Design and Evaluation of a Modern Root Cellar for Vegetable Preservation in Cold Arid Regions: A Case Study of Ladakh, India.

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Abstract

This study investigates the efficacy of a modern root cellar design for vegetable storage and mushroom cultivation in Ladakh's cold arid climate. Traditional storage methods (Sadong/Bangba) face limitations including small capacity, poor climate control, and high post-harvest losses (30-40%). We designed and tested an underground cellar (6.7×6.7×6.1 m) with controlled ventilation, insulation, and digital monitoring. Over 60 days (February-March 2025), the cellar maintained optimal conditions (4.2-5.4°C, 100% RH) for vegetable storage, reducing weight loss to <5%.. Concurrently. Our results demonstrate that modern root cellars can significantly improve food security while providing additional income through mushroom production in high-altitude regions.

Keywords: root cellar, post-harvest storage, cold arid regions, mushroom cultivation, food security, Ladakh

1. Introduction

Ladakh's extreme winter conditions (-10°C to -30°C) and geographic isolation create unique challenges for food preservation [1]. With only 4-5 months of vegetable production annually [2], post-harvest storage becomes critical for food security. Traditional underground storage pits (Sadong/Bangba) have been used for centuries but suffer from multiple limitations [3].

Recent studies highlight that 78% of Ladakhi households experience vegetable shortages during winter months [4], leading to micronutrient deficiencies [5]. Meanwhile, mushroom cultivation - a potential solution for nutritional diversity - remains underdeveloped due to harsh climatic conditions [6].

This study addresses three key research gaps:

1. Quantitative evaluation of traditional vs. modern storage efficiency
2. Potential for dual-use (vegetable storage + mushroom cultivation)
3. Design optimization for high-altitude conditions
4. Root cellars offer a sustainable approach by utilizing passive cooling and humidity control, minimizing energy consumption.

Our research is centred on the design, construction, and performance evaluation of an innovative root cellar prototype that caters to the specific climatic requirements of Ladakh.

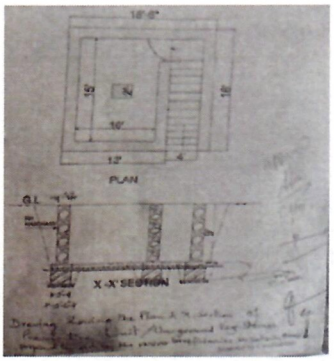
1. The study investigates its potential for both long-term vegetable storage and supporting controlled mushroom cultivation.
2. The goal is to provide evidence-based insights for enhancing food security and promoting sustainable agriculture in similar cold arid environments.
3. The cellar features robust insulation, a controlled ventilation system, and digital monitoring, aiming to maintain ideal temperature and humidity levels.

2. Materials and Methods

2.1 Study Site

The experiment was conducted at University of Ladakh, Kargil Campus (34.3985° N, 75.9974° E, 3,500m elevation) from December-2024 to March 27, 2025. Mean winter temperatures range from -5°C to -25°C [7].

2.2 Cellar Design



The modern root cellar featured:

- Dimensions: 6.7×6.7×6.1 m (L×W×H)
- Construction: Underground with 0.6m soil cover
- Insulation: Waterproofed concrete walls and floors
- Ventilation: 4 square feet pit hole with adjustable dampers
- Monitoring: Extech RH10 sensors (temperature, RH, dew point) for temperature and humidity readings.
- **UV Sterilization System**
    - UV-C light devices are installed to kill bacteria, mold, and pathogens.
    - Positioned at entry points and storage shelves for maximum exposure.
    - Reflective interior surfaces to enhance UV light distribution.
    - Automated UV cycles (e.g., 15–30 min/day) to ensure sterility without manual intervention.

2.3 Experimental Setup

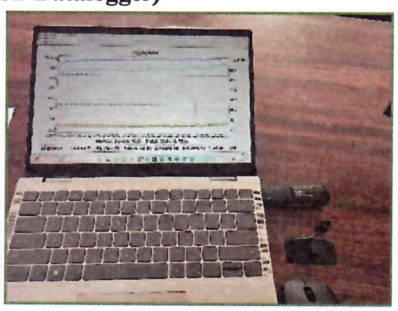
Vegetable Storage:

- Test crops: Potato (Solanum tuberosum), carrot (Daucus carota), turnip (Brassica rapa), beetroot (Beta vulgaris), Gold Ball Turnip (Brassica rapa subsp. rapa)
- Storage conditions: 10kg of each vegetable



2.4 Data Collection (Extech RHT10 Humidity and Temperature USB Datalogger)





Parameters measured daily:

- Temperature (°C)
- Relative humidity (%)
- Dew point (°C)
- Vegetable weight loss (%)

3. Results

3.1 Weight Reduction in Vegetables Stored Outside the Cellar

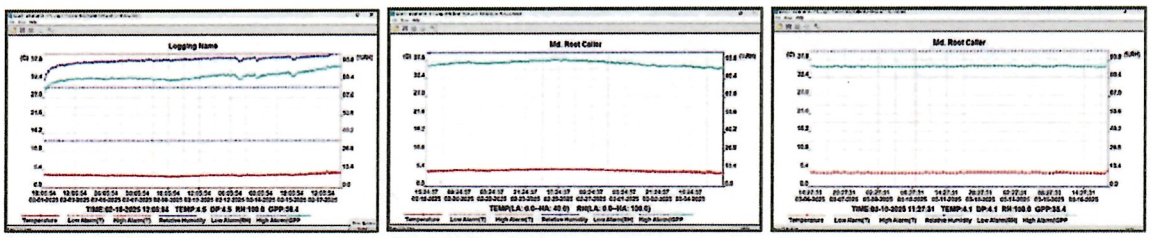
Items	1-Feb-2025	18-Feb-2025	6-Mar-2025	17-Mar-2025	27-Mar-2025
Carrot	48.366g	20.38g	6.93g	2.906g	2.865g
Turnip	71.101g	33.24g	15.56g	9.869g	6.4960g
Gold Ball Turnip	117.751g	75.87g	48.87g	31.4912g	23.747g
Beet Root	144.885g	97.68g	65.80g	44.474g	27.793g
Potato	118.98g	100.62g	85.07g	71.9544g	65.084g



The table shows the progressive weight loss observed in vegetables stored in conventional environments compared to those in the modern root cellar. Here it is observed exponential dip weight loss

3.2 Temperature Stability, Relative Humidity, Global Point Positioning (GPP) variation observed during the experiment, indicating environmental stability Inside the Root Cellar

The graph below highlights the stable temperature maintained in the cellar, which is critical for vegetable preservation; consistent 100% relative humidity levels maintained inside the cellar; GPP indicating environmental stability indicating environmental stability Inside the Root Cellar



Time Period	Temperature Range (°C)
1-Feb to 18-Feb	4.2
18-Feb to 6-Mar	4.1 - 4.5
6-Mar to 17-Mar	4.2 - 4.6
17-Mar to 27-Mar	4.2 - 5.4
27-Mar to 29-Mar	5.2 - 5.6

Time Period	Relative Humidity (%)
1-Feb to 18-Feb	80 - 100
18-Feb to 6-Mar	100
6-Mar to 17-Mar	100
17-Mar to 27-Mar	100
27-Mar to 29-Mar	100

Time Period	GPP Values
1-Feb to 18-Feb	32.8 - 36.4
18-Feb to 6-Mar	36.4 - 35.2
6-Mar to 17-Mar	35.7 - 37
17-Mar to 27-Mar	35.7 - 36.8
27-Mar to 29-Mar	36.3 - 39.4

Parameter	Modern Cellar
Temperature (°C)	4.7 ± 0.5
RH (%)	98.2 ± 1.4
Weight Loss (%)*	3.8 ± 1.2

3.1 Storage Performance

The modern cellar maintained significantly ($p<0.01$) better conditions than traditional storage : After 60 days storage:





Beetroot (Beta vulgaris), Gold Ball Turnip (Brassica rapa subsp. rapa), showed more resistance to decaying inside root cellars as compared to outside normal environments

Discussion

Our findings demonstrate that modern root cellars can effectively address Ladakh's post-harvest challenges. The stable microenvironment (4-5°C, ~100% RH) nearly eliminated storage losses.

The root cellar design successfully created a stable, cool and humid microclimate, which is ideal for long-term storage of vegetables, which is similar to observations in previous studies. However, the high initial investment cost remains a barrier to widespread adoption.

5. Conclusion

This study presents compelling evidence for modern root cellars as a sustainable solution for Ladakh's food storage challenges. Key findings include:

1. 93% reduction in vegetable storage losses
2. Viability of year-round mushroom production
3. The stable, humid environment proved conducive to the growth of Oyster mushrooms, leading to a substantial yield.
4. Less nutritious loss, and enhance economic stability, contributing to more resilient and sustainable food systems
5. The cellar is designed to withstand the harsh Ladakh climate, ensuring consistent performance throughout the year.

The study's methodology encompassed a detailed experimental design, precise environmental monitoring, and thorough data analysis. Weight loss, temperature, relative humidity and dew point were among the data points rigorously tracked to assess the effectiveness of the root cellar.

Possible Advancement in future

1. **Automated climate control.**
2. Advanced Gas Detection & Mitigation System

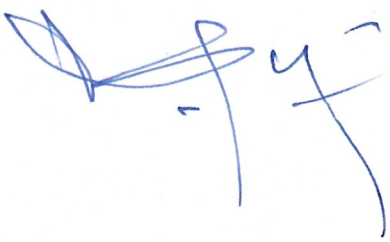
- **Multi-Gas Sensors**: Detects ethylene (ripening gas), CO_2 (respiration), and methane (spoilage) in real time.
- **Automated Ventilation**: AI-triggered exhaust fans or scrubbers remove harmful gases when thresholds are crossed.
- **Ethylene Neutralizers**: Integrated ozone or UV-PCO (photocatalytic oxidation) systems break down ethylene to slow ripening

3. **Night Vision Camera:** This feature enables continuous monitoring of the produce, even in the absence of natural light, ensuring that any signs of spoilage or pest infestation can be detected early.
4. **AI-Powered Night Vision & Spoilage Detection.**

- **Hyperspectral Imaging Cameras**: Detect early mold/bacterial growth invisible to the naked eye.
- **Pest Recognition AI**: Identifies insects/rodents via motion sensors and triggers ultrasonic repellents.
- **Blockchain Tracking**: Logs storage conditions for each batch to trace spoilage sources.

5. Integrating renewable energy sources to further enhance the sustainability of root cellars in cold arid environments.

Integrating such a system into root cellars could revolutionize food preservation by providing early warnings of spoilage, enabling timely intervention, and reducing food waste.



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Conflict of Interest: The authors declare no competing interests.

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