Development of designed evaporative cooled onion storage structure to mitigate postharvest losses and enhance storage efficiency

Sudama R. Kakade[1], Vikram P. Kad[1], Ganesh N. Shelke[1], Rajvardhan K. Patil[2], Govind B. Yenge[3], Shivani S Desai[4], Nashi K. Alqahtani[5], Suzan Harara[6], Areej S. Alamer[7], Awatif Almehmadi[8], Norah E. Aljohani[9], Ameerah Almaski[9], Rokayya Sami[10*], Mahmoud Helal[11]

(1. *Department of Agricultural Processing Engineering, Dr. Annasaheb Shinde College of Agricultural Engineering and Technology, Mahatma Phule Agricultural University, Rahuri, Ahilyanagar, 413722, Maharashtra, India*;
2. *ICAR- National Institute of Secondary Agriculture, Namkum, Ranchi 834010, Jharkhand, India*;
3. *Regional Sugarcane and Jaggery Research Station, Mahatma Phule Agricultural University, Kolhapur 416 005, Ahilyanagar, Maharashtra, India*;
4. *National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonipat 131028, Haryana, India*;
5. *Department of Food and Nutrition Sciences, College of Agricultural and Food Sciences, King Faisal University, P.O. Box 400, Al-Ahsa 31982, Saudi Arabia*;
6. *Graphic Design Department, College of Design and Applied Arts, Taif University, P.O. 11099, Taif 21944, Saudi Arabia*;
7. *Department of Clinical Nutrition, Riyadh Third Health Cluster, Ministry of Health, Riyadh 13424, Saudi Arabia*;
8. *Department of Clinical Nutrition, Faculty of Applied Medical Sciences, Umm AL-Qura University, Makkah, P.O. BOX. 715. 21955, Saudi Arabia*;
9. *Department of Clinical Nutrition, College of Applied Medical Sciences, Taibah University, Madinah 42353-4028, Saudi Arabia*;
10. *Department of Food Science and Nutrition, College of Sciences, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia*;
11. *Department of Mechanical Engineering, Faculty of Engineering, Taif University, P.O. 11099, Taif 21944, Saudi Arabia*)

Abstract: Onions, often referred to as the "Queen of the kitchen", play a vital role in enhancing dishes with their distinctive flavor, phenols, and flavonoids. Despite their significance, the onion market faces considerable volatility due to seasonal variations and substantial postharvest losses, resulting in significant price fluctuations. These losses can reach up to 40%, primarily due to improper handling, sprouting, rotting, inadequate storage, and limited infrastructure, with microbial spoilage alone accounting for 15%-20% of the total losses. Conventional onion storage methods demand substantial investments but often fail to effectively manage temperature and relative humidity (RH) fluctuations, which are critical for maintaining bulb shelf life. This study focuses on developing an on-farm evaporative cooled onion storage structure (ECOSS) to provide a long-term storage solution for onions. Results demonstrated that the ECOSS maintained internal temperatures between 24.5°C-31.3°C (average 27.1°C) and suitable RH levels throughout the storage period, with minimum values between 63.7%-67.2% and maximum values between 74.1%-75.5%. Physiological loss in weight (PLW), sprouting, and rotting were lowest at the 0.91 m storage height compared to 1.82 m after 5 months of storage. Onion firmness decreased over time, with the lowest firmness observed at 1.82 m (14.68 N). The net profit per ton of onions stored from May to September was INR6021 for the ECOSS, compared to INR2553 for traditional onion storage structure (TOSS). The ECOSS offers a cost-effective and efficient solution for reducing postharvest losses and enhancing onion storage.

Keywords: evaporative cooling, firmness, postharvest losses, rotting, sprouting
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1 Introduction

Onions (*Allium cepa L.*), esteemed globally for their culinary versatility, rank as a crucial vegetable crop cultivated across diverse climates[1]. India, the world's largest onion producer, produces 26.91 million t from 16.28 million hm^2, underscoring its significant

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Biographies: Sudama R. Kakade, Assistant Professor, research interest: food processing, Email: sudamakakade05@gmail.com; **Vikram P. Kad**, Professor, research interest: agricultural processing, Email: vikramkad2014@gmail.com; **Ganesh N. Shelke**, Assistant Professor, research interest: food processing, Email: shelkeganesh838@gmail.com; **Rajvardhan K. Patil**, Scientist, research interest: agricultural processing, Email: rajvardhanp4545@gmail.com; **Govind B. Yenge**, Assistant Professor, research interest: agricultural processing, Email: govindyenge89@gmail.com; **Shivani S Desai**, PhD candidate, research interest: food processing, Email: shivanidesai1756@gmail.com; **Nashi K. Alqahtani**, Professor, research interest: food processing, Email: nalqahtani@kfu.edu.sa; **Suzan Harara**, Assistant Professor, research interest: design, Email: smharara@tu.edu.sa; **Areej S. Alamer**, Assistant Professor, research interest: food science, Email: asalaamer@moh.gov.sa; **Awatif Almehmadi**, Assistant Professor, research interest: food science, Email: amsmehmadi@uqu.edu.sa; **Norah E. Aljohani**, Professor, research interest: food processing, Email: nmrefaei@taibahu.edu.sa; **Ameerah Almaski**, Assistant Professor, research interest: food science, Email: amaski@taibahu.edu.sa; **Mahmoud Helal**, Professor, research interest: mechanical engineering, Email: mo.helal@tu.edu.sa.

***Corresponding author: Rokayya Sami**, Professor, research interest: food science. Department of Food Science and Nutrition, College of Sciences, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia. Email: rokayya.d@tu.edu.sa.

economic impact[2]. Onion, commonly known as “Queen of the kitchen”, enriches dishes with its unique flavor and nutritional benefits, offering a rich profile of vitamins, minerals, fiber, phenols, and flavonoids[3]. Despite its importance, the onion market experiences significant volatility due to seasonal variations and substantial postharvest losses, which lead to dramatic price fluctuations, with steep drops during oversupply and soaring prices during shortages[4]. Onion alone is resulting in losses of up to INR 11 000 crores annually in India[5]. The essential criteria for evaluating onions’ quality include soundness, dryness, uniformity, intact scales, and the absence of mechanical damage. However, up to 40% of the harvested crop is lost to poor management, sprouting, decay, inadequate storage, and insufficient infrastructure[5], with microbial spoilage alone causing 15%-20% of these losses[6].

These issues are compounded when onions are stored in the warm, humid conditions typical of the Indian subcontinent, as these conditions increase the rate of respiration in bulbs and provide a conducive environment for microbial growth. These conditions not only destroy the quality of the bulbs and their storage life but also threaten health because of the possible creation of toxins by the new postharvest diseases[7]. Development of onion storage buildings has immensely led to more efficiency and quality of onion bulb handling in the short term, as well as long-term stores. The majority of onions are packed in modern storage plants, whereby the adverse conditions under which the onions can be affected during the storage period are taken into consideration, thus subjecting them to the optimum possibilities to uphold the physiological condition of the product during the storage period[8]. In comparison with the classical way of storage that implies simply filling onions and not controlling such important parameters as temperature, relative humidity (RH), and fumigation, modern advances in the field of storage will help to control these more effectively[5]. This kind of progress can minimize sprouting, putrefaction, and contamination by pathogens since there is good temperature control, management of RH, and aeration, which enhance the physiology of stored onion[5].

Maintaining onion bulbs under high temperature and high humidity conditions, as found in zones receiving high temperature and high humidity fronts, will enhance their respiration rate and also develop an environment favorable to microbial growth, thus shortening the shelf life of the onion bulbs[9]. The temperatures under which onions should be stored could reduce the pathogen infection between 10% and 20%[10]. Potential losses have been found to be substantially lowered by forced ventilation systems in which the temperature is maintained at 25℃ and the RH value is maintained between 60% and 70%[11]. According to Dabhi and Patel[12], the weight loss in the forced ventilated storage system was only 10.24%, with low sprouting rate (0.34%) as compared to conventional techniques (0.63%). The research study investigated by Ghodki et al.[13] led to the introduction of a cost-effective desiccation system made out of some agricultural waste products such as guar straw and wood wool used to maintain the temperature and moisture in the storage of onions and has successfully prolonged its shelf life by an average of 5 months. According to Imoukhuede and Ale[14], the roofing materials influence temperature and humidity, thus making it essential that appropriate roofing materials be used as well as ventilation systems be in place to maximize the profitability of storing onions. They also have refrigerated storage, which has been identified as an eco-friendly way to prolong the shelf life of onions[11]. In addition to conventional refrigeration, advanced storage methods such as controlled atmosphere storage (CAS) further enhance preservation efficiency. The possible benefits of CAS include a significant reduction in respiration rate, inhibition of pathogens, delay in senescence, and regulation of ethylene production, thereby enabling long-term storage while maintaining quality over an extended period[15]. When subjected to controlled atmosphere storage (CAS) conditions, such as 1% oxygen and 99% nitrogen at 5°C, fresh onions can retain optimal bulb quality with minimal changes in flavor. However, maintaining such controlled conditions requires strict temperature regulation, and storage at constant temperatures of 24°C and 30°C is neither practical nor economical for large-scale commercial applications[16]. Furthermore, despite the quality advantages offered by cold storage and CAS, their adoption in commercial practice remains limited due to high initial investment, the need for large storage volumes, and substantial maintenance and operational costs, making them unaffordable for many farmers[14].

Since the physiological characteristics of onion bulbs change dramatically during storage due to sudden climatic changes, it is necessary to seek better storage methods. The existing sheds used for onion storage require significant capital investment and do not effectively regulate temperature and RH variations, which are essential for preserving the bulbs’ shelf life. Therefore, this study aims to develop an on-farm evaporative cooled onion storage structure (ECOSS)[3] designed to provide long-term storage solutions for onions with the following objectives: First, to design and develop an evaporative cooled onion storage structure on farmers’ farms; second, to conduct a comparative study between ECOSS and traditional onion storage structures (TOSS); and third, to evaluate the performance of both structures based on the physiological parameters of the stored onion bulbs.

2 Materials and methods

2.1 Sample collection and study location

For storage purposes, 300 t well-matured, healthy onion bulbs with uniform size and color were procured from local growers from Nashik, Maharashtra, India. The study was conducted from May to September, after the harvesting seasons of 2023 and 2024. The reasons for choosing the study location are that, firstly, Nashik is considered Asia’s largest onion producer belt; secondly, during storage of bulbs, unstable climatic conditions are observed during May to September, such as high temperatures and fluctuating RH, which are unfavorable for onion storage. It is more effective to compare the effects of the two storage methods in an environment with significant temperature fluctuations.

2.2 Material selection, construction, and development of storage structures ECOSS and TOSS

2.2.1 Construction of the main frame and roof of ECOSS

The structural elements of a roof truss system were designed in accordance with IS: 800-2007, focusing on purlins, principal rafters, the roof truss, columns and column bases, girt rods, bracing, and struts made of mild steel. The box sections of each component are detailed in Table 1. The evaporatively cooled onion storage structure measured 42.30 m in length and 17.57 m in width, with center and side heights of 4.57 m and 3.04 m, respectively, as shown in Figure 1. The cement concrete base, raised 0.60 m above ground level, provided ventilation and moisture protection, as shown in Figure 2c. Two hundred pipe columns MS (80 mm×80 mm×4 mm), spaced 1.52 m apart, were erected on the base. The triangular trusses, each 17.57 m long with a 1.69 m rise, were constructed using 60 mm×60 mm×4 mm and 40 mm×40 mm×

2.6 mm pipes. Each column was supported by a 200 mm×200 mm×8 mm plate, fastened with 0.40 m nut-bolts. Nine trusses, spaced 4.7 m apart, were integrated into the structure as shown in Figure 1. Galvanized iron sheets were used for roofing.

Table 1 Details of sections used in the newly designed onion storage structure: According to the steel table

Sr No.	Name of section	Size/mm	Weight/kg·m^{-1}
1	Box section for struts	40×40×2.6	4.20
2	Box section for principal rafter	60×60×4.0	6.71
3	Box section for bottom chord	60×60×4.0	6.71
4	Rectangular section for purlins	80×40×4.0	6.71
5	Box section for bracings	50×50×3.6	4.98
6	Box section for bracings	40×40×3.2	3.49
7	Box section for column	80×80×4.0	9.22

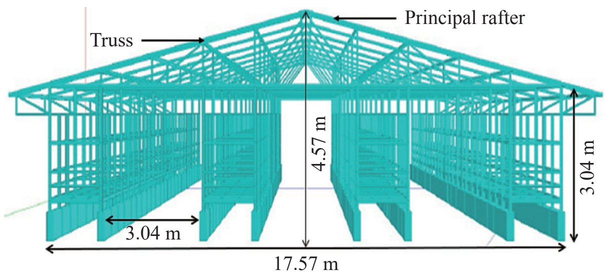
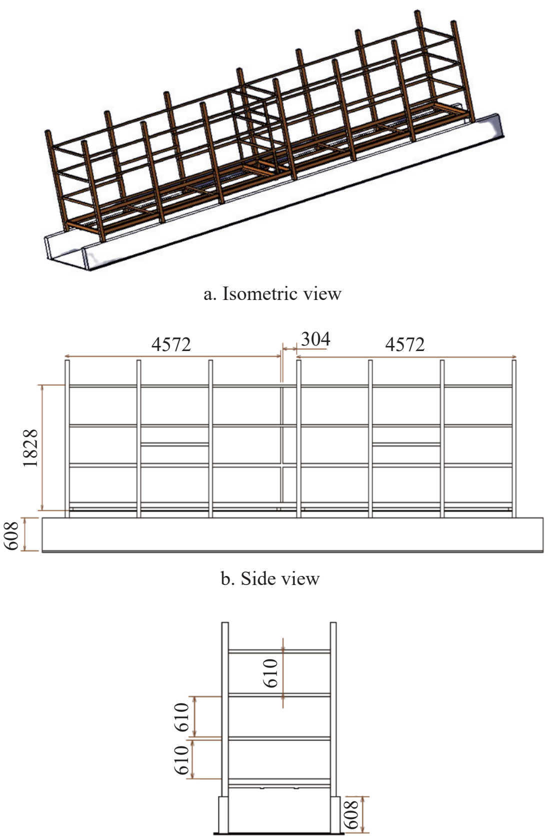


Figure 1 Front view of the ECOSS with nine trusses



a. Isometric view

b. Side view

c. Front view

Figure 2 Schematic diagrams of the ECOSS compartment

2.2.2 Construction of internal storage compartment

The storage compartment was constructed with frame dimensions of 4.52 m in length, 1.52 m in width, and 1.82 m in height, as shown in Figure 2b. The frame columns were made from MS pipes measuring 80 mm×80 mm×4 mm. The supporting pipes were covered with galvanized wire mesh with a perforation size of 0.0381 m×0.0381 m and a gauge of 10. The storage compartment was supported by four side walls and a base, each side wall containing four pipes measuring 80 mm×40 mm×4 mm, spaced 0.61 m apart. The base incorporated four pipes measuring 50 mm×50 mm×3.6 mm, spaced 0.38 m apart. This construction ensured structural integrity and appropriate ventilation for the storage compartment, as shown in Figure 2b. A double-door system was installed at the center of the storage compartment to facilitate the loading and unloading of onions. The door frame was constructed using 50 mm×25 mm×3.2 mm rectangular MS pipes, with each door measuring 0.91 m×1.5 m. During the experiment, the bulk density of onion bulbs was considered to be 636 kg/m^3. Consequently, the capacity of a single storage compartment was determined to be 8-9 t. With a total of 32 compartments available, the storage structure can hold approximately 250 to 288 t of onions for up to five months.

2.2.3 Temperature control system of ECOSS

Polyurethane foam (PUF) panels were mounted around the storage structure to protect onions from the external atmosphere and maintain proper storage conditions. The panels were installed 1 m away from the compartments, as shown in Figures 3d and 3e. Galvanized sheets were used for roofing to shield onions from rain, wind, and sunlight, preventing water leakage and the entry of external elements, as shown in Figure 3b. To counteract the potential rise in temperature caused by the galvanized sheets, thermal insulation (bubble sheet) was installed below the roofing to maintain optimal temperature and prevent heat transmission within the storage structure.

2.2.4 Selection of fans and cooling pads

Exhaust fans were installed on the front side of the onion storage structure to remove warm air and allow fresh air in, as shown in Figures 3a and 3c. These fans, operated by sensors, automatically activated based on temperature or humidity levels. The fans drew air through cooling pads to control relative humidity and temperature, and reduce carbon dioxide concentration. A 1.1 kW (1.5 hp), single-phase, 1440 r/min exhaust fan (Supreme Equipment Pvt. Ltd., Nashik, Maharashtra, India) was used. The required air circulation volume was measured in cubic meters per minute as per Equation (1)[17].

$$\text{Required airflow rate}\left(\text{cubic meters per minute}\right)=\frac{\text{Volume of storage structure}\times\text{Air changes per hour}}{60\ \text{min}} \tag{1}$$

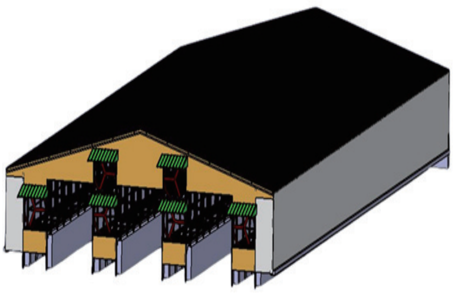
Calculations of inadequate ventilation can increase humidity, leading to rotting and sprouting of onions. To prevent this, recommended ventilation conditions include 60-80 air cycles per hour and a continuous supply of fresh air, selected through trial and error. To meet the ventilation requirements of the onion storage structure, six exhaust fans with a capacity of 594.65 m^3/min were chosen from the market. As per the company recommendation (Supreme Equipment Pvt. Ltd., Nashik, Maharashtra, India), each fan requires four cooling pads to effectively cool the air. Hence, 24 cooling pads were needed to ensure a proper cooling system for the six fans.

Evaporative cooling involves circulating hot, humid air over a wet surface, causing water to evaporate and the air to gain latent heat at the expense of sensible heat, thereby reducing the air temperature[18]. The cooling effect depends on the amount of water evaporated; greater evaporation results in more cooling. As air gains latent heat, its relative humidity increases. This system is especially efficient in hot, dry climates with low humidity, where evaporation can significantly lower temperatures, making it a cost-effective cooling method[19]. An evaporative cooling pad was installed on the rear wall of the onion storage structure. In this fan and pad system, water is pumped to the top of horizontal pads and released through evenly spaced openings to ensure uniform wetting. Exhaust fans remove warm air and draw fresh air through the wet pads. Excess water at the bottom of the pads is collected and returned to a sump tank for reuse, as shown in Figure 4.

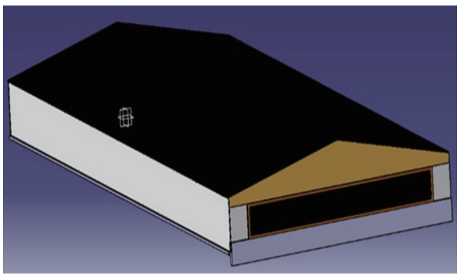
a. Photographic front view of the ECOSS

b. Front view of the internal compartment of ECOSS

c. Photographic front view of ECOSS with exhaust fan



d. Isometric view of ECOSS with exhaust fan



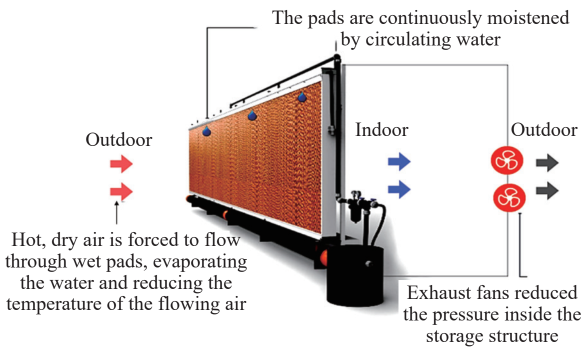
e. Back view of ECOSS with cooling pad and PUF panel

Figure 3 Visualization of ECOSS

2.2.5 Electronic controller

The onion storage structure is equipped with six groups of exhaust fans that are activated based on pre-set temperature and humidity offsets. The cooling system is operated by an on/off timer and is regulated by the humidity and temperature sensors in the controller. Once the parameters are set to the required level, the system automatically maintains them. If the humidity level exceeds the set limit, the cooling system is stopped by the humidity sensor. An alarm relay output is also installed in the controller system to alert for high and low temperature or humidity levels. Additionally, a real-time clock with an automatic temperature reduction curve is included to further optimize the system's efficiency. A humidity sensor was used in the onion storage structure to measure and monitor relative humidity levels, transmitting data to electronic temptron climate controllers for display and monitoring. Additionally, two temperature sensors were installed to measure temperature and send signals to the same controllers. This setup ensures the regulation and maintenance of optimal storage conditions for onions.

a. Photographic view



b. Isometric view

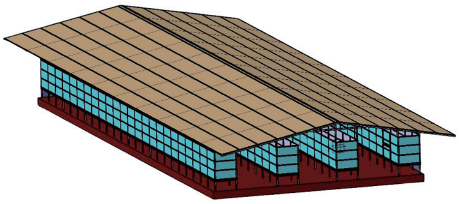
Figure 4 Representation of evaporative cooling pad of ECOSS

2.2.6 Controlled parameters in ECOSS

The controlled storage conditions of 25°C-30°C and 65%-75% relative humidity, maintained for 5 months, significantly influenced the quality and shelf life of the onions. To assess the environmental conditions at the experimental site, temperature and relative humidity were measured both inside and outside the ECOSS. Exhaust fans were used to remove warm air and admit fresh air into the structure. They were operated by sensors that automatically activated in response to deviations in temperature or humidity levels.

2.2.7 TOSS

For the traditional onion storage structure (TOSS), the same structure was constructed as described in the previous section 2.2. However, in TOSS, thermal insulation, evaporative cooling systems, and temperature and RH controllers were not used. The same amount of onion bulbs was stored in TOSS under ambient conditions, as shown in Figure 5.



a. Isometric view

b. Photographic view

Figure 5 Representation of TOSS

3 Performance evaluation of structure and quality analysis of stored onion bulbs

3.1 Comparative study between structures and storage height

Both ECOSS and TOSS were evaluated using four compartment heights, namely 0.91 m, 1.21 m, 1.52 m, and 1.82 m, during 2023–2024, with onions stored for five months under controlled and ambient conditions, respectively, as shown in Figures 6 and 7, and assessed at 30 d intervals for physiological loss in weight, sprouting, rotting, and firmness.

a. 0.91 m

b. 1.21 m

c. 1.52 m

d. 1.82 m

Figure 6 Onion stored at different heights in ECOSS

a. 0.91 m

b. 1.21 m

c. 1.52 m

d. 1.82 m

Figure 7 Onion stored at different heights in TOSS

3.1.1 Physiological weight loss (PLW)

Initial and final weights of bulb samples were measured at three replicate points during storage using a digital weighing balance with 0.01 g accuracy, as described by Murumkar et al.[20] Weight loss was calculated using Equation 2.

$$\text{Physiological weight loss}(\%) = \frac{(\text{Initial weight} - \text{Final weight}) \times 100}{\text{Final weight}} \tag{2}$$

3.1.2 Rotting losses

The weight of the rotted bulbs at the end of the storage period was recorded and calculated by Equation 3[5].

$$\text{Rotting losses}(\%) = \frac{\text{Weight of rotted onion bulbs} \times 100}{\text{Initial weight of onion bulbs}} \tag{3}$$

3.1.3 Sprouting losses

The sprouting percentage was determined on the stipulated days after storage; bulbs showing a sprout were separated from the bag and weighed on an electronic balance. The sprouting percentage, which indicated the weight of the bulbs sprouted on days after storage, was calculated by using the Equation 4 given below[5].

$$\text{Sprouting losses}(\%) = \frac{\text{Weight of sprouted onion bulbs} \times 100}{\text{Initial weight of bulbs}} \tag{4}$$

3.1.4 Firmness

The puncture (penetration) load/strength was determined using a Stable Micro Systems TMS-Pro Texture Analyzer. The P/4 needle (4.0 mm diameter) probe was used to measure the puncture resistance of the onion bulb. Individual onion bulbs were supported at an angle (45° from the polar axis) so as to enable the probe to penetrate the onion through the shoulder. The force required to penetrate the onion was recorded. Five replications were done[3].

3.1.5 Statistical analysis

The data obtained in the study were statistically analyzed by Factorial Completely Randomized Design, and the data were analyzed by ANOVA at a level of significance $p<0.05$ using the mean significant value. The analysis of variance (ANOVA) and mean values for different process parameters were tabulated, and the level of significance between various treatments was recorded.

4 Results

4.1 Fan selection and performance of evaporative cooled system

Initially, the study calculated CFM for the selection of the proper fan size and number of fans for working out evaporative cooling in the structure[21]. The total area of the structure as well as the number of air cycles required for proper ventilation were calculated as follows.

Dimensions of the newly designed onion storage structure:

Volume of storage structure = Length × Width × Height = 3396.47 m^3 where, length of storage structure was 42.30 m, width of storage structure was 17.57 m, and height of storage structure was 4.57 m.

By considering the economics, initial cost, and size of compartment, we selected a fan with a capacity of 594.65 m^3/min and a number of air cycles per min taken as 62 on a trial-and-error basis[21].

As per Supreme Equipments Pvt. Ltd., Nashik, Maharashtra, India, the company’s recommendations were four cooling pads per fan; therefore, 24 cooling pads were installed in the ECOSS structure. In contrast, the TOSS structure was not equipped with cooling fans and pads to control temperature and relative humidity during storage.

During storage of onion bulbs in ECOSS and TOSS, temperature and RH were recorded both inside and outside the structures, as listed in Table 2. In the summer season (May and June), outside temperatures ranged from 35.5°C to 37.4°C, with RH between 47.1% and 50.3%. During the rainy season (July to September), outside temperatures ranged from 30.5°C to 30.9°C, with RH between 55.8% and 76.9%. Similar temperature and RH conditions were observed in TOSS throughout the storage period. However, inside the ECOSS, temperature and RH were continuously monitored and controlled using sensors, an evaporative cooling system, and an electronic controller, maintaining temperatures between 24.5°C to 25.4°C and RH between 65.1% to 71.4%. These controlled conditions in the ECOSS align with the recommended parameters for prolonging the shelf life and preserving the quality of onion bulbs.

Table 2 Variation in temperature and RH during storage study

Month	Year	Inside temp/°C	Inside RH/%	Outside temp/°C	Outside RH/%
May	2023	25.2	67.4	36.4	47.8
	2024	24.8	66.3	37.4	47.1
June	2023	25.1	65.2	35.5	50.3
	2024	25.4	66.2	37.1	49.8
July	2023	24.7	67.1	32.4	53.2
	2024	25.1	65.1	33.5	55.8
August	2023	25.2	71.4	31.4	76.8
	2024	24.5	70.4	33.4	76.2
September	2023	25.2	69.2	30.9	76.9
	2024	25.1	70.5	32.3	74.2

4.2 Effect of ECOSS and TOSS on the quality parameters of the onion bulb

The study investigated various quality parameters of onion bulbs, including physiological weight loss, rotting, sprouting, and firmness, during storage in ECOSS and TOSS. These parameters were monitored over a five-month period from May to September, with storage heights of 0.91, 1.21, 1.52, and 1.82 m, as shown in Table 3. Across all parameters and storage heights, the results consistently indicated that ECOSS outperformed TOSS.

Table 3 Effect of storage height on total capacity of storage structure, good bulbs selling (%), and net profit (INR/t) after five months of storage for ECOSS and TOSS

Parameter	ECOSS				TOSS			
	0.91 m	1.21 m	1.52 m	1.82 m	0.91 m	1.21 m	1.52 m	1.82 m
Total capacity of storage structure/t	144	192	233	280	144	192	233	280
Good bulbs selling/%	123.17	160.10	188.36	235.94	110.23	142.71	143.27	166.25
Net profit/INR·t^{-1}	5879	5952	6021	5960	5004	5220	2553	1967

The results show significant differences in PLW across storage heights, storage periods, and their interaction, as indicated by the *p*-values (p<0.01). Furthermore, the replicated data showed that these factors also had statistically significant effects on PLW. At all storage heights, ECOSS consistently exhibited lower weight loss (PLW) compared to TOSS. At 0.91 m, ECOSS weight loss increased from 2.01% in May to 7.89% in September, while TOSS increased from 3.70% to 15.23%. At 1.21 m, ECOSS rose from 2.28% to 8.68%, whereas TOSS escalated from 4.33% to 16.33%. At 1.52 m, ECOSS increased from 3.52% to 11.91%, in contrast to TOSS, which surged from 5.96% to 30.62%. At 1.82 m, ECOSS grew from 3.99% to 13.29%, while TOSS experienced a sharp rise from 7.18% to 34.91% as detailed in Table 4 and Figure 8. These results clearly demonstrate that ECOSS is more effective in minimizing physiological weight loss of onions during storage across all heights and over the entire storage duration, with the disparity between ECOSS and TOSS becoming more pronounced with increased storage time and height.

Table 4 Effect of storage height, storage month, and type of storage structure on PLW (%), sprouting (%), rotting (%), and firmness (N) for ECOSS and TOSS

Height/m	Month	ECOSS				TOSS			
		PLW/%	Sprouting/%	Rotting/%	Firmness/N	PLW/%	Sprouting/%	Rotting/%	Firmness/N
0.91	May	2.01±0.26^{Dex}	0.00±0.00^{Dex}	0.00±0.00^{Dex}	21.29±1.650^{Aex}	3.70±1.27^{Dey}	0.87±0.21^{Dey}	1.23±0.45^{Dey}	21.42±1.004^{Aex}
	June	2.92±0.17^{Ddx}	1.10±0.28^{Ddx}	0.51±0.52^{Ddx}	20.02±0.643^{Adx}	5.68±0.39^{Ddy}	2.13±0.55^{Ddy}	2.67±0.48^{Ddy}	20.34±1.287^{Adx}
	July	3.80±0.11^{Dcx}	1.95±0.59^{Dcx}	1.46±0.85^{Dcx}	19.44±0.014^{Acx}	8.72±1.32^{Dcy}	3.93±0.53^{Dcy}	4.12±0.81^{Dcy}	18.47±1.336^{Acy}
	August	5.03±0.44^{Dbx}	4.02±1.53^{Dbx}	2.84±0.62^{Dbx}	18.31±1.061^{Abx}	11.57±0.75^{Dby}	5.96±0.86^{Dby}	6.08±0.94^{Dby}	17.20±1.096^{Aby}
	September	7.89±0.00^{Dax}	5.40±0.30^{Dax}	3.56±0.55^{Dax}	16.73±2.425^{Aax}	15.23±0.67^{Day}	7.58±0.85^{Day}	8.34±0.82^{Day}	15.74±1.372^{Aay}
1.21	May	2.28±0.43^{Cex}	0.00±0.00^{Cex}	0.00±0.00^{Cex}	21.3±0.198^{Bex}	4.33±1.14^{Cey}	1.27±0.38^{Cey}	1.85±0.53^{Cey}	20.80±0.919^{Bex}
	June	3.89±0.20^{Cdx}	1.15±0.28^{Cdx}	1.03±0.19^{Cdx}	20.21±0.071^{Bdx}	7.14±1.81^{Cdy}	2.79±0.14^{Cdy}	3.42±0.51^{Cdy}	18.92±0.707^{Bdy}
	July	4.74±0.41^{Ccx}	2.47±0.68^{Ccx}	1.60±0.60^{Ccx}	19.01±0.629^{Bcx}	10.05±0.39^{Ccy}	4.54±1.24^{Ccy}	5.17±0.48^{Ccy}	17.62±1.124^{Bcy}
	August	6.94±0.16^{Cbx}	4.85±1.53^{Cbx}	3.57±0.72^{Cbx}	18.22±0.035^{Bbx}	12.49±0.11^{Cby}	6.70±1.36^{Cby}	7.83±0.19^{Cby}	17.02±0.184^{Bby}
	September	8.68±0.30^{Cax}	6.30±1.27^{Cax}	5.18±0.41^{Cax}	15.52±0.856^{Bax}	16.33±1.44^{Cay}	9.24±0.55^{Cay}	10.26±0.61^{Cay}	14.78±0.870^{Bay}
1.52	May	3.52±0.14^{Bex}	0.00±0.00^{Bex}	0.00±0.00^{Bex}	20.46±0.014^{Cex}	5.96±1.42^{Bey}	1.11±0.22^{Bey}	2.08±0.34^{Bey}	20.65±1.075^{Cex}
	June	5.50±0.38^{Bdx}	1.43±0.69^{Bdx}	1.10±0.11^{Bdx}	19.57±0.007^{Cdx}	9.08±0.50^{Bdy}	3.70±1.84^{Bdy}	4.35±0.87^{Bdy}	18.78±1.916^{Cdx}
	July	7.48±0.63^{Bcx}	2.55±0.91^{Bcx}	2.05±0.16^{Bcx}	18.75±0.431^{Ccx}	15.29±0.71^{Bcy}	6.04±0.55^{Bcy}	7.12±0.43^{Bcy}	17.19±0.247^{Ccy}
	August	9.27±0.31^{Bbx}	6.26±1.51^{Bbx}	4.67±0.75^{Bbx}	18.02±0.707^{Cbx}	23.19±1.100^{Bby}	8.34±0.11^{Bby}	9.58±0.92^{Bby}	16.11±0.445^{Cby}
	September	11.91±0.79^{Bax}	9.23±0.81^{Bax}	7.23±0.91^{Bax}	15.14±0.403^{Cax}	30.62±1.28^{Bay}	12.08±1.22^{Bay}	13.45±0.86^{Bay}	14.09±0.170^{Cay}
1.82	May	3.99±0.51^{Aex}	0.00±0.00^{Aex}	0.00±0.00^{Aex}	20.80±0.636^{Dex}	7.18±1.24^{Aey}	1.85±0.68^{Aey}	2.67±0.41^{Aey}	19.05±0.714^{Dey}
	June	5.92±0.89^{Adx}	1.58±0.44^{Adx}	1.33±0.20^{Adx}	19.74±0.255^{Ddx}	11.17±0.30^{Ady}	4.24±0.59^{Ady}	5.03±0.28^{Ady}	17.91±0.926^{Ddy}
	July	7.98±0.14^{Acx}	3.10±0.13^{Acx}	2.43±0.86^{Acx}	18.94±0.693^{Dcx}	17.10±0.65^{Acy}	6.44±1.49^{Acy}	7.89 ± 0.82^{Acy}	16.33±0.368^{Dcy}
	August	10.42±0.10^{Abx}	7.45±0.21^{Abx}	4.86±0.17^{Abx}	17.55±0.007^{Dbx}	28.46±1.48^{Aby}	9.69±0.71^{Aby}	11.24±0.74^{Aby}	15.22±0.007^{Dby}
	September	13.29±0.45^{Aax}	10.01±0.25^{Aax}	8.63±0.64^{Aax}	14.68±0.587^{Dax}	34.91±1.48^{Aay}-	15.39±0.57^{Aay}	13.62±0.45^{Aay}	13.99±0.057^{Day}

Note: means±SD with different superscripts ^{A}-^{D} indicate significant differences among heights within same month and storage type, ^{a}-^{e} among months within same height and storage type, and ^{x}-^{y} between storage structures for same height and month (p<0.05).

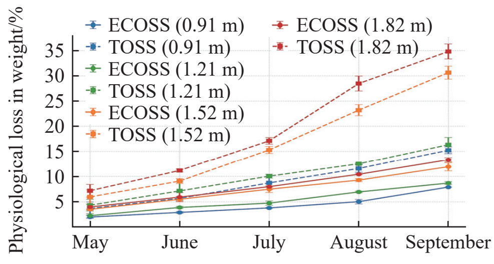


Figure 8 PLW in ECOSS and TOSS across months by storage height

As indicated by the p-values ($p<0.01$), storage height, storage duration, and their interaction significantly influenced the sprouting of stored onions. At a height of 0.91 m, ECOSS showed lower sprouting rates, increasing from 0 in May to 5.40% in September, while data for TOSS at this height were 0.87% to 7.58%. At 1.21 m, ECOSS sprouting rose from 0 to 6.30%, whereas TOSS increased from 1.27% to 9.24%. At 1.52 m, ECOSS saw sprouting rates climb from 0 to 9.23%, while TOSS escalated from 1.11% to 12.08%. At 1.82 m, ECOSS sprouting increased from 0 to 10.01%, in contrast to TOSS, which surged from 1.85% to 15.39% as detailed in Table 4 and Figure 9. The results indicate that sprouting is minimal in May but increases significantly over the storage period for both structures, with TOSS consistently exhibiting higher rates of sprouting across all heights. This trend becomes more pronounced with increased storage time and height, suggesting that ECOSS is more effective in inhibiting the sprouting of onions during storage.

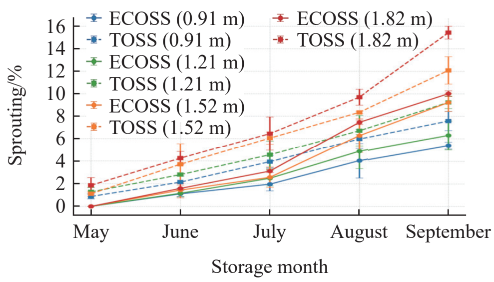


Figure 9 Sprouting in ECOSS and TOSS across months by storage height

As indicated by the p-values ($p<0.01$), storage height, storage duration, and their interactive effects significantly influenced the rotting of the stored onions. At all heights, ECOSS consistently exhibited lower rotting rates than TOSS. At 0.91 m, rotting in ECOSS increased from 0 in May to 3.56% in September, while TOSS increased from 0 to 6.67%. At 1.21 m, ECOSS rose from 0 to 5.18%, and TOSS from 0.38% to 7.81%. At 1.52 m, ECOSS saw an increase from 0 to 7.23%, in contrast to TOSS, which surged from 0.49% to 10.68%. At 1.82 m, ECOSS grew from 0 to 8.63%, while TOSS experienced a substantial rise from 1.09% to 13.62% as detailed in Table 4 and Figure 10. The results clearly indicate that ECOSS is more effective in minimizing onion bulb rotting during storage across all heights and over the entire duration from May to September. This effectiveness is attributed to the controlled environment in ECOSS, which likely maintains lower humidity and temperature than TOSS, thereby more effectively inhibiting the rotting process. The disparity in rotting rates between ECOSS and TOSS becomes more pronounced with increased storage time and height.

The statistical analysis of the replicated data revealed highly significant differences in firmness ($p<0.01$) by storage height, storage period, and their interaction. At all levels and all months, firmness of onions was lowered over the period of storage at both structures, but at all heights, the level of the firmness was slightly higher in ECOSS than in TOSS, as detailed in Table 4 and Figure 11. At the 0.91 m storage height, bulb firmness in the ECOSS decreased from an initial value of 21.29 N in May to 16.73 N in September. Similarly, firmness in the TOSS fell from 21.42 N in May to 15.74 N in September. At a storage height of 1.21 m, bulb firmness in the ECOSS decreased from 15.85 to 15.52 N, while in the TOSS, it dropped from 16.64 to 14.78 N. In the 1.52 m height, ECOSS firmness reduced from 20.46 to 15.14 N, compared to a reduction from 20.65 to 14.09 N in the TOSS. Finally, at the 1.82 m storage height, firmness in the ECOSS fell from 20.80 to 14.68 N, whereas the TOSS firmness decreased from 19.05 to 13.99 N. These findings show that ECOSS performs better than the others in maintaining the onion bulbs' firmness during storage, both at all the heights and throughout the five-month period, probably because of its constant storage temperatures that counter the conditions that cause the firmness to be lost.

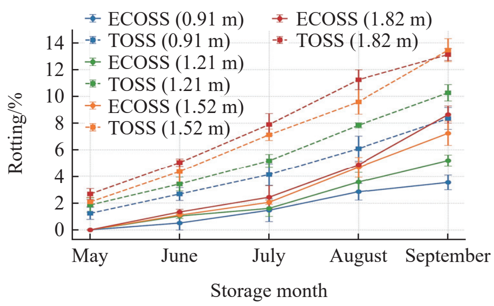


Figure 10 Rotting in ECOSS and TOSS across months by storage height

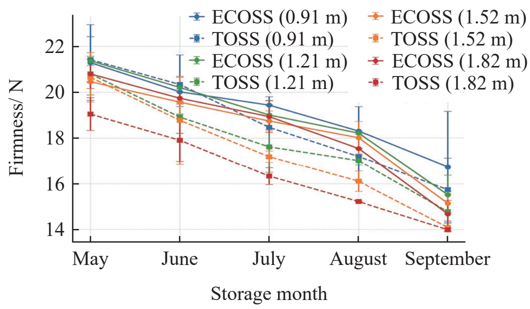


Figure 11 Firmness in ECOSS and TOSS across months by storage height

4.3 Comparative study between ECOSS and TOSS

In the study, the storage performance between ECOSS and TOSS at varied heights was compared as in Table 4. Both ECOSS and TOSS compartments contained 144 t of onions in the case of a structure that was 0.91 m high, and the capacity rose to 280 t in the case of a 1.82 m-high structure. In the ECOSS, the physiological loss in weight was 7.89% and 8.68% at the 0.91 m and 1.21 m heights, respectively. Also, PLW in the 1.82 m height was significantly higher, with 13.29% in ECOSS and 34.91% in TOSS, as detailed in Table 4 and Figure 8. The loss due to sprouting and rotting was also in the same trend: 0.91 m ECOSS and TOSS structures had 5.40% and 7.58% (sprouting) and 3.56% and 6.67% (rotting) loss respectively, whilst the 1.21 m structures had 6.30% and 9.94% (sprouting) and 5.18% and 7.82% (rotting) loss in ECOSS and TOSS respectively, as detailed in Table 4, Figure 9, and Figure 10. In the 1.82 m height, the higher sprouting and rotting losses were found in both structures, 10.01% and 15.39% (sprouting) and 8.63% and 13.62% (rotting), respectively, indicating that larger structures suffered higher losses.

The final yield of marketable bulbs varied depending on the storage height. The ECOSS structures retained 123.1 t and 160.10 t of sellable bulbs at the 0.91 m and 1.21 m heights, respectively. Although the overall percentage of sellable bulbs generally decreased in taller structures, the ECOSS consistently outperformed the TOSS in total marketable yield. Specifically, at the 1.52 m height, the ECOSS yielded 188.36 t compared to 143.27 t in the TOSS, and at the 1.82 m height, the ECOSS retained 235 t compared to 166.25 t in the TOSS, as detailed in Table 3.

The study revealed that, among all treatments, ECOSS with a storage height of 1.52 m resulted in the highest net profit of INR6021/t, with the lowest losses, followed by the 1.82 m height, which achieved a net profit of INR5960/t. In contrast, TOSS recorded significantly lower net profits of INR2553/t and INR1967/t for 0.91 m and 1.82 m heights, respectively, as detailed in Table 3. The statistical analysis and economic demonstration of the ECOSS at 1.52 m storage height minimized physiological loss in weight (PLW) to 10.43% and exhibited superior firmness of 15.14 N. Additionally, sprouting and rotting losses were reduced to 9.23% and 7.22%, respectively, by the end of the storage period.

5 Discussion

Storage conditions play an important role in maintaining the quality and shelf life of onion bulbs. Onions are vulnerable to changes in temperature and humidity levels, and this might result in spoilage unless temperature and humidity levels are maintained appropriately. The fact that ECOSS was able to sustain lower temperatures and higher, more stable humidity than outside is important. Summer temperatures soared, and the RH levels were so high that they had the potential of causing dehydration and rotting of the onion bulbs. The rainy season, on the other hand, combined lower temperatures with significantly higher RH, which may encourage mold growth and humidity-related problems.

The ECOSS mitigated external variability by providing a controlled environment by maintaining a balance of temperature and humidity. Warm temperatures in the storage building may make onions have a greater respiration rate, an outcome that may lead to the loss of onion propagation through loss of moisture, and consequent development of soft, moldy, and rotten onions; too low temperatures may result in sprouting, darkening, softness, and decay. Thus, it is important to keep proper and constant temperature to maintain the quality and shelf life of onions. Based on current literature, there is a recommended temperature range of 25ºC-30ºC[5], which is the most suitable temperature for storing onions. ECOSS recorded internal temperatures of 24.5ºC-31.3ºC, with an average of 27.1ºC. The ideal range of RH during onion storage is from 65% to 75%[5], and the facility developed by the ECOSS had the capability to control and maintain the RH at a fixed level, with minimum and maximum values ranging between 63.7%-67.2% and 74.1%-75.5%, respectively, providing the same level of storage environment within the course. These factors minimize the speed of the metabolism of onions, which slows the respiration, as well as postponing sprouting and decay[8].

Onions showed higher PLW when used in TOSS than in ECOSS, and PLW also depended on storage height. This might be due to the fact that the 0.91 m height compartment was smaller in terms of storage space, hence imparting less weight on the onions packed below. Consequently, the bottom-placed onions were not pressurized and did not spoil, but rather attained sufficient ventilation, unlike in the cases where the height of the compartment was 1.21 m, 1.52 m, and 1.82 m. The high temperatures and long storage time could cause higher respiration rates, causing greater moisture loss of the onions and an increase in PLW[22]. According to Adu et al.[21], storing onion bulbs in a forced-air ventilated storage bin for six months significantly improved their quality. Past researches support the trend in PLW with storage period. It could also be concluded that longer storage of onions caused more PLW[23]. Likewise, Dabhi and Patel[24] reported that the onions stored in the top, middle, and bottom layers of forced-ventilated storage structures recorded PLW values of 9.49%, 9.51%, and 11.73%, respectively. According to Tripathi et al.[5], prolonged storage duration exacerbates onion weight loss, primarily due to ongoing variations in environment temperature and relative humidity. Within the structure, the onions at the top of the compartment likely experienced greater transpiration due to increased air circulation, resulting in lower moisture content. This observation goes in line with another study by Dabhi and Patel[12], in which they had noted that the moisture levels of onions stored at the top had reduced. One can also refer to the aging of the onions, which makes their cells lose the ability to be liquid water pockets, which leads to the loss of moisture because of the process[8]. This shows that the findings of this study are consistent with a past study by Siddiqui, who noted a decrease in onion moisture content during storage.[11], in which they stated that there was a reduction in the moisture content of the onions during storage[8,25].

Onion sprouting steadily increased across all compartments as the storage period progressed. This result is in line with the prior research works on onion storage, which also found that storing the onion over a prolonged period may induce more sprouting due to fluctuations in physiological and metabolic reactions in onions[8]. The proportion of sprouting further increased with time, which can be explained by the spontaneous development of onions to the end of the dormancy stage, resulting in the sprouting and later deterioration of quality[26]. Similarly, as the compartment height was increased, the percentage of sprouting also increased. This could be attributed to temperature and moisture differences across height within the storage structure, which may influence onion dormancy and germination. The thickness of the onion piles are increased, which may lead to faster sprouting of the stored onions. Several kinds of stress-wounds, exposure to extreme temperatures like cold shock, or heat shock, also play a role in initiating sprouting. These results are comparable to those of other studies conducted by Dabhi et al.[5]. However, the sprouting percentage of onions in the present study was observed to be 5.40%-10.01%, demonstrating a lower incidence of sprouting compared to the findings of Vethamoni et al., who reported sprouting levels up to 16.96%[27].

The lowest sprouting was observed at the 0.91 m storage height of the compartment, which can be attributed to low relative humidity, which reduced sprouting and also improved air movement amongst the bulbs pile, which probably reduced the sprouting and prolonged the dormancy period[28]. In contrast, the highest sprouting (15.39%) was observed in the 1.82 m storage height of the traditional storage structure by the end of the storage period, as shown in Figure 9. This might be due to the temperature, relative humidity fluctuations, and poor ventilation, which could result in the buildup of humidity pockets within the onion pile, helping to promote sprouting and sustain the continued, more vigorous growth of these sprouts[5].

Kleman et al.[29] found that sprouting in onions is initiated by the induction of cytokinins with the reduction of the concentration of abscisic acid and stress, due to wounds, cold or heat shock[28]. Furthermore, an extended storage period has been shown to enhance endogenous enzyme activity, thereby promoting the sprouting of onions[30,31].

There are several factors that contribute to this decrease in firmness over time, including changes in cellular composition, respiration loss, and alterations to cell wall components[25]. One of the main factors is PLW, which can occur during storage due to the natural respiration of onions. Moreover, handling practices can also impact respiration rates and ultimately affect onion firmness[21,32]. A significant decrease in bulb firmness was observed across all storage compartments in the traditional storage structure over the five-month storage. Similar results were obtained by Tripathi et al.[22] and Ríos-González et al.[33] observing a decrease in firmness over time.

The percentage of rotting increased with increasing compartment height across all storage periods of 1-5 months. The onions stored in higher compartments, with heights of 1.82 m and 1.52 m, showed higher rotting percentage, 8.63% and 7.23% respectively, compared to those stored in compartments with heights of 0.91 m and 1.21 m, 3.56% and 5.18% respectively, as shown in Figure 10. This could be attributed to differences in temperature, humidity, and air circulation within the storage structure at different compartment heights. The air circulation in higher compartments is poor, it is more humid, and the temperatures are warm, making it possible to enhance rotting and sprouting of onions[24]. On the same note, Tripathi and Lawande[5] found that after four months, onions stored at 25ºC-30ºC and 65%-70% relative humidity experienced a high rotting rate of 10.04%. In contrast, onions subjected to cold storage at 0ºC-2ºC and 65%-70% relative humidity, followed by ambient post-storage conditions, showed a rotting rate of only 4.44%. Bacterial soft rots occur and add to the losses incurred in stored onion bulbs[6]. Onion rots showed a significantly high frequency that was highly determined by the environmental conditions and the age of the bulbs[29]. The increased level of rotting may be attributed to the elevated levels of water content and thick necks with succulent fleshy parts in the onions, which have exposed them to infection by pathogenic microorganisms, as indicated by Sami et al.[34]. The high relative humidity in the course of the storage period was the cause of the high percentage of rots of the onion bulbs as reported by Rangari et al.[35] and Joshi et al.[30]. These findings are aligned with results presented by Mota et al.[36] that the onion bulbs are highly prone to rotting even in storage, a factor that is primarily attributed to development of pathogens that thrive in areas or environments that have excessive moisture and high humidity[5]. Similarly, Vethamoni and Gomathi[27] recorded a higher rotting percentage (10.25%) when onions were stored for 90 d under ambient conditions.

On a final note, the ECOSS is an efficient onion storage system, as it maintains the bulbs in a relatively stable environment, thereby extending their shelf life and preserving their quality. This technology would be especially useful in areas situated in an extreme climate, since it can reliably minimize post-harvest losses and increase the efficiency of the onion supply chain.

6 Conclusions

The given research was oriented on designing, developing, and testing the performance of an ECOSS. The results were that the ECOSS was able to ensure an even temperature and relative humidity, which are the keys to onion quality and inhibition of spoilage. When compared with the conventional storage techniques, ECOSS recorded a significant reduction in physiological losses in weight loss, sprouting, and rotting, as well as an increase in the firmness and the nutritional value of onions.

Economic analysis revealed that the ECOSS is more economical than conventional structures and yields higher net profit, despite its higher construction cost. In general, this study concludes that the ECOSS is a feasible option to reduce post-harvest waste, enhance onion quality, and achieve healthier profits. Future studies should be directed towards the optimization of the storage conditions, the determination of the effect of long storage periods, and the investigation of the additional post-harvest practices that can be used to increase the preservation ability of onions.

Acknowledgments

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