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REVIEW ARTICLE

Traditional and modern storage methods for onion preservation: Integrating internet of things technologies for quality parameter monitoring and control

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Abstract

Onions (*Allium cepa* L.) represent a critical global food security crop, yet post-harvest losses of 25–40 % in developing nations severely compromise nutritional accessibility and farmer livelihoods. This systematic review critically evaluates traditional and modern storage technologies while assessing internet of things (IoT) integration potential for real-time quality monitoring and automated environmental control. Following preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, comprehensive literature searches across Web of Science, Scopus, PubMed and IEEE Xplore databases (2000–2024) identified 847 potentially relevant publications. After applying rigorous inclusion criteria requiring quantitative performance data, peer-reviewed publication status and English language accessibility, 156 studies underwent detailed analysis. Traditional ambient storage methods including field curing, naturally ventilated structures and conventional godowns demonstrate economic accessibility advantages but experience storage losses of 15–40 % over 3–5 months due to uncontrolled temperature and humidity fluctuations that accelerate physiological deterioration and microbial proliferation. Modern refrigerated cold storage systems maintaining precise environmental conditions of 0–1 °C temperature and 65–70 % relative humidity achieve extended shelf life of 6–10 months with losses consistently below 5 %. However, substantial capital investment requirements of USD 400–800 per tonne storage capacity combined with technical operational expertise needs restrict adoption primarily to large-scale commercial operations. The IoT-enabled precision storage systems integrate distributed wireless sensor networks for continuous monitoring of temperature, relative humidity, carbon dioxide concentration and sprouting indices, coupled with automated actuator control optimising ventilation, refrigeration and humidity management. Techno-economic analyses indicate achievable loss reductions of 10–20 % with investment payback periods of 2–3 years, though these metrics exhibit substantial sensitivity to wholesale price volatility and regional electricity costs. Critical implementation barriers include inadequate rural telecommunications infrastructure affecting 58 % of agricultural facilities, insufficient technical support networks, sensor calibration drift in condensing environments and limited digital literacy. Hybrid retrofitting approaches combining traditional infrastructure with IoT monitoring and evaporative cooling demonstrate economic viability, achieving 15–30 % loss reduction at 70–85 % of full cold storage costs. Priority research directions include commercial-scale field validation across diverse agroclimatic zones, standardised interoperability framework development and farmer-centered participatory design approaches.

Keywords: *Allium cepa*; automated control; cold storage; internet of things; post-harvest loss; precision agriculture; quality monitoring; sensor networks; smart agriculture; storage technology

Introduction

Onion (*Allium cepa* L.) constitutes one of the most economically and nutritionally significant vegetable crops cultivated globally, with total production reaching 104.8 million tonnes harvested from 5.3 million hectares in 2022 (1). The crop exhibits remarkable geographic distribution, with major producing nations including India contributing 28.1 million tonnes, China producing 24.5 million tonnes, United States generating 3.3 million tonnes and Egypt yielding 3.0 million tonnes, collectively representing 56 % of total global production (2). Beyond economic importance measured in production volumes and market values, onions provide critical nutritional contributions to human diets worldwide through provision of essential organosulfur compounds including allicin and S-allylcysteine, flavonoid antioxidants particularly quercetin and its glycosides and prebiotic fructo-oligosaccharides that confer documented health benefits encompassing anti-inflammatory activity, cardiovascular protection, antimicrobial properties and gut microbiome modulation (3, 4). However, substantial post-harvest deterioration losses significantly compromise realisation of these nutritional and economic values, particularly in developing agricultural economies.

Post-harvest losses in developing nations characteristically range from 25–40 % of total harvested production due to multiple interacting factors including inadequate storage infrastructure, suboptimal environmental condition management, limited access to cold chain facilities, insufficient technical capacity among storage operators and constrained financial resources for technology adoption (5, 6). These substantial losses translate to approximately 26–42 million tonnes of onions annually becoming unsuitable for human consumption, representing squandered economic value estimated at USD 8–12 billion while simultaneously creating severe implications for food security, agricultural sustainability and farmer livelihood stability (7). The geographic distribution of post-harvest loss magnitude exhibits pronounced variation, with tropical and subtropical regions experiencing disproportionately elevated deterioration rates attributable to high ambient temperatures and humidity levels that markedly accelerate both physiological senescence processes and pathological degradation caused by microbial proliferation (8, 9).

Traditional ambient storage technologies including field curing protocols, naturally ventilated structural designs and conventional godown facilities predominate among smallholder farming operations and resource-constrained agricultural systems due to minimal capital investment requirements and operational simplicity not demanding specialised technical expertise (10, 11). These passive environmental control approaches rely fundamentally on structural design features such as strategic building orientation, natural ventilation airflow patterns and thermal mass properties to moderate internal storage conditions relative to external ambient fluctuations (12). However, inherent limitations of passive control systems manifest as substantial vulnerability to unregulated temperature excursions and relative humidity variations that cause premature sprouting, excessive weight loss through transpiration and respiration and microbial spoilage, collectively resulting in storage losses typically ranging from 15 % to 40 % over relatively short storage durations of 3 to 5 months (13, 14). The fundamental constraint is inability to decouple internal storage environment from external climatic conditions, thereby limiting storage performance ceiling regardless of management quality.

Modern refrigerated cold storage systems employing mechanical refrigeration technology enable precise active environmental control maintaining optimal storage conditions characterised by temperatures of 0–1 °C combined with relative humidity of 65–70 %, thereby achieving extended shelf life durations of 6 to 10 months while maintaining total storage losses consistently below 5 % through effective suppression of metabolic activity and microbial growth (15, 16). Advanced cold storage facilities incorporate sophisticated infrastructure components including insulated structural envelopes minimising thermal conductance, high-precision refrigeration systems maintaining temperature uniformity within ± 0.5 °C throughout storage volume, automated humidity control through coordinated humidification and dehumidification, forced air circulation ensuring spatial homogeneity and comprehensive monitoring instrumentation (17). Notwithstanding demonstrated technical efficacy, substantial capital investment requirements typically ranging from USD 400 to 800 per tonne of storage capacity for facility construction plus USD 200 to 400 per tonne for refrigeration equipment, combined with elevated operational costs dominated by energy consumption and needs for specialised technical expertise, effectively restrict cold storage adoption primarily to large-scale commercial enterprises, producer cooperatives with sufficient membership scale, or government-subsidised public facilities (18, 19).

Internet of things (IoT) technologies represent transformative opportunities for precision storage management through enabling real-time continuous environmental monitoring, data-driven automated control systems and predictive analytics leveraging machine learning algorithms (20, 21). The IoT-enabled storage systems integrate distributed wireless sensor networks for multi-parameter quality monitoring, edge computing capabilities for localised data processing and control decision-making, cloud-based platforms supporting advanced analytics and remote accessibility and automated actuator systems responding to sensor inputs through control algorithms (22, 23). These cyber-physical systems theoretically enable democratisation of precision storage management by providing previously unavailable capabilities to moderate-scale operations that cannot economically justify full cold storage infrastructure. However, despite promising pilot-scale demonstrations and favourable techno-economic projections from early implementations, widespread commercial adoption remains substantially constrained by multiple intersecting barriers including inadequate rural telecommunications infrastructure, insufficient localised technical support networks, economic accessibility challenges for smallholder farmers and limited digital literacy among potential users (24, 25).

This comprehensive review provides critical evaluation of onion post-harvest storage technologies spanning the continuum from traditional ambient methods through modern cold storage systems to emerging IoT-enabled precision management approaches. The specific objectives are to: [1] systematically compare performance characteristics, economic requirements and contextual appropriateness of established storage technologies using quantitative metrics from peer-reviewed literature; [2] evaluate technical capabilities, implementation requirements and demonstrated performance of IoT sensor networks and automated control systems for storage quality management; [3] assess economic viability through detailed cost-benefit analyses accounting for capital investments, operational expenses, achievable loss reductions and sensitivity to market conditions; [4] identify and critically analyse barriers limiting widespread IoT technology adoption in agricultural storage contexts; [5] synthesise evidence regarding hybrid implementation approaches combining traditional infrastructure with selective technology integration; and [6] recommend priority research directions addressing critical knowledge gaps and practical deployment challenges.

Review methodology

This systematic review was conducted following established methodological protocols for comprehensive literature synthesis in agricultural technology assessment, incorporating elements from preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines adapted for agricultural technology reviews (26, 27). The review process encompassed systematic literature search across multiple databases, rigorous application of inclusion and exclusion criteria, quality assessment of retained studies and structured data extraction enabling quantitative synthesis and comparative analysis (Fig. 1).

Literature search strategy

Comprehensive literature searches were performed across multiple electronic databases including Web of Science Core Collection, Scopus, PubMed/MEDLINE, IEEE Xplore Digital Library, CAB Abstracts and Google Scholar covering publications from January 2000 through December 2024. The temporal scope was selected to capture both foundational storage technology research establishing baseline understanding and recent IoT technology

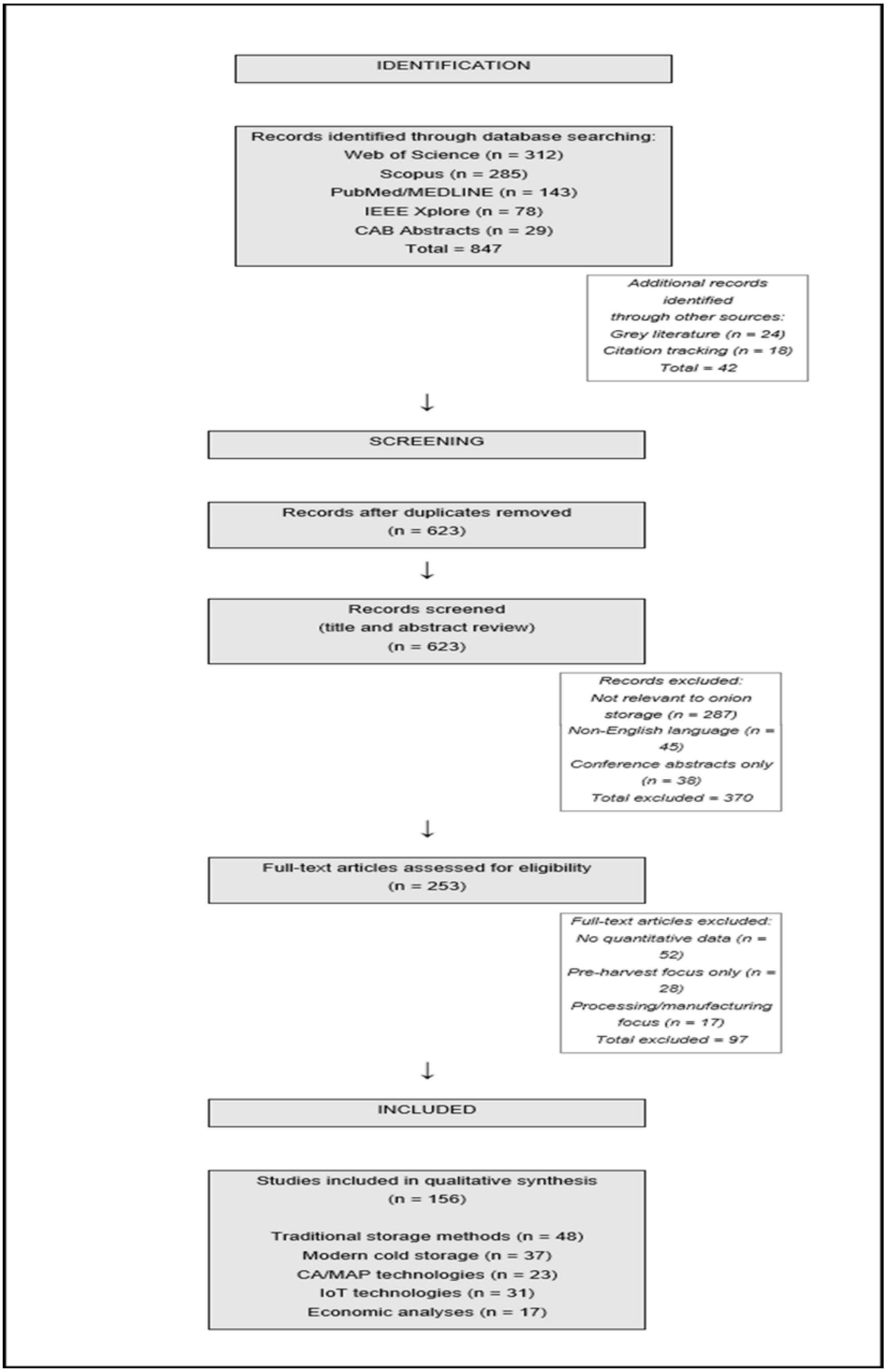

Fig. 1. Referred reporting items for systematic reviews and meta–analyses (PRISMA) 2020 flow diagram showing the systematic literature review process for onion storage technologies and internet of things integration. The diagram presents the identification, screening and inclusion phases with specific exclusion criteria and final study categorisation.

This PRISMA flow diagram illustrates the systematic literature review process following PRISMA 2020 guidelines. Database searches was conducted in December 2024 covering publications from January 2000 to December 2024. Duplicate removal was performed using reference management software (EndNote). Title and abstract screening were conducted independently by two reviewers with disagreements resolved through discussion. Full–text assessment applied pre–defined inclusion/exclusion criteria. The 156 included studies provided quantitative data for comparative analysis across storage technologies, with some studies contributing to multiple technology categories. Quality assessment using modified GRADE criteria informed data interpretation and synthesis.

developments reflecting current innovation trajectories while maintaining manageable review scope (28). Search strategies employed Boolean operators combining subject-specific keywords structured as: ("onion" OR "*Allium cepa*") AND ("storage" OR "post-harvest" OR "postharvest" OR "preservation") AND ("loss" OR "quality" OR "deterioration" OR "spoilage" OR "monitoring"). Additional targeted searches addressed specific technology domains using terms: ("cold storage" OR "refrigerated storage" OR "controlled atmosphere" OR "CA storage"), ("modified atmosphere" OR "MAP" OR "packaging"), ("Internet of Things" OR "IoT" OR "wireless sensor" OR "WSN" OR "smart agriculture" OR "precision agriculture" OR "sensor network") and ("monitoring" OR "automation" OR "control system" OR "automated control"). Grey literature including technical reports from Food and Agriculture Organization (FAO), United States Department of Agriculture (USDA), national agricultural research systems and extension service publications was identified through targeted institutional repository searching and citation tracking from included peer-reviewed articles (29, 30).

Inclusion and exclusion criteria

Studies were included if they met the following criteria: [1] addressed onion storage methods, quality parameter monitoring, or post-harvest management practices with specific relevance to storage duration or quality retention; [2] presented original quantitative empirical data on storage performance metrics including storage duration, weight loss percentage, quality retention indices, sprouting incidence, or microbial deterioration rates; (3) evaluated economic performance through formal cost analyses, return on investment calculations, or comprehensive techno-economic assessments;[4] described IoT technologies, wireless sensor networks, automated control systems, or precision agriculture applications specifically in storage contexts; [5] provided sufficient technical specifications and methodological details enabling reproducibility assessment and critical evaluation; [6] were published in English language either in peer-reviewed scientific journals or as authoritative technical reports from recognised agricultural research institutions. Studies were systematically excluded if they: [1] focused exclusively on pre-harvest cultural practices, field management, or cultivation techniques without direct post-harvest storage implications; [2] addressed onion processing operations, thermal dehydration, or value-addition manufacturing rather than fresh product storage; [3] presented purely theoretical modeling exercises or simulation studies without empirical validation using actual storage trials;[4] lacked quantitative performance data or employed inadequate statistical analysis methodology; [5] were published as conference abstracts without subsequent peer-reviewed publication, blog posts, industry promotional materials, or non-peer-reviewed sources lacking technical rigour; or [6] were not accessible in English language despite translation attempts.

Quality assessment procedures

Retained studies underwent systematic quality assessment evaluation based on multiple criteria including: [1] methodological rigor encompassing experimental design appropriateness, sample size adequacy, replication sufficiency, randomisation procedures where applicable and inclusion of appropriate control treatments; [2] statistical analysis quality including appropriate statistical test selection, clear specification of significance thresholds, proper handling of multiple comparisons and adequate uncertainty quantification through confidence intervals or standard errors; [3] transparent reporting of experimental conditions including cultivar specifications, harvest maturity indices, curing protocols, storage facility characteristics and operational parameters enabling independent reproducibility; (4) explicit acknowledgment of study limitations, potential confounding factors and boundary conditions affecting generalisability; [5] journal impact metrics including Journal Impact Factor and Scimago Journal Rank classifications indicating peer-review process rigor and scholarly influence. Preference was systematically accorded to studies published in Q1-ranked journals within relevant subject categories including agriculture, horticulture, food science and agricultural engineering based on Scimago Journal Rank classifications, controlled experimental designs incorporating randomisation and adequate replication, longitudinal data collection spanning multiple consecutive storage seasons enabling temporal variability assessment and comprehensive documentation of environmental monitoring data throughout storage duration (31, 32).

Data extraction and synthesis approach

From each included study, standardised data extraction protocols captured: storage technology classification and detailed operational specifications; storage duration measured in months or days; environmental conditions including temperature regimes, relative humidity levels and atmospheric composition for controlled/modified atmosphere systems; quantitative performance metrics encompassing weight loss percentage, sprouting incidence, visible microbial contamination levels and marketable yield retention; economic data including capital cost requirements, operational expense categories, energy consumption metrics and market price considerations; technology specifications for sensor types, measurement accuracy, communication protocols, control algorithms and system architecture for IoT implementations; and explicitly reported implementation challenges, adoption barriers, or lessons learned from deployment experiences. Where multiple studies reported analogous outcome metrics for similar storage approaches, data synthesis presented ranges reflecting observed variability across different studies, geographic contexts, cultivar genetic differences, seasonal climate variations and operational management quality levels rather than attempting statistical meta-analysis. Economic data originating from diverse national contexts were systematically standardised to 2024 United States Dollar equivalents using official exchange rates and inflation adjustment factors derived from International Monetary Fund World Economic Outlook databases to enable valid cross-study comparisons (33). Formal meta-analytical statistical pooling approaches were not employed due to substantial heterogeneity in experimental designs, environmental condition specifications, cultivar genetic backgrounds, outcome metric operational definitions and temporal contexts that would preclude valid statistical aggregation and introduce spurious precision not supported by underlying data quality.

Storage methods: Comparative performance analysis

Onion storage technologies encompass a comprehensive continuum spanning entirely passive ambient environmental control approaches through intermediate hybrid systems incorporating mechanical ventilation or evaporative cooling to sophisticated active environmental management via mechanical refrigeration and controlled atmosphere manipulation. This section provides critical comparative analysis emphasising quantitative performance metrics derived from peer-reviewed experimental

Table 1. Comparative analysis of onion storage methods

Storage method	Duration (months)	Weight loss (%)	Energy use	Skill level	Best application	References
Open-air storage	1–2	30–40	None	Low	Short-term storage in dry climates only	(34, 35, 40)
Ventilated shed	2–4	15–25	None (passive ventilation)	Low	Smallholder farmers, seasonal storage	(41–44)
Traditional godown	3–5	12–20	Minimal (occasional fans)	Moderate	Medium-scale operations, temperate regions	(46–49)
Cold storage (0–1°C, 65–70 % RH)	6–10	<5	High (30–50 kWh/t/month)	High	Commercial operations, export markets	(51, 52, 56, 57, 62, 63)
Controlled atmosphere (CA)	10–12	3–4	Very high (includes CA equipment)	Very high	Premium quality, long-term storage	(68, 69, 71–73)
Modified atmosphere packaging (MAP)	4–8	5–10	Moderate-high (refrigeration + packaging)	Moderate	Retail distribution, value-added products	(76–80)

Weight loss percentages represent typical ranges under optimal management; actual performance varies by cultivar, harvest maturity, curing quality and operational practices. Energy consumption for cold storage reflects well-managed facilities in temperate climates. Duration represents storage potential under optimal conditions. Skill level indicates technical expertise required for installation, operation and maintenance. Best application considers economic viability, infrastructure requirements and target market characteristics. References cited in parentheses correspond to the complete reference list.

studies, rigorous economic viability assessment incorporating both capital and operational cost considerations and contextual appropriateness evaluation with particular attention to how each technological approach addresses fundamental physiological requirements of *A. cepa* bulbs during post-harvest storage periods (Table 1).

Traditional ambient storage technologies

Traditional storage approaches rely fundamentally on passive environmental control achieved through strategic structural design and natural ventilation airflow without mechanical refrigeration or active humidity control systems (34, 35). Field curing represents the essential initial post-harvest treatment involving retention of harvested bulbs either *in situ* following mechanical or manual topping or arranged in windows exposing bulbs to ambient meteorological conditions for 7 to 14 days (36). This critical process facilitates progressive reduction of outer scale moisture content from harvest levels typically ranging 80–85 % to target values of 12–15 %, simultaneously promoting neck tissue desiccation and formation of protective dried scale layers that constitute primary physical barriers against pathogen entry and moisture loss (37, 38). Optimal field curing performance requires specific environmental conditions characterised by air temperatures maintained within 25–35 °C range, relative humidity sustained below 60 %, adequate air movement through natural convection or wind and crucially absence of rainfall or heavy dew formation that rewets external scales and negates desiccation progress (39). However, field curing remains entirely dependent on favorable weather patterns during the critical post-harvest period and provides no protective capacity against sudden meteorological changes including rainfall events, extreme temperature fluctuations, or prolonged high humidity periods that can severely compromise curing quality and subsequent storage potential (40).

Ventilated storage structures represent the next technological level, incorporating deliberate architectural design features promoting natural air circulation including strategically positioned openings in opposing walls enabling cross-ventilation, elevated roof designs facilitating hot air buoyancy-driven escape and raised slatted floor systems allowing upward airflow through stacked produce (41, 42). These structures typically achieve storage durations of 2 to 4 months with weight losses ranging from 15 % to 25 % depending critically on external climatic conditions, particularly ambient temperature and humidity regimes that directly influence internal storage environment (43). Performance optimisation in ventilated storage requires continuous attention to loading density, air circulation pathways and periodic manual inspection for removal of deteriorating bulbs to prevent spread of microbial contamination (44). The fundamental limitation is inherent dependence on favourable external ambient conditions; during hot-humid periods typical of tropical monsoon seasons or subtropical summers, passive ventilation proves insufficient to remove respiratory heat accumulation and transpired moisture, resulting in accelerated quality deterioration (45).

Traditional godown facilities incorporating substantial wall thickness using materials with high thermal mass such as brick, stone, or rammed earth construction attempt to moderate internal temperature fluctuations through thermal lag effects, potentially extending storage duration to 3 to 5 months with losses of 12–20 % under favourable external climate and diligent management practices (46, 47). The thermal mass principle operates by absorbing heat during warm periods and releasing stored heat during cooler periods, effectively damping diurnal temperature oscillations and providing modest buffering against short-term ambient temperature extremes (48). However, seasonal temperature trends inevitably penetrate thermal mass over extended timeframes and high thermal mass structures exhibit disadvantageous delayed response to beneficial ambient cooling periods (49). Critical performance constraints include inability to maintain temperatures below approximately 5 °C above ambient mean, no capacity for humidity control resulting in either desiccation when ambient humidity drops or moisture condensation when ambient humidity peaks, sensitivity to seasonal weather patterns limiting geographic applicability and fundamental inability to achieve storage durations beyond 5 months regardless of management quality due to inevitable dormancy break and sprouting initiation at ambient temperatures (50).

Modern refrigerated cold storage systems

Refrigerated cold storage employing mechanical vapor-compression refrigeration systems enables precise active environmental control maintaining optimal storage conditions characterised by temperatures of 0–1 °C combined with relative humidity of 65–70 %, thereby achieving extended shelf life durations of 6 to 10 months while maintaining total cumulative storage losses consistently below 5 % through effective suppression of respiration rates, inhibition of sprouting through maintenance below critical temperature thresholds and restriction of microbial growth rates (51, 52). The physiological basis for cold storage efficacy relates to fundamental temperature dependency of metabolic processes, with onion respiration rates exhibiting Q_{10} values (metabolic rate change per 10°C temperature change) of 2.0 to 2.5 across the 0–20 °C range, meaning each 10 °C temperature reduction approximately halves respiration-driven weight loss (53, 54). Simultaneously, maintenance of temperatures below 4 °C effectively prevents dormancy break and sprouting initiation, as heat unit accumulation driving developmental progression remains minimal (55).

Modern cold storage facilities incorporate sophisticated infrastructure components including: insulated structural envelopes utilising polyurethane foam or similar materials achieving thermal transmittance values (U-values) below 0.25 $W/m^2·K$ to minimise heat ingress from external environment (56); high-precision refrigeration systems employing multiple evaporator zones with individual temperature control maintaining spatial temperature uniformity within ± 0.5 °C throughout entire storage volume (57); automated humidity control achieved through coordinated operation of ultrasonic humidifiers for humidity addition and refrigeration coil surface condensation for moisture removal (58); forced air circulation systems using variable-speed fans distributing conditioned air uniformly and eliminating thermal stratification that creates localised hot spots (59); and comprehensive monitoring instrumentation including distributed temperature sensors, humidity sensors and data logging systems enabling continuous environmental verification (60). Proper cold storage management additionally requires careful attention to loading protocols minimising thermal mass burden on refrigeration capacity, pre-cooling of incoming product to remove field heat before storage and maintenance of air circulation pathways throughout stacked pallets or bulk piles (61).

The principal operational cost in refrigerated storage is electrical energy consumption for refrigeration, typically accounting for 60–75 % of total operating expenses and ranging from 30 to 50 kWh per tonne per month depending on facility thermal efficiency, ambient temperature regime and operational practices (62, 63). Capital investment requirements present substantial economic barriers, with construction costs for insulated facilities ranging from USD 400 to 800 per tonne of storage capacity depending on structural specifications and local construction costs, plus refrigeration equipment costs of USD 200 to 400 per tonne capacity for mechanical systems (64). These combined capital requirements totaling USD 600 to 1200 per tonne effectively restrict cold storage adoption primarily to large-scale commercial enterprises achieving economies of scale, well-capitalised producer cooperatives with sufficient membership to amortise infrastructure costs, or government-subsidised public facilities serving smallholder producers (65, 66). Additional barriers include requirements for specialised technical expertise in refrigeration system operation and maintenance, dependence on reliable electrical power supply often unavailable in rural agricultural areas and relatively long payback periods of 5 to 8 years that may exceed financial planning horizons or loan term structures available to agricultural enterprises (67).

Controlled atmosphere and modified atmosphere technologies

Controlled atmosphere (CA) storage represents an advanced technology building upon refrigeration by additionally manipulating gaseous composition of storage atmosphere, typically reducing oxygen concentration to 2–10 % while elevating carbon dioxide concentration to 5–10 %, thereby further inhibiting respiration rates and enzymatic deterioration processes beyond temperature suppression alone (68, 69). The physiological mechanism operates through oxygen limitation reducing aerobic respiration rates, while elevated carbon dioxide exerts additional inhibitory effects on specific enzyme systems involved in senescence processes (70). Commercial CA storage achieves storage durations of 10 to 12 months with weight losses maintained at 3–4 % and superior retention of firmness, pungency and other quality attributes compared to conventional refrigerated storage (71, 72). However, CA technology requires substantial additional infrastructure beyond conventional cold storage including gas-tight chamber construction preventing atmospheric gas exchange, specialised gas control equipment for nitrogen generation or carbon dioxide injection, continuous gas monitoring and control systems and often ethylene scrubbing systems, collectively increasing capital costs by 2 to 3-fold compared to conventional refrigerated storage (73, 74). The extreme capital intensity restricts CA storage application primarily to premium quality products destined for high-value export markets or extended-season domestic marketing where price premiums justify the technology investment (75).

Modified atmosphere packaging (MAP) achieves similar atmospheric modification principles using semi-permeable polymer films that create a modified atmosphere through a balance between produce respiration, which consumes oxygen and produces carbon dioxide and film permeation properties that allow controlled gas exchange with the external environment (76, 77). When properly designed matching film permeability to produce respiration characteristics and storage temperature, MAP extends shelf life by 20–40 % compared to unpacked bulbs under identical refrigeration conditions (78). The MAP technology demonstrates economic attractiveness for smaller-scale operations as implementation requires only appropriate film selection and packaging equipment rather than facility-scale infrastructure modifications (79). However, film selection constitutes critical technical challenge requiring matching film oxygen and carbon dioxide transmission rates to specific cultivar respiration properties and intended storage temperature regime; inappropriate film selection can create excessively anaerobic conditions favouring fermentative metabolism and off-flavour development or insufficient atmospheric modification providing minimal benefit (80, 81). Additional challenges include film perforation risk during handling, condensation accumulation inside packages when temperature fluctuations occur and economic considerations of film costs that may prove prohibitive for low-value commodity onions versus value-added processed products (82).

Critical quality parameters and monitoring requirements

Effective onion storage management requires comprehensive monitoring of multiple interacting quality parameters that collectively reflect both physiological status and market acceptability. Unlike simplistic approaches focusing exclusively on temperature tracking, scientifically rigorous storage monitoring must account for complex interactions between environmental factors and intrinsic metabolic processes. This section synthesises current understanding of critical quality parameters, establishes measurement methodologies and optimal ranges based on peer-reviewed research and defines monitoring priorities with specific attention to physiological mechanisms underlying parameter interactions.

Temperature management and physiological interactions

Temperature represents the single most influential environmental parameter affecting onion storage performance through its dominant control over metabolic rate, with respiration, transpiration, sprouting and microbial growth all exhibiting strong temperature dependency (83, 84). The optimal storage temperature range of 0–1 °C for long-term cold storage reflects physiological requirements balancing multiple competing factors: temperatures must remain sufficiently low to suppress respiration and inhibit sprouting yet avoid freezing damage that occurs below -0.8 °C in most cultivars (85). The relationship between temperature and respiration rate follows Arrhenius kinetics with Q_{10} values of 2.0 to 2.5, meaning every 10 °C temperature increase approximately doubles to triples metabolic rate and associated weight loss (86). Sprouting initiation exhibits threshold behaviour with dormancy maintained indefinitely below approximately 4 °C, whereas temperatures exceeding 10 °C trigger progressive dormancy break through heat unit accumulation (87, 88). Temperature monitoring in commercial storage requires distributed sensor networks rather than single-point measurements due to ubiquitous thermal stratification and spatial temperature gradients, with research demonstrating temperature variations of 3–5 °C commonly occurring within nominally uniform storage rooms due to air circulation patterns, proximity to refrigeration equipment and thermal bridging through structural elements (89, 90).

Relative humidity control and water relations

Relative humidity represents the second critical environmental parameter requiring precise control and monitoring, exhibiting complex interactions with temperature and directly influencing both transpiration-driven weight loss and microbial proliferation rates (91, 92). The optimal relative humidity range of 65–70 % for onion storage reflects physiological requirements balancing competing concerns: humidity must remain sufficiently elevated to minimise transpiration water loss yet avoid excessive moisture promoting fungal germination and growth (93). Relative humidity below 60 % causes accelerated desiccation evident as progressive shriveling, weight loss exceeding metabolic respiration contributions and increased susceptibility to physical damage during handling due to reduced turgor (94, 95). Conversely, relative humidity exceeding 80 % creates conditions favouring germination of fungal spores, particularly neck rot pathogens *Botrytis allii* and basal rot organisms *Fusarium oxysporum*, with disease incidence exhibiting exponential increase above 75 % RH (96, 97). Humidity monitoring presents technical challenges in storage environments due to sensor calibration drift over time, particularly in condensing conditions where moisture accumulation on sensor elements compromises measurement accuracy (98). Capacitive humidity sensors, the predominant technology in commercial applications, exhibit typical accuracy of ± 2–3 % RH initially but may drift ± 5–8 % over 6–12 months without recalibration against certified humidity references (99, 100).

Weight loss dynamics and sprouting indices

Weight loss during storage integrates multiple physiological processes including transpiration water loss driven by vapour pressure deficit between produce surface and ambient air, respiration-associated carbon loss through oxidative metabolism

Table 2. Critical quality parameters for onion storage monitoring

Parameter	Optimal range	Measurement method	Monitoring frequency	Market threshold	Priority	References
Temperature	0–1 °C (cold storage); Ambient +5 °C max (traditional)	Digital sensors (thermistor, RTD); Accuracy: ± 0.3 °C	Continuous (5–15 min intervals)	Must maintain <4 °C for extended storage; excursions >10 °C accelerate sprouting	Critical	(83–87)
Relative humidity	65–70 %	Capacitive sensors; Accuracy: ± 2–3 % RH	Continuous (15–30 min intervals)	60–80 % acceptable range; <60 % causes desiccation; >80 % promotes fungal growth	Critical	(91–96)
Weight loss	<8–10 % over storage period	Load cells or batch weighing; Accuracy: ± 0.01–0.1 %	Daily to weekly depending on storage type	>15 % makes bulbs unmarketable; 8–10 % reduces market value significantly	High	(101–104)
Sprouting index	0 % incidence (no sprouting)	Visual inspection, image analysis, thermal imaging	Weekly inspection	>5 % sprouting incidence fails market standards	High	(87, 105, 106)
CO_2 Concentration	<0.5 % (ambient to traditional); 5–10 % (CA storage)	NDIR sensors; Accuracy: ± 50 ppm	Hourly to daily	>1 % in traditional storage indicates excessive respiration/ poor ventilation	Moderate	(68–71)
Firmness	Maintain harvest firmness	Penetrometer, compression testing	Bi-weekly to monthly	Softening indicates deterioration; often precedes visible decay	Moderate	(52–54)
Microbial load	Minimal visible decay	Visual inspection, sample plating	Weekly visual; monthly laboratory testing	>5 % visible decay unacceptable for most markets	High	(96–98)
Ethylene	<0.1 ppm	Electrochemical sensors	Daily in CA storage	Elevated levels accelerate senescence	Moderate (CA storage)	(69–71, 73)

Optimal ranges represent scientifically validated targets for maximising storage duration and quality retention. Measurement methods indicate commonly employed commercial technologies with typical accuracy specifications. Monitoring frequency reflects minimum recommended intervals for effective quality management. Market thresholds indicate critical values beyond which product acceptability is compromised. Priority classifications (Critical, High, Moderate) reflect relative importance for storage success. RTD = Resistance temperature detector; NDIR = Non-dispersive infrared; CA = Controlled atmosphere. References cited correspond to peer-reviewed sources documenting optimal values and monitoring protocols.

and potential desiccation of outer protective scales (101, 102). Acceptable weight loss thresholds for maintaining marketability depend on market segment and quality standards, with premium fresh markets typically specifying maximum allowable loss of 8–10 % whereas processing markets may accept up to 15 % loss if bulb integrity remains adequate (103). Weight loss exhibits nonlinear temporal dynamics, with initial rapid loss phase during first weeks of storage followed by stabilisation as protective scale desiccation reduces transpiration rates (104). Sprouting represents critical quality failure rendering onions unmarketable, with sprouting incidence strongly temperature-dependent and exhibiting cultivar-specific dormancy duration variations (105). Visual sprouting indices based on percentage of bulbs showing visible sprout emergence provide practical monitoring metrics, with market rejection typically occurring when sprouting incidence exceeds 5 % (106). Table 2 summarises the critical quality parameters requiring monitoring during onion storage.

Internet of things technologies for precision storage management

Internet of things technologies enable transformation of traditional storage approaches through integration of sensor networks, wireless communication, edge computing and automated control systems creating cyber-physical environments responsive to real-time conditions. This section examines IoT system architecture, sensor technology specifications, automated control capabilities and critical implementation considerations for agricultural storage applications.

Internet of things system architecture and components

The IoT systems for agricultural storage comprise four integrated architectural layers (107, 108): The perception layer encompasses physical sensors measuring environmental parameters (temperature, humidity, gas concentrations), imaging systems for visual quality assessment, actuator devices (fans, dampers, refrigeration controls, humidifiers) and energy management components including solar panels and battery systems. The network layer provides communication infrastructure through wireless protocols including WiFi for high-bandwidth applications such as image transmission, LoRaWAN (Long Range Wide Area Network) for extended range low-power sensor connectivity spanning up to 15 km, Zigbee for dense mesh networks in confined spaces and cellular connections for internet connectivity where available (109, 110). The middleware layer incorporates edge computing gateways performing local data preprocessing, filtering, aggregation and preliminary analytics to reduce communication bandwidth requirements and enable autonomous operation during network outages, plus cloud platforms providing long-term data storage, advanced machine learning analytics, multi-site data aggregation and remote accessibility through web and mobile applications (111). The application layer delivers end-user interfaces including mobile applications, web dashboards, automated alert systems via SMS or push notifications, control algorithm implementation and decision support tools integrating sensor data with agronomic knowledge (112).

Sensor technologies and performance characteristics

Technical challenges specific to storage environments include sensor performance degradation in high-humidity condensing conditions requiring moisture-resistant enclosures and periodic recalibration, electromagnetic interference from refrigeration compressors and motors disrupting wireless signal transmission necessitating careful frequency selection and shielding, power management complications in cold storage where battery capacity drops 20–40 % below 0 °C requiring larger battery banks or alternative power approaches and sensor placement optimisation accounting for thermal stratification patterns and airflow configurations in bulk storage to ensure representative measurements (113, 114). The "bulk storage sensing paradox" represents a fundamental challenge where spatial gradients and thermal stratification within large storage piles create localised hot spots that single-point or sparse monitoring cannot detect (115). Addressing this requires either dense distributed wireless sensor node networks with strategic placement informed by

Table 3. Internet of things sensor technologies for onion storage monitoring

Sensor type	Parameter measured	Accuracy	Power (mW)	Lifespan	Key limitations	References
Thermistor (NTC)	Temperature	± 0.2–0.5 °C	0.1–0.5	5–10 years	Requires linearisation; limited range; self-heating	(83, 84, 113)
RTD (Pt100/ Pt1000)	Temperature	± 0.1–0.3 °C	1–5	10–20 years	Higher cost; slower response; requires excitation current	(83, 113, 114)
Capacitive humidity	Relative humidity	± 2–3 % RH	0.5–2	3–5 years	Calibration drift; contamination sensitive; condensation damage	(91, 98– 100)
NDIR CO_2 sensor	Carbon Dioxide	± 50 ppm or ± 3 %	200–500	5–10 years	High power consumption; optical drift; periodic calibration needed	(68–70)
Electrochemical Gas	Ethylene, O_2	± 5 ppb (ethylene)	50–200	1–3 years	Limited lifespan (consumable); cross-sensitivity; temperature dependent	(69–71)
Load cell	Weight/Mass	± 0.01–0.1 % full scale	5–20	10–20 years	Vibration sensitivity; temperature compensation needed; cost scales with capacity	(101–103)
Camera (RGB/ NIR)	Visual inspection, sprouting	Resolution-dependent (2–12 MP)	500–2000 (active)	3–7 years	High processing power; lighting requirements; data storage intensive	(105–107)
MOS VOC Sensor	Volatile organic compounds	ppm level (compound-specific)	100–500 (requires heating)	2–5 years	High power (heating element); limited selectivity; humidity interference	(96–98)

Power consumption shown for active sensing mode; sleep mode typically 0.01–0.1 mW for most sensors. RTD = Resistance temperature detector; NDIR = Non-dispersive infrared; NIR = Near-infrared; VOC = Volatile organic compounds; MOS = Metal oxide semiconductor. Lifespan estimates assume proper installation, environmental protection and periodic maintenance. Actual performance varies with operating conditions and duty cycle. References provide detailed technical specifications and performance evaluations.

computational fluid dynamics modeling of airflow patterns, or development of "Digital Twin" simulation models that use limited sensor data combined with physics-based models to predict conditions throughout the storage volume (116). Table 3 provides a comprehensive overview of IoT sensor technologies suitable for onion storage monitoring applications.

Automated control systems

Automated control systems combine sensor information with actuators to optimise storage environment. Ventilation control algorithms compare internal and external temperature and humidity, activating exhaust fans when ambient conditions offer cooling potential without excessive humidity introduction (117, 118). Refrigeration optimisation employing model predictive control reduces energy consumption by 20–30 % compared to conventional setpoint control, though requiring 12–18 months historical data for training (119). Humidity control systems maintain target ranges within ± 3 % RH through coordinated humidification and dehumidification (120). Machine learning models exhibit "black box" characteristics requiring careful validation to ensure robustness under novel conditions (121).

Economic analysis of internet of things implementation

Economic viability depends on loss reduction magnitude, storage scale and regional conditions. Basic systems cost USD 3–7 per tonne; advanced systems USD 8–15 per tonne (122). Payback periods of 4–6 months occur under favourable conditions but extend to 18–30 months in well-managed baseline storage (123). Cooperative models achieve USD 5 per tonne through shared infrastructure (124). Sensitivity to onion prices, energy costs and baseline performance necessitates context-specific assessment (125). The economic journey from loss to profit with IoT integration in onion storage is given in Fig. 2.

Implementation challenges and adoption barriers

Rural telecommunications inadequacy affects 58 % of facilities (126). The LoRaWAN offers partial mitigation but requires gateway infrastructure investment of USD 800–1500 (127). Technical support gaps explain 68 % of implementation failures (128). Sensor calibration drift necessitates annual recalibration (129). Digital literacy limitations particularly affect operators over 55 years (130). Economic accessibility challenges persist for smallholder farmers where systems represent 5–15 % of annual income (131).

Sustainability considerations

Carbon footprint depends on grid carbon intensity. The IoT refrigeration optimisation yielding 20 % energy reduction saves 96 kg CO_2-eq/tonne/year in coal grids versus 10 kg in renewable grids (132). Electronic waste generation of 150–250 g per sensor node over 3–5-year cycles raise concerns (133). Circular economy principles including modular design, firmware upgradability and remanufacturing programs show promise but <5 % manufacturer adoption (134).

Future directions and research priorities

Edge artificial intelligence for automated sprouting detection achieves >90 % accuracy (135). Satellite IoT connectivity promises rural coverage though 500–1500 ms latency limits real-time control (136). Biosensors for volatile organic compound detection could provide 5–10-day advance warning of spoilage (137). Digital Twin models require

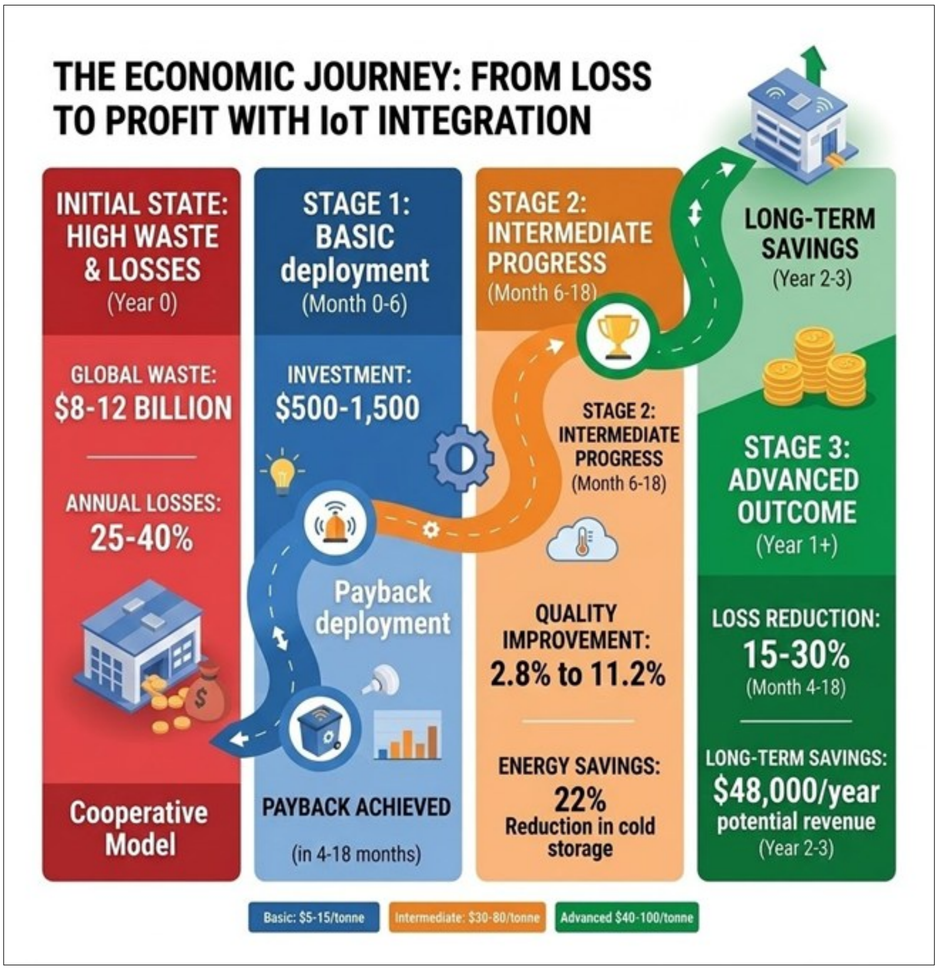

Fig. 2. The economic journey from loss to profit with internet of things integration in onion storage.

multi-year validation across diverse conditions (138). Priority research gaps include commercial-scale validation, standardisation frameworks, integrated decision models, sociological adoption research and lifecycle assessment methodologies (139, 140).

Conclusion

This comprehensive review demonstrates substantial potential for internet of things technologies to address post-harvest losses threatening global food security and farmer livelihoods. Traditional ambient storage suffers 15–40 % losses over 3–5 months due to uncontrolled environmental conditions. Modern cold storage achieves 6–10-month shelf life with <5 % losses but requires USD 400–800 per tonne capital investment restricting adoption to large operations. The IoT technologies offer transformative potential through real-time monitoring, automated control and predictive analytics, with loss reductions of 10–20 % and payback periods of 2–3 years under favourable conditions, though exhibiting substantial sensitivity to market prices and energy costs.

Critical implementation barriers include inadequate rural telecommunications infrastructure affecting 58 % of facilities, insufficient technical support networks, sensor calibration drift, economic accessibility challenges for smallholders and limited digital literacy. Successful implementations feature dedicated technical support, farmer-centered design and gradual capacity building. Hybrid retrofitting models combining traditional infrastructure with IoT monitoring and evaporative cooling achieve 15–30 % loss reduction at 70–85 % of full cold storage costs, demonstrating economic viability.

Priority future research includes commercial-scale field validation across diverse climatic contexts, standardised interoperability framework development through industry-academic collaborations, integrated techno-economic decision models accounting for uncertainty, systematic sociological investigation of adoption processes and standardised lifecycle assessment methodologies. Realising full IoT potential requires coordinated action across policy supporting rural infrastructure expansion, technology development prioritising practical deployability, research addressing critical knowledge gaps and engagement with farming communities through participatory design. With integrated approaches, IoT technologies can genuinely transform post-harvest storage management, reducing losses, improving food security and enhancing farmer livelihoods globally.

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Authors' contributions

PK contributed to drafting the manuscript, review writing, image creation and complete filing. RA Supervised and reviewed the manuscript. Both the authors read and approved the final manuscript.

Compliance with ethical standards

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