize grain were varied from 0.41–0.56, kgh^{-1}, 44.4–57.2%, and 24.0–32%, and from 0.47–0.58, kgh^{-1}, 44.4–57.2%, and 24.6–33%, for SCID and for SCMD, respectively (Table 2). In this study, almost similar drying rate has been observed in both dryers. But, higher overall dryer efficiency was recorded in SCMD than SCID. However, statistically both dryers have no significant difference in drying rate (with P- value of 0.3676) as well as in overall dryer system efficiency (with P- value of 0.4061) under this natural convection system. The 95% confidence interval for a drying rate was from −0.09265 to 0.03642 and for overall system efficiency was from −5.71122 to 2.43322. However, Singh [3] has reported higher drying rate and larger overall efficiency for forced type mixed than indirect and Simate et al. [13] also reported higher drying rate for mixed type than indirect under natural condition which constructed from wood. In this study, it is observed that, drying rate for thick layer in both SCMD and SCID was much higher than that of thin layer drying process.

Table 2. Comparative study of different drying methods for freshly harvested maize grain

Solar dryer type	Sample weight (kg)	Initial moisture (d.b)	Final moisture (d.b)	Total drying time (h)	Drying rate (kg H_2O/h)	Average radiation (W/m^2)	Collector thermal efficiency (%)	Overall dryer system efficiency (%)
SCID	75	29.0	14.1 ± 0.00	32	0.406 ± 0.014	982	57.23	24.69 ± 0.85
	100	28.2	14.7 ± 0.002	31	0.511 ± 0.015	1267	44.36	23.97 ± 0.72
	150	31.1	14.0 ± 0.001	53	0.563 ± 0.015	1039	54.09	32.22 ± 0.87
SCMD	75	30.7	13.6 ± 0.003	32	0.464 ± 0.022	982	57.23	28.09 ± 1.36
	100	28.2	14.3 ± 0.003	31	0.523 ± 0.014	1267	44.36	24.56 ± 0.68
	150	31.1	13.4 ± 0.002	53	0.579 ± 0.008	1039	54.09	33.11 ± 0.47

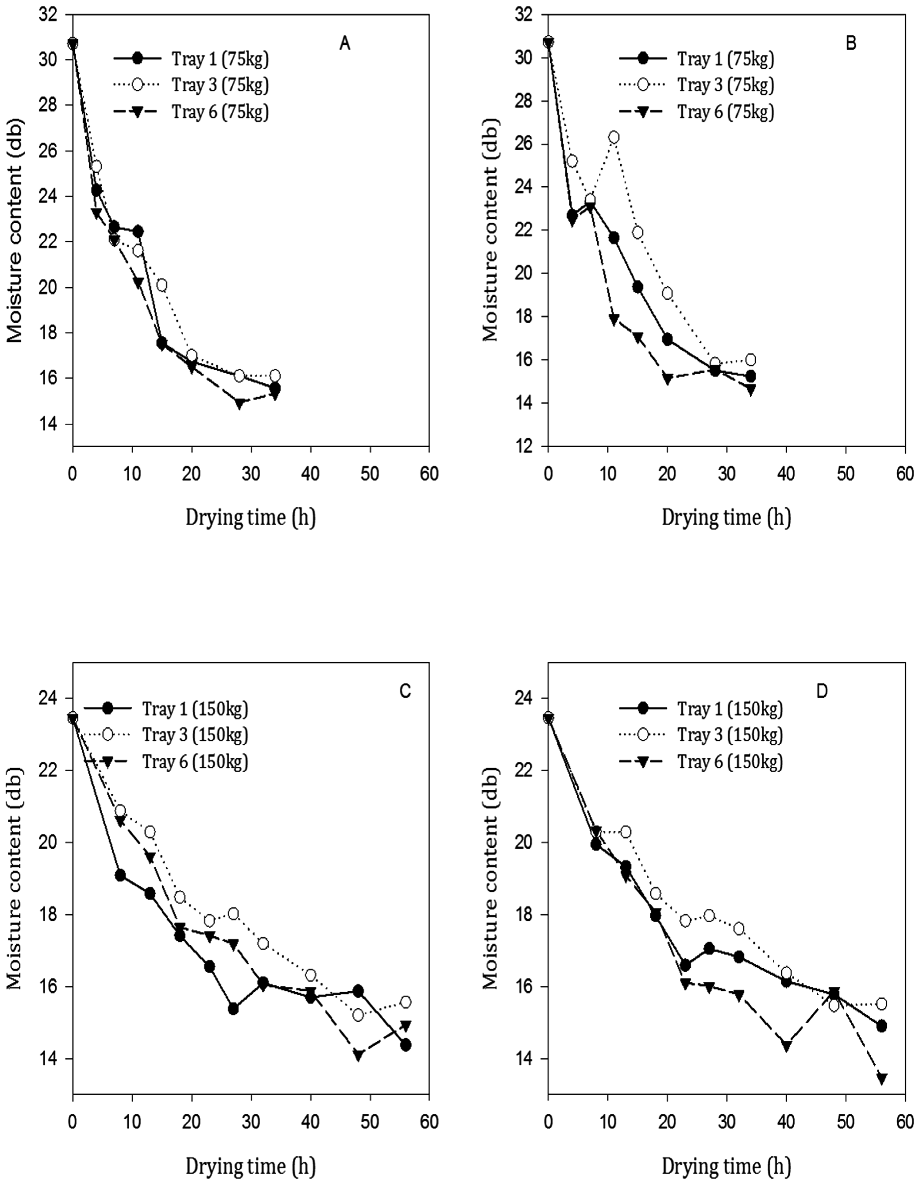

Fig. 6. Moisture distribution along the number of trays; A and C for SCID and B and D for SCMD for drying of BH-660 maize grain

4 Conclusion

A simple and inexpensive mixed and indirect-mode solar cabinet dryers were designed and constructed using locally available materials and their performance was compared for the drying of freshly harvested maize grain. The hourly variation of the temperatures inside the cabinet dryers is higher than the ambient temperature during the most hours of the day-light. The temperature rise inside SCMD and SCID were up to 15 °C for about three hours immediately after 11:00 AM. For a particular experiment, drying rate, collector efficiency and percentage of moisture removed (dry basis) for drying of freshly harvested maize grain were varied depending on dryer type and amount of sample loaded. In this study, statistically no significant difference has been observed between SCID and SCMD both in drying rate and overall dryer system efficiency. Both dryers exhibited sufficient ability to dry freshly harvested maize grain reasonably to a safe moisture level for storage and simultaneously it ensures a superior quality of the dried product especially the thin layer drying process products. However, a lot still has to be done to improve the performance of these passive solar dryers. A possible area of improvement is on the use of solar energy storage systems in the dryer to store heat for use in the night time when solar radiation is totally absent.

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