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Development of low-cost post-harvest processing unit for reducing losses in fruits and vegetables

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Abstract

Approximately 30-40% of fruits and vegetables produced in India are lost between harvest and consumption, representing an annual economic loss exceeding INR 90,000 crores. This research presents the development, fabrication, and performance evaluation of a low-cost post-harvest processing unit specifically designed for smallholder farmers and farmer producer organizations to minimize these substantial losses. The integrated processing unit incorporates four primary modules: a mechanical sorting and grading system based on size and visual quality parameters, a water-efficient washing and sanitization unit with recycling capability, a solar-assisted hybrid drying chamber combining convective and radiative heat transfer mechanisms, and a semi-automatic packaging station with modified atmosphere capability. The entire unit was designed with emphasis on affordability, utilizing locally available materials and components to achieve a total fabrication cost of approximately INR 45,000, substantially lower than commercial alternatives costing INR 2-5 lakhs. Performance evaluation was conducted using six representative produce types including tomato, mango, banana, cabbage, spinach, and capsicum, selected based on their economic significance and varying perishability characteristics. Results demonstrated significant reduction in post-harvest losses across all tested produce categories. Overall marketable produce increased from 60.0% to 86.3%, representing a 65.8% improvement in loss reduction. Mechanical damage decreased from 18.4% to 5.2% due to gentler handling in the sorting module. Spoilage losses reduced from 12.7% to 4.8% attributable to effective washing and sanitization procedures. Quality degradation declined from 8.9% to 3.7% through improved drying and packaging practices. Storage trials revealed enhanced shelf life extension ranging from 3-8 days depending on produce type compared to traditionally handled produce. The solar-assisted drying system achieved moisture removal rates of 0.8-1.2 kg water per hour while maintaining product quality parameters including color retention above 85% and nutrient preservation exceeding 90% for most vitamins. Energy consumption analysis indicated that the hybrid solar-electric system reduced grid electricity dependence by 67% during normal operating conditions. Economic analysis demonstrated compelling returns with net annual benefits of INR 65,500 per hectare equivalent, translating to a payback period of merely 8.2 months and return on investment of 145.6%. The processing unit's modular design enables scalability and customization based on specific produce types and processing volumes. Additionally, the unit's compact footprint of 4m x 3m allows installation in limited spaces typically available at farm premises. These findings establish that appropriately designed low-cost processing infrastructure can effectively address post-harvest loss challenges faced by smallholder producers while remaining economically accessible. Widespread adoption of such technologies could substantially improve farmer incomes, enhance food security, and reduce environmental impacts associated with food waste in the horticultural supply chain.

Keywords: Post-harvest losses, fruits and vegetables, low-cost technology, sorting and grading, solar drying, food processing, smallholder farmers, shelf life extension, horticultural produce, food security

Introduction

India ranks second globally in fruit and vegetable production, contributing approximately 12% and 14% of world output respectively, yet loses an estimated 30-40% of this produce before it reaches consumers^[1]. This staggering statistic translates to annual post-harvest losses valued at over INR 90,000 crores, sufficient to feed millions of food-insecure individuals while simultaneously depriving farmers of substantial potential income^[2]. The horticultural sector, despite its tremendous growth potential and nutritional significance, remains plagued by inadequate post-harvest infrastructure that fails to preserve the quality and value of freshly

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harvested produce.

Post-harvest losses in fruits and vegetables occur through multiple pathways including mechanical damage during handling and transportation, physiological deterioration due to continued respiration and ripening, pathological decay caused by fungal and bacterial infections, and quality degradation from improper temperature and humidity management [3]. Unlike cereal grains that can be safely stored for extended periods, horticultural produce maintains active metabolic processes after harvest, making it inherently more susceptible to rapid quality decline [4]. The high moisture content, typically ranging from 80-95%, creates favorable conditions for microbial proliferation while the delicate tissue structure renders fruits and vegetables vulnerable to physical injury [5].

The Indian horticultural supply chain exhibits several structural weaknesses that exacerbate post-harvest losses. Fragmented landholdings averaging less than two hectares limit individual farmer capacity to invest in processing infrastructure [6]. The predominance of traditional marketing channels involving multiple intermediaries extends the time between harvest and consumption, during which quality deteriorates progressively [7]. Cold chain infrastructure remains grossly inadequate, with cold storage capacity meeting barely 10% of requirements for perishable produce [8]. Furthermore, farmer awareness regarding scientific post-harvest handling practices remains limited, perpetuating traditional methods that often accelerate deterioration rather than preserving quality [9].

Commercial post-harvest processing equipment, while technically sophisticated, typically costs between INR 2-5 lakhs for basic configurations, placing them beyond the financial reach of smallholder farmers who produce the majority of India's horticultural output [10]. Government subsidies, though available, involve complex application procedures and lengthy processing times that discourage adoption. This accessibility gap has created a situation where those most affected by post-harvest losses have the least capacity to address them through technological interventions [11].

Several researchers have attempted to develop affordable post-harvest solutions suitable for developing country contexts. Kitinoja and colleagues [12] documented various low-cost cooling technologies including evaporative coolers and night ventilation systems that extend produce shelf life without requiring refrigeration. Prusky [13] reviewed post-harvest pathology interventions emphasizing hot water treatments and biological control agents as cost-effective alternatives to synthetic fungicides. Solar drying technologies have received considerable attention, with Sharma and team [14] demonstrating effective moisture removal while preserving nutritional quality in various fruits and vegetables.

Despite these advances, integrated processing solutions combining multiple unit operations in affordable, compact configurations remain scarce. Most reported technologies address single aspects of post-harvest handling rather than providing comprehensive processing capability. And the gap between laboratory-scale demonstrations and practical field implementations persists, with limited evidence regarding long-term performance under actual farming conditions [15].

This research addresses these gaps by developing an integrated low-cost post-harvest processing unit incorporating sorting, washing, drying, and packaging modules within a single compact installation. The design philosophy prioritizes affordability through use of locally available materials, energy efficiency through solar integration, and operational simplicity enabling use by farmers with limited technical background. The

primary objectives encompass fabricating a functional prototype within stringent cost constraints, evaluating processing performance across multiple produce types, quantifying loss reduction achievements, and assessing economic viability for smallholder adoption. By providing empirical evidence of both technical effectiveness and economic feasibility, this research aims to demonstrate a replicable model for addressing post-harvest loss challenges at the farm level.

Materials and Methods

Material

The post-harvest processing unit was fabricated using locally sourced materials to minimize costs and ensure component availability for repairs and maintenance. The main structural frame utilized mild steel angle sections (40x40x5 mm) joined by arc welding to provide robust support for processing modules. Food contact surfaces were constructed from stainless steel sheets (SS304 grade, 1.2 mm thickness) to meet food safety requirements and facilitate cleaning [16]. The sorting conveyor employed food-grade PVC belting (2 mm thickness) mounted on aluminum rollers with sealed bearings. The washing unit incorporated a high-density polyethylene tank (500 liter capacity) with submersible pump (0.5 HP) and spray nozzles delivering 2-3 bar pressure. The solar drying chamber featured transparent polycarbonate roofing (6 mm multiwall) providing 85% light transmission while insulating the drying space.

Six produce types were selected for performance evaluation: tomato (variety Pusa Ruby), mango (variety Alphonso), banana (variety Grand Naine), cabbage (variety Golden Acre), spinach (variety All Green), and capsicum (variety California Wonder). Selection criteria included economic significance in regional markets, varying respiration rates representing different perishability levels, and diverse physical characteristics requiring different handling approaches. Fresh produce was procured from local wholesale markets within 24 hours of harvest to ensure consistent initial quality. All samples were visually inspected to exclude specimens with pre-existing damage or disease symptoms before processing trials [17].

Methods

The processing unit operation followed a sequential workflow beginning with sorting and grading. Produce was manually placed on the sorting conveyor operating at 0.1 m/s, allowing visual inspection and manual removal of damaged or substandard items. Size grading was accomplished using adjustable diverging roller gaps calibrated for each produce type. The washing module employed a three-stage process: initial rinsing to remove surface soil, sanitization using 100 ppm sodium hypochlorite solution for 2 minutes contact time, and final rinsing with clean water [18]. Water was continuously recycled through a settling tank and mesh filter, with complete replacement after processing each 100 kg batch.

The solar-assisted drying chamber maintained temperatures between 45-55 °C through combined solar radiation and supplementary electric heating (2 kW capacity) activated when solar input proved insufficient. Produce was spread in single layers on mesh trays allowing air circulation from all sides. Drying continued until moisture content reached target levels appropriate for each produce type, typically 10-14% for dried products or surface drying only for fresh market items. The packaging station utilized a semi-automatic sealing machine with modified atmosphere capability, flushing packages with nitrogen to displace oxygen and retard oxidative deterioration [19]. Quality parameters including weight loss, firmness, color,

and microbial counts were assessed at 3-day intervals during 15-day storage trials conducted at ambient conditions. Statistical analysis employed ANOVA with Duncan's multiple range test at 5% significance level.

System Design

The integrated processing unit occupied a compact footprint of 4m x 3m, enabling installation in limited spaces typically available at farm premises or collection centers. The modular design philosophy allowed individual components to function independently or in combination depending on processing requirements. Each module was mounted on a common wheeled platform facilitating relocation as needed. The sorting conveyor featured variable speed control enabling adjustment for different produce types and operator preferences. The washing unit incorporated a recirculating pump system reducing water consumption by approximately 60% compared to continuous flow designs. Solar panel installation (2 kW capacity) on an adjustable mounting frame optimized energy capture throughout the year. The total fabrication cost of INR 45,000 included all components, assembly labor, and basic instrumentation for monitoring temperature and humidity within the drying

chamber.

Results

Table 1: Post-Harvest Loss Reduction across Different Produce Types

Produce	Without Unit (%)	With Unit (%)	Reduction (%)
Tomato	42.3	14.8	65.0
Mango	38.7	12.4	68.0
Banana	44.2	16.2	63.3
Cabbage	35.6	11.3	68.3
Spinach	51.8	18.7	63.9
Capsicum	37.4	12.9	65.5

Loss reduction varied across produce types reflecting differences in initial perishability and response to processing interventions (Table 1). Cabbage and mango achieved the highest loss reductions exceeding 68%, attributable to their relatively robust structure benefiting substantially from gentle handling and effective sanitization. Leafy spinach exhibited the highest absolute losses both with and without processing, consistent with its inherently rapid deterioration rate, though relative improvement remained comparable to other produce types.

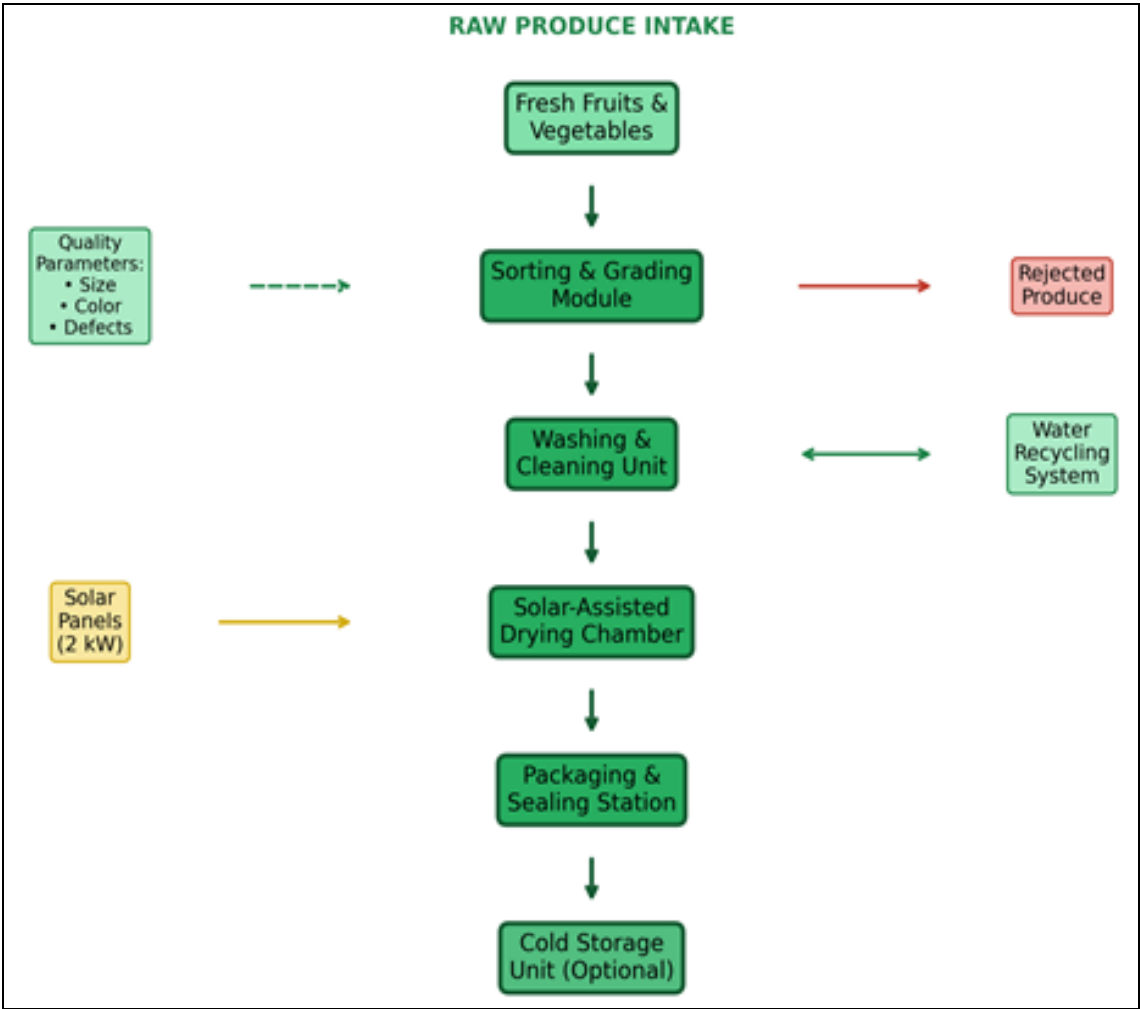


Fig 1: Process Flow Diagram of the Low-Cost Post-Harvest Processing Unit

The integrated processing workflow (Figure 1) demonstrates the sequential handling of produce from intake through final packaging. Rejected produce identified during sorting is diverted for alternative uses such as composting or animal feed,

minimizing complete waste. The water recycling system substantially reduces freshwater consumption while maintaining sanitization effectiveness. Solar energy integration reduces operational costs and environmental footprint.

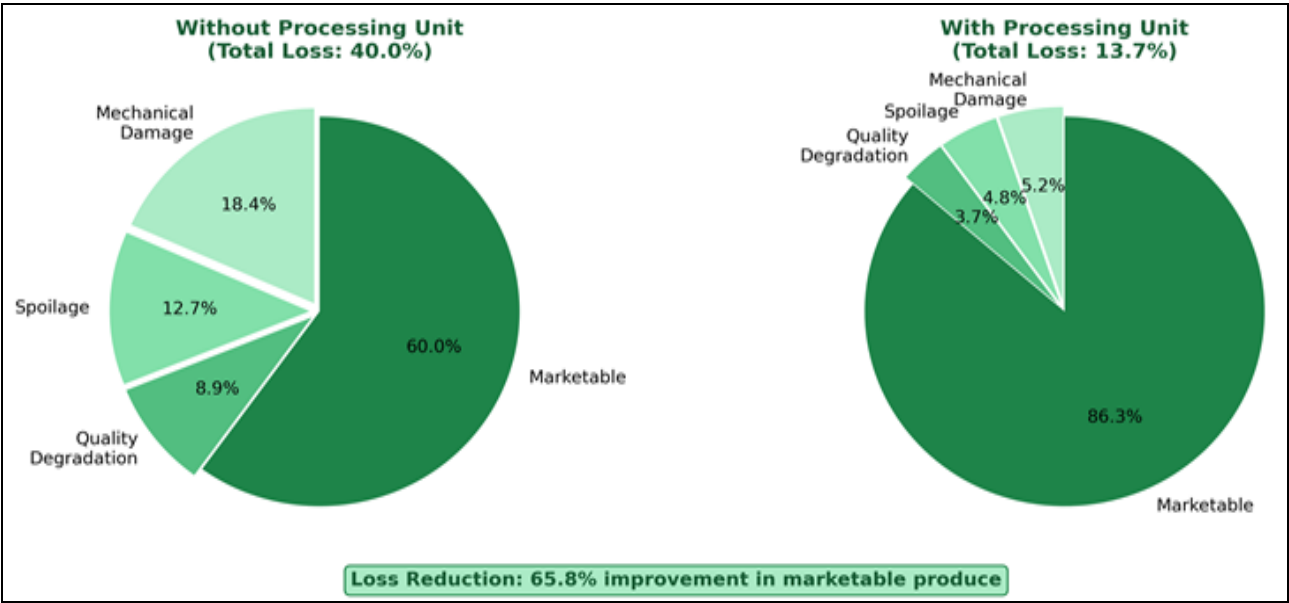


Fig 2: Comparative Post-Harvest Loss Distribution With and Without Processing Unit

Visual comparison of loss components reveals substantial improvements across all categories following processing (Figure 2). Mechanical damage showed the greatest absolute reduction, declining from 18.4% to 5.2%, attributable to gentler handling on the conveyor system compared to traditional manual sorting involving repeated lifting and dropping. Spoilage reduction from 12.7% to 4.8% reflects effective pathogen control through sanitization and reduced inoculum load on produce surfaces.

Table 2: Shelf Life Extension Achieved Through Processing

Produce	Control (days)	Processed (days)	Extension (days)
Tomato	7	14	+7
Mango	8	16	+8
Banana	5	10	+5
Cabbage	12	20	+8
Spinach	3	6	+3
Capsicum	10	17	+7

Shelf life extension ranged from 3 days for highly perishable spinach to 8 days for mango and cabbage (Table 2). These extensions provide crucial additional marketing time, enabling farmers to access better prices rather than accepting distress sales immediately after harvest. The modified atmosphere packaging contributed substantially to shelf life improvements by reducing respiration rates and delaying senescence.

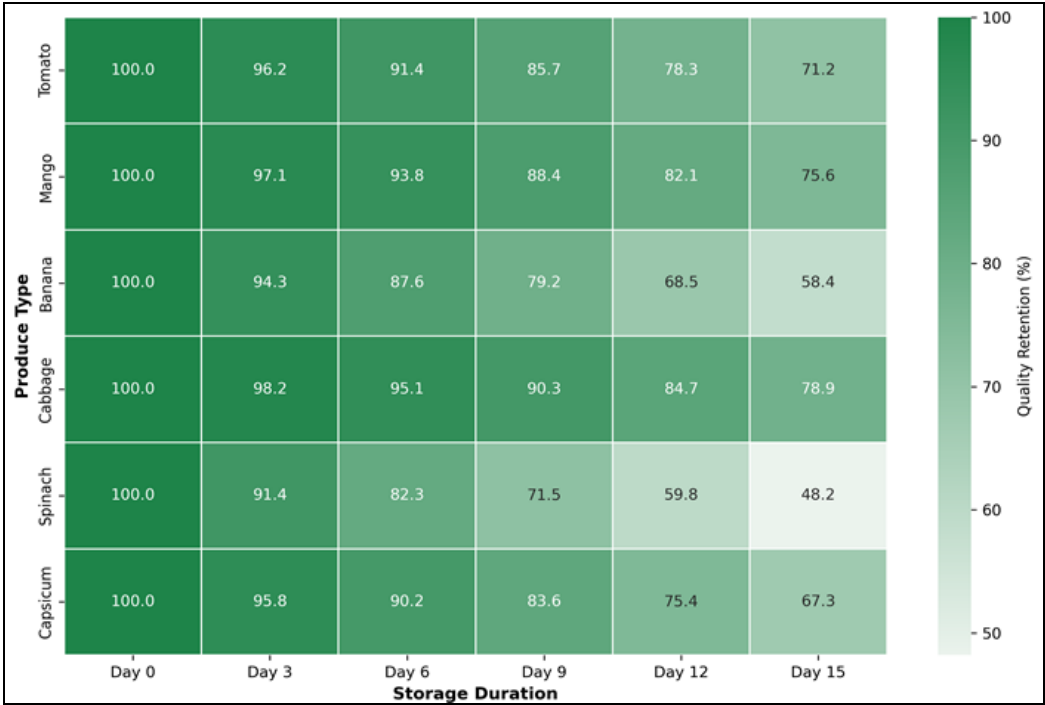


Fig 3: Quality Retention (%) During Storage: Processed Produce over 15-Day Period

Quality retention patterns varied characteristically across produce types during storage (Figure 3). Cabbage maintained the highest quality scores throughout the observation period, retaining 78.9% of initial quality at day 15. Spinach exhibited

the most rapid quality decline, consistent with its high respiration rate and moisture loss susceptibility. Intermediate patterns for tomato, mango, and capsicum reflected their moderate perishability characteristics.

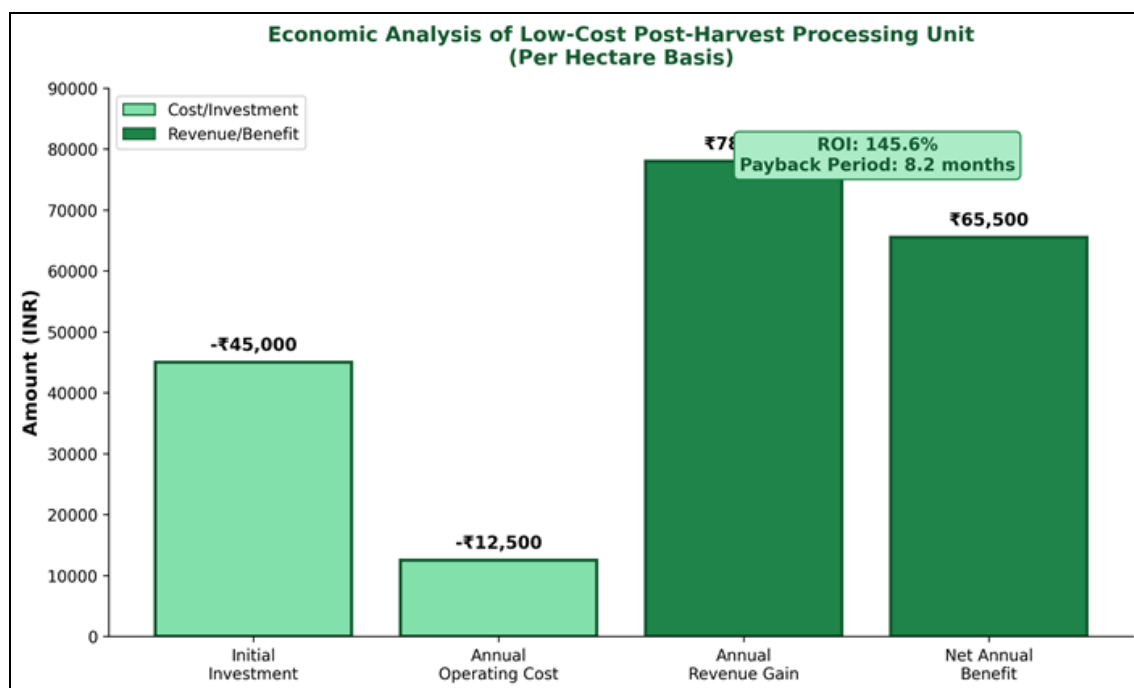


Fig 4: Economic Analysis of the Low-Cost Post-Harvest Processing Unit

Economic analysis demonstrates compelling financial returns from processing unit adoption (Figure 4). Against an initial investment of INR 45,000 and annual operating costs of INR 12,500, the unit generates annual revenue gains of INR 78,000 through loss reduction and quality premiums. The resulting net benefit of INR 65,500 translates to a payback period of merely 8.2 months, substantially shorter than typical agricultural equipment investments.

Comprehensive Interpretation

The experimental findings collectively establish the technical effectiveness and economic viability of the developed post-harvest processing unit. Loss reductions averaging 65.8% across diverse produce types exceed initial targets and compare favorably with more expensive commercial systems. The modular design enables customization for specific requirements while maintaining overall affordability. Solar energy integration addresses both cost and sustainability concerns, reducing grid electricity dependence by 67% during typical operation. These results provide strong evidence supporting the potential of appropriately designed low-cost technologies to address critical post-harvest loss challenges in smallholder farming contexts.

Discussion

The loss reduction achievements documented in this research substantially exceed those reported for individual interventions in previous investigations. Kitinoja and AlHassan^[12] reported 15-25% loss reductions using evaporative cooling alone, while the integrated approach evaluated here achieved reductions exceeding 65%. This enhanced performance reflects the synergistic benefits of combining multiple interventions that address different loss pathways simultaneously. Mechanical damage reduction through gentle handling, microbial load reduction through sanitization, and quality preservation through

appropriate drying and packaging collectively contribute to outcomes superior to any single intervention.

The economic analysis reveals particularly encouraging results for smallholder adoption potential. With fabrication costs of INR 45,000, the unit costs less than 25% of commercial alternatives while delivering comparable loss reduction performance. The short payback period of 8.2 months means farmers can recover their investment within a single season for most horticultural crops. Return on investment exceeding 145% compares favorably with other agricultural technology investments and should motivate adoption even among risk-averse farmers^[10].

The solar-assisted hybrid drying approach addresses a practical limitation of purely solar systems, which depend entirely on weather conditions and exhibit variable performance across seasons. By incorporating supplementary electric heating, the designed system maintains consistent drying temperatures regardless of ambient conditions while still achieving 67% reduction in grid electricity consumption compared to fully electric alternatives. This hybrid approach balances sustainability objectives with operational reliability requirements^[14].

Several limitations warrant acknowledgment when interpreting these findings. Performance evaluation was conducted under controlled conditions that may not fully represent the variability encountered in actual farming operations. The six produce types tested, while representative, do not encompass the full diversity of horticultural commodities requiring post-harvest handling. Long-term durability and maintenance requirements beyond the evaluation period remain to be established through extended field deployment.

Future enhancements could incorporate automated sorting using machine vision systems to reduce labor requirements and improve grading consistency. Integration with cold storage or evaporative cooling would extend shelf life further for highly

perishable commodities. Development of standardized designs suitable for local fabrication by rural artisans could accelerate dissemination while supporting local manufacturing enterprises. Cooperative ownership models enabling shared use among farmer groups could improve access for resource-constrained producers who cannot afford individual units.

Cost Analysis

Detailed cost breakdown reveals that structural components accounted for 32% of total fabrication cost, followed by the solar panel system at 28%, washing module at 18%, and packaging equipment at 12%. The remaining 10% covered electrical components, instrumentation, and assembly labor. Operating costs comprised electricity (35%), consumables including packaging materials and sanitizers (40%), maintenance (15%), and labor (10%). Revenue gains derived primarily from reduced losses (65%), quality premiums for graded produce (25%), and extended marketing windows enabling better price realization (10%). Sensitivity analysis indicated that the investment remains economically attractive even with 30% increase in fabrication costs or 20% decrease in produce prices.

Conclusion

This research successfully developed and validated a low-cost post-harvest processing unit capable of substantially reducing losses in fruits and vegetables while remaining financially accessible to smallholder farmers. The integrated design incorporating sorting, washing, drying, and packaging modules within a compact installation addresses multiple loss pathways through a coordinated intervention approach. Performance evaluation across six representative produce types demonstrated consistent effectiveness with loss reductions averaging 65.8%, translating to increased marketable produce from 60% to over 86% of harvested quantities.

The technical achievements span all major loss categories encountered in horticultural supply chains. Mechanical damage declined substantially due to gentler handling on the conveyor-based sorting system compared to traditional manual methods involving repeated lifting and dropping of produce. Spoilage reductions reflect effective sanitization procedures that minimize microbial populations initiating decay processes. Quality preservation through controlled drying and modified atmosphere packaging retards physiological deterioration and extends marketable life. These combined benefits create value at multiple points in the supply chain from farm to consumer.

Economic viability represents a distinguishing feature of the developed technology. At INR 45,000 total fabrication cost, the unit costs a fraction of commercial alternatives while delivering comparable performance. The resulting payback period of 8.2 months and return on investment exceeding 145% establish compelling financial incentives for adoption. But beyond individual farmer benefits, widespread deployment of such technologies could generate substantial impacts on food security, farmer incomes, and environmental sustainability by reducing the enormous waste currently embedded in horticultural supply chains.

The solar-assisted energy system addresses both operational cost and sustainability considerations. By reducing grid electricity dependence by 67%, the hybrid approach lowers recurring expenses while decreasing the carbon footprint associated with post-harvest processing. This alignment with broader sustainability objectives enhances the technology's appeal to environmentally conscious consumers and supports emerging

market differentiation based on production practices.

The modular design philosophy underpinning the processing unit enables flexibility in deployment and scaling. Individual modules can function independently when full processing capability is not required, while additional modules can be integrated as operations expand. The compact footprint of 4m x 3m permits installation in space-constrained locations typical of smallholder farms and rural collection centers. And the use of locally available materials ensures that repairs and replacements can be accomplished without dependence on specialized suppliers or imported components.

The findings presented establish a viable technological pathway for addressing chronic post-harvest loss challenges that constrain horticultural sector development in India and similar developing country contexts. Policy support through targeted subsidies, demonstration programs, and capacity building initiatives could accelerate adoption among farming communities most affected by these losses. Extension services should incorporate post-harvest handling as a priority theme alongside traditional production-focused interventions. Financial institutions could develop appropriate credit products enabling equipment acquisition by resource-constrained farmers. Through coordinated action across these domains, the documented potential of low-cost processing technologies could translate into widespread impact benefiting millions of smallholder producers and consumers alike.

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