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Development of a Solar-Based Onion Storage Structure to Reduce Post-Harvest Losses: A Review

[1]Dilip R. Rangari, [2]Sandip S. Jawre, [3]Dr. Chandrakant B. Kothare, [4]Umesh N. Galat, [5]Poonam P. Tagade, [6]Abhijit A. Kanaskar, [7]Shubham Deulkar

[1,2,3,4,5,6,7]Department of Mechanical Engineering, Shri Shankarprasad Agnihotri College of Engineering, , Wardha, Maharashtra, India

[1]diliprangari54@gmail.com, [2]sandipjawre1991@gmail.com, [3]chandrakant.kothare@rediffmail.com, [4]galatumesh0@gmail.com, [5]pptagade@gmail.com, [6]abhijitkanaskar007@gmail.com, [7]shubhamdeulkarsd@gmail.com

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ABSTRACT

A significant problem that is affecting the small-scale farmers is post-harvest losses of onions, which is mostly caused by poor storage facilities and poor environmental conditions like high temperature and poor ventilation conditions. These aspects usually cause severe losses due to the moisture build up, sprouting and rotting of the stored onions. The paper under discussion demonstrates the design of a solar powered onion storage system that intends to enhance the ventilation of the storage facility, as well as the appropriate temperature and humidity levels inside the storage facility. The suggested system employs solar power to drive a ventilation system to increase circulation of air in the storage unit and to help eliminate excessive moisture within the storage unit. The system will strive to eliminate deterioration and increase the longevity of onions by having a more controlled storage environment. The storage facility is made with cheap and locally sourced materials and thus affordable and viable to be adopted by small-scale and rural farmers. The solar-powered storage system developed offers an energy efficient, sustainable yet cost effective solution to the reduction of post-harvest losses and enhancing the shelf-life and overall quality of onions in storage.

1. INTRODUCTION

Onion (Allium cepa L.) is one of the most widely cultivated and consumed vegetable crops in the world. It belongs to the family Amaryllidaceae and is valued for its culinary, nutritional, medicinal, and economic importance. Onion bulbs are rich in vitamins, minerals, antioxidants, and bioactive compounds that contribute significantly to human health and nutrition [2]. The crop is grown in more than 170 countries and is considered an essential ingredient in the daily diet of millions of people worldwide [3].

India is the second-largest producer of onions globally and contributes substantially to world onion production. Onion cultivation occupies a significant area under vegetable production, particularly in the states of Maharashtra, Karnataka, Madhya Pradesh, Gujarat, Rajasthan, and Andhra Pradesh [1,7]. Among these states, Maharashtra accounts for the largest share of onion production and is recognized as a major supplier to domestic and international markets [12]. Onion cultivation provides livelihood opportunities to millions of farmers and plays an important role in the agricultural economy of the country [10].

Although onion production has increased steadily over the years, substantial post-harvest losses continue to be a major concern. Post-harvest losses occur during harvesting, curing, handling, transportation, storage, and marketing of onion bulbs. Studies have reported that onion storage losses may range from 20 to 40 percent, depending on storage conditions, climatic factors, and storage duration [4,8]. The major causes of storage losses include sprouting, rotting, microbial infection, pest infestation, moisture accumulation, and physiological loss in weight [18,22].

Storage is an essential component of onion production because harvesting is concentrated during specific seasons, whereas market demand exists throughout the year [5]. Effective storage helps maintain bulb quality, ensures continuous market supply, prevents distress sales immediately after harvest, and enables farmers to obtain better prices during periods of lower availability [13,20]. Therefore, the development of efficient onion storage systems has become a priority for researchers, agricultural engineers, and policymakers.

Traditional onion storage structures used by farmers generally depend on natural ventilation and ambient environmental conditions. Although these structures are relatively inexpensive, they often fail to provide adequate control over temperature, relative humidity, and airflow [11,14]. In tropical and subtropical regions, high temperature and humidity conditions accelerate physiological deterioration, resulting in increased sprouting and rotting of onion bulbs [6,23]. Consequently, significant economic losses are incurred by farmers and traders due to poor storage performance.

Several improved onion storage structures have been developed by research organizations such as the National Horticultural Research and Development Foundation (NHRDF) to address these challenges [11,13]. These structures incorporate enhanced ventilation systems, elevated platforms, and improved construction materials to facilitate air circulation and reduce moisture accumulation. Research studies have demonstrated that improved storage structures can significantly reduce storage losses compared to conventional storage methods [8,20].

In recent years, renewable energy technologies have emerged as sustainable solutions for agricultural applications. Among various renewable energy sources, solar energy has gained considerable attention due to its abundance, environmental friendliness, and economic viability [5,17]. Solar photovoltaic (PV) systems convert solar radiation into electrical energy, which can be utilized to power fans, sensors, controllers, and monitoring equipment in agricultural storage facilities [19]. The utilization of solar energy reduces dependence on conventional electricity sources and supports sustainable agricultural development.

Solar-powered storage systems have shown promising results in preserving the quality of agricultural commodities by maintaining favorable storage conditions [17,19]. In onion storage applications, solar-powered ventilation systems can improve airflow within the storage structure and remove excess heat and moisture generated during storage [25]. Proper ventilation is critical for preventing condensation, reducing relative humidity, and minimizing the growth of spoilage microorganisms [22]. Consequently, solar-assisted storage systems contribute to lower physiological weight loss, reduced sprouting, and improved shelf life of stored onions [24].

Recent advances in agricultural engineering have facilitated the integration of smart technologies into storage systems. Internet of Things (IoT)-based monitoring systems, environmental sensors, and automated control units can continuously monitor temperature, humidity, and airflow within storage structures [16]. Such systems enable real-time data collection and automated operation of ventilation equipment, thereby ensuring optimal storage conditions with minimal human intervention. The combination of solar energy and intelligent monitoring technologies provides an efficient and sustainable approach to post-harvest management [21].

The development of solar-based onion storage structures is particularly important for rural areas where reliable electricity supply may not be available. Solar-powered systems can operate independently of the electrical grid and provide continuous ventilation using renewable energy [17]. Furthermore, these systems contribute to environmental sustainability by reducing greenhouse gas emissions and promoting clean energy utilization in agriculture [5,21].

Considering the magnitude of post-harvest losses in onion storage and the increasing need for sustainable agricultural technologies, the development of solar-based onion storage structures represents a promising solution. Such systems have the potential to improve storage efficiency, reduce economic losses, enhance farmer income, and strengthen food security. Therefore, this review focuses on the design, development, operation, and performance evaluation of solar-based onion storage structures aimed at reducing post-harvest losses and improving the overall sustainability of onion storage systems [8,17,25].

A. Need for the Study

Large quantities of onions are lost annually due to inadequate storage infrastructure and unfavourable storage conditions. Traditional storage structures often fail to maintain the required temperature, humidity, and ventilation levels, resulting in considerable post-harvest losses. The use of solar energy for operating ventilation and environmental control systems offers a sustainable, economical, and environmentally friendly alternative. Therefore, there is a need to develop solar-based onion storage structures capable of reducing storage losses and improving onion quality during long-term storage.

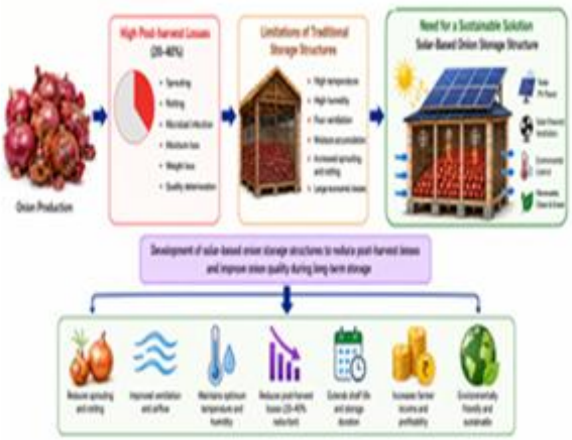

Figure 1: Need for the study

B. Objectives of the Study

1. To study the post-harvest losses occurring during onion storage.
2. To review existing onion storage technologies and structures.
3. To investigate the application of solar energy in agricultural storage systems.
4. To develop a solar-based onion storage structure for improved storage performance.
5. To evaluate the effects of temperature, humidity, and ventilation on onion storage.
6 To reduce sprouting, rotting, and physiological weight loss during storage.
7. To promote sustainable and energy-efficient onion storage technologies for farmers.

2. Importance of Onion Storage

Onion is one of the few vegetable crops that is consumed throughout the year irrespective of season and geographical location. However, its production is concentrated during specific growing seasons, resulting in a large quantity of produce entering the market immediately after harvest. During this period, market prices often decline substantially because of excess supply. In the absence of suitable storage facilities, farmers are compelled to sell their produce at lower prices, leading to reduced economic returns. Therefore, storage plays a crucial role in balancing seasonal production with year-round consumption requirements [5,13].

The primary objective of onion storage is to preserve bulb quality for an extended period while minimizing quantitative and qualitative losses. Proper storage allows onions harvested during peak production seasons to be made available during periods of lower production. This not only ensures a continuous supply of onions to consumers but also contributes significantly to market stabilization. By regulating the flow of produce into the market, storage helps prevent extreme fluctuations in prices and protects both producers and consumers from economic uncertainty [1,20].

Figure 2: Importance of Onion Storage

Another important aspect of onion storage is the reduction of post-harvest losses. Onion bulbs remain biologically active even after harvest and continue to undergo physiological processes such as respiration and transpiration. If storage conditions are not properly maintained, these physiological activities accelerate deterioration, resulting in weight loss, sprouting, rotting, and reduction in market quality. Scientific storage systems are designed to regulate environmental conditions and thereby reduce these losses significantly [4,22].Storage also enhances the profitability of onion cultivation. Farmers who have access to efficient storage facilities can delay marketing their produce until favourable market prices are available. Numerous studies have shown that onions stored under improved storage conditions generate substantially higher returns compared to onions sold immediately after harvest. Thus, storage serves not only as a preservation technique but also as an important economic tool for increasing farmer income and improving rural livelihoods [8,11].

From a national perspective, onion storage contributes significantly to food security and supply chain management. Since onion is an essential component of the daily diet of millions of people, ensuring its availability throughout the year is a matter of considerable importance. Effective storage systems reduce wastage, improve resource utilization, and support sustainable agricultural development. Consequently, the development of advanced storage technologies has become a priority area for researchers, policymakers, and agricultural engineers [21].

3. SOLAR ENERGY APPLICATIONS IN AGRICULTURAL STORAGE

Agriculture is one of the most energy-intensive sectors, requiring energy for irrigation, processing, drying, storage, transportation, and preservation of agricultural commodities. Conventional energy sources such as electricity generated from fossil fuels are becoming increasingly expensive and environmentally unsustainable. As a result, renewable energy technologies, particularly solar energy, have gained significant attention in agricultural applications. Solar energy is abundant, clean, renewable, and readily available in most agricultural regions, making it an ideal alternative energy source for farming operations and post-harvest management systems [5, 19, 21].

Post-harvest losses of fruits and vegetables remain a major challenge worldwide. These losses are particularly significant in developing countries where storage infrastructure is inadequate. Proper storage conditions are essential to maintain the quality, nutritional value, and marketability of agricultural produce. Solar energy-based storage technologies offer a sustainable solution by providing controlled environmental conditions without excessive dependence on grid electricity [4, 18, 22].

A. Solar Energy and Its Importance in Agriculture

Solar energy refers to radiant energy emitted by the sun that can be converted into thermal or electrical energy through various technologies. Agricultural sectors have increasingly adopted solar technologies due to their reliability, environmental benefits, and economic viability. Solar energy can be utilized for water pumping, greenhouse heating, crop drying, refrigeration, ventilation, and storage applications [5, 19].

India receives an average solar radiation of approximately 4–7 kWh/m^2 per day, making solar-based agricultural systems highly feasible throughout the year. The utilization of solar energy reduces dependence on fossil fuels, lowers greenhouse gas emissions, and promotes sustainable agricultural development [21]. Furthermore, solar-powered systems are particularly beneficial in rural areas where access to reliable electricity is limited.

B. Types of Solar Energy Technologies Used in Agricultural Storage

Solar energy applications in agricultural storage primarily involve solar thermal systems and solar photovoltaic (PV) systems.

1. Solar Thermal Systems: Solar thermal systems capture solar radiation and convert it into heat energy. The generated heat is utilized for drying agricultural products, maintaining suitable storage temperatures, and reducing moisture accumulation within storage structures. Solar air heaters are commonly employed in agricultural storage facilities to improve ventilation and maintain appropriate storage conditions [17].

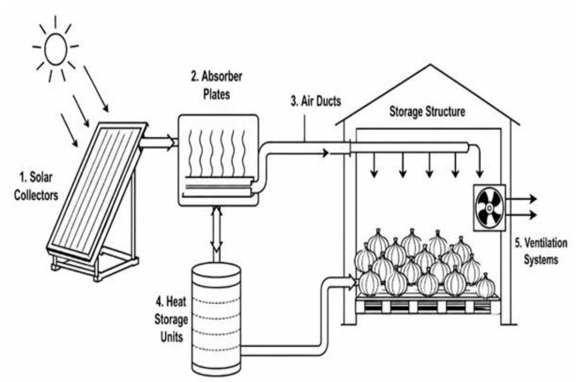

Figure 3: Solar Thermal System

These systems generally consist of:

- Solar collectors
- Absorber plates
- Air ducts
- Heat storage units
- Ventilation systems

Solar thermal technology can effectively reduce relative humidity and prevent microbial growth, thereby minimizing storage losses [5].

2. Solar Photovoltaic Systems: Solar photovoltaic systems directly convert sunlight into electrical energy using photovoltaic cells. The electricity generated can be used to operate fans, sensors, ventilation systems, monitoring devices, and refrigeration units in storage facilities [19]

The major components of photovoltaic systems include:

- Solar panels
- Charge controllers
- Batteries
- Inverters
- Electrical loads

Solar PV technology provides uninterrupted operation of storage systems, especially in remote agricultural regions lacking reliable grid connectivity [21].

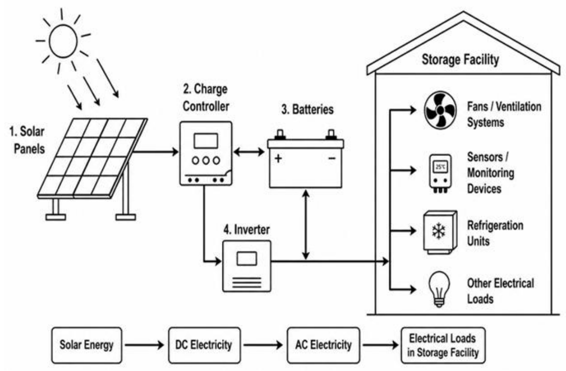

Figure 4: Solar Photovoltaic System

3. Solar-Powered Ventilation Systems:
Ventilation is a critical factor in agricultural storage because excessive heat and moisture accumulation can accelerate deterioration of stored produce. Solar-powered ventilation systems utilize electricity generated by photovoltaic panels to operate exhaust fans and air circulation devices [25].
Proper ventilation helps to:

- Remove excess moisture from storage structures.
- Reduce temperature fluctuations.
- Maintain uniform airflow.
- Minimize fungal and bacterial infections.

Prevent sprouting and rotting of stored bulbs [25].
Research has demonstrated that solar-powered ventilation systems significantly improve storage conditions while reducing energy consumption compared to conventional electrically powered systems [17].

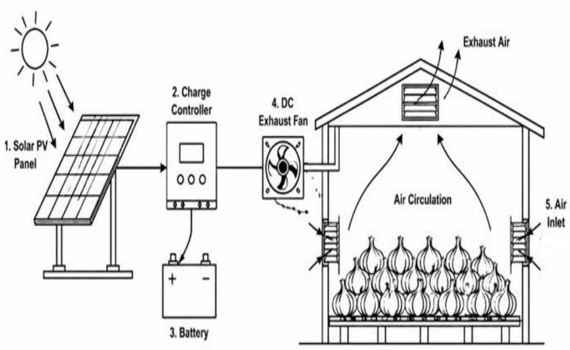

Figure 5: Solar-Powered Ventilation System

4. Solar-Based Storage Structures for Horticultural Crops: Several solar-assisted storage systems have been developed for horticultural crops including onions, potatoes, garlic, fruits, and vegetables. These structures incorporate solar panels, ventilation units, thermal insulation materials, and environmental monitoring devices to create favorable storage conditions [23].
The main objectives of solar-based storage structures are:

- Temperature regulation.
- Humidity control.
- Reduction of physiological losses.
- Prevention of microbial spoilage.

Enhancement of shelf life [4, 23].
Studies have shown that maintaining optimal temperature and relative humidity significantly reduces weight loss and quality deterioration during storage [9].

5. Application of Solar Energy in Onion Storage:
Onion bulbs are highly sensitive to storage conditions. Excessive temperature and humidity can lead to sprouting, rotting, and moisture loss. Therefore, maintaining proper ventilation and environmental control is essential for successful onion storage [10, 20].
Solar energy can be effectively integrated into onion storage systems through:

- Solar-powered ventilation fans.
- Solar air heating units.
- Solar-powered environmental monitoring systems.

Hybrid photovoltaic-thermal systems [17, 25].
The generated solar electricity operates ventilation fans that continuously remove warm and humid air from storage chambers. This process maintains favorable storage conditions and minimizes post-harvest losses [11]. Solar-assisted storage systems have demonstrated improved bulb quality retention and reduced spoilage compared to conventional storage methods [8, 15].

6. Smart Solar Storage Technologies: Recent technological advancements have enabled the development of smart storage systems integrating solar energy with Internet of Things (IoT) technologies. These systems continuously monitor environmental parameters such as temperature, humidity, carbon dioxide concentration, and airflow [16].

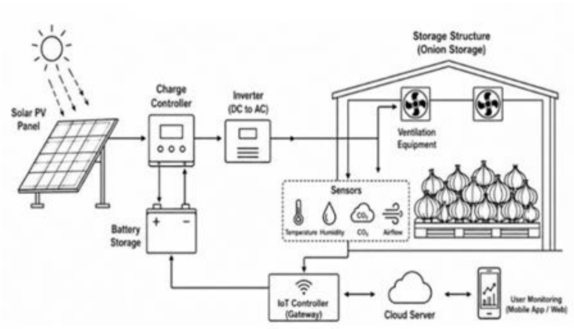

Figure 6: Smart Solar Storage System with IoT

Sensors collect real-time data and automatically regulate ventilation equipment powered by solar energy. Such automated systems improve storage efficiency, reduce labor requirements, and provide better control over storage conditions [16].

The integration of IoT and solar photovoltaic systems represents a promising approach for future onion storage structures, particularly in rural agricultural regions.

7. Advantages of Solar Energy in Agricultural Storage: The application of solar energy in agricultural storage offers numerous benefits:

- Renewable and environmentally friendly energy source.
- Reduction in operating costs.
- Improved storage conditions.
- Enhanced shelf life of agricultural produce.
- Reduced dependence on grid electricity.
- Lower greenhouse gas emissions.
- Suitable for remote rural locations.

Sustainable post-harvest management solution [5, 17, 19, 21].

These advantages make solar-based storage systems increasingly attractive for preserving horticultural commodities.

8. Limitations of Solar-Based Storage Systems:

Despite numerous benefits, solar storage technologies face certain challenges:

- High initial installation costs.
- Dependence on weather conditions.
- Requirement for battery storage systems.
- Periodic maintenance of solar panels and electrical components.

Limited awareness among farmers regarding renewable energy technologies [17, 21].

Addressing these limitations through technological improvements and government support can enhance the adoption of solar-powered storage systems in agriculture.

Solar energy has emerged as a sustainable and efficient solution for agricultural storage applications. Both solar thermal and photovoltaic technologies play significant roles in maintaining suitable storage environments for horticultural crops. In onion storage, solar-powered ventilation and environmental control systems help reduce post-harvest losses by minimizing sprouting, rotting, and moisture loss. Recent advancements in smart monitoring technologies further enhance storage performance and energy efficiency. Consequently, solar-based storage structures offer substantial potential for improving post-harvest management and ensuring long-term sustainability in agricultural production systems [5, 17, 19, 25].

4. Onion Storage Technologies

Onion (Allium cepa L.) is one of the most important vegetable crops cultivated worldwide and occupies a significant position in India's horticultural economy. India is among the leading producers of onion, contributing substantially to domestic consumption and export markets [1, 7]. However, onions are highly susceptible to post-harvest losses during storage due to physiological, pathological, and environmental factors. These losses may range from 20–40% depending on storage conditions, variety, and duration of storage [10, 13, 20].

Storage technology plays a vital role in preserving onion quality, extending shelf life, stabilizing market supply, and reducing economic losses. Effective storage systems are designed to minimize sprouting, rotting, moisture loss, and weight reduction while maintaining bulb quality for extended periods [2, 4, 9].

A. Storage Requirements of Onion Bulbs

Successful onion storage depends on maintaining appropriate environmental conditions. Onion bulbs continue to respire after harvest, resulting in moisture loss and biochemical changes. Therefore, storage structures should provide adequate ventilation and protection from excessive humidity and temperature fluctuations [6, 9].

The major storage requirements include:

- Proper curing before storage.
- Adequate ventilation and air circulation.
- Protection from rainfall and direct sunlight.
- Maintenance of low relative humidity.
- Prevention of fungal and bacterial infections.
- Reduction of sprouting and rooting [10, 20].

Environmental factors significantly influence onion storage performance. High temperatures and humidity levels accelerate sprouting, microbial growth, and physiological deterioration, leading to substantial storage losses [6].

B. Traditional Onion Storage Methods

Traditional onion storage systems are commonly used by farmers in developing countries due to their low construction cost and simplicity. These structures typically consist of bamboo, wooden poles, thatched roofs, and locally available materials [3].

Common traditional storage methods include:

1.Heap Storage: In this method, onions are stored in piles on the floor under sheds or open structures. Although easy to implement, heap storage often suffers from poor ventilation, resulting in heat accumulation and increased spoilage [3, 20].

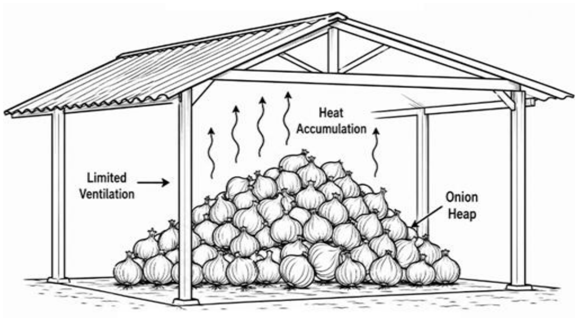

Figure 7: Heap Storage of onions

2.Rope and Hanging Storage: Farmers frequently tie onion bulbs into bunches and hang them from ceilings or support structures. This method provides better air circulation compared to heap storage but is suitable only for small-scale storage operations [2].

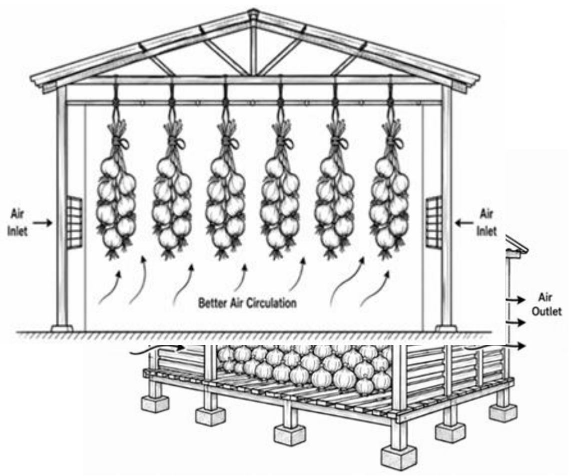

Figure 8: Rope and Hanging Storage of onions

3. Bamboo and Wooden Structures: Traditional ventilated structures constructed from bamboo or wood allow moderate airflow around stored bulbs. However, these systems offer limited control over environmental conditions and are susceptible to weather-related damage [3].

Although traditional methods are inexpensive, they generally result in higher storage losses due to inadequate environmental control [20].

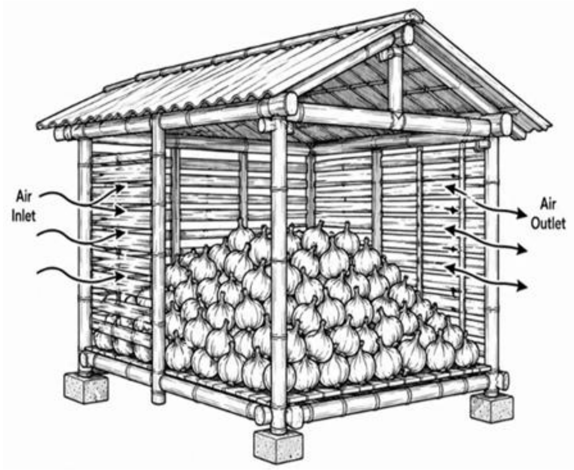

Figure 9: Bamboo and Wooden Storage Structure

C. Improved Onion Storage Structures

To reduce storage losses, several improved storage structures have been developed by agricultural research organizations and extension agencies. These structures are specifically designed to enhance ventilation and maintain favorable storage conditions [11, 14].

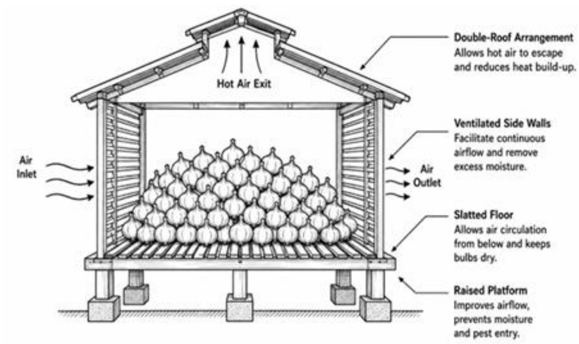

Figure 10: Improved Onion Storage Structure

Naturally Ventilated Storage Structures: Naturally ventilated structures utilize elevated platforms, side openings, and ventilated walls to facilitate continuous airflow. These systems help dissipate heat generated through respiration and reduce moisture accumulation [11].

Major design features include:

- Raised platform construction.
- Slatted floors.
- Ventilated side walls.
- Double-roof arrangements.

- Adequate spacing between bulbs [14].

Studies have shown that naturally ventilated storage structures significantly reduce storage losses compared to traditional storage methods [8].

1. NHRDF Improved Onion Storage Structures

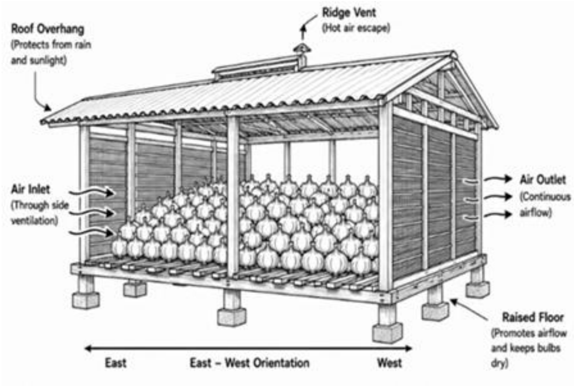

Figure 11: Improved Onion Storage Structures

The National Horticultural Research and Development Foundation (NHRDF) has developed improved onion storage structures widely adopted across India. These structures incorporate scientific design principles to maximize ventilation and minimize bulb deterioration [11, 14].

Key features include:

- Elevated storage floor.
- East-west orientation.
- Proper roof overhang.
- Adequate side ventilation.

Capacity ranging from small to commercial scale [11].

Research indicates that NHRDF structures can substantially reduce sprouting, rotting, and physiological weight loss during long-term storage [13].

D. Cold Storage Technologies

Cold storage systems provide precise control over temperature and humidity, significantly extending the storage life of onions. These facilities utilize refrigeration equipment to maintain low temperatures and suitable relative humidity levels [9, 22].

The advantages of cold storage include:

- Reduced respiration rate.
- Lower moisture loss.
- Delayed sprouting.
- Better preservation of bulb quality.
- Extended storage duration [4, 9].

However, cold storage facilities involve high capital investment, operating expenses, and energy requirements. Consequently, their adoption among small and marginal farmers remains limited [23].

E. Modern Controlled Environment Storage Systems

Recent technological advancements have led to the development of controlled environment storage systems that regulate temperature, humidity, and airflow using automated monitoring and control mechanisms [15].

These systems typically include:

- Environmental sensors.
- Ventilation systems.
- Humidity control devices.
- Automated control units.
- Data monitoring platforms [15].

Controlled environment storage significantly improves onion quality retention while reducing storage losses compared to conventional storage methods [24].

F. IoT-Based Smart Storage Technologies

The integration of Internet of Things (IoT) technology has revolutionized post-harvest management practices. IoT-based storage systems continuously monitor environmental parameters and automatically adjust storage conditions to maintain optimal preservation environments [16].

Key components include:

- Temperature sensors.
- Humidity sensors.
- Wireless communication modules.
- Cloud-based monitoring platforms.
- Automated ventilation controls [16].

These systems enable real-time monitoring and predictive management of storage conditions, improving storage efficiency and reducing labor requirements.

G. Solar-Assisted Onion Storage Technologies

The increasing focus on sustainable agriculture has encouraged the development of solar-assisted onion storage systems. These technologies combine renewable energy with improved storage structures to provide energy-efficient preservation solutions [17, 19].

Solar-assisted systems generally incorporate:

- Solar photovoltaic panels.
- Solar-powered ventilation fans.
- Environmental monitoring devices.
- Battery backup systems [25].

Solar-powered ventilation improves airflow within storage structures and helps maintain favorable temperature and humidity conditions. Such systems are particularly beneficial in rural areas where electricity supply is unreliable [17, 21].

Research has demonstrated that solar-assisted storage structures can effectively reduce post-harvest losses while minimizing operating costs and environmental impacts [25].

H. *Comparative Analysis of Onion Storage Technologies*

Different storage technologies vary in terms of cost, efficiency, storage duration, and management requirements.

Table 1: Comparative Analysis of Onion Storage Technologies

Storage Technology	Initial Cost	Storage Efficiency	Energy Requirement
Traditional Storage	Low	Low	None
Improved Ventilated Storage	Moderate	Moderate to High	None
Cold Storage	High	Very High	High
Controlled Environment Storage	Very High	Very High	Moderate to High
Solar-Assisted Storage	Moderate	High	Renewable Energy

Improved ventilated and solar-assisted storage systems offer a practical balance between affordability and storage performance, making them suitable for large-scale adoption among onion growers [8, 11, 15]. Onion storage technologies have evolved from simple traditional methods to advanced controlled-environment and solar-assisted systems. traditional storage methods remain widely used due to their low cost but often result in significant post-harvest losses. improved ventilated storage structures developed by organizations such as NHRDF have substantially enhanced storage efficiency. modern technologies, including cold storage, controlled environment systems, IoT-based monitoring, and solar-assisted storage, offer superior preservation performance and reduced losses. among these technologies, solar-assisted onion storage structures provide a promising and sustainable solution for reducing post-harvest losses while ensuring economic and environmental benefits [11, 15, 16, 25].

5. Design and Performance of Solar-Based Onion Storage Structures

Post-harvest losses in onion are primarily caused by sprouting, rotting, physiological weight loss, and deterioration resulting from unfavourable storage conditions. Conventional storage structures often fail to provide adequate environmental control, particularly in regions experiencing high temperature and humidity. Solar-based onion storage structures have emerged as a sustainable and energy-efficient solution for reducing post-harvest losses while maintaining bulb quality during extended storage periods [10, 11, 17].

Solar-assisted storage systems integrate renewable energy technologies with scientifically designed storage structures to provide controlled ventilation, temperature regulation, and humidity management. These systems are especially beneficial in rural areas where access to reliable electricity is limited [5, 19, 21].

A. *Design Considerations for Solar-Based Onion Storage Structures*

The design of a solar-based onion storage structure must ensure adequate ventilation, protection from environmental factors, and efficient utilization of solar energy. Several factors influence the design and performance of such systems [6, 20].

Important design considerations include:

- Storage capacity requirements
- Local climatic conditions
- Temperature and humidity management
- Airflow distribution
- Solar radiation availability
- Structural durability
- Economic feasibility
- Ease of operation and maintenance

The objective is to maintain an environment that minimizes moisture accumulation and heat build-up while ensuring continuous air circulation around stored onion bulbs [6, 9].

B. *Components of Solar-Based Onion Storage Structures*

Storage Chamber: The storage chamber serves as the main compartment for storing onion bulbs. It is generally constructed using materials that provide adequate strength, ventilation, and thermal protection. Raised platforms are commonly employed to prevent moisture migration from the ground and facilitate airflow beneath the stored produce [11, 14].

Essential features include:

- Elevated storage floor
- Ventilated side walls
- Adequate storage depth
- Weather-resistant roofing
- Easy loading and unloading arrangements

Solar Photovoltaic System: Solar photovoltaic (PV) panels convert solar radiation into electrical energy. The generated electricity is used to operate ventilation fans, environmental monitoring systems, and other electrical components within the storage structure [19].

Major PV system components include

- Solar panels
- Mounting structures
- Charge controller
- Battery bank
- Electrical wiring
- Inverter (if required)

The use of photovoltaic systems reduces dependence on conventional electricity and lowers operational costs [19].

Ventilation System: Ventilation is the most critical component of onion storage structures. Solar-powered fans facilitate continuous air movement through the stored onion mass, preventing heat accumulation and moisture condensation [25].

Functions of the ventilation system include:

- Removal of excess heat
- Reduction of relative humidity
- Prevention of fungal growth
- Maintenance of uniform storage conditions
- Reduction of sprouting and rotting

Proper ventilation significantly improves storage performance and extends the shelf life of onion bulbs [6, 25].

Environmental Monitoring System: Modern solar storage structures may incorporate sensors to continuously monitor storage conditions. These sensors provide information regarding:

- Temperature
- Relative humidity
- Airflow rate
- Carbon dioxide concentration

The collected data assists in maintaining optimal storage conditions and improving storage efficiency [16].

C. Working Principle of Solar-Based Onion Storage Structures

The operation of a solar-based onion storage structure begins with the conversion of sunlight into electrical energy through photovoltaic panels. The generated power is stored in batteries and supplied to ventilation fans and monitoring devices [17, 19].

During daylight hours, solar panels generate sufficient electricity to operate the ventilation system continuously. Air is drawn through ventilated sidewalls and circulated through the onion bulbs. Warm and humid air generated due to bulb respiration is expelled through exhaust openings.

The continuous circulation of fresh air helps maintain suitable storage temperature and relative humidity, thereby reducing physiological and microbial deterioration [25].

Simplified Working Flow.

Solar Radiation
↓
Solar PV Panel
↓
Charge Controller
↓
Battery Storage
↓
Ventilation Fans & Sensors
↓
Temperature and Humidity Regulation
↓
Reduced Onion Storage Losses

D. Performance Parameters of Solar-Based Onion Storage Structures

The effectiveness of a storage system is evaluated using several performance indicators.

Temperature Control: Temperature is a critical factor affecting onion storage life. Elevated temperatures accelerate respiration, sprouting, and moisture loss. Solar-powered ventilation systems help maintain lower and more uniform temperatures inside storage structures compared to conventional storage methods [6, 17].

Relative Humidity Control: Excessive humidity promotes microbial growth and bulb rotting. Continuous ventilation reduces moisture accumulation and maintains relative humidity within acceptable limits [4, 25].

Physiological Weight Loss: Weight loss occurs due to moisture evaporation and respiration. Improved airflow and environmental control significantly reduce physiological weight loss during storage [8, 20].

Sprouting Percentage: Sprouting reduces bulb quality and market value. Solar-assisted storage structures provide environmental conditions that delay sprouting and extend storage duration [13].

Rotting Losses: Proper ventilation reduces fungal and bacterial infections, thereby minimizing rotting losses during long-term storage [11].

E. Performance Evaluation of Solar-Based Onion Storage Systems

Several studies have reported improved performance of solar-assisted onion storage structures compared with traditional storage systems [8, 15].

Reported benefits include:

- Reduction in physiological weight loss
- Lower incidence of sprouting
- Reduced rotting percentage
- Improved bulb quality retention
- Longer storage duration
- Reduced dependence on grid electricity

Jadhav et al. reported that improved ventilated storage systems significantly reduced storage losses and enhanced bulb quality retention during extended storage periods [8]. Similarly, solar-powered ventilation systems have demonstrated environmental control and reduced deterioration of stored agricultural products [25].

F. Integration of Smart Technologies

Recent developments have focused on integrating solar energy systems with IoT-based monitoring and control technologies [16].
Smart storage systems offer:

- Real-time monitoring
- Remote access through mobile devices
- Automated ventilation control
- Data logging and analysis
- Predictive maintenance

These technologies improve storage efficiency while minimizing human intervention [16].

G. Economic and Environmental Benefits

Solar-based onion storage structures provide several economic and environmental advantages.

- Economic Benefits
- Reduced electricity costs
- Lower storage losses
- Improved marketable yield
- Increased farmer income
- Reduced maintenance expenses
- Environmental Benefits
- Renewable energy utilization
- Reduced greenhouse gas emissions
- Sustainable post-harvest management
- Lower carbon footprint [5, 19, 21]

These benefits support the adoption of solar-powered storage systems as a sustainable agricultural technology.

H. Limitations

Despite their advantages, solar-based onion storage structures face certain limitations:

- High initial installation cost
- Dependence on solar radiation availability
- Requirement for battery backup systems
- Maintenance of photovoltaic components
- Limited awareness among farmers

Addressing these challenges through government support, technological innovation, and farmer training can accelerate adoption [21].
Solar-based onion storage structures represent an effective and sustainable approach for reducing post-harvest losses. By combining improved storage design with solar-powered ventilation and environmental monitoring systems, these structures provide better control of temperature and humidity compared with conventional storage methods. Research findings indicate significant reductions in weight loss, sprouting, and rotting, leading to improved bulb quality and extended storage life. The integration of smart technologies and renewable energy systems further enhances the potential of solar-assisted onion storage for sustainable agricultural development [8, 16, 17, 25].

6. Challenges and Future Prospects

A. Challenges

Despite the advantages of solar-based onion storage systems, several challenges limit their widespread adoption. One of the primary constraints is the high initial investment required for solar photovoltaic panels, batteries, ventilation systems, sensors, and storage infrastructure. Small and marginal farmers often find it difficult to afford such technologies without financial assistance or government support [19, 21].

The performance of solar-powered systems is highly dependent on the availability of solar radiation. During cloudy weather, rainy seasons, or prolonged periods of low sunlight, power generation may decrease, affecting the operation of ventilation and environmental control systems [5, 19]. Although battery backup systems can provide temporary solutions, they increase the overall cost of the storage facility.

Maintaining optimal temperature and humidity conditions within storage structures is another challenge. Improper environmental control can lead to sprouting, rotting, moisture loss, and quality deterioration of stored onion bulbs [6, 9]. In addition, regular maintenance of solar panels, batteries, fans, and monitoring equipment is essential for efficient system operation [19].

Limited awareness and technical knowledge among farmers regarding renewable energy technologies and modern storage practices also hinder the adoption of solar-assisted storage systems. In many rural areas, inadequate infrastructure, lack of technical support, and limited access to credit facilities further restrict implementation [11, 21].

B. Future Prospects

The future of solar-based onion storage systems is highly promising due to increasing emphasis on sustainable agriculture and renewable energy utilization. Advancements in solar photovoltaic technology are continuously improving energy conversion efficiency while reducing installation costs, making solar-powered storage systems more affordable and accessible [19].
Integration of Internet of Things (IoT) technology offers significant opportunities for intelligent storage management. Smart sensors can continuously monitor temperature, humidity, airflow, and other environmental parameters, allow automated control of ventilation systems and ensure optimal storage conditions [16].
Future storage systems may also incorporate artificial intelligence, cloud-based monitoring platforms, and mobile applications for real-time management and decision-making. These technologies can improve storage efficiency,

reduce labour requirements, and minimize post-harvest losses [16].

The development of hybrid renewable energy systems combining solar energy with other energy sources may enhance reliability and ensure continuous operation during periods of low solar radiation [5, 21]. Furthermore, ongoing research on improved storage designs, advanced ventilation mechanisms, and energy-efficient environmental control systems is expected to enhance the overall performance of onion storage facilities [15, 25].

Government initiatives promoting renewable energy adoption, sustainable agriculture, and post-harvest management are likely to accelerate the deployment of solar-assisted onion storage structures in the coming years [21].

CONCLUSION

Onion is an economically important horticultural crop, but substantial post-harvest losses occur during storage due to sprouting, rotting, microbial infection, and physiological weight loss. Effective storage technologies are therefore essential for preserving bulb quality and ensuring market availability throughout the year [2, 10, 20].

Solar-based onion storage structures represent a sustainable and energy-efficient approach to reducing storage losses. By integrating solar photovoltaic systems with improved ventilation and environmental control mechanisms, these storage structures help maintain favorable temperature and humidity conditions, thereby minimizing deterioration and extending storage life [17, 25].

Research studies have demonstrated that improved storage structures can significantly reduce post-harvest losses while enhancing bulb quality and economic returns to farmers [8, 11]. The incorporation of smart monitoring technologies further improves storage efficiency and operational reliability [16].

Although challenges related to cost, maintenance, and awareness remain, continued technological advancements and supportive government policies are expected to encourage wider adoption of solar-assisted storage systems. Overall, solar-based onion storage structures offer a practical, environmentally friendly, and economically viable solution for reducing post-harvest losses and promoting sustainable agricultural development [5, 17, 21, 25].

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