Vol. 14(7) pp. 192-200, August 2020
DOI: 10.5897/AJFS2020.1968
Article Number: 10D5A6164541
ISSN: 1996-0794

http://www.academicjournals.org/AJFS

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African Journal of Food Science

Full Length Research Paper

Performance of a fabricated solar-powered vapour compression cooler in maintaining post-harvest quality of French beans in Kenya

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Received 15 May, 2020; Accepted 21 July, 2020

The quality and shelf life of French beans can be affected within hours of harvesting if the produce is not cooled after harvest. Solar-powered cooling systems are suitable for use in rural areas that are not connected to the grid. This study aimed at developing a solar powered cooling system to improve the quality of French beans in smallholder farms in Kenya. Freshly harvested French beans were stored under conventional field shed conditions and a solar-powered prototype cooler, after which weight and temperature were measured at intervals of 2 h and later packed in modified, atmosphere packaging bags. The bags were stored for 7 days in a cold room. Accumulated gas levels of oxygen and CO_2 in the packaging bags were measured at the end of the shelf life. Significant differences ($P \leq 0.05$) in weight loss between produce stored in the conventional shed and those in the solar cooler prototype were observed. The weight of French beans reduced by 5 and 2.8% after 7 h under a conventional field shed and a fabricated solar cooler respectively. The volume of CO_2 and O_2 released from produce stored in a conventional shed and those in a fabricated solar cooler prototype were significantly different ($P \leq 0.05$).

Key words: Conventional cooling method, French beans, temperature, solar cooler, weight loss.

INTRODUCTION

French beans (*Phaseolus vulgaris* L.) require tender care and handling after harvest so as to maintain high quality until the produce gets to the consumer. Speed and efficiency of operations are key during production, transportation and storage (Okello et al., 2007). Deterioration of French beans is very temperature dependent, as an increase in temperature results in increases in metabolic reactions, thereby causing foods to be unfit for consumption due to changes in sensory characteristics and microbial contamination (Rawat, 2015).

Losses after harvest are due to lack of appropriate storage facilities (Kumar and Kalita, 2017). In developing countries, losses as high as 30-40% have been reported due to faults in handling, transportation, storage and marketing have been reported (Atanda et al., 2011).

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Storage losses are mainly due to respiration, evaporation, post-harvest diseases and changes in the chemical composition of the produce (Arah et al., 2016). However, the losses can be reduced by maintaining suitable environmental conditions within the store (Ogumo et al., 2017).

The majority of large exporters has the capacity and is able to meet strict standards. However, small scale and medium sized farmers face a myriad of challenges associated with the implementation of the standards. Optimum temperature and relative humidity control are key to prolonging the storage life and marketable quality of French beans (Basediya et al., 2013). Conventional storage systems such as field-sheds are not only inappropriate but are also becoming unsustainable due to heavy reliance on charcoal and grass which contribute to environmental degradation (Olosunde et al., 2015). Basediya et al. (2013) reported that solar-powered cooling systems maintained a temperature of 21–25°C with 80–90% RH in freshly harvested potatoes. This suggests that it can offer practical solutions to farmers in rural areas. Solar energy is slowly proving to be an alternative source of clean and renewable energy (Zheng et al., 2019).

A cold chain-controlled system is very important in managing the quality of French beans. Freshly harvested French beans have to be cooled immediately to reduce deterioration of quality and loss of weight. French beans require storage temperatures ranging from 5-15ºC (Kitinoja and Thompson, 2010). Any storage below 4-5°C is not ideal, as it may cause chilling injury. Harvested produce continues to respire after harvesting and any delay in cooling the produce will enhance the respiration rate and eventually degradation. Under conventional field conditions, with no refrigerated coolers, storage is normally done in field sheds with no temperature control. At temperatures between 5-10ºC, French beans can be stored for up to 7 days. Generation of electricity contributes to global warming through production of nitrogen dioxide and sulphur dioxide which are both responsible for acid rain, in addition to emissions of carbon dioxide (Gorle et al., 2016). Solar powered cooler systems have a reduced running cost and this is relevant in tropical environments where adequate amounts of solar energy are received throughout the season. Therefore, it is essential to devise a storage system that is solar powered to ensure small scale farmers can afford to store produce with minimum energy input.

MATERIALS AND METHODS

Development of a solar powered cooler prototype

The design was based on the existing coolers so as to overcome the gaps identified in coolers currently used by farmers in Kenya. The prototype was developed based on Hottel-Vhillier (H-V) model that have been developed for solar cooling of meat and milk products.

Design consideration

The cold room rectangular walls were made of 100 mm Expanded Polystyrene (EPS) insulated, sandwiched by 10 mm MDF outer shell and 5 mm confute polyethylene sheeting interior (Figure 1). Extra energy was required to cool the storage chamber 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 for running the cooling system. During the day, excess energy was used to freeze water into ice. A temperature sensor was centrally placed to record temperature fluctuations. A fan, with power of *Ef* (kW) was fitted at the corner to maintain air circulation. Using the Spick platform, data on conditions within the cooler could be configured and transmitted through the internet and notifications would be sent to the user.

Refrigeration operation cycle, temperature and carbon dioxide control

The system was designed to maintain produce temperature between 6 to 10°C and maintain CO_2 levels below 3%. The cold chamber comprises of a compressor, condenser (heat exchanger), radiator with water/ice (phase change material in a radiator, refrigerant (R600), evaporator plate and fan (Figure 2) and the produce chamber. Within the two chambers, two cooling processes occur; the first process begins in the cold chamber. This is where water contained in a heat exchanger/radiator, is used as the phase change material to "store negative thermal energy as ice and is maintained between -1 and 4°C via thermostatic control. The cold chamber control consists of a digital thermostat mounted externally, but with an internal probe. The probe monitors the temperatures between -1 and 4°C by turning off the compressor when the temperature falls below -1°C and again turns it on when the 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 batteries were installed to store energy to run the system when solar energy is unavailable. The water is cooled below 0°C by a 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 organic, biodegradable and Chlorofluorocarbon (CFC) free, thereby making it compliant with current international standards. The compressor compresses the refrigerant, which liquefies at -40°C and at a pressure of 3.5 bar, thereby pushing the refrigerant through the evaporator and forcing it to liquefy and the temperature drops 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 this process that the cold 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 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 with 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 to 10°C. When the temperature rises beyond 10°C the thermostat switches on the fan which blows the cold air from the cold chamber into the storage chamber.

This is achieved by a DC fan installed between the walls of the

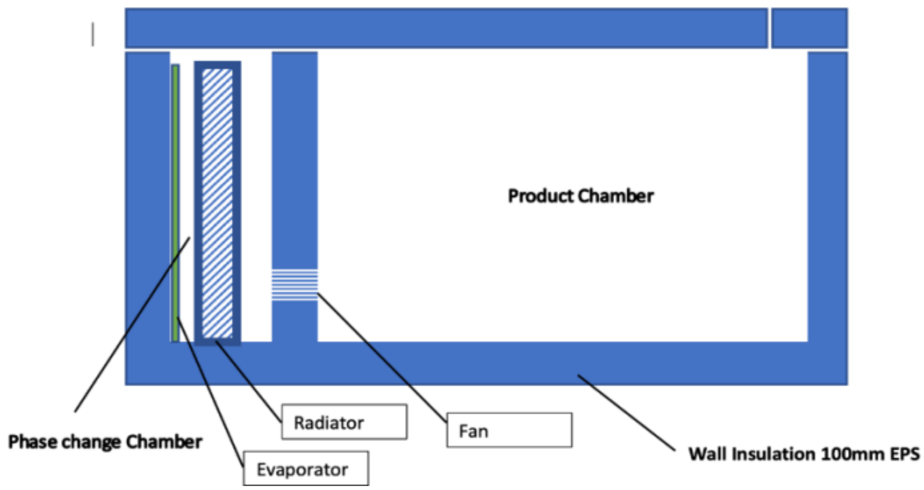

Figure 1. Schematic diagram of the solar cooler.

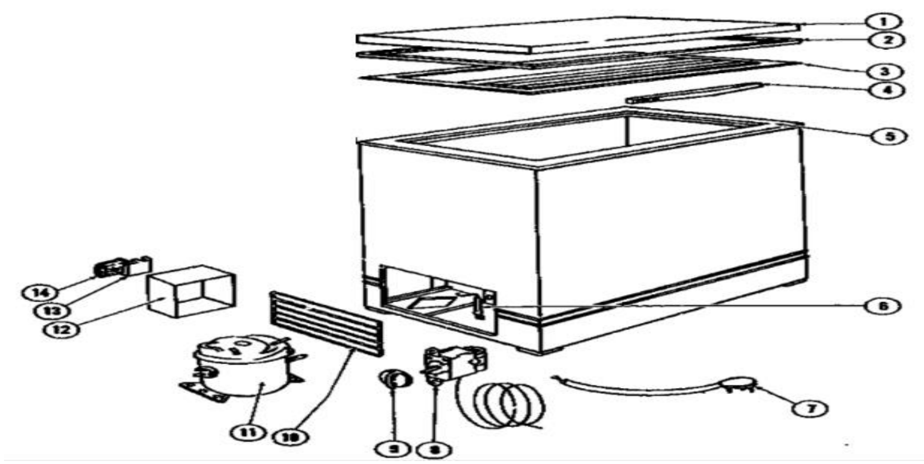

Figure 2. Structural layout of the solar cooler measurements and control system. 1. Lid 100 mm EPS1 insulated; 2. Foam rubber air seal; 3. Evaporator; 4. Sensor Rack; 5. Walls 100 mm Expanded Polystyrene (EPS) insulated sandwiched by 10 mm MDF2 outer shell and 5 mm confute polyethylene sheeting interior; 6. Compressor compartment; 7. 12v DC Power; 8. Plug; 9. External temperature sensor; 10. Dial; 11. Condenser; 12. 24DC Compressor; 13. Danfoss BD50K; 14. 12v DC condenser Fan; 15. Frozen chamber Digital thermostat and compressor controller; 16. Produce chamber digital thermostat and fan controller

cold and produce chamber that blows cold air from the cold chamber into the produce chamber. The system is equipped with sensors, which collect data and send information to the control system. This in turn actuates solenoids and fans that send the data to the spick platform where the data is analyzed in graphical format and can be configured and sent as an email 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 30000 ppm 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 and ensures that the CO_2 levels in the chamber are maintained within the range of 400 - 30000 ppm into (0.01-0.03%) thereby, reducing the rate of breakdown of the produce.

Conventional cooling system

The conventional cooling system was a simple structure with a roof and walls made of iron sheets, with provisions for ventilation provided by use of chicken mesh wires halfway up the sides of the wall. This is the most widely used cooling system by smallholder farmers in Kenya.

Harvesting of French bean

The French bean samples were harvested at different times; 8am, 10am, 12pm and 2pm at a commercial field of beans in, AAA Thika farm and immediately sorted, weighed into 500 g portions and

Table 1. Physiological weight of French beans harvested and stored at 8.00am in conventional and solar powered prototype cooling.

Time of day	Conventional method(g)	Percent change in weight	Solar-powered method(g)	Percent change in weight
8am	500.0[a]	0.0[i]	500.0[a]	0.0[i]
9am	497.6[a]	0.4[h]	497.8[a]	0.4[hi]
10am	495.5[b]	0.9[gh]	497.2[a]	0.6[h]
11am	487.0[c]	2.6[de]	496.2[b]	0.7[gh]
12pm	484.1[c]	3.2[cd]	494.6[b]	1.1[gh]
1pm	481.1[d]	3.7[bc]	492.0[b]	1.6[fg]
2pm	478.4[e]	4.3[ab]	489.0[c]	2.2[ef]
3pm	475.0[e]	4.9[a]	486.8[c]	2.6[de]
Mean	487.4	2.5	494.2	1.2
LSD (P≤0.05)	2.1	0.49	2.1	0.49
CV (%)	0.3	21.5	0.3	21.5

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

labeled as per the harvesting time and storage condition; FS for field shade and SC for solar powered cooler. The harvested French bean samples were kept in the two storage conditions until 4pm. At 4pm, the harvested samples were transported to the pack house within the farm and kept in a cold room at temperatures ranging from 4-8°C. The following day, the 500 g portions were re-packaged into two packs of 200 g each, packed into a modified atmosphere packaging (MAP) bag to ensure that 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 during the seven days shelf life window. On the seventh day, the packed products were analyzed for accumulation of oxygen and carbon dioxide.

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 3pm in the afternoon. The mean weight and the mean change in the weight of the samples were determined with time during the storage period and was expressed as a percentage 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 (g).

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 reading the temperature sensor 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 was subjected to a two way analysis of variance using GenStat statistical package version 15 and the least significant difference was used at 5% significance level.

RESULTS

Physiological weight of French beans stored in solar cooler and conventional cooler

The results of the physiological weight loss for the produce stored under both conventional conditions and the solar powered cooler harvested at 8am is presented in Table 1. A significant difference (P ≤ 0.05) in weight loss at different storage durations in the two storage methods was observed. There was higher physiological weight loss in the conventional storage method, compared to the solar powered cooler and it changed from 500 g to 475 g after eight hours of storage. In the solar powered cooler, there was a small reduction in physiological weight from the initial 500 g to 486.8 g after 7 h of storage. Figure 3 shows weight loss in French beans. Weight loss in French beans stored using the conventional method was observed to be 5% of the original weight at harvesting after 7 h of storage, while only 2.6% of the original weight was lost after 7 h of storage for French beans produce stored in the solar powered cooler.

The differences in physiological weight loss were significant (P ≤ 0.05) for the storage duration in the two storage methods (Figure 3). The weight loss of French beans using the conventional storage method was higher compared to those that were stored in the solar powered cooler and it changed from 500 g to 476 g after 6 h of storage. In the solar powered cooler, there was a small reduction in physiological weight from the initial 500 to 490 g after 5 hof storage.

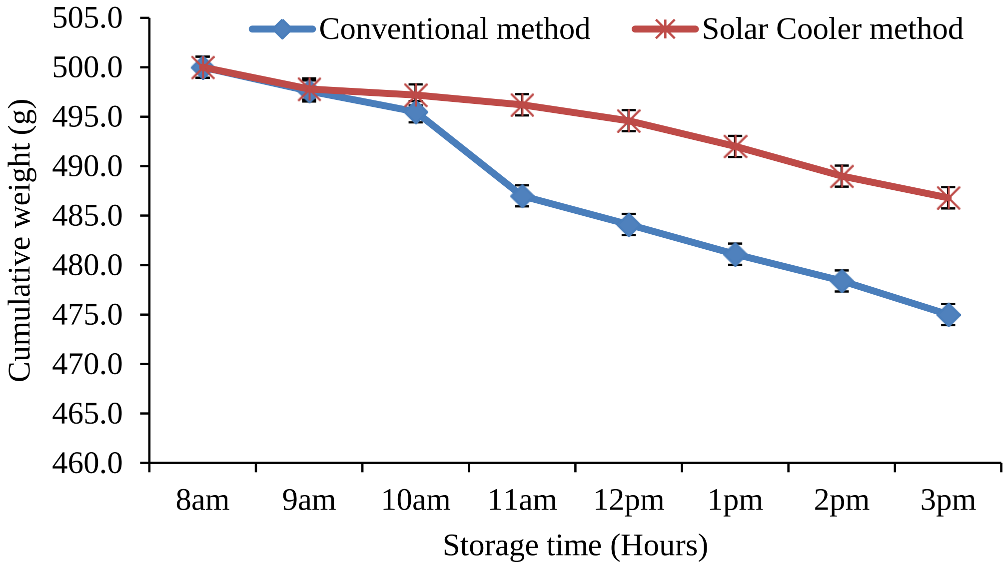

Figure 3. Cumulative weight loss of French beans stored in conventional and solar powered cooler.

Table 2. Physiological weight of French beans stored in conventional and solar powered cooler for produce harvest at 12 noon and 2.00pm.

Time of day	Conventional method (g)	% change in weight	Solar cooler method (g)	% change in weight
12.00pm	500.0[a]	0.0[e]	500.0[a]	0.0[e]
1.00pm	496.2[c]	1.5[c]	498.2[ab]	0.4[de]
2.00pm	487.4[d]	2.5[b]	497.3[b]	0.5[d]
3.00pm	481.4[e]	3.7[a]	495.8[b]	0.8[d]
Mean	490.1	1.9	497.8	0.4
LSD (P≤0.05)	1.5	0.32	1.5	0.32
CV (%)	0.2	20.8	0.2	20.8
Time of day	Conventional method(g)	% change in weight	Solar Cooler method(g)	% change in weight
2.00pm	500.0[a]	0.0[c]	500.0[a]	0.0[c]
3.00pm	496.3[c]	0.7[a]	498.3[b]	0.3[b]
Mean	498.2	0.36	499.2	0.17
LSD (P≤0.05)	0.65	0.12	0.65	0.12
CV (%)	0.1	35.0	0.1	35.0

Values followed by the same letter within the same column are not significantly different between the treatments using Fishers Protected LSD test (P ≤ 0.05).

The results of the physiological weight loss for the produce harvested at noon and at 2pm and stored under both conventional conditions and the solar powered cooler is presented in Table 2. There were significant differences (P≤0.05) between the storage duration in the two storage methods. The weight loss of French beans in the conventional storage method was high compared to those that were stored in the solar powered cooler. For the French beans harvested at 2pm, there was a slight reduction in weight in the two storage methods.

Effects of both cooling systems on the produce temperatures

There was a significant difference in the temperature of produce (p ≤ 0.05) between the storage time in the two cooling methods (Table 3). Under conventional cooling, the temperature of produce was lower in the morning hours and increased in the afternoon, while there were no significant differences in temperature of the produce stored in a fabricated solar-powered cooling system. The

Table 3. Effect of cooling methods on the temperature of French beans harvested and stored at 8am.

Time of day	Conventional cooling (ºC)	Solar-powered cooling(ºC)
8.00am	14.2^{g}	15.6^{cde}
9.00am	14.4^{g}	15.7^{cde}
10.00am	15.1^{f}	15.6^{def}
11.00am	16.2^{c}	15.4^{ef}
12.00pm	17.4^{ab}	15.4^{ef}
1.00pm	17.6^{a}	15.8^{cde}
2.00pm	17.8^{a}	15.9^{cd}
3.00pm	16.8^{b}	15.9^{cd}
Mean	16.2	15.7
LSD (P≤0.05)	0.3	0.3
CV (%)	1.5	1.5

Values followed by the same letter within the same column are not significantly different between the treatments using Fishers Protected LSD test (P ≤ 0.05).

Table 4. Effect of both Conventional and Solar powered cooling systems on the temperature of French beans harvested at 10.00am.

Time of day	Conventional method(ºC)	Solar Cooler method (ºC)
10.00am	17.2^{c}	16.2^{cd}
11.00am	16.4^{c}	16.3^{cd}
12.00pm	17.4^{ab}	16.0^{cd}
1.00pm	18.2^{a}	15.9^{d}
2.00pm	17.7^{a}	15.4^{d}
3.00pm	17.4^{ab}	16.1^{cd}
Mean	17.4	15.9
LSD (P≤0.05)	0.67	0.67
CV (%)	3.1	3.1

Values followed by the same letter within the same column are not significantly different between the treatments using Fishers Protected LSD test (P ≤ 0.05).

produce temperature in the conventional cooler increased by 20% after 7 h of storage. For produce harvested at 10am, there was a significant difference ($p \leq 0.05$) between the storage condition and the storage duration (Table 4). There were significant differences between storage duration and the harvesting time for both the cooling conditions (Table 6). The produce harvested at 12pm and at 2pm had high temperature levels of 18.7 and 18.3°C respectively, however, the temperature levels continued to decline with the number of hours of cooling. In the conventional cooling system, the temperature levels declined by about 7% after 4 h while the temperature levels for produce in the fabricated solar-powered cooling system reduced by about 18%.

Figure 4 shows the relationship between the product temperature and storage duration. The temperature for the produce stored in a conventional shed increased by about 28% from 14 to 18°C after 7 h of storage. The produce stored in a solar powered cooler had an average product temperature of 15.7°C.

Effect of cooling system and harvesting time on cooling efficiency

For the produce harvested at 10 am, the mean degree of cooling for the produce in a conventional cooling system was 0.36 while the solar powered cooling system was 0.68 (Table 5). Consequently, the effectiveness and efficiency of the fabricated solar powered cooling system was 47% more than the conventional cooling method. For the duration of the experiment, for the produce harvested at noon, the mean degree of cooling was 0.4 and 0.95 for both the conventional and solar powered cooler respectively. Consequently, the effectiveness of the solar powered cooling system was 58% more than the conventional cooling method.

Effect of cooling systems on gaseous production

The level of gas released from the produce is presented

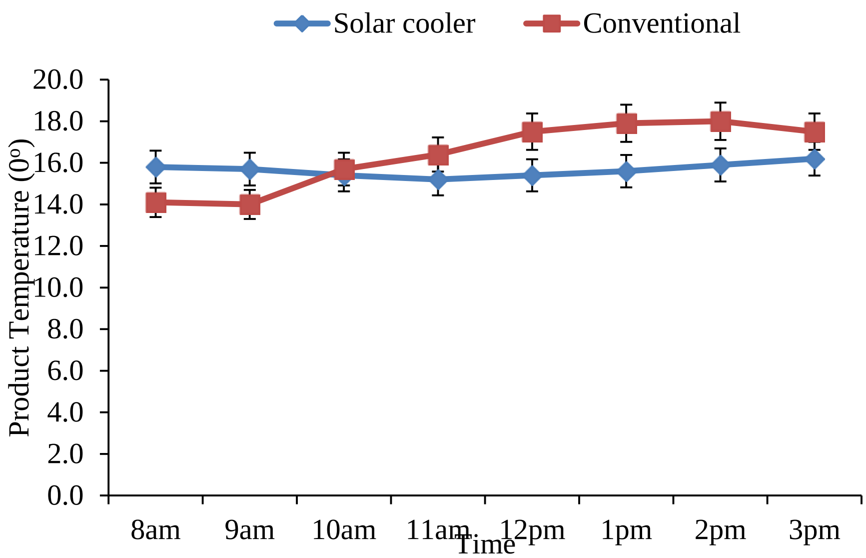

Figure 4. Product temperature loss of French beans stored in conventional and solar powered coolers.

Table 5. The efficiency of the different method of cooling systems on produce harvested at 10am.

Harvesting time- 10am	Conventional method	Solar cooler method
Storage time		
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 ($P \leq 0.05$)	0.198	0.198
CV (%)	30.0	30.0

Values followed by the same letter within the same column are not significantly different between the treatments using Fishers Protected LSD test ($P \leq 0.05$).

in Table 6. There was a significant difference ($p \leq 0.05$) in the volume of carbon dioxide released between the two cooling systems. Sample 5A, which was harvested at 8am and stored until 3pm accumulated more CO_2 compared to the rest in the conventional cooling system. There were significant differences ($p \leq 0.05$) in the volume of oxygen released by the produce in the conventional cooling system. French samples harvested at 8am, 10am and 12 noon and stored in the conventional shed accumulated more oxygen levels compared with other samples.

Figure 5 shows the reduction in concentration of oxygen and an increase in concentration of carbon dioxide over a period of eight hours causing a gradient. Initially, the amount of CO_2 released is less, but continues to increase with storage time at the same time. The amount of oxygen within the chambers reduces to lower levels after an eight-hour storage period. Thus, inside the cooling chambers, the oxygen amount reduces while the amount of carbon dioxide increases.

DISCUSSION

The study has demonstrated that a fabricated solar-powered cooler was more efficient in maintaining quality and freshness of French beans than the conventional field shed. Produce stored in a fabricated solar-powered

Table 6. Gaseous levels from French beans stored in solar powered and conventional cooling systems.

Sample	Conventional method (Units)		Solar cooler method (Units)	
	Carbon dioxide	Oxygen	Carbon dioxide	Oxygen
1A	13.4[b]	9.9[a]	10.2[a]	10.4[a]
2A	12.6[b]	9.2[a]	9.5[a]	10.7[a]
3A	14.6[ab]	9.3[a]	10.6[a]	9.6[a]
4A	16.7[a]	7.2[b]	10.2[a]	10.6[a]
5A	17.3[a]	7.8[b]	10.5[a]	9.8[a]
Mean	14.9	8.7	10.2	10.2
LSD (P≤0.05)	3.3	1.3	3.3	1.3
CV (%)	18.2	8.8	18.2	8.8

Values followed by the same letter within the same column are not significantly different between the treatments using Fishers Protected LSD test (P ≤ 0.05).

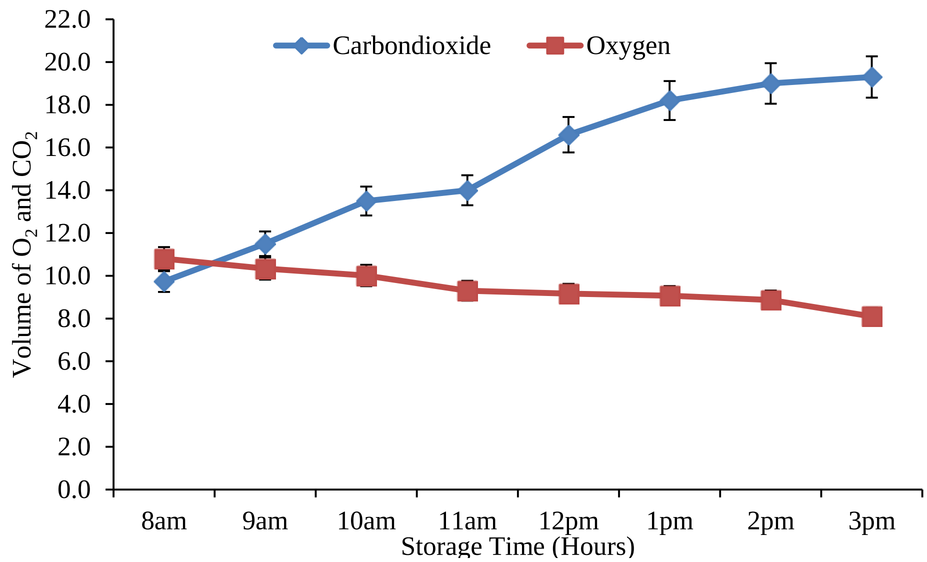

Figure 5. Changes in CO_2 and O_2 concentrations (ppm) with time within the conventional cooling chambers.

cooler had less weight loss, only losing 2.8% weight, compared with a 5% weight loss for those stored in a conventional field shed. Similar results were reported by Dirpan et al. (2018) where the loss in weight of mangoes was lower (3.1%) in cold storage when compared to 14.5% in storage at ambient conditions.

The physiological loss of weight for French beans is a result of both the evaporation of water and respiratory losses (Olosunde et al., 2015). Water evapotranspiration depends on the atmospheric temperature and relative humidity within the store (Dzivama, 2000). Olosunde et al. (2015) stated that low temperature reduces respiratory activity, while high relative humidity reduces the rate of evaporation from the produce. At harvesting, the produce contains field heat and respiratory heat meaning that, in the initial stage there is field heat within the produce in both the conventional and the solar powered cooler. The study has revealed that the fabricated solar-powered cooler was more efficient than the conventional field shed in maintaining produce temperature during storage. French beans stored under conventional cooling had increases in temperature of 18% in 4 h compared to an increase of 7% for the produce stored in the fabricated solar-powered cooler. The increase in temperature could be a result of physiological factors such as respiration that results in heat emission that increases temperature (Sanchez-Mata, 2003).

French bean samples stored in conventional cooling systems accumulated more CO_2 and less oxygen compared with those in a solar-powered cooler. The difference in CO_2 accumulation can be attributed to the efficiency of the CO_2 sensors installed in the solar-powered cooling system to sense high CO_2 levels and trigger the fans to expel excess CO_2 from the produce chamber. The produce consumes the oxygen inside the system as it respires and CO_2 is released, the volume of oxygen decreases while the volume of CO_2 increases. The high amount of CO_2 within the conventional cooler is an indication of a 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 of the produce by causing a bad flavour, internal breakdown, and other abnormal physiological conditions (Silva, 2008). According to Kader et al. (1989) exposure of a commodity to high levels of CO_2 above the limits can results in increased anaerobic respiration, which in turn causes buildup of ethanol and acetaldehyde that causes off-flavors. Vegetables such as French beans have high respiration rates and an increase in the amount of CO_2 released may have an effect on the shelf life of the produce. Conventional storage systems are characterized by high temperature conditions that lead to faster respiration; an increase in temperature of 10°C doubles the process of respiration (Silva, 2008).

Conclusion

A fabricated solar-powered prototype cooler maintains and reduces the produce temperature, maintains the balance between CO_2 and oxygen and reduces the metabolic activity of the French beans within the optimum level, thereby keeping the produce fresh for longer.

ACKNOWLEDGEMENTS

The authors sincerely appreciate the voluntary support of Mrs. Louise Foxton, Mrs. Sue Homer and Mrs. Bronagh Owako for taking their time to proof-read this manuscript. The authors are grateful to the management of AAA Growers for allowing the study to be conducted in their farm and packhouse in Thika, Kenya. In addition, they also thank Mbili Mbebe, Faith Nkirote, and Nickson Mashati for their support during this study. The authors also acknowledge the support of Engineer Fredrick Jura for his support in designing and fabrication, turning the vision into a reality.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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