Development of a photovoltaic driven ventilation system to modified traditional Ethiopian *gombisa* for on-cobs-maize drying and storage

Chemeda Abedeta Garbaba[1,2*], Christoph Stache[2], Franz Román[2], Oliver Hensel[2]

(1. *Jimma University, College of Agriculture and Veterinary Medicine, P. O. Box 307, Jimma, Ethiopia*;
2. *Universität Kassel - FG Agrartechnik, Nordbahnhofstr. 1a, 37213 Witzenhausen, Germany*)

Abstract: Unsafe moisture content at loading and the climatically uncontrolled nature of traditional storage structure (*gombisa)* together with ventilation dependent on wind alone, results in mycoflora growth and development on maize in the system. Therefore, this paper was aimed to develop and test a photovoltaic driven ventilation system fitted to a *gombisa* for natural air in-bin drying of on-cobs-maize and increase the shelf life of the stored product. A modified *gombisa* was constructed from locally available materials in Germany. An appropriate fan type and size, humidistat set at 70% and two 20 W_p photovoltaic panels were utilized for ventilation purpose, fan control and to power the fan, respectively. In total 1.76 m^3 of on-cobs-maize with an average moisture content of 0.22 on d.b. (kg/kg) were also used for the study. Data was collected on solar irradiance, photovoltaic voltage, current, inlet duct air velocity and temperature and relative humidity inside the storage system. Similarly, moisture content of on-cobs-maize, ambient temperature and relative humidity data was also collected for both experiments. The result for the temperature and relative humidity trends revealed higher variability and fluctuation for ambient compared with inside the modified *gombisa*. Ventilation of on-cobs-maize for 10-12 days resulted in a reduction of moisture content (d.b.) to almost 0.14 (kg/kg) which generally is considered safe for mould growth conditions. A computational fluid dynamics simulation result revealed the uniformity of the drying of on-cobs-maize using the ventilation system fitted to the modified *gombisa*. Secondary data of solar irradiance obtained from Jimma area, Ethiopia compared to the current experiment show higher energy availability, demonstrating high potential to apply ventilation and drying system to the region. Storing maize inside modified *gombisa* plays a role in protecting the stored product from outside weather conditions. Also, monitored temperature, relative humidity and energy output showed the system was able to bring the product to safe moisture content for storage without mould development. This promising research result needs to be tested and validated in tropical regions of the world.

Keywords: modified g*ombisa*, maize in cobs, temperature, relative humidity, ventilation system

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1 Introduction

Fungal pathogen growth and development has been commonly reported from traditional maize storage structures of southwestern Ethiopia. It is evident that both high quantity and quality losses were recorded from the aforementioned region of the country (Dubale et al., 2014; Garbaba et al., 2017). The region is characterized by hot and humid climatic conditions that favors fungal growth in both pre- and post-harvest maize. More importantly, farmers in study areas mostly leave the maize in the field to dry for harvesting which coincides with rain showers. This, in addition with the climatically non-controlled nature of the traditional storage structures, results in mycoflora growth and development. Unsafe moisture content of maize at the harvesting and loading stage of

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***Corresponding Author: Garbaba, C. A.,** Universität Kassel - FG Agrartechnik, Nordbahnhofstr. 1a, 37213 Witzenhausen, Germany. Email: chemedaa@yahoo.com.

16%-28% (db) and moisture re-wetting during the whole storage duration result in nutritional quality deterioration (Dubale et al. 2014; Garbaba et al., 2017).

In Ethiopia, harvested maize is stored for gradual consumption until next season's harvest, also to fetch a better price and to keep the seed for the next planting season for subsistence farmers where maize is the main and dominant staple food crop for rural society. Therefore, for long-term storage, the product should be dried to a safe moisture content to overcome concern of mycotoxin-producing fungal growth. *Gombisa* is the dominate storage structure used to store maize in southwestern of Ethiopia. However, losses during storage using this structure is very high particularly due to mould development and other storage pests (Rashid et al., 2010, Dubale et al., 2012; Befikadu, 2014). Moisture content at harvesting and loading is one of the key factors for maize post-harvest losses in store. This necessitates drying technology and design of climatically controlled storage structures that prolong shelf life of the stored commodity. Such type of technology should be as low cost as possible, accessible and of simple technology so poor farmers are able to tackle the main constraints they are facing. Therefore, one of the possibilities can be improving locally available traditional storage structure, *gombisa*, for on-cobs-maize drying and storage.

Basically, grain drying is broadly categorized into hot air drying, ventilation and nearly ambient/low temperature methods (Jayas and Ghosh, 2006). Hot air drying methods can adversely affect the quality of dried maize (Brown et al., 1979; Jayas and Ghosh, 2006; Abasi and Minaei, 2014). More importantly, it may not be economically viable for subsistence farmers due to its elevated cost (Jayas and Ghosh, 2006; Singh et al., 2014). On the other hand, low-temperature drying provides a better quality of maize and energy efficient techniques (Brown et al., 1979; Mittal and Otten, 1982). Its reasonable cost, less supervision requirements and low fire hazard are among some of the basic benefits of nearly ambient or unheated grain drying. On the other hand, drying grains with unheated air is a slow process and depends on local weather conditions (Foster, 1953; Sharp, 1982; Atungulu and Zhong, 2016). The main factor to be considered for low temperature dryer design is the airflow rate necessary to dry the grain to a safe storage level without significant losses in quality (Sharp, 1982). In general, the efficiency of natural air in-bin drying depends on ambient conditions, initial moisture content, gain depth, airflow rate, fan control strategies (intermittent or continuous ventilation) and storage-bin configuration type (Sharp, 1982; Atungulu and Zhong, 2016).

For drying purposes use of fossil fuels as an energy source can be either inaccessible or economically unaffordable for subsistence farmers located in rural areas. Therefore, using solar energy is more feasible, most abundant and economically affordable especially in tropical regions of the world where solar power is as available as natural resources but less exploited (Noyes et al., 2002; Hossain and Bala, 2007). For the last couple of decades, research has focused on possible use of solar energy for low temperature in-bin drying to overcome the increasing cost of drying using other sources of energy. Musembi et al. (2016) also described the cost of energy and minimizing post-harvest loss damages during food processing.

Several studies have been conducted on fan control strategies for the drying of different commodities to a safe moisture content level, either experimentally or by means of mathematical modeling (Foster, 1953; Mittal and Otten, 1982; Smith and Bailey, 1983; Sharp, 1984; Moreira and Bakker-Arkema, 1992; Lawrence et al., 2015; Atungulu and Zhong, 2016). The easiest way of fan control is to allow it to run until drying is completed. However, such conditions result in carrying moist air into the stored products. As a result, a fan control system with a humidistat or a clock to switch off/on is recommended (Sharp, 1982). Fan control strategies are important in the conditioning of the final grain and avoiding damp air intake to the storage by controlling ambient humidity (Sharp, 1984). A review by Moreira and Bakker-Arkema (1992) summarized 23 fans and heaters control strategy used for in-bin drying. The review showed several of them are more complicated with only five of them employed for the in-bin drying control scheme. Among them, humidistat control of the upper relative humidity (RH) limits is among the few currently in use for similar purposes. Smith and Bailey (1983) stated that setting relative humidity at 70% to 80% as an upper limit could overcome the problem of mould growth during the drying process.

A *Gombisa* is not climatically controlled to overcome problems of external weather variables that facilitate mycotoxin-producing fungal growth. To overcome the problem, a modified *gombisa* was constructed for the experiment. In addition, photovoltaic panels were used to generate power for ventilation and drying purposes of on-cobs-maize to safe moisture content during storage. Therefore, this research was commenced with the aim to develop photovoltaic fitted ventilation systems to modified *gomibsa* for natural air in-bin drying of on-cobs-maize to increase the shelf-life of the product.

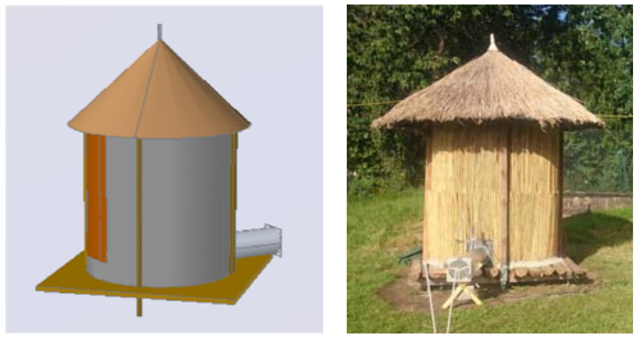
2 Materials and methods

2.1 Study site

The study was carried out at the solar and irrigation research station of the Agricultural and Biosystems Engineering Department, Witzenhausen campus of Kassel University based in the north eastern Hesse region of Germany during the summer of 2016. The research was carried out between July and September 2016.

2.2 Construction of modified *gombisa*

Gombisa is a cylindrical granary type and made up of locally available materials, mostly bamboo, by farmers for maize storage. The roof is covered by natural or thatch grass. For the current study, a similar structure was initially constructed with locally available materials with little modification from the traditional ones. The base of the *gombisa* was supported with four pillars that hold all the weight on it and pillars were deep rooted and cemented to make the supports strong. Each support was 1.5 m apart from the adjacent ones and the base of the storage structure covered an area of 4 m^2. A perforated floor was established 30 cm above the base of the storage structure for the ventilation process. The erected portion of the *gombisa* was made up of three layers, the inner one of strong mesh wire to hold up the system, followed by a plastic sheet with the main objective of minimizing the influence of the external environmental conditions on the stored product. Finally, to protect direct contact of moisture and temperature, the plastic sheet was covered with bamboo. The storage structure had a diameter of 1.5 m and a height of 1.8 m. Four poles were also deep rooted into the ground to support the structure from four directions. The roofing was covered by a plastic sheet and its upper layer was of elephant grass to avoid raising the temperature and leakage of water during rainy periods. A window like structure was installed for loading and unloading the product (Figure 1).



(a) Three dimensional drawing of modified *gombisa* (b) Constructed modified *gombisa*.

Figure 1 Storage structure (*Gombisa*) used for current study

2.3 Installation of ventilation system

2.3.1 Fan type and size

The necessary characteristics of the fan were calculated based on the diameter of *gombisa* (1.5 m), maize bulk height (1 m), and the volume of maize cobs to be stored (1.767 m^3). According to Mujumdar (2006), adequate air flow rate in-cobs-maize ranged from 250 to 500 m^3 h^{-1}, which for the *gombisa* results in 441 to 883 m^3 h^{-1} of the total air flow rate and 0.0694 to 0.1389 m s^{-1} for superficial velocity. Pressure drop of ear maize was calculated using the ASAE Standards D272.3 (2007) as

$$\Delta P/L = aQ^2/\ln(1+bQ) \quad (1)$$

where, a is 1.04E+04 while b = 325 constant values for on-cobs-maize. P is pressure drop in Pa; L is height of maize in cob form in m and Q is airflow in m^3/h-m^3. Taking a superficial velocity of 0.1 m s^{-1} which corresponds to 636.17 m^3 h^{-1} for the *gombisa*, the formula gives us a pressure drop of 29.6 Pa.

A brushless direct current (DC) axial fan type was selected which can approximately produce the required airflow rate. Since the fan would be directly coupled to a photovoltaic panel, the actual working point of the system will vary with the weather conditions. The fan has a nominal voltage of DC 48 V and a nominal current of 0.5 A. Its dimensions were 200 × 200 × 60 mm. The air duct was connected to a plenum chamber and fan to force the air to directly enter the perforated floor and move up to the stored maize in cobs for drying and ventilation.

2.3.2 Photovoltaic system

Two 20 W_p photovoltaic panels were used to power the fan. One solar panel had an open circuit voltage of 22.18 V and a short circuit current of 1.33 A. The second panel had an open circuit voltage of 22.3 V and a short circuit current of 1.22 A. The panels were connected in series to give an open circuit voltage of 44.38 V, which is close to the fan's nominal voltage.

2.3.3 Fan control

An automatic fan control system for the ventilation system was employed based on the relative humidity of the external environmental conditions. For this purpose a low cost battery powered humidistat was constructed. The device consisted of a digital temperature and relative humidity sensor connected to a microcontroller board. Based on the relative humidity measurement made at specified short intervals, the fan can be turned on/off by a relay. The set point of the humidistat (the relative humidity above which the fan is to be disconnected) can be changed with a linear potentiometer. For the tests, the humidistat was set to RH 70% relative to control and allow the fan to run and reduce the risk of moist air entering the *gombisa* and re-weting the stored maize in cobs. The humidistat was sheltered with a small cover for protection from any external damage.

2.4 Maize sample, experimental procedure and data acquisition

Maize in cobs was used for both experiments. In total 1.767 m^3 of on-cobs-maize with an average length of 22 cm was used in this study. In order to raise the moisture content to an average of 22%, preconditioning for adsorption was carried out in June 2016 for the first experiment and in August 2016 for the second experiment. Absorption was done in a controlled climatic chamber approximately one month before each experiment by controlling temperature and relative humidity. Once the moisture content reached 22%, which is the average moisture content at which farmers harvest and load the product into *gombisa*, on-cobs-maize were transferred to the *gombisa* for drying and ventilation.

Maize drying and ventilation was carried out approximately two weeks for both experiments. A photodiode type pyranometer was placed near the photovoltaic panels to measure solar irradiance. The voltage of the photovoltaic panels was directly measured by a data logger (Fluke Hydra) for data acquisition. The current of the panels and air velocity were measured using a shunt resistor (10 Ω ± 0.01%) and hot wire anemometer with accuracy of ± 1%, respectively. All sensors except the hot wire anemometer, which was directly connected to separate computer were coupled to the Fluke Hydra data logger to record measurements every five minutes, which was also connected to the computer for data storage (Figure 2).

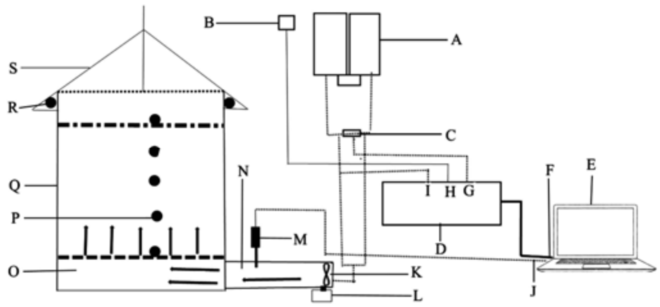


Figure 2 Sketch for experimental set-up of modified *gombisa* for on-cobs-maize ventilation and drying

Where: A = Photovoltaic (PV)-panels, B = Pyranometer, C = Shunt resistor, D = Fluke Hydra Data logger, E = Computer, F = point for connection of data logger with computer, G = Current, H = Solar irradiance, I = Voltage form PV-panels, J = Air velocity from hotwire anemometer, K = Fan, L = Humidistat connected to fan, M = hot wire anemometer, N = Air duct, O = Air plenum, P = Testo 174 H kept at 25 cm interval inside stored maize, Q = Body part of modified *gombisa*, R = Testo 174 H data logger for ambient condition and S = Roofing of *gombisa*.

Data loggers (Testo 174 H, Testo SE & Co. KgaA, Lenzkirch, Germany), with an accuracy of ±3% for relative humidity and ±0.5°C for temperature were kept outside under the roofing of the *gombisa* on both sides to record ambient weather conditions. Five similar data loggers were spaced uniformly down the vertical centerline of the *gombisa* with a 25 cm interval inside the stored maize to record both temperature and relative humidity. Before data collection, each data logger was configured to record data every five minutes. In order to monitor the moisture content of the stored product along the experimental period, three cobs from different levels (0, 25, 50, 75 and 100 cm) above the plenum chamber of stored maize were tagged (Figure 2). The weight of each cob was measured early in the morning each day (7:30 am) and late afternoon (7:30 pm) using a sensitive balance, KERN PRS (0.001 g). At the end of each trial, the sample cobs were oven dried to calculate moisture content (ASAE standard D245.5, 2007; Chen, 2003).

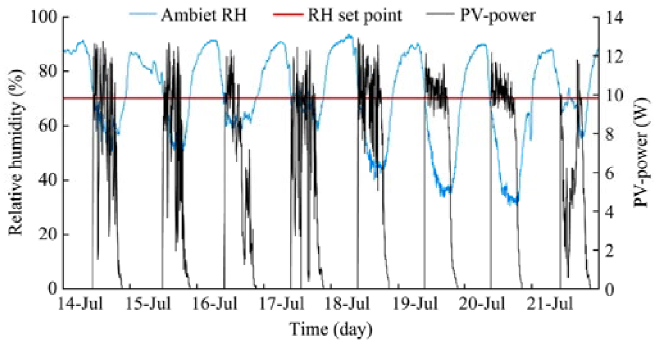
2.5 Computational fluid dynamics simulation

A computation fluid dynamics (CFD) simulation was done to evaluate the airflow distribution and uniformity in the *gombisa* using the software ANSYS Fluent. The *gombisa* geometry was drawn and a grid produced which consisted of about 500000 elements. Only one half of the actual *gombisa* was drawn due to its symmetry. The 1 m column of maize in cobs was modeled as a porous medium using resistance coefficients calculated from a pressure drop data to the ASAE standard D272.3 (2007). At the air inlet the air velocity was set at 5.63 m s^{-1} which corresponds to an airflow rate of 636.17 m^3 h^{-1}. The k-ε realizable turbulence model was used.

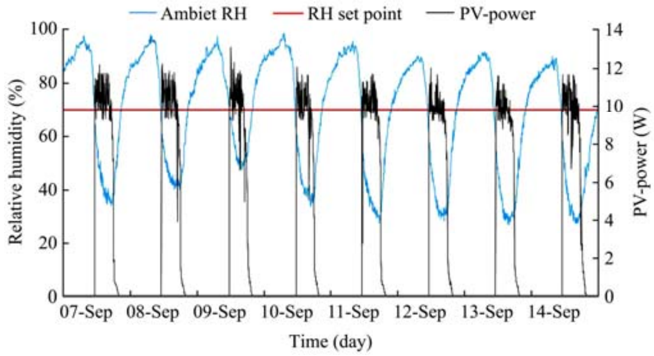
3 Results and discussion

3.1 Fan control system

Figure 3 shows the trend for ambient relative humidity, PV-power and relative humidity set point for first and second experiments. The result showed the fan switched on and off perfectly at the relative humidity set point (70%) for both experiments. During the first experiment, a slight fluctuation in PV-power was observed due to cloudy days (Figure 3). However, better and more constant values were recorded for the second experiment during fan operation. On average the fan operated 10.8 h per day with mean average PV-power of 7.12 W for the first experiment. However, it was 8.13 daily average fan operating hours with a mean value of 8.04 W PV-power per day for the second experiment. During the second experiment the fan switched on around 11:30 am most of the days due to external weather conditions that made short ventilation hours compared to the first experiment. On the other hand, during the first experiment the fan switched on at around 9:30 am, as weather conditions were better and longer day time during July compared to September that made the fan operating hours longer.



(a) First experiment (07-14 July 2016)

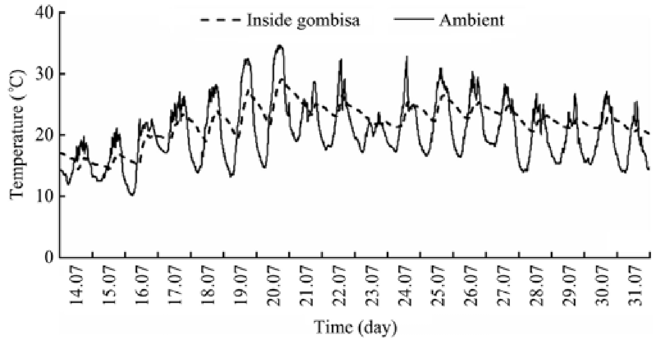


(b) Second experiment (14-21 September 2016)

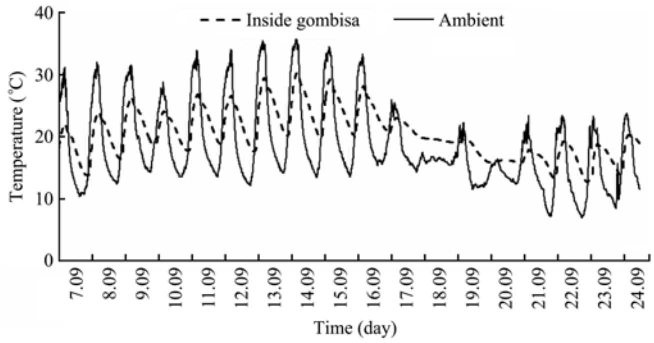
Figure 3 Plot of ambient relative humidity, photovoltaic power and relative humidity set point for consecutive eight days Witzenhausen, Germany

3.2 Temperature and relative humidity trend

The directly coupled photovoltaic ventilation system for on-cobs-maize drying was assessed based on temperature and the relative humidity trend inside the store (Testo data logger 50 cm above perforated floor) and ambient conditions for both experiments. The mean daily variation of temperature inside the stored on-cobs-maize was 3.7±1.9°C, with minimum daily deviation of 1.6°C and maximum value of 8°C. On the contrary, daily mean variation of ambient temperature was 12.6±3.4°C, with a maximum of 17.9 and minimum 5.6°C for the first experiment. Comparably, daily mean variation of temperature throughout the second experiment was 6.6±3.3, 11.8°C (maximum) and 1.1°C (minimum) inside the stored on-cobs-maize. However, a high mean daily variation (15.9±6.1°C), maximum value of 23.3°C and minimum value of 3.1°C was recorded for ambient weather conditions (Figure 4). Generally, ambient temperature showed high variability within a day, but temperature inside the store revealed very slight variation, indicating that the modified *gombisa* played a role in protecting the maize from external weather conditions.



(a) First experiment (July 2016)

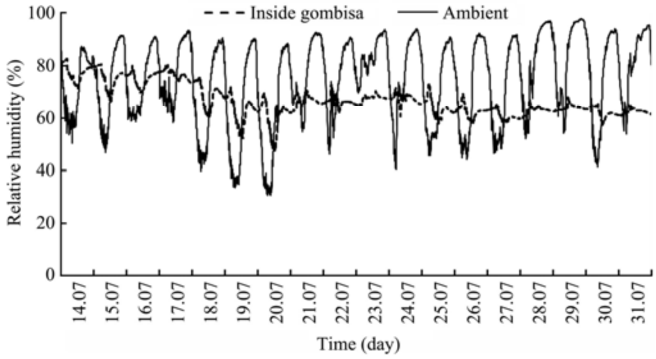


(b) Second experiment (September 2016)

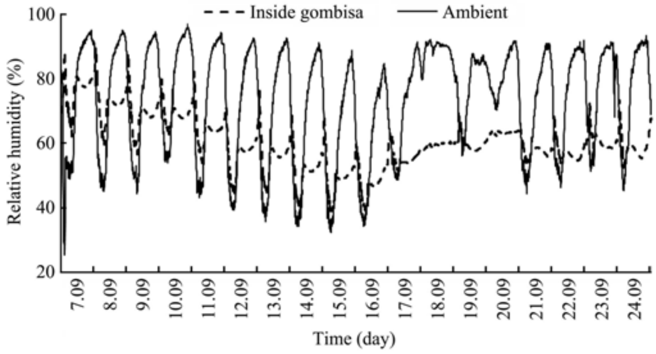
Figure 4 Plot of temperature inside modified *gombisa* and ambient condition versus drying time of on-cobs-maize at Witzenhausen, Germany

Daily relative humidity variation inside the *gombisa* showed a maximum value of 22.2 percentage points, minimum variation of 5.4 and a mean value of 10.8±5.0% during the first experiment. The ambient relative humidity had a maximum variation of 57.8, a minimum of 24 and a mean value of 44.1±8.7 percentage points. In a similar manner, the daily variation of relative humidity inside the *gombisa* showed a maximum of 32.3, a minimum of 6.1 and an average value of 20.5±8.9 percentage points for the entire duration of the second experiment. However, a higher ambient daily variation with a maximum of 58.9, a minimum of 17.6 and an average value of 44.9±12.6 percentage points were recorded for the second experiment. It can be seen from Figure 5a & b that for both experimental trials there was less daily variation of relative humidity inside stored on-cobs-maize as opposed to ambient conditions.

Monitored data during both experiments for temperature and relative humidity showed ambient conditions demonstrated a high variation compared to inside the modified *gombisa* of stored on-cobs-maize. The result clearly showed that even though external environmental conditions showed a high variability within a day, inside the store relatively depicts less variation. This demonstrates that the storage system can play a role in protection from the impact of external weather variations that key role in the growth and development of mycotoxin-producing fungi.



(a) First experiment (July 2016)



(b) Second experiment (September 2016)

Figure 5 Plot of relative humidity inside modified *gombisa* and ambient condition versus drying time of on-cobs-maize at Witzenhausen, Germany

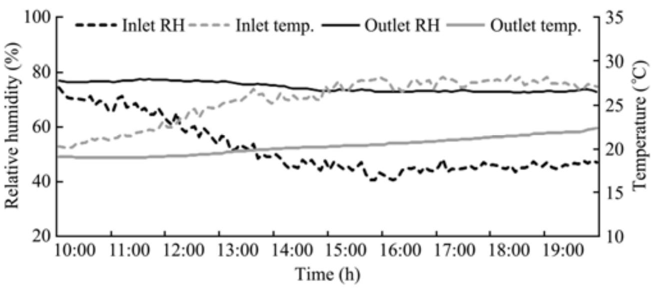
Person's correlation results showed that there is positive association between ambient relative humidity and inside the store. Also, holds true for ambient temperature and inside the store. For both weather variables and experiments, it yields statistically highly significant relationship between ambient and inside the store (p<0.000, Table 1), indicating that the probability of this correlation occurring by chance is less than 1 in 1000.

Table 1 Pearson's correlation for temperature and relative humidity comparing inside modified *gombisa* with ambient conditions during both experiments

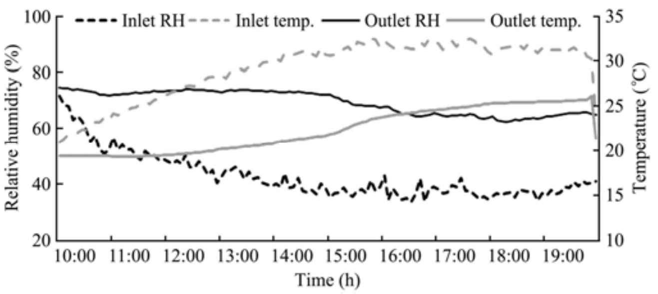
Experiment time	Weather variable			
	Temperature		Relative humidity	
	r-value	P-value	r-value	P-value
July 2016	0.661	0.000	0.331	0.000
September 2016	0.705	0.000	0.340	0.000

3.3 Temperature and relative humidity during fan operations

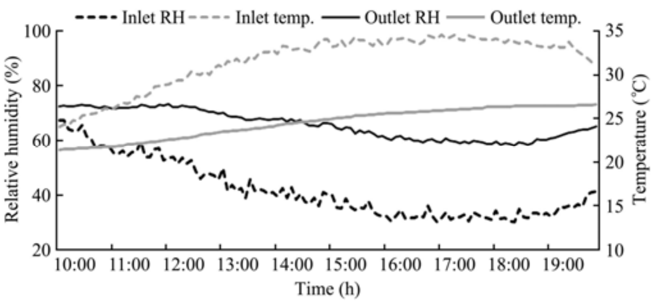
Five minute interval data of the inlet (0 cm above perforated floor) and outlet (100 cm above perforated floor) for temperature and relative humidity during fan operation were shown in Figure 6 and 7. The trend showed as the fan operated inlet temperatures significantly increased, while outlet temperatures changed very slowly. On average 5.30°C, 6.87°C and 7.87°C higher temperatures were recorded for the inlet compared with the outlet during 18 July, 19 July and 20 July 2016, respectively (Figures 6a-c). Similarly, the average differences between outlet and inlet relative humidity were significantly different during drying of on-cobs-maize. The outlet relative humidity was higher by an average value of 22.62, 26.61 and 23.87 percentage points compared to the inlet relative humidity (Figures 6a-c). Similarly, Figures 7a-c showed a comparison of inlet and outlet temperature and relative humidity during fan operating hours for second experiment. Inlet temperature was higher by 10.24°C, 8.45°C and 7.21°C compared to the outlet for 12 Sept. 13 Sept. and 14 Sept. 2016, respectively. However, outlet relative humidity was higher by 23.71, 23.40 and 16.8 percentage points compared to the inlet condition during respective days of the second experiments. During the drying process of on-cob-maize, inlet relative humidity was lower than outlet conditions as the outlet contain more water that was carried out from the drying process. However, it resulted in reducing the outlet temperature compared to inlet conditions.



(a) 18 July 2016

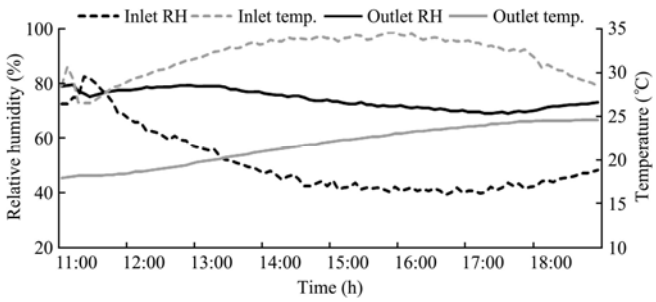


(b) 19 July 2016

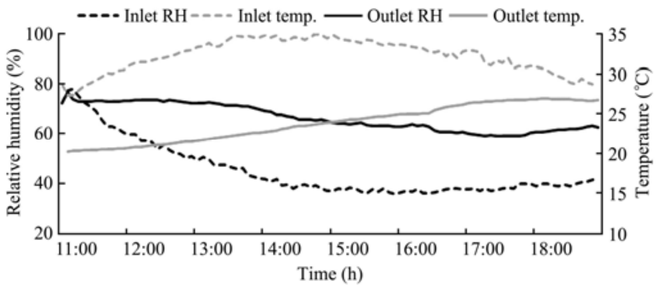


(c) 20 July 2016

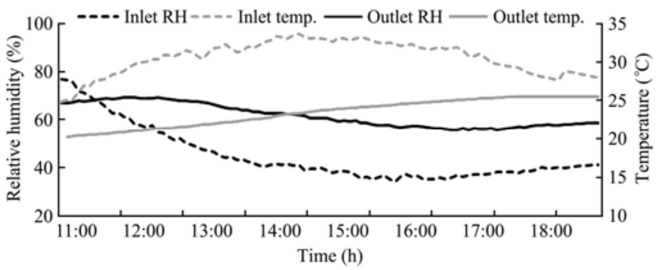
Figure 6 Plot of inlet and outlet temperature and relative humidity versus time during fan operating hours for first experiment at Witzenhausen, Germany



(a) 12 September 2016



(b) 13 September 2016



(c) 14 September 2016

Figure 7 Plot of inlet, outlet and ambient temperature and relative humidity versus time during fan operating hours for second experiment, Witzenhausen, Germany

3.4 Assessment of solar irradiance, air velocity and photovoltaic panels' power

The variations of solar irradiance, air velocity and photovoltaic panels' power of hourly average for a day are presented for both experiments on Figure 8a & b. On the 20th July 2016 the trend of solar irradiance increased sharply from 09:30 and reached a maximum value of 864 W m^{-2} at 13:00, and then very slightly decreased until the fan switched off. Similarly, air velocity inside the duct also slightly increased and reached a maximum average per hour of 4.69 m s^{-1} for the day. However, the maximum pick value recorded for a day was 4.95 m s^{-1}. Photovoltaic panels generated mostly about 10 W throughout fan operating hours of the day. Generally, the 20th July 2016 was one of the cloud free days. Consequently, it showed less fluctuations in all parameters considered for data measurement for the day.

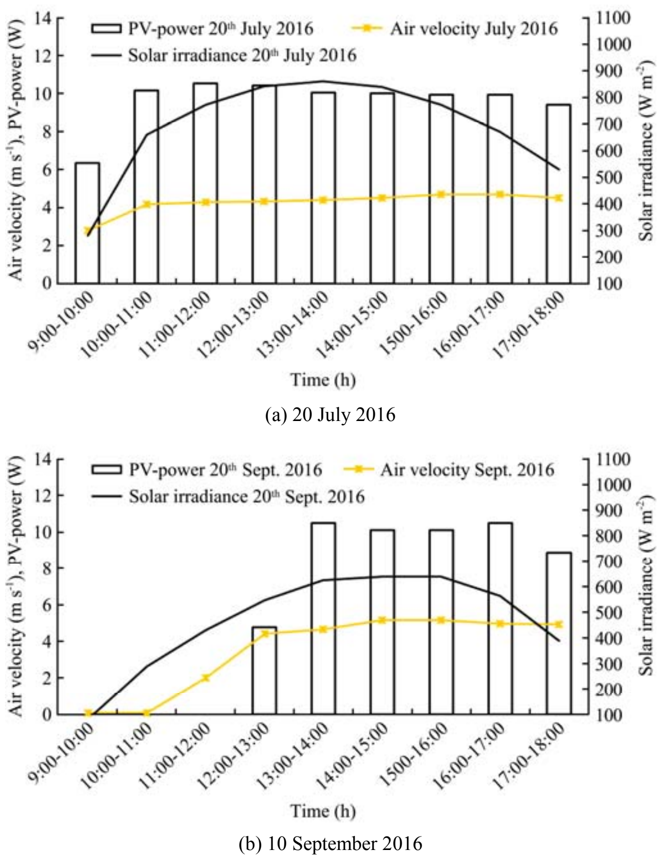


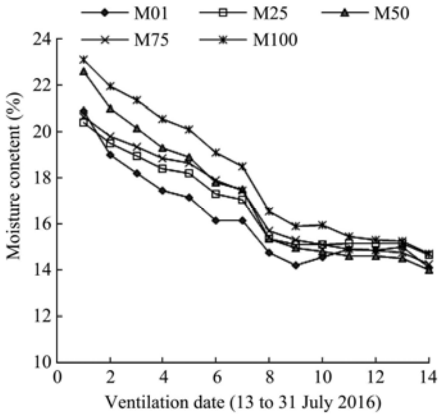
Figure 8 Shows hourly averages for solar irradiance, PV-power and air velocity during fan operating hours at Witzenhausen, Germany

Throughout the second experiment, the fan usually switched on after 11 am due to high morning relative humidity (RH >70%, at which the fan switched on) due to seasonal change. However, during the experiment most of the days were cloud free for ventilation and drying process. The measurements on 10 September 2016 showed a maximum hourly average of 655 W m^{-2} of solar irradiance. Similar to the first experiment throughout the day photovoltaic panels produced nearly 10 W except morning section. Maximum mean hourly average of 5.17 m s^{-1} of air velocity was recorded for September 10, 2016. Average value per hour of solar irradiance, air velocity and photovoltaic panels' power for 20th July 2016 were 658 W m^{-2}, 4.22 m s^{-1} and 9.65 W, respectively. Similarly, values of 439 W m^{-2}, 3.34 m s^{-1}, and 9.14 W were recorded for the second trial (10 September 2016).

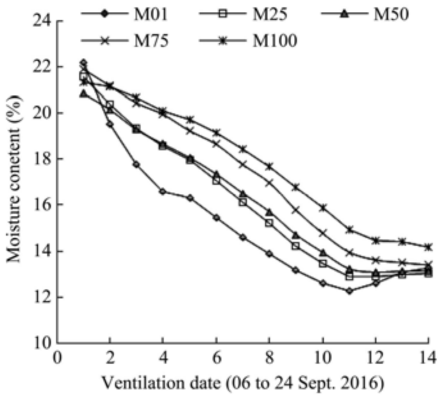
3.5 Drying of on-cobs-maize

It can be observed from Figure 9 that moisture content (d.b.) decreased as ventilation and the drying duration increased for both experimental periods. Figure 8a revealed that within 10 to 12 days of the ventilation period moisture content decreased nearly to 14% (d.b.). Similarly a second experiment (Figure 9b) took nearly 12 days to bring moisture content to a similar level of content nearly 14% (d.b.). There were cloudy days during the first experiment which reduced the photovoltaic ventilation system efficiency for the drying process especially during last days of the experiment, though the result still showed a reasonable and acceptable trend to reduce the moisture content to a safe level. Coincidentally there was good weather with mostly bright sun-shine for the period of the second experiment which gave us a good trend of reduction in moisture content during ventilation days (Figure 9b). However, generally shorter ventilation hours per day were observed for the second experiment compared to first round experiment.

A fan control strategy was set at ambient relative humidity of maximum 70% to switch on for ventilation and drying purposes. A simulation study conducted using long-term weather data by Atungulu and Zhong (2016) for the assessment of fan control strategies for natural-in-bin rough rice drying from a moisture content of 22% to a safe moisture content which took 10 days for an airflow rate of 2.77 m^3 min-t^{-1}. In a similar study with an airflow rate of 2.08 m^3 min-t^{-1} using five fan control strategies (continuous fan operating, fan running only at night, only during the day, set window of equilibrium moisture content of natural air and set window of air equilibrium moisture content with supplementary heating), all operation strategies could dry the rough rice from an initial moisture content of 16%, 18%, 20% and 22% to an average and safe moisture content (13%) in the bin (Atungulu and Zhong, 2016).



(a) First experiment (July 2016)



(b) Second experiment (Septumber 2016)

Figure 9 Drying curve for on-cobs-maize showing moisture content (db) *vs* ventailation time at various postions inside modified *gombisa* at Witzenhausen, Germany

Where: M01; M25; M50; M75 and M100 are 0 cm, 25 cm, 50 cm, 75 cm and 100 cm of on-cobs-maize samples kept above plenum chamber, respectively.

3.6 CFD simulation

The CFD simulation result in Figure 10 showed air velocity distribution in the maize bulk 10 cm and 50 cm above the bottom of the maize bulk. It can be seen that a slightly higher air velocity developed at the side opposite to the air inlet. However, as the air moved upwards through the bulk the air velocity rapidly equalized and halfway through the bulk the airflow was nearly uniform.

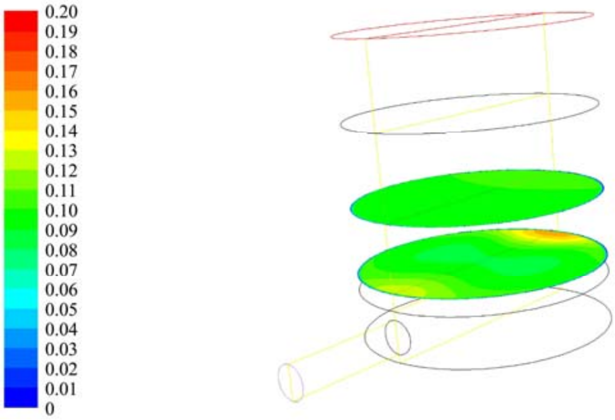
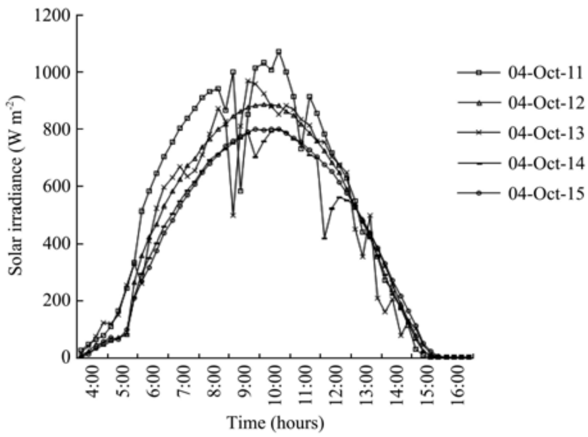


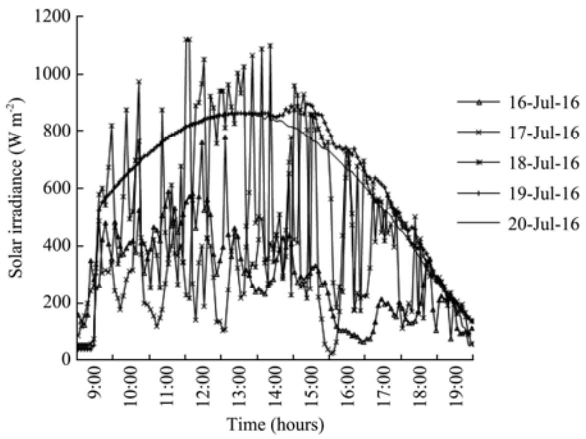
Figure 10 Velocity profiles at 0.1 and 0.5 m above perforated floor

3.7 Application of the system to tropical regions

It is hardly possible to find electricity in rural parts of Ethiopia, including the southwestern part where the extent of maize PHLs is very high mainly due to high moisture content at harvest and loading, which leads to growth of mycotoxin-producing fungi. Therefore, use of directly coupled photovoltaic fan for ventilations system can be suited for on-cobs-maize drying to reduce moisture content to a safe level where the electric grid is not available. The prototype of directly coupled PV-ventilation systems developed and tested showed promising result which can be used in the tropical regions. For this purpose secondary data of solar irradiance during maize harvesting and the loading stage of the Jimma area was obtained and compared with the current experiment. The result showed solar irradiance of the Jimma area showed a better trend with energy output compared with five consecutive days compared with Witzenhausen, Germany (Figure 11). The figure clearly indicated that



(a) 04 Oct. 2011, 04 Oct. 2012, 04 Oct. 2013, 04 Oct. 2014 and 04 Oct. 2015 of the Jimma, Ethiopia (source: EMA, 2016)



(b) 16 to 20 July 2016

Figure 11 Solar irradiance *versus* time in hours at Jimma, Ethiopia and Witzenhausen, Germany there is by far less fluctuation of solar irradiance of Jimma area (Figure 11a) compared with solar irradiance values of Witzenhausen, Germany area (Figure 11b). Solar energy of Jimma area depicted better trend and abundantly accessible which can be applied for intended research work. Therefore, solar energy could be a potential resource and also feasible renewable energy in the area where it is most abundant in nature for ventilation and on-cobs-maize drying purposes.

4 Conclusions

A photovoltaic module fitted ventilation system to modified traditional Ethiopian *gombisa* for on-cobs-maize drying and storage was developed and tested under field conditions. The experimental results showed that the developed fan control systems performed as expected during both experiments. A computational fluid dynamics simulation result revealed the uniformity of the drying of on-cobs- maize using a photovoltaic panels fitted ventilation system to traditional modified Ethiopian *gombisa*. Ambient temperatures and relative humidity showed a high variability compared with the inside of the store indicating the structure playing a role in protecting the stored product from external climatic variables that favor development of mycoflora. The solar irradiance, air velocity, photovoltaic panels voltage and its current average for a day were able to reduce the moisture content of the stored product to nearly 0.14%(db) within 10 to 12 days of ventilation. The results also highlighted that the system can be a potential technology to be tested and used in tropical regions. Future research needs to evaluate quantity and quality losses of stored on-cobs-maize product in tropical regions compared with traditional storage systems.

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