Performance Evaluation of a Free-Energy Cooling Chamber for Reducing Post-Harvest Tomato Losses in Tropical Island Conditions: Evidence from Unguja, Zanzibar

Said Suleiman Bakari (Corresponding author)
School of Social and Natural Science, the State University of Zanzibar
P.O. BOX 146, Zanzibar, Tanzania.
Tel: 255-24-2230724/2233337 E-mail: said.bakari@suza.ac.tz
Kombo Ali Kombo
School of Social and Natural Science, the State University of Zanzibar
P.O. BOX 146, Zanzibar, Tanzania.
Tel: 255-24-2230724/2233337 E-mail: kkombo204@gmail.com
Jamal Kussaga
Department of Food Technology, Nutrition and Consumer Sciences, Sokoine University of Agriculture,
P.O. BOX 3006, Morogoro, Tanzania.
Tel: Tel 255 23 260 3511 E-mail: kussaga@sua.ac.tz
Rashid Suleiman
Department of Food Technology, Nutrition and Consumer Sciences, Sokoine University of Agriculture,
P.O. BOX 3006, Morogoro, Tanzania.
Tel: Tel 255 23 260 3511 E-mail: rashid@sua.ac.tz

The research is financed by Tanzania Commission for Science and Technology (COSTECH, Project Number CST / NFAST- RG/CRG/2018.012 (Sponsoring information)

Abstract

This study evaluated the effectiveness of Free Energy Cooling Chambers (FECC) in preserving postharvest tomatoes on Unguja Island, Zanzibar. The FECC created a cooler and more humid microclimate, reducing internal temperature by more than 8°C and increasing relative humidity by over 25% compared to ambient storage conditions.

Tomatoes stored in the FECC exhibited a shelf life of up to 15 days, significantly longer than those kept under ambient conditions. Weight loss was limited to less than 10% in the FECC, compared to more than 25% under non-cooled storage. In addition, tomatoes stored in the FECC retained higher nutritional quality, including lycopene and vitamin C content, while total soluble solids increased more gradually, indicating slower ripening. Vitamin C content in FECC-stored tomatoes reached a peak of 20 mg/100 g, whereas under ambient storage it declined to 13.5 mg/100 g by day 12, highlighting the importance of cool and humid conditions in preserving antioxidants.

Overall, the findings demonstrate that FECC technology is a low-cost, energy-independent solution capable of reducing postharvest losses and maintaining the biochemical integrity of tomatoes in resource-limited settings, thereby benefiting smallholder farmers.

Keywords: Free Energy Cooling Chamber (FECC); Postharvest preservation; Tomato quality; Vitamin C and lycopene retention; Tropical Island

DOI: 10.7176/JNSR/17-1-04

Publication date: February 28th 2025

1. Introduction

Horticultural produce is very perishable and has high post-harvest loss (PHL), and in many cases in developing countries, this involves more than half of the produce. These losses are especially acute in the horticultural value chains based on smallholders when scarce resources, proper infrastructure, and the lack of knowledge about proper post-harvest management practices are the dominant issues (Kamaldeen O. S et al., 2022; Samuel et al., 2023). Poor handling, ineffective storage, poor transportation, poor packaging, and poor retail practices are the major causes of PHL. This decreases the income of the farmers, increases poverty, and decreases access to micronutrient-rich foods, leading to malnutrition (Springael et al., 2018; Wan et al., 2018; Berck et al., 2018). Post-harvest losses are present in every phase of the supply chain and are depicted by quantitative, qualitative, and economic losses (Lufu et al., 2025; Longdong et al., 2025; Yu et al., 2024). Quantitative losses are physical decreases in weight or bulk, and qualitative losses are biological losses due to microbial spoilage, mechanical damage, respiration, and water stress. Losses in the economic sector are caused by a lower market itself because of diminishing quality and quantity (Rubagumya et al., 2023; Gouda & Duarte-Sierra, 2024; Strecker et al., 2022). Despite the ease of quantifying losses, qualitative and economic losses can have more implications on food security and livelihoods. Therefore, reducing PHL through cultivar selection, handling, and the use of suitable storage technologies is commonly recommended (Caruana et al., 2023; Defraeye et al., 2023; Yeneneh & Walle, 2025). Fresh fruits and vegetables are still metabolically active, and deterioration increases when they are kept at high temperatures. Low-temperature and high-humidity storage is thus needed to retard physiological activities and lengthen shelf life (Aked, 2002; Bhowmik & Dris, 2004; Nicolaï et al., 2003). In most tropical and rural areas, such as Zanzibar, however, there is no ready access to electricity and traditional cold storage. A low-cost alternative that can be viable, especially for smallholder farmers and traders, is passive or free-energy cooling technologies. Evaporative cooling systems would be capable of lowering storage temperatures within the ambient temperature range and keeping the humidity favorable, which would extend shelf life without the use of electricity (Umeohia & Olapade, 2024; Zainalabidin et al., 2019; Yang et al., 2019). Tomato (Solanum lycopersicum) is one of the most popular and economically significant vegetables in the world, which can be appreciated based on its nutritional benefits, such as lycopene, vitamin C, and β-carotene. Tomatoes are sensitive to deterioration within a relatively short time after harvest, despite their importance, even under the climatic conditions of the tropical islands, like in Zanzibar, where losses are up to 50% because of the inappropriate storage facilities (Almeida et al., 2024; Kedir et al., 2025; Liu et al., 2025; Kunwar et al., 2024). Mechanical refrigeration, as efficient as it is, is still out of reach for most of the small-scale producers due to high capital and operational expenses. An alternative that is a sustainable, low-cost, and non-polluting alternative is Free Energy Cooling Chambers (FECCs), which are founded on the principles of evaporative cooling. Past research shows that these systems may enhance the shelf life and preserve the quality of produce significantly (Yimer & Sahu, 2014; Patel et al., 2022a; Verploegen et al., 2018; Sipho & Tilahun, 2020). Although evaporative cooling technologies have been extensively studied, most studies have been focused on isolated quality attributes or non-island conditions. Consequently, observed evidence on the integrated performance of Free Energy Cooling Chambers (FECCs) under tropical island environments remains limited. Although evaporative cooling technologies vary in body of research work, there is a paucity of empirical studies on their performance in tropical island environments with high humidity, salty air, and limited infrastructure. Also, limited research has been conducted to concurrently assess physiological and nutritional quality properties of a variety of tomato variants under field-based Free Energy Cooling Chamber (FECC) conditions (Cuce, 2017; Ruangsuwan et al., 2025; Sibanda & Workneh, 2020). Consequently, the extent to which FECC technology can be applicable and robust in agro-ecological settings like Zanzibar, which are islands, has not been adequately reported. Moreover, the study indicates that spite in social media is emerging as a prevalent issue of concern, making it predominantly an emotional phenomenon. This research aimed at assessing the effectiveness of a Free Energy Cooling Chamber (FECC) to decrease the postharvest losses of tomatoes at tropical island conditions in Zanzibar. In particular, the research evaluated the effects of storage temperature and relative humidity, physiological weight loss, shelf life, and such specific quality parameters as pH, total soluble solids, vitamin C, and lycopene under FECC and ambient conditions (Pradhan & Srijaya, 2022; Nkolisa et al., 2018; Mugwaneza et al., 2024).

2. Materials and Methods

2.1 Study Area

The fieldwork was carried out on Zanzibar, a tropical island between **6°08′–6°28′ S** and **39°05′–39°23′ E** on Unguja Island, Tanzania. It has a humid tropical climate with an average temperature of **26 to 33°C** and a relative humidity of 70% or more, which encourages faster post-harvest degradation of fresh horticultural products. Free Energy Cooling Chambers were built and tested in Nyamanzi (West B District) and Bungi and Dunga (Central District), which are locations that reflect smallholder tomato production systems having relatively low access to conventional cold storage. These locations offer an appropriate experimentation area for the evaluation of the performance of evaporative cooling technology in the tropical island environment.

2.2 Construction and Operating Principle of the Evaporative Cooling Chamber

Three evaporative cooling chambers (ECCs) were made using locally available materials. The chambers were made of two walls of burnt bricks, the space between one wall and the other filled with clean lake sand. The rooms were painted with dried coconut leaves so that direct sunrays were minimized, with protection against rain. To facilitate evaporative cooling, the sand-filled cavity was maintained constantly wet with frequent sprinkling of water. The temperature of the air in the environment picked up as the water evaporated off the sand, which decreased the internal chamber temperature and enhanced the relative humidity. (Dadhich et al., 2008; Birhanu & Belay, 2023; Patel et al., 2022b; Ibiyeye et al., 2022a). Cooling of this kind is based on the thermodynamic principle of latent heat of vaporization. As dry air of the atmosphere moves over wet surfaces, which may include moistened bricks or sand, the water undergoes evaporation, absorbs heat from the air, and creates cool and moist air indoors. (Ibiyeye et al., 2022b; Alam et al., 2017; Abdullah et al., 2023). This microclimate lowers the rates of respiration and microbial activity in stored fruits and vegetables and thereby increases the shelf life (Figure 1).

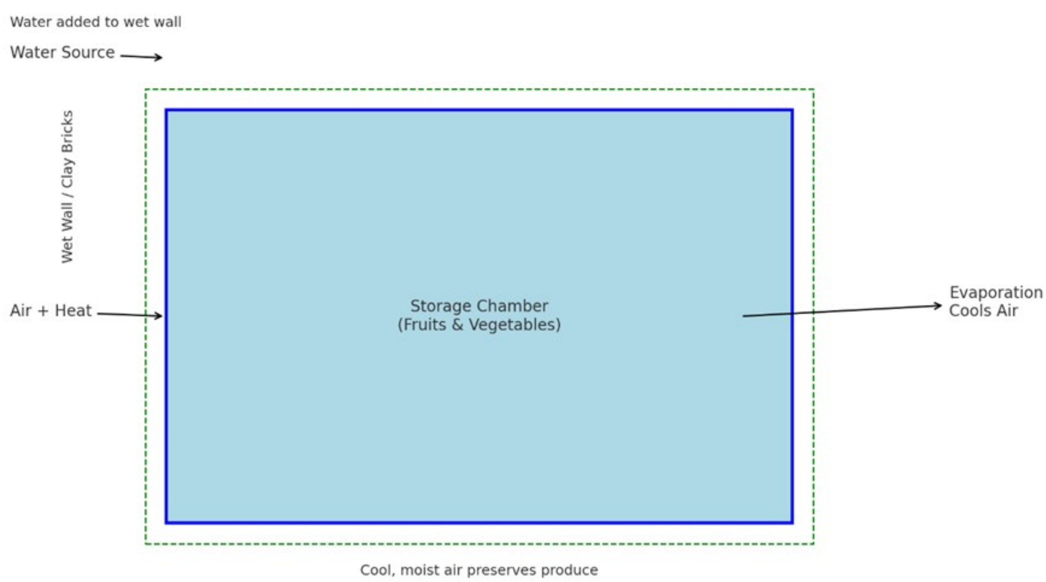

Figure 1. The concept diagram for evaporative cooling system for small-scale produce storages.

2.3 Sampling Design and Laboratory Analysis

Three tomato types were tested, namely, Roma (egg-shaped), Roma (round-shaped), and Cherry. Each of two bulk samples (5 kg) of Roma (egg-shaped) and Roma (round-shaped) tomatoes was obtained from local farmers at similar stages of maturity and sorted by similarity and lack of visible damage. The samples were documented in the Free Evaporative Cooling Chamber (FECC) and allocated to two storage conditions, which included FECC and ambient conditions. The experiment on storage took place within 15 days. In the analyzed parameters, 0.05 kg sub-samples in each of the treatments were collected after 3 days (day 0, day 3, day 6, day 9, day 12, and day 15) and put in plastic bags. In cases where delivery by lab took more than 1 h, the samples were kept in refrigeration bags at 10-15°C and transported in labelled ice bags to the laboratory at Sokoine University of Agriculture (SUA), Morogoro, where they were analyzed. Laboratory tests were done to determine the performance of the cooling chambers and cold storage facilities. This involved spoilage analysis, identification of qualitative and quantitative losses, temperature and relative humidity monitoring, quality analysis of stored fresh fruits and vegetables (FFV), finding out the maximum storage, and analysis of power utility in cold storage facilities. Parameters that are analyzed with methods summarized in Table 1.

Table 1. Summary of analyzed parameters and methodologies used

Parameter	Methodology
Temperature/RH	Thermohygrometer (daily reading)
Weight Loss (%)	[(Initial – Final weight) / Initial] × 100
pH	Digital pH meter
Total Soluble Solids	Hand refractometer (°Brix)
Lycopene	Spectrophotometry at 503 nm
Ascorbic Acid (Vitamin C)	Titration using 2,6-Dichlorophenol-indophenol

2.4 Post-Harvest Loss (PHL) Analysis

The post-harvest loss (PHL) was calculated according to Boiteau & Pingali, (2022) and was reported as the percentage weight loss (Thole et al., 2020; Tiwari et al., 2020). The weight of tomato samples was measured at the beginning of the storage (W1) and at the end of every storage period (W2). PHL was calculated as:

$$\text{PHW}(\%) = \frac{W_1 - W_2}{W_1} \times 100\% \quad (1)$$

where W_1 is the initial fruit weight (g), and W_2 is the final fruit weight (g).

2.5 Measurement of Relative Humidity and Cooling Efficiency

The air humidity was measured with the help of a psychrometer according to the temperature difference between dry-bulb and wet-bulb thermometers. Plots were made at the inside and the outside of the evaporative cooling chambers (ECCs) from 12:00 to 14:00 h. The cooling efficiency (e) of the ECCs was obtained based on (Haile et al. 2024 and Niu et al., (2020) According to Equation (2):

$$\eta = \frac{(Tdb - Ts)}{(Tdb - Tw)} x100\% \quad (2)$$

Where Tdb = dry bulb temperature in °C, Tw = wet bulb temperature in °C, Ts = Storage temperature in °C

2.6 Data Analysis

The statistical analysis was done on all the experimental data in order to test the impacts of storage conditions and storage time on tomato quality characteristics. Before the analysis, the data were tested with regard to normality and homogeneity of variances. The comparison of mean values was performed with the help of the analysis of variance (ANOVA), which was conducted with the help of SPSS version 20. In cases where there were notable differences, separation of means was done at the level of confidence ($p < 0.05$) of 95%. Trends in temperature, relative humidity, physiological weight loss, and quality parameters in storage were shown after summarizing the trends using descriptive statistics. Microsoft Excel 2010 was used to create graphical illustrations of the changes over time under FECC and ambient storage conditions. Findings are given in the form of means, and statistical significance was established using the effects of treatment.

3. Results and Discussion

3.1 Temperature and Relative Humidity

Relative humidity and temperature have a great impact on the shelf life of perishable produce. The Free Energy Cooling Chamber (FECC) was at a lower temperature (22-23°C) and higher relative humidity (>90%) than the ambient temperature and humidity (exceeding 30°C and 55-60%, respectively) (Fig. 2). That is why this beneficial microclimate decreased the speed of tomato metabolism and mitigated the dryness during the 15 days of storage, which testifies to the effectiveness of the FECC in maintaining tomato quality. (Paull, 1999; Zuo et al., 2025 and Jawed Ahmad Rizawi et al., 2024).

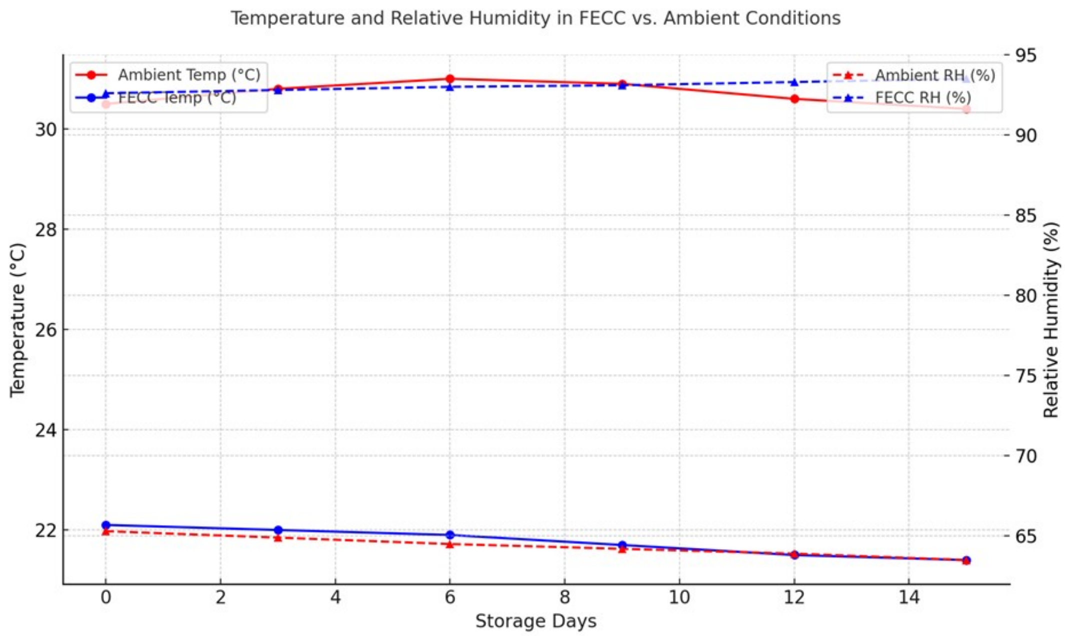

Figure 2: Temperature and relative humidity trends in FECC and ambient storage over 15 days, showing the FECC's effectiveness in maintaining lower temperatures and higher humidity compared to ambient conditions.

3.2 Weight Loss

The FECC-stored tomatoes showed reduced physiological loss of weight, which attained 4.7% after 15 days as opposed to 10% in the ambient environment. Due to the high relative humidity in the FECC, moisture evaporation was reduced, which is in line with the results of (Han et al., 2023); (Xie et al., 2025).

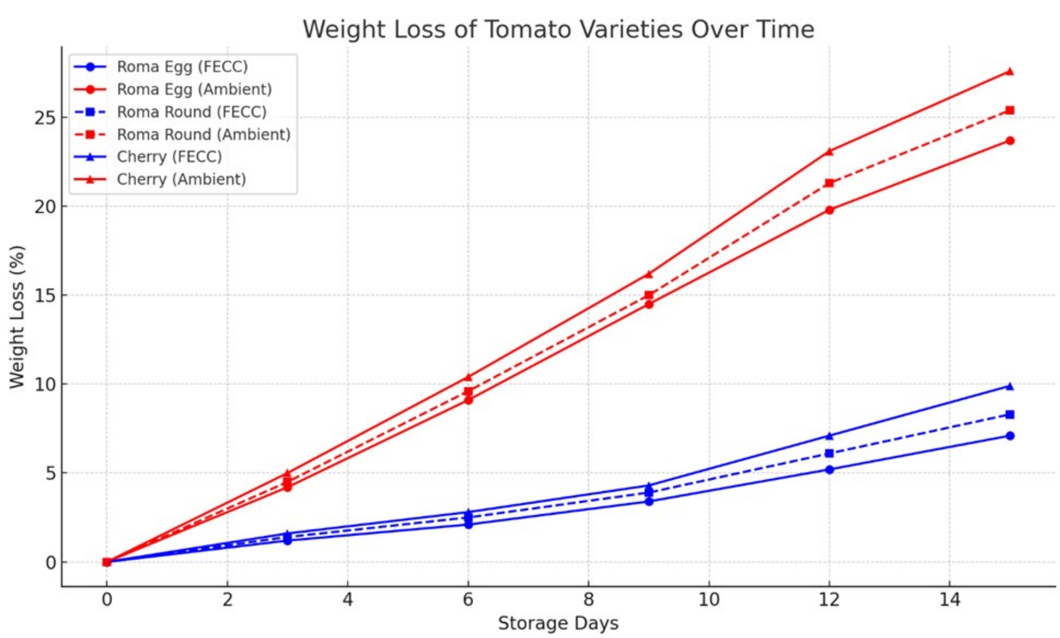

Figure 3: Percentage weight loss of different tomato varieties over 15 days. Tomatoes stored in FECC show significantly lower weight loss than those under ambient conditions, highlighting the chamber's effectiveness in reducing physiological water loss.

3.3 pH

Ripening and biochemical degradation also raised the pH of tomatoes stored either under FECC or ambient temperatures. The increase was, however, lower in FECC (between 4.1 and 4.5) than in ambient storage (between 4.1 and 5.3), which was because the cooler and more humid conditions were more conducive to the preservation of acidity. (Aftab et al., 2025; Karakas & Fernie, 2025).

3.4 Total Soluble Solids (°Brix)

Total soluble solids (°Brix) continued to increase in both storing conditions, which indicated ripening, and the sugar content (°Brix) of FECC-stored tomatoes steadily increased (3.0 to 4.2) and ambient-stored samples sharply (5.4), usually suggesting an increased rate of overripening or loss of moisture.

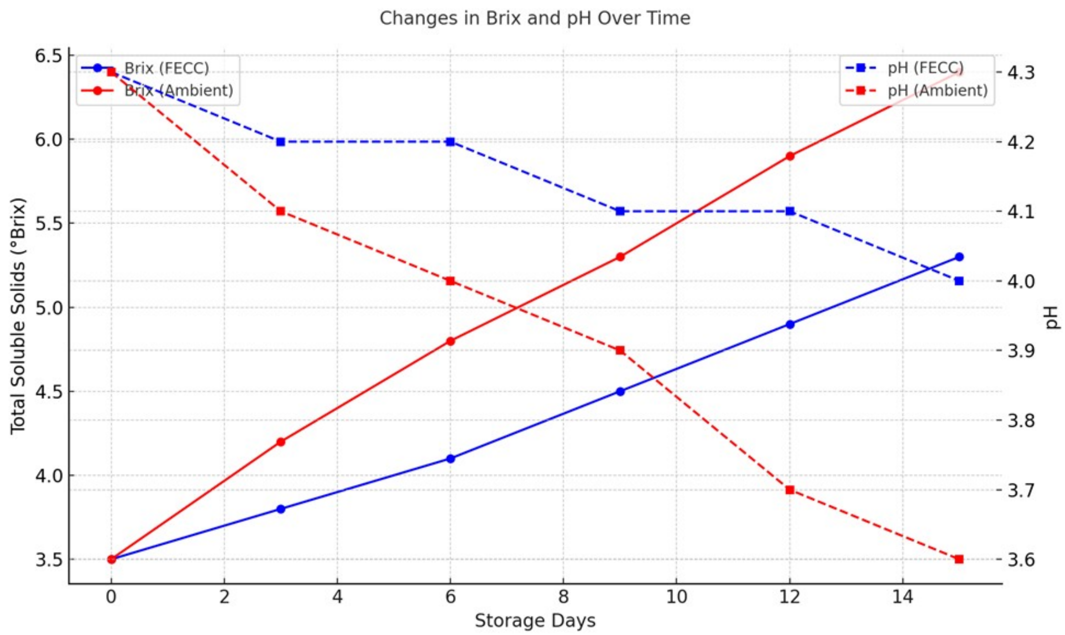

Figure 4: Changes in total soluble solids (°Brix) and pH of tomatoes over time, showing slower increases in °Brix and reduced pH decline in FECC compared to ambient storage, indicating better quality retention.

3.5 Lycopene

The tomatoes that were stored in FECC had a progressive rise in their lycopene content, with 2.0 to 6.1 mg/100 g, which is a sign of healthy ripening. Conversely, tomatoes stored in the ambient had reached their peak earlier and then dropped after the 12th day, a fact that demonstrates their damage by high temperatures and oxidative stress. (Fiza et al., 2022).

3.6 Vitamin C (Ascorbic Acid)

There was also an increase in the content of vitamin C during the ripening and a decrease during ambient storage after day 12. Tomatoes kept in Free Energy Cooling Chambers (FECC) showed a higher level, with a peak of 20 mg/100 g, as opposed to a reduction of tomatoes to 13.5mg/100g under ambient conditions. The above trends indicate the role of cool, damp storage conditions in the preservation of antioxidants. It is also possible to explain the improved quality of tomatoes during FECC storage due to the combined effect of lower temperature and higher relative humidity that, in turn inhibit the rate of respiration, transpiration, and enzymatic oxidation. Reduced thermal stress retards metabolic responses to ripening and senescence, and reduced humidity reduces moisture loss and accompanying physiological stress. The conditions inhibit the breakdown of important nutritional substances like ascorbic acid and lycopene, slow the build-up of sugars, and stabilize fruit acid. Accordingly, FECC storage builds a condition that has a positive microenvironment, extending the shelf life without degrading the physical or biochemical qualities of tomatoes under the conditions of the tropical island (Chen et al., 2020, and Alenazi et al., 2020).

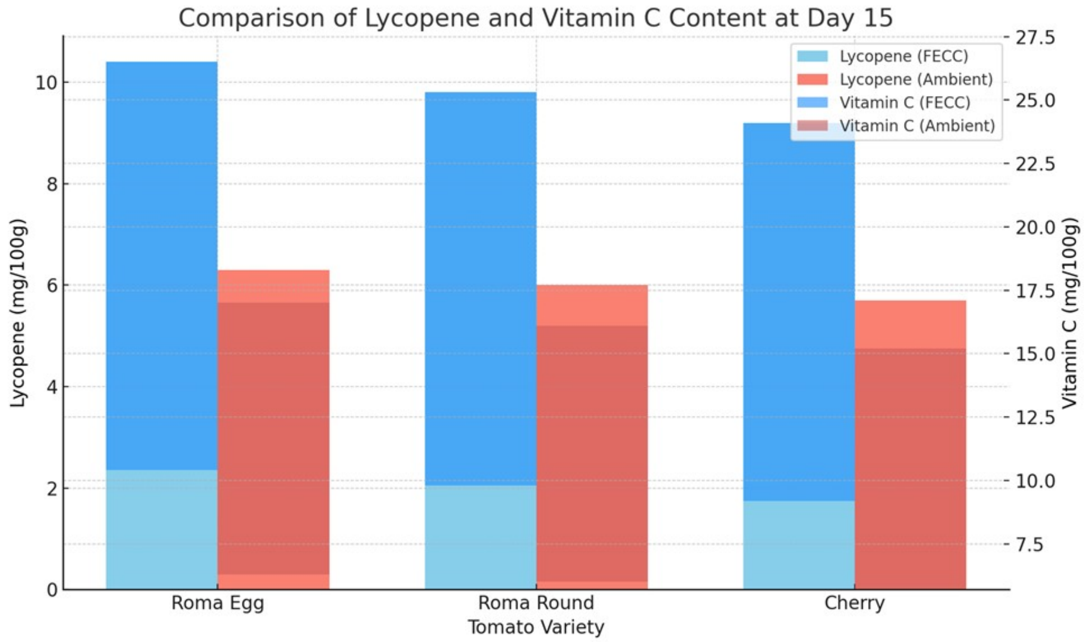

Figure 5: Lycopene and vitamin C contents of three tomato varieties after 15 days of storage under FECC and ambient conditions, showing higher retention in FECC.

The evaluation of the FECCs in Zanzibar revealed that post-harvest tomato preservation through the FECCs was much better than ambient tomato storage. The chambers lowered the internal temperature to a point (greater than 8°C) and enhanced relative humidity more than 25% to provide a microclimate that retarded ripening and microbial spoilage. This means the ability of FECCs to model-controlled storage conditions without the input of external energy. The shelf life had been significantly increased, and tomatoes kept in FECC remained as long as 15 days, more than twice in ambient conditions. This was aided by the fact that it reduced the deterioration and the weight loss of all tomato varieties. FECC-stored tomatoes did not drop below 10% weight loss after 15 days, as compared to ambient-stored tomatoes, which dropped by more than 25%, especially cherry tomatoes, which are more susceptible to dehydration. FECC conditions also ensured that better nutrition was maintained. Lycopene, a major antioxidant and the color determinant, was found to decay faster on ambient storage, whereas vitamin C contents were much higher in the samples stored in FECC, which is a sign that there was less oxidation degradation. These differences in FECC-stored tomatoes are characterized by an increase in °Brix expressed as total soluble solids (°Brix), which is a measure of sweetness and tomato ripening, at a slower rate, indicating slower conversion of sugars into other food components by metabolic processes. In the meantime, the pH was still rather stable, which showed slower acidification. Taken together, such findings indicate that FECCs increase marketable shelf life without affecting the biochemical quality of tomatoes. The system provides a cost-effective, energy-saving approach to address the smallholder farmers in Zanzibar to overcome the heat stress and postharvest spoilage in the resource-constrained conditions.

4. Conclusion and Recommendations

4.1 Conclusion

This research gives empirical evidence to the fact that Free Energy Cooling Chambers (FECCs) are efficient, inexpensive, and independent of energy postharvest storage devices in tomatoes in tropical islands. The FECC system has repeatedly provided a favorable microclimate of storage with significantly reduced temperatures and increased relative humidity compared to ambient conditions, thus inhibiting physiological degradation and microbial decay. FECCs resulted in significantly increased marketable shelf life in tomatoes of up to 15 days, more than two times longer than in tomatoes stored in ambient conditions. The physiological weight loss was highly minimized, meaning that it was effective in suppressing transpiration and moisture loss. Besides physical maintenance of quality, FECC storage also recorded better biochemical quality, which is demonstrated by the increased retention of vitamin C and lycopene, slower rise in total soluble solids, and more stable pH. These findings establish that FECCs are good at retarding ripening and oxidative degradation and maintaining nutritional value. Notably, the technology was robust and adaptable across various tomato varieties, as FECC's performance was similar across different tomato varieties. Resource-limited and climate-vulnerable environments, such as Zanzibar, are among the most critical limitations of FECCs since the model does not require electricity and instead utilizes all materials that are available locally and employs evaporation cooling principles. Comprehensively, this paper confirms FECC technology as a feasible climate-resilient solution in the reduction of postharvest losses, food quality, and income stability in the small-scale horticulture value chains. Its implementation could play a significant role in food security, nutrition, and sustainable agricultural development in the agro-ecological setting of tropical islands, etc. Despite the fact that the study was done in the field and tested a small storage time and number of crop varieties, the results are well-founded to support further large-scale and long-term tests of FECC performance in various crops and weather conditions.

4.2 Recommendations

In light of the conclusions of this paper, we can suggest the implementation of Free Energy Cooling Chambers (FECCs) as an effective approach that would allow increasing the shelf life of tomatoes and other perishable horticultural products in Zanzibar and other tropical areas, based on the practicality, cost-effectiveness, and energy independence of implementing the new measure. In a bid to achieve effective implementation, training on the construction, operation, and maintenance of FECCs based on locally available materials should be offered to the smallholder farmers and local cooperatives on the use of bricks, sand, and straw. Moreover, good postharvest handling practices, such as proper harvesting, sorting, and packaging, should be considered together with FECC technology to ensure the highest level of preservation of quality and to minimize losses. More studies are advised to evaluate the performance of FECCs with other perishable products, assess their steady operation in the field, and optimize design parameters to make them more efficient in cooling across different agro-ecological conditions.

5. Acknowledgements

The authors sincerely acknowledge the financial support provided by the Tanzania Commission for Science and Technology (COSTECH) for this study. We also extend our appreciation to the State University of Zanzibar (SUZA) and Sokoine University of Agriculture (SUA) for their institutional support and provision of laboratory facilities.

Our gratitude goes to the Association of Fruit and Vegetable Farmers in Zanzibar (UWAMWIMA) and to the local farmers who actively participated in the fieldwork and sample collection for their cooperation and assistance.

We further recognize the valuable contributions of the technical staff and colleagues whose expertise and support were instrumental to the successful implementation of this study. Their input greatly enhanced the quality and practical relevance of the research.

References

1. Abdullah, S., Zubir, M. N. B. M., Muhamad, M. R. B., Newaz, K. M. S., Öztop, H. F., Alam, M. S., & Shaikh, K. (2023). Technological development of evaporative cooling systems and their integration with air dehumidification processes: A review. *Energy and Buildings*, *283*, 112805. https://doi.org/10.1016/j.enbuild.2023.112805
2. Aftab, R. A., Ahmad, F., Monish, M., & Zaidi, S. (2025). Postharvest quality assessment of tomato during storage: An experimental and ML fusion. *Journal of Stored Products Research*, *112*, 102643. https://doi.org/10.1016/j.jspr.2025.102643
3. Aked, J. (2002). Maintaining the post-harvest quality of fruits and vegetables. In W. Jongen (Ed.), *Fruit and Vegetable Processing*. CRC Press. https://doi.org/10.1201/9781439823187.ch7
4. Alam, Md. F., Sazidy, A. S., Kabir, A., Mridha, G., Litu, N. A., & Rahman, Md. A. (2017). *An experimental study on the design, performance and suitability of evaporative cooling system using different indigenous materials*. 020075. https://doi.org/10.1063/1.4984704
5. Alenazi, M. M., Shafiq, M., Alsadon, A. A., Alhelal, I. M., Alhamdan, A. M., Solieman, T. H. I., Ibrahim, A. A., Shady, M. R., & Al-Selwey, W. A. (2020). Improved functional and nutritional properties of tomato fruit during cold storage. *Saudi Journal of Biological Sciences*, *27*(6), 1467–1474. https://doi.org/10.1016/j.sjbs.2020.03.026

6. Almeida, P. V., Gando-Ferreira, L. M., & Quina, M. J. (2024). Tomato Residue Management from a Biorefinery Perspective and towards a Circular Economy. *Foods*, *13*(12), 1873. https://doi.org/10.3390/foods13121873
7. Berck, C. S., Berck, P., & Di Falco, S. (Eds.). (2018). *Agricultural Adaptation to Climate Change in Africa: Food Security in a Changing Environment* (1st ed.). Routledge. https://doi.org/10.4324/9781315149776
8. Bhowmik, P. K., & Dris, R. (2004). Enzymes and Quality Factors of Fruits and Vegetables. In R. Dris & S. M. Jain (Eds.), *Production Practices and Quality Assessment of Food Crops* (pp. 1–25). Kluwer Academic Publishers. https://doi.org/10.1007/1-4020-2534-3_1
9. Birhanu, G. A., & Belay, A. N. (2023). Enhancing the shelf life of injera: Design of an evaporative cooler clay chamber derived from local clay in Bahir Dar, Ethiopia. *Design Science*, *9*, e8. https://doi.org/10.1017/dsj.2023.6
10. Boiteau, J. M., & Pingali, P. (2022). Food loss of perishable produce from farm to retail: Evidence from tomato supply chains in South India. *The American Journal of Clinical Nutrition*, *115*(6), 1535–1548. https://doi.org/10.1093/ajcn/nqac039
11. Caruana, R., De Antonellis, S., Marocco, L., & Guilizzoni, M. (2023). Modeling of Indirect Evaporative Cooling Systems: A Review. *Fluids*, *8*(11), 303. https://doi.org/10.3390/fluids8110303
12. Chen, L., Pan, Y., Li, H., Liu, Z., Jia, X., Li, W., Jia, H., & Li, X. (2020). Constant temperature during postharvest storage delays fruit ripening and enhances the antioxidant capacity of mature green tomato. *Journal of Food Processing and Preservation*, *44*(11). https://doi.org/10.1111/jfpp.14831
13. Cuce, P. M. (2017). Thermal performance assessment of a novel liquid desiccant-based evaporative cooling system: An experimental investigation. *Energy and Buildings*, *138*, 88–95. https://doi.org/10.1016/j.enbuild.2016.12.029
14. Dadhich, S. M., Dadhich, H., & Verma, R. (2008). Comparative Study on Storage of Fruits and Vegetables in Evaporative Cool Chamber and in Ambient. *International Journal of Food Engineering*, *4*(1). https://doi.org/10.2202/1556-3758.1147
15. Defraeye, T., Shoji, K., Schudel, S., Onwude, D., & Shrivastava, C. (2023). Passive evaporative coolers for postharvest storage of fruit and vegetables: Where to best deploy them and how well do they perform. *Frontiers in Food Science and Technology*, *3*, 1100181. https://doi.org/10.3389/frfst.2023.1100181
16. Fiza, S., Imran, S., & Tanweer, A. (2022). Thermal Processing and Lycopene Content Of Tomatoes- A Public Health Perspective. *NURTURE*, *14*(1), 12–17. https://doi.org/10.55951/nurture.v14i1.9
17. Gouda, M. H. B., & Duarte-Sierra, A. (2024). An Overview of Low-Cost Approaches for the Postharvest Storage of Fruits and Vegetables for Smallholders, Retailers, and Consumers. *Horticulturae*, *10*(8), 803. https://doi.org/10.3390/horticulturae10080803
18. Haile, M. G., Garay-Martinez, R., & Macarulla, A. M. (2024). Review of Evaporative Cooling Systems for Buildings in Hot and Dry Climates. *Buildings*, *14*(11), 3504. https://doi.org/10.3390/buildings14113504
19. Han, J.-W., Ren, Q.-S., Li, J.-C., Zhu, W.-Y., & Yang, X.-T. (2023). Numerical analysis of coupled heat and mass transfer processes in packaged tomatoes throughout the cold chain. *Case Studies in Thermal Engineering*, *42*, 102687. https://doi.org/10.1016/j.csite.2022.102687
20. Ibiyeye, D., Olunloyo, O., Aderemi, A., Bamigboye, T., & Nathaniel, H. (2022a). Development and performance evaluation of a double chamber evaporative cooling system for storage of vegetables. *Technology Audit and Production Reserves*, *5*(3(67)), 34–39. https://doi.org/10.15587/2706-5448.2022.267580
21. Ibiyeye, D., Olunloyo, O., Aderemi, A., Bamigboye, T., & Nathaniel, H. (2022b). Development and performance evaluation of a double chamber evaporative cooling system for storage of vegetables. *Technology Audit and Production Reserves*, *5*(3(67)), 34–39. https://doi.org/10.15587/2706-5448.2022.267580
22. Jawed Ahmad Rizawi, Habtom Berhan, Hermon Hsabu, Tomas Semere, Yonatan Alem, Mehari Ghebreyesus, & Jeevan Jyoti Kaushik. (2024). Sustainable cooling solutions: Designing a zero-energy chamber with local materials in Eritrea. *World Journal of Biology Pharmacy and Health Sciences*, *20*(3), 111–119. 23. https://doi.org/10.30574/wjbphs.2024.20.3.0982

23. Kamaldeen O. S, Okedokun O. W, & Moshood E. S. (2022). Effects of NSPRI wall-in-wall evaporative coolant on physical properties of stored tomato. *Global Journal of Engineering and Technology Advances*, *13*(1), 027–029. https://doi.org/10.30574/gjeta.2022.13.1.0172
24. Karakas, E., & Fernie, A. R. (2025). What metabolomics has taught us about tomato fruit ripening and quality. *Journal of Experimental Botany*, *76*(21), 6245–6258. https://doi.org/10.1093/jxb/eraf209
25. Kedir, H. J., Tilinti, B. Z., & Mekonnen, K. T. (2025). Physicochemical Characterization of Fresh and Powdered Tomato in Arba Minch, Ethiopia. *Recent Progress in Nutrition*, *05*(02), 1–12. https://doi.org/10.21926/rpn.2502013
26. Kunwar, A., Bist, D. R., Khatri, L., Dhami, R., & Joshi, G. R. (2024). OPTIMIZING POST-HARVEST HANDLING PRACTICES TO REDUCE LOSSES AND ENHANCE QUALITY OF FRUITS AND VEGETABLES. *Food and Agri Economics Review*, *4*(2), 78–82. https://doi.org/10.26480/faer.02.2024.78.82
27. Liu, X., Fu, Y., Li, M., Xiong, S., Huang, L., Zhang, S., Zhang, W., Liang, X., Wang, W., Tang, K., & Shen, Q. (2025). Biofortification of tomatoes with beta-carotene through targeted gene editing. *International Journal of Biological Macromolecules*, *327*, 147396. https://doi.org/10.1016/j.ijbiomac.2025.147396
28. Longdong, I. A., Tooy, D., Mochtar, J. Y., Lengkey, L. C. Ch. E., Pinatik, H. F., & Saroinsong, D. (2025). Design and Technical Evaluation of Evaporative Cooling for Prolonging Fresh Potato Shelf Life in Tropical Climates. *Jurnal Penelitian Pendidikan IPA*, *11*(7), 722–728. https://doi.org/10.29303/jppipa.v11i7.12163
29. Lufu, R., Ambaw, A., & Opara, U. L. (2025). Evaporative Cooling Systems for Perishables in Sub-Saharan Africa—A Review. *Journal of Food Process Engineering*, *48*(5), e70127. https://doi.org/10.1111/jfpe.70127
30. Mugwaneza, E., Wafula, N., & Nyaanga, D. M. (2024). Effect of desiccant evaporative cooler on quality attributes and shelf life of different tomato varieties. *International Journal of Postharvest Technology and Innovation*, *9*(4), 349–363. https://doi.org/10.1504/IJPTI.2024.144957
31. Nicolaï, B. M., Bobelyn, E., Hertog, M., Marquenie, D., Verboven, P., & Verlinden, B. (2003). QUALITY MANIPULATION AND MONITORING IN PROCESSES: PRODUCT-CLIMATE INTERACTION, QUALITY CONTROL. *Acta Horticulturae*, *604*, 265–275. https://doi.org/10.17660/ActaHortic.2003.604.27
32. Niu, G., Kozai, T., & Sabeh, N. (2020). Physical environmental factors and their properties. In *Plant Factory* (pp. 185–195). Elsevier. https://doi.org/10.1016/B978-0-12-816691-8.00011-X
33. Nkolisa, N., Magwaza, L. S., Workneh, T. S., & Chimphango, A. (2018). Evaluating evaporative cooling system as an energy- free and cost- effective method for postharvest storage of tomatoes (Solanum lycopersicum L.) for smallholder farmers. *Scientia Horticulturae*, *241*, 131–143. https://doi.org/10.1016/j.scienta.2018.06.079
34. Patel, D. P., Jain, S. K., Lakhawat, S. S., & Wadhawan, N. (2022a). A low-cost storage for horticulture commodities for enhancing farmer's income: An overview on evaporative cooling. *Journal of Food Process Engineering*, *45*(10), e14134. https://doi.org/10.1111/jfpe.14134
35. Patel, D. P., Jain, S. K., Lakhawat, S. S., & Wadhawan, N. (2022b). A low-cost storage for horticulture commodities for enhancing farmer's income: An overview on evaporative cooling. *Journal of Food Process Engineering*, *45*(10), e14134. https://doi.org/10.1111/jfpe.14134
36. Paull, RobertE. (1999). Effect of temperature and relative humidity on fresh commodity quality. *Postharvest Biology and Technology*, *15*(3), 263–277. https://doi.org/10.1016/S0925-5214(98)00090-8
37. Pradhan, A., & Srijaya, M. (2022). Postharvest Quality and Storability of Organically versus Conventionally Grown Tomatoes: A Comparative Approach. *The 1st International Electronic Conference on Horticulturae*, 29. https://doi.org/10.3390/IECHo2022-12513
38. Ruangsuwan, T., Phanprasit, W., Yoosook, W., Boonyayothin, V., Konthonbut, P., Cherrie, J. W., & Nankongnab, N. (2025). Sustainable Hybrid Cooling: Integrating Indirect Evaporative and Split Air Conditioning for Improved Indoor Air Quality in Tropical Climates. *Buildings*, *15*(8), 1313. https://doi.org/10.3390/buildings15081313

39. Rubagumya, I., Komakech, A. J., Menya, E., Kizito, S., Zziwa, A., & Kabenge, I. (2023). Postharvest Losses of Fruits and Vegetables Along Their Urban Supply Chain in Eastern Africa: A Case Study of Uganda Towards Sustainable Management. *Journal of Biosystems Engineering*, *48*(2), 105–114. https://doi.org/10.1007/s42853-023-00177-x
40. Samuel, O. O., K, O., O, I. A., O, I., & Bt, A. (2023). EVALUATION OF SYNERGISTIC EFFECT OF EVAPORATIVE COOLING SYSTEM AND POTASSIUM PERMANGANATE ON EXTENDING THE SHELF LIFE AND QUALITY OF PLANTAIN. *Innovare Journal of Agricultural Sciences*, 1–5. https://doi.org/10.22159/ijags.2023.v11i2.46512
41. Sibanda, S., & Workneh, T. S. (2020). Performance evaluation of an indirect air cooling system combined with evaporative cooling. *Heliyon*, *6*(1), e03286. https://doi.org/10.1016/j.heliyon.2020.e03286
42. Sipho, S., & Tilahun, S. W. (2020). Potential causes of postharvest losses, low-cost cooling technology for fresh produce farmers in Sub-Sahara Africa. *African Journal of Agricultural Research*, *16*(5), 553–566. https://doi.org/10.5897/AJAR2020.14714
43. Springael, J., Paternoster, A., & Braet, J. (2018). Reducing postharvest losses of apples: Optimal transport routing (while minimizing total costs). *Computers and Electronics in Agriculture*, *146*, 136–144. https://doi.org/10.1016/j.compag.2018.02.007
44. Strecker, K., Bitzer, V., & Kruijssen, F. (2022). Critical stages for post-harvest losses and nutrition outcomes in the value chains of bush beans and nightshade in Uganda. *Food Security*, *14*(2), 411–426. https://doi.org/10.1007/s12571-021-01244-x
45. Thole, V., Vain, P., Yang, R., Almeida Barros Da Silva, J., Enfissi, E. M. A., Nogueira, M., Price, E. J., Alseekh, S., Fernie, A. R., Fraser, P. D., Hanson, P., & Martin, C. (2020). Analysis of Tomato Post-Harvest Properties: Fruit Color, Shelf Life, and Fungal Susceptibility. *Current Protocols in Plant Biology*, *5*(2), e20108. https://doi.org/10.1002/cppb.20108
46. Tiwari, I., Shah, K. K., Tripathi, S., Modi, B., Shrestha, J., Pandey, H. P., Bhattarai, B. P., & Rajbhandari, B. P. (2020). Post-harvest practices and loss assessment in tomato (Solanum lycopersicum L.) in Kathmandu, Nepal. *Journal of Agriculture and Natural Resources*, *3*(2), 335–352. https://doi.org/10.3126/janr.v3i2.32545
47. Umeohia, U. E., & Olapade, A. A. (2024). Physiological Processes Affecting Postharvest Quality of Fresh Fruits and Vegetables. *Asian Food Science Journal*, *23*(4), 1–14. https://doi.org/10.9734/afsj/2024/v23i4706
48. Verploegen, E., Sanogo, O., & Chagomoka, T. (2018). Evaluation of Low-Cost Evaporative Cooling Technologies for Improved Vegetable Storage in Mali. *2018 IEEE Global Humanitarian Technology Conference (GHTC)*, 1–8. https://doi.org/10.1109/GHTC.2018.8601894
49. Wan, P., Toudeshki, A., Tan, H., & Ehsani, R. (2018). A methodology for fresh tomato maturity detection using computer vision. *Computers and Electronics in Agriculture*, *146*, 43–50. https://doi.org/10.1016/j.compag.2018.01.011
50. Xie, L., Guerra, M., Tijskens, L. M. M., Schoevaars, A. M., Verdonk, J. C., Woltering, E. J., & Schouten, R. E. (2025). Weight loss revisited: Tomato weight loss modelling as affected by genotype, relative humidity and temperature. *Postharvest Biology and Technology*, *230*, 113747. https://doi.org/10.1016/j.postharvbio.2025.113747
51. Yang, Y., Cui, G., & Lan, C. Q. (2019). Developments in evaporative cooling and enhanced evaporative cooling—A review. *Renewable and Sustainable Energy Reviews*, *113*, 109230. https://doi.org/10.1016/j.rser.2019.06.037
52. Yeneneh, K., & Walle, M. (2025). Performance evaluation of evaporative cooling systems for mitigating post-harvest losses in Ethiopian horticultural crops. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *239*(7), 2591–2607. https://doi.org/10.1177/09544062241299532
53. Yimer, S., & Sahu, O. (2014). Preservation and Protection Technology of Fresh Vegetables in the Tropics. *International Journal of Vegetable Science*, *20*(3), 216–226. https://doi.org/10.1080/19315260.2013.788596

54. Yu, L., Huang, Y., Li, W., Shi, C., Sheldon, B. W., Chen, Z., & Chen, M. (2024). Radiative-coupled evaporative cooling: Fundamentals, development, and applications. *Nano Research Energy*, *3*(2), e9120107. https://doi.org/10.26599/NRE.2023.9120107
55. Zainalabidin, F. A., Sagrin, M. S., Wan Azmi, W. N., & Ghazali, A. S. (2019). Optimum postharvest handling-effect of temperature on quality and shelf life of tropical fruits and vegetables. *Journal of Tropical Resources and Sustainable Science (JTRSS)*, *7*(1), 23–30. https://doi.org/10.47253/jtrss.v7i1.505
56. Zuo, X., Wang, J., Li, Y., Zhang, J., Wu, Z., Jin, P., Cao, S., & Zheng, Y. (2025). Recent advances in high relative humidity strategy for preservation of postharvest fruits and vegetables: A comprehensive review. *Food Chemistry*, *481*, 144130. https://doi.org/10.1016/j.foodchem.2025.144130