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Comparison of the efficiency of solar-powered prototype vapour compression cooler with evaporative charcoal cooler in maintaining quality of French beans

[1*]OGUMO E O., [1]KUNYANGA CN., KIMENJU J., OKOTH M W

[1]Department of Food Science, Nutrition and Technology, University of Nairobi, Kenya
[2]Department of Plant Science and Crop Protection, University of Nairobi, Kenya

***Corresponding Author**: eogumo@gmail.com

Abstract

The quality and shelf life of French beans is affected by the time of harvesting and storage period. Cooling immediately after harvesting is important. Use of solar evaporative cooling system is suitable for use in rural areas with no power grid connections. This study compared evaporative charcoal cooler and the solar cooling systems on improving the quality and shelf life of French beans. The prototype was made using mathematical modeling equations and was powered by solar power while the evaporative charcoal cooler was made from iron sheets with charcoal walls. Freshly harvested French beans were stored under the two cooling systems. Weight and temperature of the stored produce was checked hourly. At the end of the day, produce was packed into modified atmosphere packaging (MAP) bags and stored for 7 days in cold room. After seven days, oxygen and carbon dioxide levels were measured using Bridge gas analyzer. The results show significant differences in weight loss between produce stored in evaporative charcoal shed and solar cooler prototype with those stored in evaporative charcoal cooler having 5% weight reduction while those solar coolers having 3% weight loss. Higher accumulation of CO2 was realized in the evaporative charcoal cooler than in solar-powered cooler. The solar-powered cooler-maintained weight, reduced temperature of produce and maintained the balance between carbon dioxide and oxygen thus reduction in metabolic activities. This enhanced the shelf life and quality of the produce.

Keywords: *Charcoal cooling method; French beans; temperature; solar cooler; weight loss*

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Introduction

French beans (*Phaseolus vulgaris L*) are very important export crop in Kenya. It accounts for nearly 60% of the total vegetable exports from Kenya (USAID-KHCP, 2013). French bean production has created a lot of employment and income opportunities for smallholder farmers in Kenya, those who would otherwise be unable to invest in capital-heavy crop production. Kenyan farmers have mastered the production of French beans for nearly forty years now and Kenya French beans are widely known in the export market for its quality and great taste. Even though Kenya remains the main exporter for French beans from Africa into the European Union and United Kingdom, other African countries are slowly getting into the French bean production and taking up some of the market share.

The global retailers are slowly getting concerned about environmental conservation and greenhouse gas (GHG) emission, and as a result, the distance travelled by the fresh produce has been a major area of focus, which has resulted into more preference to sea freights. This move has encouraged the development of French bean in the West and North Africa region in countries like Senegal, Ghana, Egypt, and Morocco. Unlike Kenya which entirely depends on air freight for export of French beans into the European and United Kingdom market destinations, these West and Northern African countries have access to sea freight options, and this makes them more cost competitive (Capineri *et al*., 2006).

Large supermarket chains have dominated the fresh produce export business from Kenya to the UK. This has resulted in increased flexible contractual arrangements along fresh produce supply chain. Consequently, this has resulted in increased scrutiny to ensure safety and quality of the fresh produce. The contractual arrangements ensure that the risks are transferred to other actors and agencies along the supply chain. Multiple retailers enforce regulations to ensure the quality requirements for United Kingdom are met and they satisfy the new consumer demands. Leading marketing chains link the growers with high quality horticultural produce in Kenyan with the UK retailers. The first chain has independent retailers who are supplied by wholesale markets while the subsequent chain is comprises of large supermarket multiples. The supermarket chains depend on agreements and contracts that outline product specifications and how the products are handled in order to guarantee quality and safety. The supermarket chains account for almost 70% of the exports to the UK (Laguerre *et al*., 2013).

Strict controls along the supply chain are a prerequisite to ensure high quality French beans get to the consumers. The perishability of the produce demands an operative and constant cold chain. Consumers' demand for high quality produce has been the major driving force behind this. Cold storage has increasingly been viewed as an integral part of supply chain. It is recommended that French beans are stored at 7 – 8 ^{0}C if storage is to be done for about two weeks (Snowdon and Ahmed, 1981). Research indicates existing development of cold chains with sophisticated machinery which requires huge investments. Previous researches indicate that there are over 200,000 small scale growers of French beans in Kenya who supply the export market (USAID-KHCP, 2013).

Small-scale mechanical cooling technologies have been developed for storage of fresh horticultural produce. According to Winrock, (2009), on average, such technologies cost about $7000 for a ton of refrigeration capacity. However, majority of small-scale growers do not have adequate resources for these huge investments in the sophisticated machinery. They are therefore forced to go through intermediaries or for them to group themselves to increase their economies of scale. In addition, the long distances between the production and packing sites have been a great challenge as some produce may take up-to 30 hours to be delivered to the packing sites for it to get proper conventional cooling in the pack-house cold-room. These coupled with inadequate infrastructure to run commercial refrigeration systems in the rural areas aggravate produce quality loss and reduction in shelf-life (Anon, 2011).

Over the last two years research conducted in Kenya have contributed to many small-scale farmers adopting the solar power enabled and low-cost cooling chambers that rely on renewable energy. Charcoal cooler is one of the innovations that is locally made for adoption by small holder farmers to ensure yield while awaiting collection by the exporters remain in good quality. Various designs for small-scale evaporative-cooling storage systems have been developed for fresh produce (Kitinoja and Thompson, 2010). The storage system has space sandwiched between walls that are filled with charcoal and is slowly humidified with water. Alternatively, the whole chamber may be enclosed with a moist rush mat which can maintain an inside temperature between12 and 16 °C, which is almost 10 °C lower than the ambient temperature. Many researchers have reported that majority of small-scale farmers either store their produce under the tree, in farm structures with no adequate supply of humidity and temperature controls while others do not have any cooling structures but rely on other farmers with cooling systems (Olayemi et al., 2010). This study was intended to explore the possibility of using renewable energy to develop a simple solar cooling system that can be used to address the challenges of cold chain management of French beans to maintain quality and shelf stability.

French bean requires great handling to maintain high quality therefore speed and efficiency of operations are required during production, transportation, storage or any other process (Okello *et al.,* 2007). Fresh produce like French beans continue to metabolize after harvesting during storage, packing, distribution and marketing. During this period, respiration, enzymatic breakdown, pathogenic contamination and degradation may cause breakdown of nutrients into simpler compounds that reduce the quality and quantity of the produce. Infection by bacteria or fungi results in molds, rots, and the fruits appear wilted, shriveled, and darkened because of water loss (Warriner, 2005). In conducive environments, these microbes contaminate fresh produce causing faster deterioration. Potential sources of contamination can be at the pre-harvest stage, and these include soil, irrigation water, manure, and even domestic animals (Buyukunal *et al*., 2015).

To maintain quality, a cold chain system to control temperature at all points of the supply chain is important. Temperature and humidity levels are extremely important and alterations in the desired temperature can have devastating effects on the stability and shelf life of the produce (Basediya *et al*., 2013). Evaporative charcoal cooler storage systems are not only inappropriate but are also becoming unsustainable due to heavy reliance on charcoal and grass which have great impacts on environmental degradation. Solar powered cooling systems can achieve favorable temperatures for storage of vegetables. The economic performance of solar powered cooling systems is better than that of charcoal cooling system, however, the equipment cost of solar cooling system is higher than that of charcoal. Again, the tropical environment provides adequate amount of solar energy through the season that can be utilized for energy. Therefore, it is essential to devise a storage system that is solar powered to ensure an average farmer can afford to store produce with minimum energy input.

Materials and Methods

Development of a solar powered cooler prototype and Evaporative charcoal cooler

The design process of the cooler involved the use of data collected on the existing coolers, in order to overcome the gaps identified in coolers currently used by farmers. The prototype used existing mathematical modeling equations that have been developed for solar cooling of meat and milk products to check on feasibility of similar systems for French beans. The prototype of size 2m by 1.2m by 1m was developed based on Hottel-Vhillier (H-V) model developed for meat and milk products. The fabricated solar cooler's rectangular walls were made of 100mm insulated Expanded Polystyrene (EPS), sandwiched by 10mm Medium Density Fiber (MDF) board outer shell and 5mm confute polyethylene sheeting interior.

Extra energy required to cool was estimated with the Fourier heat conduction equation and appropriate photovoltaics used to generate this energy. Photovoltaics were fitted on the roof to convert solar power to electrical energy. Solar energy was used to run cooling system in the store during the day with excess energy being used to freeze water into ice. A temperature sensor was centrally placed in the cooler to record temperature fluctuations. A fan, with power of *Ef* (kW) was also fitted at the corner to maintain air is circulation. The system was also equipped with sensors that were connected to the control system. Using the Spick platform, data on conditions within the cooler could be configured and transmitted through the internet and send notifications to the user.

The system was designed to maintain produce temperature between 6^{o}C to 10^{o}C and maintain CO_2 levels below 3%. It consisted of two chambers, the cold chamber and the produce chamber. The cooling cycle comprises of the following components: compressor, condenser (heat exchanger), radiator with water/ice (phase change material in a radiator, refrigerant (R600), evaporator plate and fan. Within the two chambers two cooling processes occur, the first process begins in the cold chamber where water contained in a heat exchanger/radiator is used as the phase change material to "store negative thermal energy as ice and maintained between -1°C and 4°C via thermostatic control. The cold chamber control consists of digital thermostat mounted externally but with internal probe which monitors the temperatures between -1°C and 4°C by turning off the compressor when temperature falls below -1°C and again turns it on when temperature goes above 4°C to start extracting energy from the cold chamber.

In the cold chamber, there is water which is the phase change material held in a radiator. Water provides cooling even without solar power. In addition, two lead acid gel battery were installed to run the system even beyond the solar availability. The water is cooled below 0°C by typical refrigeration cycle that employs a solar-powered DC compressor. The refrigeration cycle is a closed-loop cycle that consists of a compressor, a condenser, an evaporator plate and a refrigerant (R600) which is an organic, biodegradable and Chlorofluorocarbon (CFC) free thereby making it compliant with current International Standards. The compressor compresses the refrigerant which is liquifies at -40°C and at pressure of 3.5 bar, thereby pushing the refrigerant through the evaporator thereby forcing it to liquify and drops the temperature to - 40°C.

The refrigerant then absorbs thermal energy from the cold chamber to the condenser/heat exchanger which is mounted outside the chamber. The thermal energy is released to the exterior of the chamber and exhaled with the help of the fans. It is through the above process that the cols chamber gets cooled. The aim of the above process is to keep the phase change material (water) below its freezing point.

The main chamber is set to maintain the produce temperature between 6°C and 10°C, it achieves this through a closed-loop control system that includes a DC powered fan blowing cool air from the cold chamber into the produce chamber. The control within this loop is achieved a second digital thermostat and a digital temperature probe mounted in the produce chamber. The temperature range in the produce chamber is set at 6°C to 10°C. When temperature rises beyond 10°C the thermostat switches on the fan which blows the cold air from the cold chamber to the storage chamber to maintain the temperatures within the range of 6°C to 10°C. This is achieved by a DC fan installed between the walls of cold and produce chamber that blows cold air from the cold chamber into the produce chamber.

Using the Baird and Gaffney (1976) equation, size, shape, thermal property of the product, the convective coefficient, and flow rate of the cooling medium was used to design the chamber. The system is equipped with sensors which collects data and sends it to the control system which in turn actuates solenoids and fans it also sends the data to things Spick platform where the data is analyzed in graphical format and can be configured to send email and short message notification to the user.

When the produce stored in the cooler respires, it emits CO_2. The storage chamber is equipped with an air quality sensor. When the CO_2 level rises beyond 30000ppm the control system powers the solenoid which opens an air valve, a fan located next to the solenoid blows the CO_2 out of the chamber this ensures that the CO_2 levels in the chamber are maintained within the range of 400ppm-30000ppm into (0.01-0.03%) thereby reducing the rate of breakdown of the produce.

The evaporative charcoal cooler was made of iron sheets, with some provisions for ventilation provided by use of chicken mesh wires at halfway the sides of the wall. Charcoal was stuck in between chicken mesh to create a wall of 3m in height, giving rise to the name charcoal cooler.

Harvesting of French bean

The French bean samples were harvested at 10am, 12pm and 2pm, sorted and weighed into 500g portions. Proper care was taken to avoid mechanical injury in order to reduce deterioration. The 500g packs were subjected to two different storage conditions, evaporative charcoal cooler while the other was stored in the developed solar-powered cooler system. The samples were labeled as per the harvesting time and storage condition, FS for field shade and SC for solar powered cooler. The harvested French beans samples were kept in the various storage conditions until 4pm then transported using cool boxes to the pack house with a cold room for further processing.

The following day, the 500g portions were processed into 2 packs of 200g each, packed into a modified atmosphere packaging (MAP) bag to ensure the product remained fresh for the longest possible duration. The packed products were stored in cold rooms at temperature between 4-8°C. Quality parameters such as product weight and temperature were monitored and from each batch a sample was taken for gas analysis. The performance and efficiency of the field shed, and the solar cooler were evaluated.

Determination of physiological weight loss

The weight loss was measured using a digital weighing scale (Constant 14192-1F model, China). The samples were weighed on the first hour of storage and then hourly until the 3pm in the afternoon. The change in weight was expressed as percentage weight loss using the following formula; Percentage weight loss = $\frac{W1-W2}{W1} \times 100$ Where W_1 = Initial weight of sample (g); W_2 = Weight of sample after storage (kg).

Determination of cooling efficiency and measurement of temperature

Cooling efficiency was determined by dividing the observed temperature decrease by the maximum potential temperature decrease. The cooling efficiency was calculated using the formula by Verploegen *et al.*, (2019).

$$\text{Cooling efficiency} = \frac{\text{Ambient Temperature} - \text{Interior Temperature}}{\text{Ambient Temperature} - \text{wet bulb Temperature}}$$

The interior temperature was determined by the reading of the temperature sensor out at the center of the cooler. A thermometer with the bulb wrapped in wet muslin was used to measure wet bulb temperature.

Data analysis

The data on weight loss, product temperature and cooling efficiency was subjected to analysis of variance using GenStat statistical package version 15 and the least significant difference was used for separation of treatment means at 5% significance level. The weight loss in relation to cooling time was also observed

Results

Comparison between physiological weight of French beans stored in solar cooler and Evaporative charcoal cooler

The differences in physiological weight loss was significant ($P \leq 0.05$) between the storage methods and the storage times (Table 1). The weight loss of French beans in evaporative charcoal cooler storage was higher compared to those that were stored in solar cooler and it changed from 500g to 476g after six hours of storage. In the solar powered cooler, there was insignificant reduction in physiological weight from the initial 500g to 490g after five hours of storage.

Table 1. Physiological weight of French beans harvested and stored at 10.00am in evaporative charcoal cooler and solar powered cooler

Time	Evaporative Charcoal cooler (g)	Change in weight (%)	Solar Cooler (g)	Change in weight (%)
10.00am	500.0^{a}	0.0^{g}	500.0^{a}	0.0^{g}
11.00am	497.4^{ab}	0.5^{fg}	496.8^{ab}	0.6^{fg}
12.00pm	491.4^{cd}	1.7^{de}	495.0^{bc}	1.0^{ef}
1.00pm	485.8^{ef}	2.8^{bc}	492.0^{cd}	1.6^{de}
2.00pm	481.3^{f}	3.8^{b}	488.8^{ef}	2.2^{cd}
3.00pm	476.0^{g}	4.8^{a}	490.2^{de}	1.6^{cd}
Mean	488.7	2.27	493.8	1.24
LSD (P≤0.05)	2.8	0.56	2.8	0.56
CV (%)	0.4	25.1	0.4	25.1

Means within column followed by different letters are significantly different based on Fishers Protected LSD test ($p \leq 0.05$).

Effects of different cooling systems on the produce temperatures

The difference in temperature of produce significantly ($p \leq 0.05$) differed between the cooling methods and storage time (Figure 1). Under evaporative charcoal cooler, the temperature of produce was lower in the morning hours and increased in the afternoon while the temperature of the produce in solar powered cooling system slightly increased from the initial 15.6°C to 15.9°C after 5 hours of storage. In evaporative charcoal cooler, French beans stored for 5 hours recorded high temperature levels (17.8°C) compared to those that had been stored in solar cooler system (15.9°C). In the evaporative charcoal cooler, the produce temperature increased between the 12 and 2pm ranging from 17.4°C to 17.8°C. However, in solar powered cooling system the produce temperature remained low ranging from 15.6°C to15.9°C.

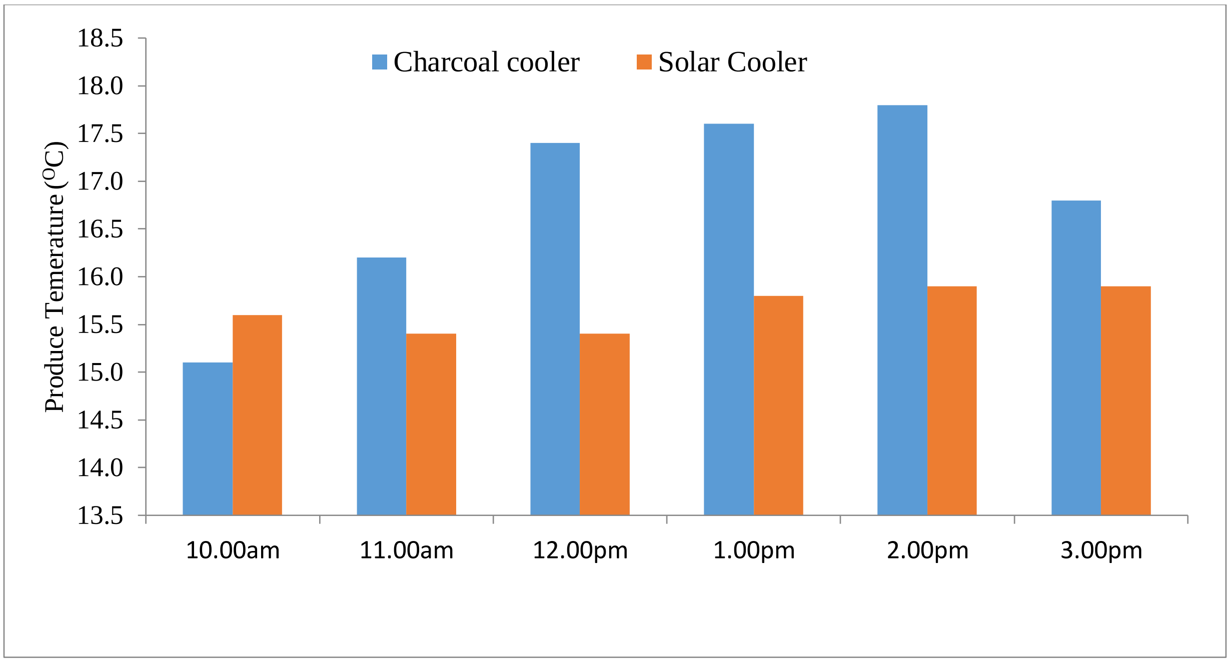

Figure 1. Effect of charcoal cooling and solar powered prototype cooling on the temperature of French beans harvested and stored from 10.00am

Effect of cooling system and harvesting time on cooling efficiency

For the produce harvested at 10am in the morning, the mean efficiency of cooling for produce stored in evaporative charcoal cooler was 0.36 while that of solar powered cooling system was 0.68 (Table 2). Consequently, the effectiveness and efficiency of the solar powered cooling system was 47% more than the evaporative charcoal cooler. For the duration of the experiment, for produce harvested at noon, the mean degree of cooling was 0.4 and 0.95 for evaporative charcoal cooler and solar powered cooler respectively. Consequently, the effectiveness of the solar powered cooling system was 58% more than the evaporative charcoal cooler.

Effect of cooling systems on concentration of gaseous production

Figure 2 shows the reduction in concentration of oxygen and an increase in concentration of carbon dioxide over a period of five hours causing a gradient. At first, the amount of carbon dioxide released was not as much but continued to increase with increase in storage time, at the same time the amount of oxygen within the chambers reduced to low levels after six hours of storage period. Thus, inside the cooling chambers, the oxygen amount reduced while that of carbon dioxide increased.

Table 2. The efficiency of the different method of cooling systems on produce harvested at 10am

Harvesting time- 10am Storage time	Charcoal cooler method	Solar Cooler method
10.00am	0.50[cd]	0.85[a]
11.00am	0.12[e]	0.78[ab]
12.00pm	0.25[de]	0.58[abc]
1.00pm	0.23[de]	0.72[ab]
2.00pm	0.89[a]	0.55[bc]
3.00pm	0.15[e]	0.58[cd]
Mean	0.36	0.68
LSD (P≤0.05)	0.198	0.198
CV (%)	30.0	30.0

Means within column followed by different letters are significantly different based on Fishers Protected LSD test (p ≤0.05)

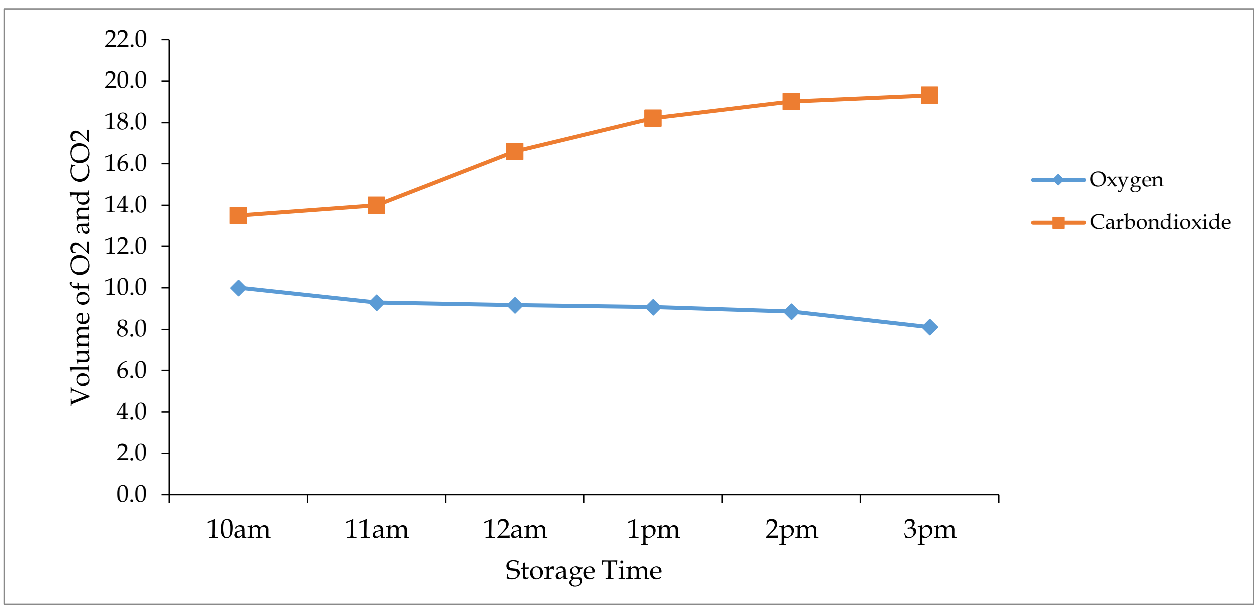

Figure 2. Changes in CO_2 and O_2 concentrations (ppm) with time within the evaporative charcoal cooler

Discussion

The study has demonstrated that solar-powered cooler was more efficient in maintaining quality and freshness of French beans than the evaporative charcoal method. Produce stored in solar-powered cooler had reduced weight loss and maintained the quality of French beans. The results are concomitant with those reported by

Molla *et al*, (2016) where mangoes increased shelf life and quality. Produce under evaporative charcoal storage method had incurred higher amount of weight loss compared to those under solar power cooler.

The study also revealed that solar-powered cooler was more efficient than evaporative charcoal cooler in maintaining produce temperature during storage. The increase in temperature could be because of physiological factors such as respiration that results in heat emission thus high temperature (Sanchez-Mata, 2003). Vegetables are mostly harvested under ambient temperature of a range of 25 to 35^{o}C and under these conditions the respiration rate is high and therefore there is increase in temperature (Basediya *et al*., 2013). Temperature and relative humidity are aspects that must be considered when handling perishable produce such as French beans. Solar cooling system becomes an efficient and cost-effective means of temperature reduction and at the same time increasing the relative humidity in storage (Susan and Durward, 1995). This is because vegetables such as French beans require high relative humidity of about 95 percent and low temperature which is achievable through the use of solar powered cooling system. From the results, solar powered cooling system had on average higher cooling efficiency when compared to evaporative charcoal cooler method

French bean samples stored in evaporative charcoal cooler accumulated more CO_2 and less oxygen compared with those in solar-powered cooler (Figure 2). The difference in CO_2 accumulation can be attributed to the efficiency of the CO_2 sensors installed in the solar-powered cooler to sense high CO_2 levels. This triggers the fans to expel excess CO_2 from the produce chamber. The oxygen inside the system is consumed by the produce as it respires, and CO_2 is released such that the volume of oxygen reduces and the volume of CO_2 increases. The high amount of CO_2 within the evaporative charcoal cooler indicates rapid respiration process that influences the quality of fresh produce like French beans (Kader and Yehoshua, 2000). The accumulation of CO_2 around the produce causes rapid deterioration by causing bad flavor, internal breakdown, and other abnormal physiological conditions.

The results indicate that solar-powered cooling system maintains and reduces the produce temperature, maintains the equilibrium between carbon dioxide and oxygen, and reduces the respiratory activity of the French beans to the optimum level thereby keeping the produce fresh with prolonged shelf life. Therefore, the technology of solar power cooling system should be adopted for use by smallholder farmers to maintain the quality fresh produce since in the long run the economic performance of solar powered cooling system is cheaper compared to charcoal powered cooling system.

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