Design Science

Enhancing the shelf life of injera: design of an evaporative cooler clay chamber derived from local clay in Bahir Dar, Ethiopia

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Abstract

Injera is Ethiopian ethnic traditional staple food, made from teff and other crops. The country's superfoods are highly regarded in many Western countries for their excellent nutritional properties ('very low gluten'), and mineral composition. Injera provides sufficient conditions for fungi to grow and ruin injera by changing the texture and making it inedible. This study aimed to develop an evaporative cooler clay chamber (ECCC) used to extend the shelf life of injera by controlling temperature and relative humidity (RH). This system is an economical and efficient way to lower the temperature and increase RH. The results show the maximum daily ambient temperature reduced from 28.98 °C to 22.90 °C and increased the RH of the storage chamber from 28.78% to 80.94%, respectively. The temperature drops up to 6.08 °C, and the RH rises to 52.16% observed. Additionally, the effects of temperature, RH and potential of hydrogen were studied for identified rotten injera and designed for injera storage. ECCC can store freshly made injera for 9 days before any visible mould stains appear, significantly reducing weight loss with an average cooling efficiency of 79.31%. Therefore, this study might help to develop low-cost cold storage for injera preservation at farms end in Ethiopia.

Keywords: ambient temperature, cooling efficiency, evaporative cooler, injera, pH, relative humidity

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1. Introduction

In Ethiopia, the most common type of food is injera (a traditional folk staple, round pancakes), usually made from teff (Eragrostis teff). However, a small portion of rice, wheat, corn, barley and *Ensete ventricosum* is consumed with injera as part of the staple food. Almost all Ethiopians consume this food at least once or twice a day and are well known in parts of Eretria and Somalia (Tadele & Hibistu 2021). Injera preparation consists of many steps from grain preparation to baking (every 3 days), and the prepared injera is preserved in traditional mosseb, as shown in Figure 1a. These steps are still carried out using indigenous knowledge and traditional practices. Because it is perishable, it quickly spoils and deteriorates in quality. In addition, mould growth and loss of texture are two major factors that make injera unsafe and unacceptable for human consumption after storage at room temperature for approximately 3–4 days. Mould is a small, dusty place that spreads to a

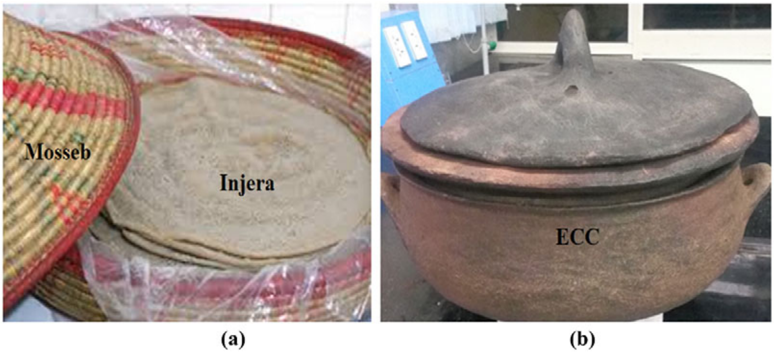

Figure 1. (a) Traditional injera storage (in Amharic called 'mosseb', made of grass) and (b) the designed evaporative cooler chamber (mosseb-designed Zeer pots, made of clay).

variety of foods and costs the economy millions of dollars each year (Bavaro *et al.* 2017). There is growing knowledge and understanding of the role mould plays in food spoilage. In particular, the discovery of mycotoxin production in foods highlighted the importance of mould to food quality. However, it is only in the last 5–10 years that great progress has been made in the prevention of mould spoilage. This is due to the recent international convention on the classification and analysis of moulds in food, which found that specific and very limited fungi (mycobiota) are responsible for all types of food spoilage. Moulds can grow at different water activity levels, potential of hydrogen (pH) levels and temperatures using different substrates such as carbohydrates, organic acids, proteins and lipids (Huis in't Veld 1996). As a result, mould can grow on acidic products such as fruits and fruit juices (Lahlali, Serrhini & Jijakli 2005) and moderately moist foods such as bread, injera and baked goods (Abellana *et al.* 1999), where other microorganisms such as bacteria cannot grow.

These conditions are often due to improper storage materials and conditions (Figure 1a) and also temperature as well as humidity that promote mould growth and moisture transfer (Kuyu & Bereka 2020). Moreover, method development is central to design studies because methods represent a formalised way of expressing knowledge about how aspects of the design can or should be performed (Gericke, Eckert & Stacey 2022). It has been a key component of academic research and design for sustainability research for decades, taking into account various environmental and economic benefits across the product life cycle and playing a role in enabling change within the industry (Bhamra & Hernandez 2021). Since ancient times, people have used different methods to preserve food from microbial spoilage, store it and eat it later. Some of these techniques include pasteurisation, drying, pickling, smoking, canning, irradiation, refrigeration and freezing (Amit *et al.* 2017). This could be due to the economic loss of a quarter of the world's food supply. However, spoiled foods become inedible and lose nutrients due to unwanted changes in appearance, colour, smell, taste and texture. Microbes are endemic to the environment (air, water, soil etc.) and can easily contaminate food at every stage from farm to fork. Therefore, food preservation is crucial for ensuring safety, preventing spoilage, extending shelf life, improving shelf life, managing food poisoning and reducing economic loss (Pal 2017). Neela & Fanta (2020) report a

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10-day shelf life of injera using chemical methods [locally available spices extracted with water and 95% ethanol (2%)] and they tried to identify the species belonging to the genera of *Penicillium, Aspergillus, Rhizopus,* and *Mucur* present in spoiled injera.

The most important quality feature of good injera is its slightly sour taste. Typical injera is round, soft, spongy, about 6-mm thick and 60 cm in diameter (average), with evenly spaced honeycomb 'eyes' on top. Injera is very valuable because it is rich in calcium and iron (Zegeye 1997). Injera is usually reported to be stored at the home level for 2–3 days. This period may vary due to treatment, hygiene, cooking method differences and ingredient composition. Fresh foods such as injera are stored, transported and sold to ensure food quality and minimise nutrient loss so that consumable foods meet consumer expectations for quality. It requires a proper temperature and humidity-controlled environment. As food markets become more accessible and food supply chains become more integrated around the world, ensuring food quality has become a major concern (You, Kang & Jun 2021). Injera's rot rate depends on temperature and various preservation methods, primarily based on low temperatures, have been used for food storage and distribution to reduce spoilage and biochemical deterioration. The most commonly used methods are refrigerated storage at 0 °C–4 °C, the use of slurry ice or ice-free ultra-refrigerated chambers freezing at 18 °C to −40 °C (Kaale *et al.* 2011). The relative humidity (RH) is also directly related to the moisture content of the atmosphere, which determines whether it exceeds shelf life, and therefore also affects food spoilage (Isaac *et al.* 2016). However, limited research has been reported on the preservation of injera by chemical constituents, natural species and microorganisms involved in fermentation and cell degradation. There are no reports specifically showing the use of evaporative cooler chambers (ECCs) for injera storage. Therefore, the purpose of this study was to develop a locally available evaporative cooler from a clay pot that could be used to extend the shelf life of injera by controlling temperature and RH.

2. Material and methods

2.1. Sample collection

The evaporative cooler clay chamber (ECCC; mosseb-designed Zeer pot) is made of clay by Kudmie Kebele of Mecha Woreda (formerly Merawi) in the West Gojam zone of Amhara, Ethiopia. Merawi has located 525 km from Addis Ababa, Ethiopia. Specifically, the city is 7 km near Koga Dam, with latitude and longitude coordinates of 11°24'31"N 37°9'39"E and 1901 m above sea level. The experiment was conducted from January 2022 to May 2022 at the Department of Chemistry and Biology, Bahir Dar University, Ethiopia. The ambient temperature varied between 22 °C and 32 °C during the study period.

2.2. Assessing shelf-life and storage mechanism of injera

During the study, over 50 questionnaires (Appendix A) were randomly distributed to different households in Bahir Dar city, Ethiopia. These questionnaires included the type of material used to store the injera, the shelf life of the injera based on the storage material used, the name and type of favourite food given daily and how the

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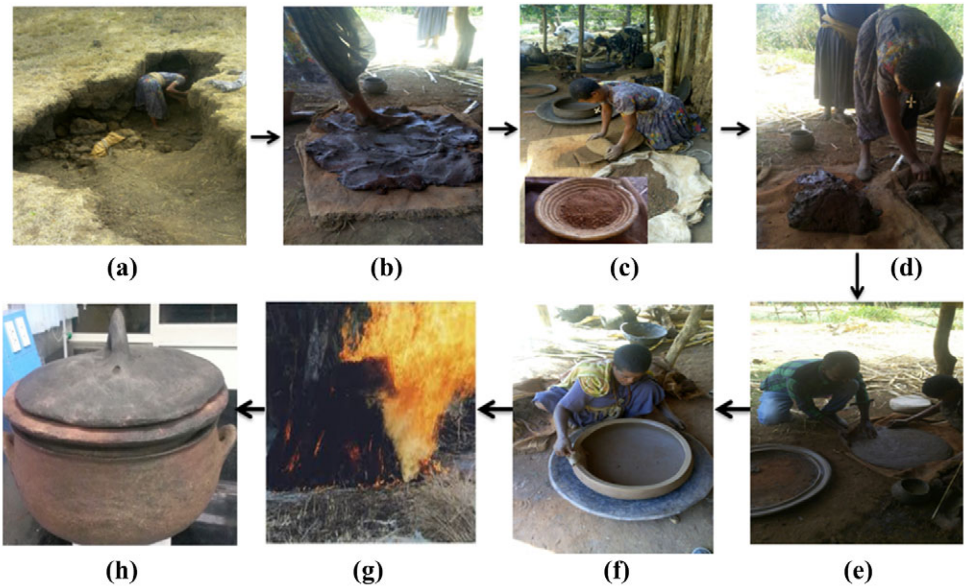

Figure 2. Photo image of the procedure for preparing and shaping a mosseb-designed Zeer pot: (a) Digging clay, (b) Making fresh clay mud, (c) Grounding old clay, (d) Mixing clay with old clay powder to make a better mud, (e) Designing a mosseb-like Zeer pot, (f) Drying a mosseb-designed Zeer pot, (g) Mosseb-designed Zeer pot firing and (h) Finished a mosseb-designed Zeer pot.

injera was made and stored. Also, it is included information such as the frequency and cost of fuel when making injera.

2.3. Procedure for preparing a mosseb-designed ECCC

Figure 2 shows the step-by-step process for preparing a mosseb-designed Zeer pot, as an evaporative cooling chamber. Here are the steps: Excavating clay from underground with workers (local Amharic potters, 'Shekilaser') → Mixing clay with water and using hands and feet to make a gel-like mud that homogenises the clay evenly and increases its strength, elasticity and resilience, then stay for 5 days → Re-stirring the clay slurry with spent clay powder improves trap passage and increases clay bonding and strength, this helps air and moisture during combustion → Create material in mosseb-designed Zeer pot → Prepared material dried for 4 days in a shaded, unventilated room → Burn dried material underground for 5 hours using wood as fuel source → Finally, smoothed and decorated a mosseb-designed Zeer pot ready for injera storage.

2.4. Description of a mosseb-designed Zeer pot

Figure 2 shows the preparation of a mosseb-designed Zeer pot chamber that consists of two clay pots (inside and outside) with a lid. The shape of the inner clay pot is circular and 0.46 m in diameter, 0.15 m in height and 0.02 m in thickness, but the shape of the outer clay pot is also circular and 0.56 m in diameter, 0.20 m in height and 0.02 m in thickness). The gap between the two pots was 0.03–0.05 m apart (top to bottom) and the cavity was filled with a mixture of 4.5 kg of sand,

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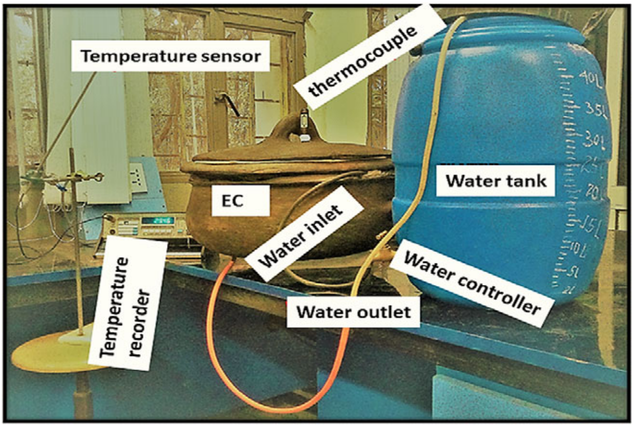

Figure 3. Complete setup of the mosseb-designed evaporative cooling chamber.

1-mm granulation and 0.5 kg of powdered sodium chloride salt. The mixture of sand and salt is continuously moistened with water droplets with a round rubber tube between the two pots and a small hole with a tube at the bottom of the outer pot to remove excess water and it is recycled to the water reservoir (Figure 3). The sand is saturated with water, but its thermal conductivity is about 2–4 W/m.k. In other words, it conducts more heat than pure water and conducts about 0.58 W/m. k. After that, as the sand dries, the thermal conductivity drops to about 0.15–0.25 W/m.k. Therefore, the high thermal conductivity of moist sand promotes heat transfer through the sand and accelerates the temperature drop in the chamber, and keeps the pot cool longer while using salt to prevent mould on the surface of the pot mosseb as the dry sand reduces thermal conductivity and acts as insulation as the water begins to evaporate. Dry-bulb temperature (DBT) and wet-bulb temperature (WBT) in the cooler were monitored using two digital thermometers permanently mounted on top of the cooling chamber (Figure 3). However, the surface of the inner pot was covered with aluminium foil for injera safety and to minimise RH in the chamber.

The parameters used in this experiment were RH, WBT and DBT, vapor pressure, dew point and enthalpy. Cooling efficiency is calculated as follows (Lertsatitthanakorn, Rerngwongwitaya & Soponronnarit 2006):

$$\eta = \frac{Tdb - Ts}{Tdb - Tw} \times 100. \tag{1}$$

The algorithm for calculating the cooling capacity of a direct evaporation cooler is

$$\mathrm{Cc} = 1.08 \times Q \times \left(Ts\text{-}\eta\left[T_{dp} - T_w\right]\right), \tag{2}$$

where T_{db} is the DBT of ambient air (°C), T_w is the WBT of the ambient air (°C), T_s is the temperature of cold air (°C), Q is the air flow rate (m^3/s), η is the evaporative effectiveness (%), and Cc is the cooling capacity.

Air enthalpy, dew point and vapor pressure were determined from psychometric diagrams and psychometric equations (using Hands Down Software with HDPsyChart, Standard Edition, and version 3.1.61). Determining air flow rate (Q) is a matter of multiplying the cross-sectional area of ECC by the air velocity, an

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anemometer was used to measure air velocity for determining the average airspeed. The dimensions of ECC are known (0.46 m in diameter), then the cross-sectional area can be easily determined and the volumetric flow (air flow rate) is calculated by $Q = u \times \pi \times D^2/4$, where u and D are the air velocity and the ECC diameter, respectively. The amount of water evaporated through the evaporation chamber was measured three times a week.

2.5. Preparation of injera for the experiment

A 16% starter ('ersho' in Amharic) was added dropwise to 8 L of tap water in 4 kg of a mixture of 80% teff and 20% cornmeal. The mixture was hand kneaded into the dough to obtain a saturated homogenised solution. The resulting dough was fermented for 3 days at ambient temperature. The watery suspension that formed on the dough was then discarded. To make smart, smooth injera, 1.5 L of water and 1 L of leaven were mixed and cooked on the stove (traditionally known as 'absit') for 1 hour. Boiled absit was added to the dough and stirred for 10 minutes until a thin saturated solution is obtained. The resulting diluted saturated solution was left for a day to stabilise the fermentation and prepared it using a metal and clay electric furnace ('methad' in Amharic) to make injera. Finally, this prepared injera was used for further research in the laboratory of Bahir Dar University, Ethiopia.

2.6. Microbiological analysis

Isolation and cultivation of moulds from spoiled injera

Injera samples were stored in a physicochemical laboratory at ambient temperature until mould colonies began to appear on the surface. This was observed from Day 3. Based on differences in colour and other colony morphology, the mould was transferred directly to potato dextrose agar (PDA) containing 60 mg/L chloramphenicol as an antibacterial agent. The culture was then incubated at room temperature for 5 days to induce fungal growth. To obtain a pure culture, each of the resulting colonies was transferred aseptically to a fresh PDA agar plate for identification. The fungi were kept on a PDA tilt in a refrigerator at 4 °C.

Characterisation and identification of moulds from spoiled injera

In this study, fungal species identification and isolation were determined based on morphological properties (colony properties), spore size and shape, using slide cultures of each isolate (Barnett & Hunter 1972). The features of the isolated colonies and microscopes served as the basis for identification. The nature of the mycelia and the reverse colour of the newly subcultured isolates were observed. After the mycelium was stained with lactophenol cotton blue, the isolate was microscopically examined. The separated mycelium was spread on a clean, grease-free glass slide, picked with an inoculum needle, followed by the addition of two drops of lactophenol cotton blue, on which the cover glass was placed. Microscopic features such as colony head, stem colour and length, vesicle shape and serration, colony shape and colour were observed with a compound microscope (Ajith & Sunita 2017).

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Effect of temperature and humidity on mould growth in injera

The optimum temperature for the mould was determined by inoculating the mould into an injera agar (IA) medium. The IA medium was prepared by the following method: Fresh injera dried in the sun ('drkosh' in Amharic) was crushed and sieved to a mesh size of 500 μm. From this, 100 g of injera powder was mixed with 7 g of agar, then 700 ml of heated water (60 °C) was poured into the mixture. The resulting mixture was stirred for 1 hour. After sterilisation at 121 °C for 15 minutes, the medium was poured into a Petri dish, and IA medium was stored in the refrigerator during the experiment. The effect of temperature was performed by rigorously inoculating spores into an IA medium infused with three isolated fungi (*Aspergillus sp.*, *Penicillium sp.* and *Rhizopus sp.*). Culture growth was assessed at 0 °C, 5 °C, 10 °C, 15 °C, 20 °C, 25 °C, 30 °C, 35 °C, 40 °C, 45 °C and 50 °C at 85% constant humidity using a refrigerator and incubator. In addition, the effect of RH was assessed at 5%, 15%, 25%, 45%, 55%, 65%, 75%, 85% and 95% at a constant temperature of 25 °C. After 5 days of culture, the growth (colony size) of each fungal species was evaluated as no growth (−), slight mould growth (+), moderate mould growth (++) and heavy mould growth (+++). A triplet of each fungus on IA plates was used for each temperature and RH treatment.

Determination of pH and moisture of injera

After calibrating with standard solutions of pH 4, 7 and 10 using an electronic pH metre (Adwa model, AD 1131B), the pH of the fresh injera suspension was measured as follows: 5 g of injera was added to 50 ml of distilled water and the dispersion was homogenised with a magnetic stirrer. The pH of the stored injera inside and outside the evaporation cooler was measured after 3 days of storage. On the other hand, the water content of the sample was also determined by drying the 2-g sample overnight in a 105 °C oven (Lal Basediya, Samuel & Beera 2013). Moisture content is calculated using the following formula:

$$\%\text{Moisture} = \frac{m_w}{m_s} \times 100, \tag{3}$$

where m_w and m_s are the mass of water and the mass of wet injera, respectively. And, the mass of water is calculated by

$$\text{Mass of water} = \text{Mass of wet injera–Mass of dried injera}. \tag{4}$$

The effect of moisture on injera rot was studied by preparing 5 g of freshly dried injera with 100%, 75%, 50%, 25% and 5% water.

Evaluation of the shelf life of injera

Microbial shelf life is defined as the number of days that microbial spoilage is first visually observed. If you have to eat food within a certain period for health or safety reasons, you need a 'best-by date'. However, the 'best-by date' applies to foods whose deterioration affects consumer acceptability without compromising health and safety. Such degradation includes rancidification, texture changes, off-flavour and microbial spoilage. Therefore, in this study, shelf life is considered the 'best-by date' in terms of fungal spoilage. Samples of injera were examined when visible signs of mould growth were observed on the surface of the injera and their

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durability was expressed in the corresponding controls (Katsinis, Rigas & Doulia 2008).

Sensory evaluation

Sensory assessments of injera preserved inside and outside an evaporative cooler were performed by an untrained panel of 15 judges and scored on a nine-point hedonic scale (1 = dislike, 2 = dislike, 3 = dislike, 4 = dislike, 5 = dislike not like, 6 = slightly like, 7 = slightly like, 8 = like a lot and 9 = like a lot) measure preference mainly in food science (Wichchukit & O`Mahony 2015).

Statistical data analysis

All existed the numeric values of correlation with different parameters data were using three measurements (mean) ± standard error was tested by one-way analysis of variance using the SPSS software for windows version 20, IBM, NY, USA. This was done after carrying out a test of homogeneity and normal distribution of each measured parameter. Mean values were compared with Tukey's honestly significant difference test and all the statistical analyses were computed with SPSS significant difference was determined at 5% ($p < 0.05$).

3. Result and discussions

3.1. Shelf life, storage mechanism and amount of injera lost by spoilage

Appendix A summarises the information from 50 household participants from the questionnaire's distribution and face-to-face interviews regarding shelf life, storage mechanisms and the amount of injera lost due to spoilage in Bahir Dar, Ethiopia. Based on the results of the above respondents, it was shown that in the city of Bahir Dar, Ethiopia, most of the commonly consumed healthy foods are injera. The common material used to store injera is a mosseb made of grass that keeps the injera in good condition for only 3 days. Up to 66% of households do not have a mechanism to prevent injera spoilage, but 12% of consumers used sun-based drying techniques. Twenty-two percentage of the participants used heating of 5–10 freshly baked injera once on the stove (methad); this shows that removing excess water from the injera can extend the shelf life of the stored injera by up to 5 days, but the texture is unacceptable. Injera rot also varies from season to season, that is, the percentage of rotten injera is highest and lowest in spring and winter, respectively, which may be related to seasonal temperature and humidity. Since, in spring, the temperature rises and the rate of putrefaction is high while in summer, the temperature is low but the humidity is very high, so the rate of putrefaction is high. And, in winter, temperatures and humidity are low and it is common for mould to grow on the surface of the injera. Overall, 88% of participants reported that 30–90 kg of injera was lost each year due to a lack of proper mechanisms to extend the shelf life of stored injera. On the other hand, 12% of participants lose up to 150 kg per year in each household. In the city of Bahir Dar, this amplifies food shortages, abuse of women's power, wasted costs, wasted energy (electricity and wood) and wasted time in Ethiopia.

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Table 1. Effect of moisture on injera mould growth

Moisture content (%)	Mould growth
100	+++
75	++
50	+
25	−
5	−

Note: (−) no growth, (+) slight mould growth, (++) moderate mould growth and (+++) high mould growth.

3.2. The moisture content of injera and its effect on the mould growth

The water content of fresh injera was calculated to be 63.5% using Eq. (3). Since injera rot increased with increasing moisture content, the effects of moisture are also shown in Table 1. This result correlates with the respondents' responses (Appendix A), and heating 3–5 fresh injera together before applying the stored material maximises storage life by 5 days.

$$\%\text{Moisture} = \frac{\text{Mass of wet injera–Mass of dried injera}}{\text{Mass of wet injera}} = \frac{2.0\,\text{g}–0.73\,\text{g}}{2.0\,\text{g}} = 63.5\%.$$

The water requirement of microorganisms is expressed by the water activity in the environment. This parameter is determined by the ratio of the vapor pressure of the food substrate to the vapor pressure of pure water at the same temperature. All microorganisms have a water activity limit, below which they do not grow, form spores or produce toxic metabolites. Water can affect chemical reactivity in a variety of ways. It can also affect the viscosity of the food system and change the mobility of the reactants by forming hydrogen bonds or complexes with the reactants. Therefore, a very important practical aspect of water activity is the monitoring and/or control of unwanted enzymatic and chemical reactions that shorten the shelf life of food (Pérez-Lavalle, Carrasco & Valero 2020). Moreover, our result was correlated with some other researchers' reports showing that moulds can grow over a wide range of water activity values, pH values and temperatures using numerous substrates such as carbohydrates, organic acids, proteins and lipids (Huis in't Veld 1996). As a result, mould can grow on acidic products such as fruits and fruit juices (Lahlali *et al.* 2005) and moderately moist foods such as bread and baked goods (Abellana *et al.* 1999), but other microorganisms such as bacteria cannot. Mould has been implicated in a wide variety of food spoilages as it can also grow in cereals, beverages, dairy and fermented products (Filtenborg, Frisvad & Thrane 1996).

3.3. Mosseb-designed Zeer pot (cooling chamber) test without loading of injera

Testing was conducted by testing the system without uploading the injera to see if the temperature decreased and the RH increased compared with the environment.

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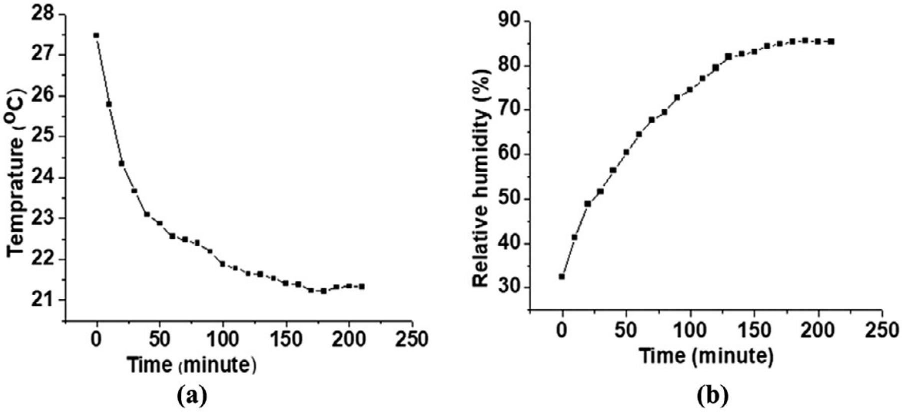

Figure 4. Temperature versus time (a) and humidity versus time (b) graph of the designed evaporative cooler.

The designed evaporative cooler lowered the maximum daily ambient temperature from 27.51 °C to 21.75 °C but increased the RH from 32% of the ambient air to 84% of the storage chamber (Figure 4). This 5.74 °C drop in temperature and 52% increase in humidity could be the nature of the cooling chamber and sand. Figure 4a shows that the cooling chamber temperature decreased over time but remained constant beyond 175 minutes, whereas the RH is reversed in Figure 4b. However, chamber humidity is also controlled by using the lid of the evaporative cooler as a dehumidifier and drying it in sunlight every 10 days to remove moisture absorbed by the lid.

3.4. Mosseb-designed Zeer pot test with the loading of injera: temperature and relative humidity

During the experiment, the inner surface of the designed ECC was covered with aluminium foil and the top lid was also made of clay; this was used as a dehumidifier to minimise the humidity of the cooler. Ten layers of injera (circular) were stored inside and outside (used as a control) of the ECC. The temperature and humidity of evaporative cooling system (ECS) inside and outside were monitored, and those values were measured continuously for 10 days. Measurements were performed three times a day in the morning, afternoon and evening (4-hour intervals), and the average value was calculated and recorded accordingly. The daily cooling capacity of the ECS was calculated using Eq. (1) when equipped with injera. Table 2 shows the results of cooling chamber cooling efficiency for 10 consecutive days. As a result, the average cooling efficiency was 79.31%, but the cooling efficiency of the system fluctuated between 69.24% and 88.34% each day of the experiment. Table 3 also summarises other thermodynamic properties such as dew point, enthalpy, vapor pressure and absolute humidity on 10 test days inside and outside the evaporation cooler. Other studies in Ethiopia have shown the cooling capacity of evaporative coolers to extend the shelf life of mangoes. It was able to reduce the ambient temperature throughout the day from a range of 23 °C –43 °C to 14.3 °C –19.2 °C with an increase in RH from 16%–79% to 70%–82.4%. On average, the temperature and RH differences were 10.7 °C and 36.7% respectively. This

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Table 2. The cooling efficiency of the evaporative cooler clay chamber each day

Day of experiment	Dry-bulb temperature (T_{db}) (°C)	Cold air temperature (T_s) (°C)	Wet-bulb temperature (T_w) (°C)	Cooling efficiency (η) (%)
1	28.92	22.18	20.96	84.50
2	29.76	23.89	21.89	74.59
3	30.54	23.34	21.66	81.08
4	29.96	23.22	21.47	79.39
5	31.98	23.79	21.35	77.05
6	28.34	22.21	21.04	83.97
7	29.46	23.44	21.79	78.49
8	26.59	22.74	21.03	69.24
9	27.43	21.54	20.06	79.92
10	26.81	22.66	21.92	84.87
Average	28.98	22.90	21.32	79.31

Table 3. Comparative thermodynamic properties of the evaporative cooler clay chamber for 10 days[a]

Thermodynamic properties	Inside the cooler	Outside the cooler
Dew point (°C)	19.46	9.05
Enthalpy (KJ/Kg)	77.13	65.34
Vapor pressure (Pa)	2268.88	1151.37
Absolute humidity (g/m^3)	16.61	8.31

[a]Using Hands Down Software with HD PsyChart, Standard Edition, and version 3.1.61.

doubled the best-by date of mangoes from 14 to 28 days and increased the number of mangoes available for sale by 55% (Getinet, Seyoum & Woldetsadik 2008). Another study in Nigeria also showed that evaporative coolers made in clay pots reduced the ambient temperature from 32 °C –40 °C to 24 °C –29 °C throughout the day (Lal Basediya *et al.* 2013).

In Figure 5a,b, the results show that the average storage temperature of the injera observed in the system ranges from 21.54 °C to 23.79 °C, the ambient temperature ranges from 26.59 °C to 31.98 °C and the relative ambient humidity level was 21.49%–38.61%, but inside the evaporative cooler, it was in the range of 78.87%–83.47%. This represents a 44.86%–57.38% increase in system RH relative to ambient conditions. Many similar studies have shown that evaporative cooling storage structures are useful for the short-term storage of farm fruits and vegetables in hot and dry areas (Jha & Chopra 2006). Evaporative cooling is an efficient and economical means of lowering the temperature of the enclosure and increasing the RH and has been widely attempted to extend the shelf life of horticultural crops (Dadhich, Dadhich & Verma 2008), which is essential for product freshness. It is an environmentally friendly air conditioning system that uses induced heat and mass transfer processes, where water and air are working fluids. With this cooling

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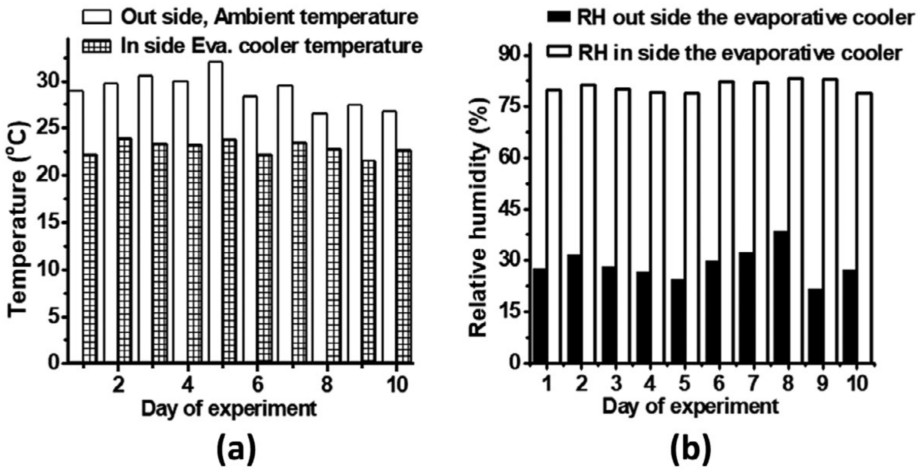

Figure 5. Average temperature (a) and relative humidity (b) versus the day of the experiment of the cooler and the ambient.

system, the temperature drops significantly and the humidity rises to levels suitable for short-term storage of perishable goods on the farm (Tejero-González & Franco-Salas 2021).

3.5. Physiological weight loss

Weight loss rates of injera with and without (ambient) evaporative cooler ranged from 0.61% to 3.48% and 3.14% to 11.40% per day, respectively, compared with mean weight loss of 2.25% and 6.83% per day (Figure 6). This indicates that the evaporative cooler was better at maintaining the weight of fresh injera than storing it under ambient conditions. Water is, therefore, an important and major component (63%) of injera and contributes to the overall weight. Losing water will lead to weight loss, dehydration will set in and it will soon become difficult to eat in a smooth and normal way. Therefore, maintaining the weight of fresh injera is very important to extend its shelf life.

3.6. Moulds responsible for injera spoilage

Small fungal colonies (visible to the naked eye) appeared on the injera surface from Day 3 after storage outside an evaporative cooling chamber; the injera was spoiled by different fungi species with IA media in a petri dish. These colonies grew gradually and exhibited different types of colony colours (white, yellow, green and black) during sporulation, as shown in Figure 7a–c, whereas Figure 8d–f shows that the injera moulds were separated at different storage times at ambient temperature and observed microscopically (Table 4). Based on colony morphological and microscopic features, three fungal species were identified for injera spoilage; these are belonging to *Penicillium* sp., *Aspergillus* sp. and *Rhizopus sp.* Contamination can arise from mould spores released from the atmosphere or surfaces during cooling, finishing and packaging operations (Gock *et al.* 2003). Based on this, we can say that injera is free of fungus when baked. Nevertheless, the large surface area of injera increases the potential for airborne fungal contamination. Therefore, the

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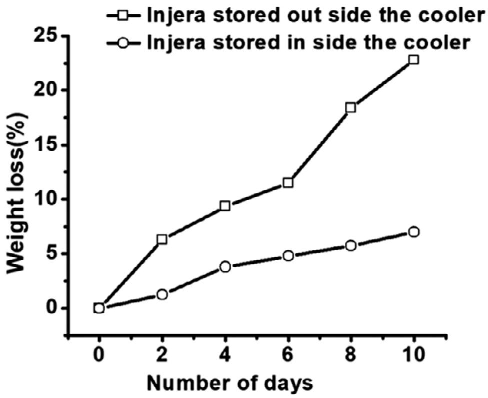

Figure 6. Physiological weight loss of injera stored inside and outside evaporative cooler chamber.

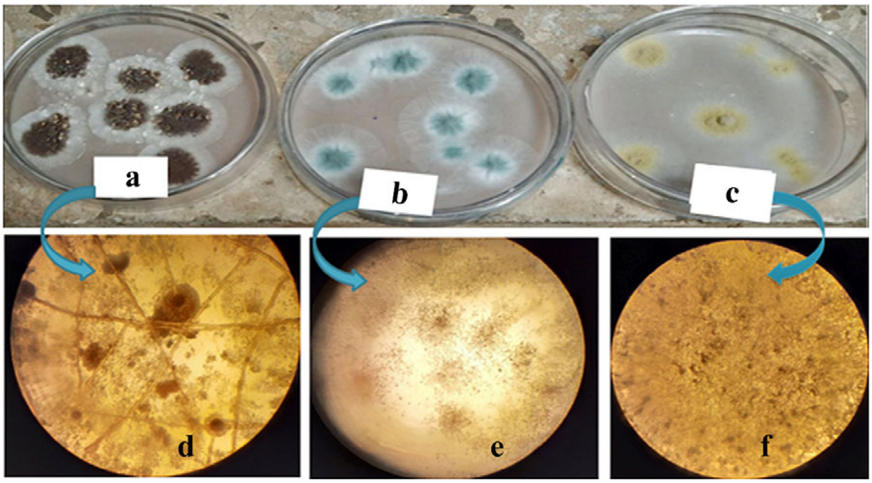

Figure 7. Different fungi species cultured on injera agar media: (a) *Rhizopus sp.* (b), *Penicillium sp,* and (c) *Aspergillus sp.*, whereas (d,e,f) were microscopic images of fungi species on spoiled injera.

first sporulation was observed in the first injera (open to air) and the fingerprint area (the injera was touched with a finger). Similar reports show that *Aspergillus niger, Penicillium sp.* and *Rhizopus sp.* were found to be liable for injera spoilage. Among these, *Penicillium* and *Rhizopus* are more dominant between 16 °C and 20 °C, whereas *Aspergillus* is more dominant between 25 °C and 32 °C (Ashagrie & Abate 2012). Hassen, Mukisa & Kurabachew (2018) determined the effects of benzoic acid (0.1%), sodium benzoate (0.1%) and potassium sorbate (0.2%) and a 1:1:1 blend of the three (0.2%) on injera shelf life, and they confirmed that chemical preservatives (0.1% benzoic acids, 0.2% potassium sorbate, 0.1% sodium benzoate and 0.2% of the three preservatives) have the capacity to the extent the shelf-life of injera up to 10 days at room temperature. Additionally, the authors reported that benzoates and benzoic acid are the most effective in the preservation of the injera (Dash *et al.* 2022). Other researchers also reported the effect of flax seed on the

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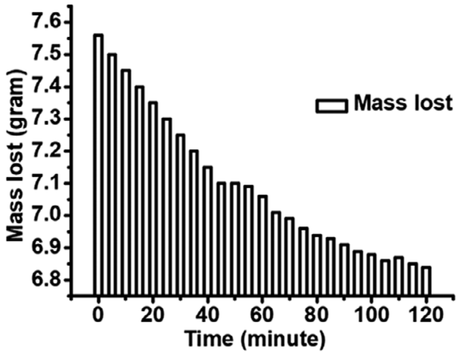

Figure 8. Mass loss of fresh injera (30-cm^2 surface area) at 26.5 °C and 37% of humidity at ambient temperature.

Table 4. Morphological characteristics of the isolates (Figure 7)

Colonial characteristics	Microscopic characteristics	A family of moulds identified
Pale bluish green to dark green	Spherical, smooth green conidia with branched septate hyphae, conidiophores are branched with chains of conidia that look like a brush.	*Penicillium*
A densely packed conidia reverse of the plant is florescent yellow on potato dextrose agar	Yellowish brown smooth conidiophores, rough globose conidiospores, biseriate and phialides.	*Aspergillus*
Fast-growing, large fluffy white milky colonies; cottony mycelia which later turns black as culture gets old	Aseptate hyphae with uptight sporangiophore connected by stolon and rhizoids, sporangiophore develops in clusters above the nodes, dark pear-shaped sporangium on hemispherical columella bears sporangiospores.	*Rhizopus*

injera shelf life from 2 to 6 days, yeast-mould (2.27–3.93 log CFU/g) and total aerobic plate counts (not detected to 3.77 log CFU/g) were reduced to 9% flax seed substitution and increased the control injera (Girma, Bultosa & Bussa 2013).

3.7. Effect of temperature and relative humidity on the growth rate of injera moulds

A digital incubator (model: NB0380B1A09001) was used to obtain temperature and humidity thermodynamic stability points to extend the shelf life of the stored injera. During the measurement, one parameter remains constant and the other variable and the growth rate for each mould species is (−) no growth, (+) moderate mould growth, (++) heavy mould growth and (+++) extreme mould growth.

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Table 5. Effect of temperature on mould growth at constant humidity (85%)

	Temperature ranges (°C)										
Types of moulds	0	5	10	15	20	25	30	35	40	45	50
Aspergillus sp.	−	−	−	−	−	−	+	+++	+++	++	−
Penicillium sp.	−	−	−	−	−	+	++	+++	+	−	−
Rhizopus sp.	−	−	−	−	−	−	+	+++	++	−	−

Table 6. Effect of humidity on the growth of mould on injera at 25 °C

Types of moulds	Relative humidity (RH) (%)									
	5	15	25	35	45	55	65	75	85	95
Aspergillus sp.	−	−	−	−	−	−	−	−	−	+
Penicillium sp.	−	−	−	−	−	−	−	−	+	+
Rhizopus sp.	−	−	−	−	−	−	−	−	−	+

The mould growth and results on IA media after 5 days are summarised in Tables 5 and 6.

From Table 5, the optimal temperature for all types of mould growth on the injera surface was 30 °C–40 °C. Since microbial growth occurs in the temperature range between −8 °C and 100 °C and is accomplished by an enzymatic reaction (for every 10 °C increase in temperature), the catalytic rate of the enzyme doubles and is halved by decreasing the temperature. *Aspergillus sp.* and related moulds generally grow faster and are more resistant to high temperatures and low water activity than *Penicillium sp.* and *Rhizopus sp.*; this tends to dominate spoilage in warmer climates. A report shows that *Aspergillus* produce mycotoxins: aflatoxins, ochratoxin, territrems and cyclopiazonic acid. These spoil a wide variety of food and non-food items (paper, leather etc.), but are probably best known for the spoilage of grains, dried beans, peanuts, tree nuts and some spices (Pérez-Lavalle *et al.* 2020). Therefore, microorganisms, both individually and in groups, grow over a very wide temperature range and it is recommended to select an appropriate temperature for storing different types of foods. Overall, important microorganisms in food are classified into three groups based on their growing temperature. The optimum temperature and growth temperature range are as follows: (1) thermophiles (grows at relatively high temperature), optimum temperature 55 °C, range 45 °C–70 °C; (2) mesophiles (grows at ambient temperature), optimum temperature 35 °C, range 10 °C–45 °C and (3) psychrophiles (growing at low temperatures), optimum temperature 15 °C, range −5 °C–20 °C, respectively, and therefore this data was correlated with our result. However, the microbial cells die when food is exposed to temperatures above the maximum and minimum growth temperatures (Lorenzo *et al.* 2018). Furthermore, decreased fungal activity at low temperatures may correspond to decreased nutrient utilisation, as fungi utilise colonised substrates more slowly. Mould contamination also plays a lesser role in cooler highland

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regions than in warmer lowland regions. Because of the large elevation differences in Ethiopia, the predominant mould-rotting injera varies from cold to hot regions of the country (Tyson & Fullerton 2004).

The RH of the storage environment for both water activity in the food and microbial growth on the surface of the injera. When food is stored in an environment with low water activity and high RH, moisture moves from the gas phase to the food, and the food absorbs water until equilibrium is reached. Similarly, foods with high water activity lose water when placed in an environment with low RH. Table 6 shows that even at humidity below 85%, no mould growth was found on the surface of the injera, whereas slight mould growth was observed above 85%. Therefore, this indicates that the injera can be stored at room temperature with less than 85% humidity. However, at ambient temperature (27.6 °C) with low RH (37%) during the experimental period, injera can be stored without spoilage, but with high water evaporation (mass loss), as shown in Figure 8, this indicates injera becoming dry. In summary, the results presented in Tables 5 and 6 demonstrate that it is possible to extend the shelf life of injera by controlling temperature and humidity. In this case, the best temperature range for growing the three fungi was 30 °C–40 °C with an RH of 85% or higher. Therefore, a designed ECC that has the most thermodynamically stable temperature and RH for improving the shelf life of injera is less than 85% at 20 °C–25 °C, with nearly 90% of the sensory evaluators listed in Table 8.

3.8. The pH and shelf life of injera

Microbial growth and metabolism are affected by pH (Lund *et al.* 2020), and some foods are characterised by an inherent acid taste. Others owe their acidity or pH to the action of certain microorganisms.

The pH of freshly prepared injera is 3.454 at 27.5 °C. After 4 days of storage inside and outside the ECC, the pH is 3.452 and 3.043, respectively. This indicates that the pH varies slightly at ambient temperature, but remains nearly constant inside the ECC (Table 7). This can be caused by fungal growth on the surface of the injera, and as the temperature increases, molecular vibrations in the solution increase and ionise to form H^+ ions. More H^+ ions lead to more acidic behaviour. Therefore, the acidity of a product can have important effects on its microbial ecology and the rate and nature of spoilage (Tewari & Abdullah 2015). The shelf life

Table 7. The pH value of injera was stored inside and outside the ECC for 5 consecutive days

No. of days	The pH of outside ECC	The pH of inside ECC
1	3.454	3.452
2	3.448	3.452
3	3.380	3.452
4	3.260	3.453
5	3.043	3.452

Abbreviation: ECC, evaporative cooler clay.

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Table 8. An average storage time on sensory evaluation of injera stored inside and outside the designed ECC

	Overall acceptance of injera storage in:	
Days of storage	Outside ECC	Inside ECC
2	7.47	8.47
4	6.69	8.63
6	ND	8.77
8	ND	8.54
10	ND	8.37
12	ND	ND
14	ND	ND

Abbreviation: ECC, evaporative cooler clay.

of injera was 3–4 days outside ECC and 9–10 days inside ECC at temperatures of 21.54 °C–23.79 °C and RH of 78.87%–83.47%.

3.9. Water consumption and sensorial quality

As shown in Figure 3 of the designed ECC, the water tanker circulates 2 L of water per week in the cooling system, maintaining moderate temperature and humidity in the ranges of 21.54 °C–23.79 °C and 78.87%–83.47%, respectively. The sensor quality results are also summarised in Table 8.

Considering overall acceptance, the average sensor scores were 8.41 and 7.08, respectively. This shows that the texture and smoothness of the injera stored inside ECC are better than those stored outside ECC. In terms of correlation with other parameters were used this study such as DBT, cold air temperature (CAT), WBT, percentage of cooling efficiency (CE%), percentage of RH of the ambient (RHOA %), percentage of RH of the ECC (RHOEC%), surrounding temperature and cooler temperature (CT) was shown in Table 9. CT was positively correlated with DBT ($r = 0.693$), CAT ($r = 1.000$), WBT ($r = 0.791$) and RHOA% ($r = 0.271$), but negatively correlated with CE% ($r = -0.412$) and RHOEC% ($r = -0.393$), respectively.

Moreover, Table 10 shows the storage temperature, RH and shelf life of several types of fruits and vegetables.

4. Conclusions

In some developing countries like Ethiopia, the high costs associated with the development of cold storage or controlled air storage are an urgent issue. The evaporative cooling chamber designed by mosseb style was an excellent system that provides an efficient and economical means of lowering the temperature inside the cooling chamber and increasing RH, which has the effect of extending the shelf life of injera up to 9 days in Bahir Dar city, Ethiopia; this is essential to keep the injera fresh and edible. Appropriate cooling storage technology is, therefore, required in

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Table 9. Pearson correlation coefficient matrix between variables

Variable	DBT	CAT	WBT	CE%	RHOA%	RHOEC%	ST	CT
DBT	1							
CAT	0.693[a]	1						
WBT	0.339	0.791[b]	1					
CE%	−0.003	−0.412	−0.009	1				
RHOA%	−0.297	0.271	0.341	−0.589	1			
RHOEC%	−0.526	−0.393	−0.489	−0.442	0.468	1		
ST	1.000[b]	0.693[a]	0.339	−0.003	−0.297	−0.526	1	
CT	0.693[a]	1.000[b]	0.791[b]	−0.412	0.271	−0.393	0.693[a]	1

Abbreviations: CAT, cold air temperature; CE%, percentage of cooling efficiency; CT, cooler temperature; DBT, dry-bulb temperature; RHOA%, percentage of relative humidity of the ambient; RHOEC%, percentage of relative humidity of the evaporative cooler chamber; ST, surrounding temperature; WBT, wet-bulb temperature.
[a]Correlation is significant at the 0.05 level (two-tailed).
[b]Correlation is significant at the 0.01 level (two-tailed).

Table 10. Comparison studies of evaporative cooler chamber for temperature, relative humidity (RH) and shelf life of fruits, vegetables and injera

Commodity	Storage temperature (°C)	RH (%)	Shelf life	References
Asparagus 95	0–2	95	2–3 weeks	You *et al.* (2021)
Beans (green)	5–7	90–95	7–10 days	
Carrot	0	90–95	2–5 months	
Cabbage	0	90–95	3–6 weeks	
Onion (dry)	0	65–70	1–8 months	
Tomatoes (green)	12–20	85–90	1–3 weeks	
Potatoes (white)	5–10	93	2–5 months	
Tomatoes (ripe)	7–10	85–90	4–7 days	
Injera	20–25	85	9 days	This work

Ethiopia for fresh injera storage in remote and inaccessible areas, to reduce losses. It requires no special skill to operate and, therefore, is most suitable for the rural application. In this study, a low-cost, low-energy, environmentally friendly cool chamber derived from locally available materials, which utilises the principles of an ECS, was, therefore, developed in response to this problem. This cooling chamber was able to maintain the maximum average daily ambient temperature from 28.98 °C to 22.90 °C and increase the RH of the inflow air in the storage chamber from 28.78% to 80.94%, depending on the season. The ECS was found to be effective and is recommended for use by rural farmers, households and injera processing factories; this might help to enhance the shelf life of injera thermodynamically especially in hot and less humid areas by controlling the temperature and humidity,

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but further study is required to increase the shelf life of injera by using solar fans and desiccators.

Glossary

ECCC	Evaporative Cooling Clay Chamber
ECS	Evaporative Cooling System
IA	Injera Agar
pH	Potential of Hydrogen
RH	Relative Humidity
T_{db}	Dry-Bulb Temperature
T_s	The Temperature of Cold Air
T_w	Wet-Bulb Temperature

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Author contribution

A.N.B. designed and supervised the project, discussed all the results and wrote the manuscript. G.A.B. conducted plant experiments to develop material conditions. Both authors analysed experiments to evaluate material properties.

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Competing interest

The authors declare that they have no competing financial interests or personal relationships that they believe influenced the work described in this paper.

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Appendix A. The raised questions and respondents' answers

Questions	Respondents in Number	Respondents in %
What is your first and common choice of food?	A. Injera = 44	88
	B. Bread = 4	8
	C. Others = 2	4
What materials are you using for the storage mechanism of injera?	A. Mosseb made of grass = 47	94
	B. Plastic container = 2	4
	C. Iron container = 1	2
	D. Others = 0	0
How many days would store injera stay on the shelf (materials that you used) without spoilage?	A. 1–2 = 0	0
	B. 2–3 = 43	86
	C. 3–4 = 7	14
	D. 4–5 = 0	0
	E. >5 = 0	0
What was your alternative mechanism for the preservation of injera?	A. Drying (physical method) = 6	12
	B. Chemical method = 0	0
	C. No storage mechanism = 33	66
	D. Others = 11	22
What was the frequency of making injera per month?	A. 1–3 = 0	0
	B. 4–6 = 31	62
	C. 7–9 = 19	38
	D. >10 = 0	0
How many kilogrammes of injera did you lose due to spoilage per month?	A. <5 = 23	46
	B. 5–10 = 21	42
	C. 10–15 = 6	12
	D. >15 = 0	0
In which season the spoilage of injera becomes very high?	A. Winter = 3	6
	B. Summer = 11	22
	C. Spring = 27	54
	D. Autumn = 9	18
What was the approximate monthly cost (in Ethiopian birr) that you lost due to spoilage of injera?	A. <50 = 21	42
	B. 50–100 = 12	24
	C. 100–200 = 11	22
	D. >200 = 0	0

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Questions	Respondents in Number	Respondents in %
How much money (in Ethiopian birr) do you pay monthly only for fuel (electric) that required heating the stove ('metad')?	A. <10 = 3	6
	B. 10–20 = 18	36
	C. 20–30 = 16	32
	D. 30–40 = 11	22
	E. >50 = 2	4
How many minutes would be taken for the process to make the first injera?	A. <10 = 6	12
	B. 10–20 = 24	48
	C. 20–30 = 17	34
	D. >30 = 3	6

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