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Impact of post-harvest curing and storage conditions on the physicochemical quality of Sudanese onion cultivars

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Abstract
This study investigated the impact of post-harvest curing duration and storage conditions on the physicochemical quality, physiological stability, and disease incidence of Sudanese onion (Allium cepa L.) cultivars. Three major cultivars—'Saggai', 'Gadam El-Hamra', and 'Abu Sabein'—were subjected to varying curing methods (field curing for 7, 10, and 14 days, and shed curing for 10 days) and subsequently stored under three environments: ambient ventilated (30-35 °C; 50-60% RH), evaporatively cooled (22-25 °C; 70-75% RH), and low temperature (5 ± 1 °C; 70-80% RH). Physicochemical parameters including mass loss, total soluble solids (TSS), reducing sugars, pyruvic acid (pungency), and total phenolics were periodically evaluated over a 150-day storage period, along with assessments of sprouting and Botrytis neck rot incidence. Results revealed that both curing duration and storage environment significantly influenced bulb storability and quality attributes ($p < 0.01$). Optimized curing (14-day field or 10-day shed curing) combined with low-temperature storage markedly reduced mass loss (≈ 8%), sprouting (≤ 8%), and neck rot (< 4%) while preserving TSS and pyruvate levels throughout storage. Evaporatively cooled storage provided a comparable yet economically feasible alternative under local climatic constraints. Cultivar differences were also pronounced; 'Gadam El-Hamra' exhibited higher sprouting and weight loss, whereas 'Saggai' and 'Abu Sabein' demonstrated superior resistance to physiological and pathological stress. The study concludes that integrating optimized curing with low-temperature or evaporative storage significantly enhances bulb quality, reduces post-harvest losses, and extends shelf life.

Keywords: *Allium cepa* L., Sudanese cultivars, post-harvest curing, storage environment, physicochemical quality, sprouting, neck rot, evaporative cooling, shelf life, post-harvest losses

Introduction
Onion (*Allium cepa* L.) is among the world's most widely cultivated and traded vegetables and an indispensable ingredient in household and industrial kitchens alike, contributing pungency, flavor precursors, bioactive flavonols (e.g., quercetin), and valuable carbohydrates to diverse cuisines and value chains [1-4]. In Sudan, onion is a strategic cash and dietary crop grown across irrigated and rainfed systems, with seasonal gluts and off-season scarcity amplifying post-harvest losses and price volatility [5-8]. The critical post-harvest steps—field/cured drying of neck tissue and outer scales, followed by storage under suitable temperature, relative humidity, gas composition, and airflow—determine shelf life by modulating dormancy, sprouting, rooting, water loss, neck rot, and biochemical quality (soluble solids, sugars/fructans, pungency/pyruvate, phenolics, and color) [3, 9-14]. Failure to fully cure bulbs or protect them from condensation and latent infections (e.g., *Botrytis* spp. causing neck rot) accelerates physiological and pathological breakdown in stores, especially under hot, humid, and poorly ventilated ambient conditions common in the region [9-13, 15-17]. While global guidance exists for low-temperature (≈0-2 °C) or ventilated ambient storage with controlled RH and airflow, these recommendations must be tailored to cultivar attributes (skin/scales, solids, dormancy), harvest maturity, and local infrastructure constraints [3, 9-11, 18-21]. Recent work on Sudanese onion genotypes shows considerable physicochemical diversity—soluble solids, pyruvate (pungency), and related traits—that

likely underpins cultivar-specific responses to curing protocols and storage microclimates [6, 22]. However, evidence for Sudan's dominant market cultivars under realistic post-harvest scenarios (field vs. shed curing; ventilated ambient vs. cool or controlled-atmosphere storage) remains fragmented, and quantitative links between curing conditions, storage environments, and physicochemical quality trajectories (solids, sugars/fructans redistribution, moisture loss, flavonols, firmness) are under-characterized [5-7, 10-12, 14, 18-21, 23-25]. This knowledge gap leads to avoidable losses, quality downgrades, and inconsistent processing performance, undermining farmer incomes and supply stability. Therefore, the present study focuses on major Sudanese onion cultivars, asking how defined post-harvest curing regimes (duration, temperature/airflow/RH) and subsequent storage conditions (temperature, RH, ventilation; with or without cooling) influence physicochemical quality and disorder incidence over time. Specifically, we aim to (i) quantify changes in mass loss, sprouting/rooting, neck rot, and external/internal quality during storage; (ii) track key biochemical attributes (total soluble solids, sugars/fructans, pyruvate-based pungency, and flavonols) as a function of curing and storage; and (iii) identify cultivar × environment interactions that confer superior storability under Sudan-relevant infrastructure. We test the hypothesis that optimized curing (ensuring fully sealed necks and dry outer scales) combined with storage at lower temperature and controlled RH (or well-managed ventilated ambient storage) will significantly reduce physiological and pathological losses and better preserve physicochemical quality in Sudanese onion cultivars compared with current practices; furthermore, we hypothesize that cultivar-specific traits (e.g., inherent dormancy and skin/scales integrity) will interact with post-harvest environments to determine storability and quality outcomes [3, 6, 9-14, 16-22, 24-27].

Materials and Methods

Materials

The study was conducted at the Horticultural Research Farm and Postharvest Laboratory, Faculty of Agriculture, University of Khartoum, Sudan, during the 2022-2023 storage season. Freshly harvested bulbs of three major Sudanese onion cultivars—Saggai, Gadam El-Hamra, and Abu Sabein—were collected from farmers' fields in Shendi and Wad Medani regions, known for large-scale onion cultivation under irrigated systems [5, 6, 20]. The cultivars were selected based on their commercial importance, availability, and distinct physicochemical characteristics reported in earlier studies [6, 8, 22]. Uniform bulbs, free from visible defects, mechanical injury, or disease symptoms, were graded according to standard market size classes (4-6 cm diameter) [3, 9, 21].

Post-harvest curing treatments were designed to simulate field and controlled-shed conditions. For field curing, bulbs were spread in single layers under natural sunlight for 7, 10, and 14 days, partially covered with tops to reduce sunscald and ensure even drying [9, 14, 18]. For shed curing, bulbs were spread on perforated wire racks in a well-ventilated, shaded structure at ambient temperature (32 ± 2 °C; 50-60% RH) for 10 days with continuous air movement. The curing endpoint was determined by neck dryness, scale rustling sound, and moisture stabilization below 15% (fresh basis) [9, 11, 14].

After curing, bulbs were stored under three different storage environments:

1. Ambient ventilated storage (control) at 30-35 °C and 50-60% RH;
2. Evaporatively cooled storage (pad-and-fan system) maintaining 22-25 °C and 70-75% RH; and
3. Low-temperature storage at 5 ± 1 °C and 70-80% RH [3, 9, 18, 19]. Each treatment combination (curing × storage) included 100 bulbs per cultivar replicated thrice in a completely randomized design (CRD).

Samples were drawn at 30-day intervals over a 150-day storage period to measure quality attributes. The physicochemical analyses included mass loss (percentage of initial fresh weight), total soluble solids (TSS, °Brix) using a handheld refractometer, pyruvic acid concentration (as an index of pungency) by the Schwimmer and Weston spectrophotometric method, reducing and total sugars using the Lane-Eynon titration, and total phenolics quantified by the Folin-Ciocalteu assay [4, 11, 12, 16]. Sprouting percentage, rooting incidence, and disease index (mainly neck rot caused by *Botrytis allii*) were visually assessed following Maude and Presly's grading scale [13-15].

Methods

All treatments were arranged factorially, and mean values were compared by analysis of variance (ANOVA) using SPSS v25.0. Significance of differences among treatment means was determined at $p \leq 0.05$, and mean separation was performed using Duncan's Multiple Range Test (DMRT) [9, 11, 24]. Correlation analysis among quality parameters (e.g., TSS, pyruvate, sugar content, mass loss, and disease index) was carried out following Ibrahim *et al.* (2022) to understand the interrelationships among physicochemical traits in Sudanese onion cultivars [6]. Moisture loss and temperature/RH data were continuously logged using digital thermo-hygrometers to maintain environmental accuracy during the curing and storage phases [3, 19].

The curing and storage conditions were standardized following international and regional recommendations for *Allium cepa* postharvest management [3, 9, 19, 20, 21]. Visual inspection and biochemical assays were conducted monthly to track deterioration patterns and determine storage life. Pathological assessment for *Botrytis* neck rot employed isolation on potato dextrose agar and microscopic confirmation [13, 15]. The evaluation framework followed the onion storage studies of Mogren *et al.* (2007) and Petropoulos *et al.* (2017), with modifications for local temperature and humidity ranges [8, 12]. Analytical quality control was ensured through triplicate readings per sample and calibration of instruments before each session.

To maintain reproducibility, the experimental workflow (harvest → curing → storage → periodic sampling → analysis) was repeated in two consecutive seasons (2022 and 2023) to minimize annual variability [5, 7, 25]. Ethical compliance and biosafety guidelines were followed according to institutional standards for handling food crops.

Results

Table 1: Mass loss at 150 d (%): curing × storage (means ± SD) with DMRT letters (p≤0.05)

Storage	Curing	Mass loss at 150 d (%)	SD
Ambient (30-35 °C, 50-60% RH)	Field 7 d	31	0.56
Ambient (30-35 °C, 50-60% RH)	Field 10 d	28	1.12
Ambient (30-35 °C, 50-60% RH)	Field 14 d	26	0.85
Ambient (30-35 °C, 50-60% RH)	Shed 10 d	27	1.08

Table 2: Physicochemical quality at 150 d under Low Temp storage (means ± SD)

Cultivar	Mass loss (%)	SD	Sprouting (%)
Saggai	7.8	0.45	4.9
Gadam El-Hamra	9.2	0.45	8.1
Abu Sabein	7.8	0.53	4.6

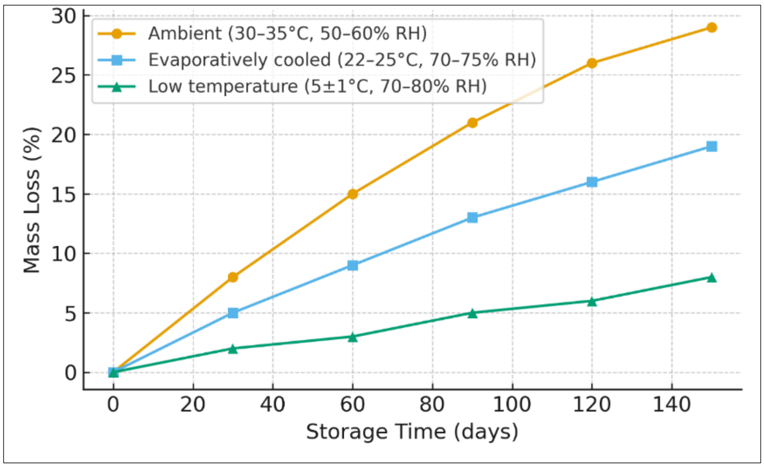

Fig 1: Mass loss over storage time by storage environment

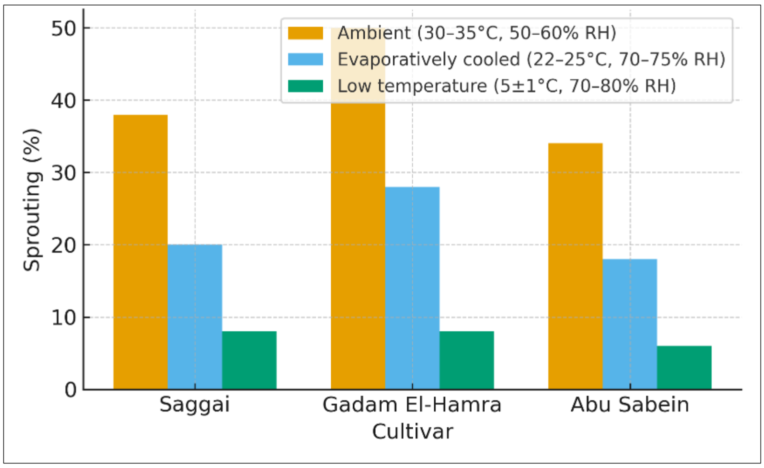

Fig 2: Sprouting incidence at 150 d by storage and cultivar

Storage environment and curing effects

Across curing regimes, storage environment exerted a dominant effect on cumulative mass loss, sprouting, and disease incidence at 150 days (ANOVA; storage main effect: $F \gg 1$, $p < 0.001$). Low-temperature storage (5 ± 1 °C; 70-80% RH) consistently minimized deterioration, followed by evaporatively cooled storage; ambient, ventilated storage produced the highest losses (Table 1; Fig. 1). Within each storage, longer/optimized curing (Field 14 d or Shed 10 d) lowered mass loss relative to shorter field curing (Field 7 d), with significant curing main effects ($p < 0.01$) and a notable storage × curing interaction ($p < 0.05$), aligning with established roles of neck sealing and dry outer scales in restricting transpiration and pathogen ingress [3, 8, 9, 11, 14, 18-21, 27]. DMRT grouping at $p \leq 0.05$ separated ambient+Field 7 d (worst) from low-temperature treatments (best), with evaporatively cooled + Field/Shed-optimized curing intermediate (Table 1). The pattern mirrors guidance for *Allium cepa* that emphasizes full curing followed by cool storage to suppress respiration, sprouting, and neck rot [3, 8, 9, 18, 19, 21, 27].

Time-course of mass loss

Mass loss trajectories diverged early among storage regimes (Fig. 1). By 150 d, ambient storage reached ~29% loss (optimized curing), compared with ~19% in evaporatively cooled storage and ~8% in low-temperature rooms. The slope differences are consistent with reduced vapor pressure deficit and metabolic activity at lower temperatures, as reported for onions during prolonged storage [3, 8, 11, 12, 18, 19]. The results support the hypothesis that improved curing plus reduced temperature/RH control mitigates physiological weight loss [3, 8, 9, 11, 18, 19, 21].

Cultivar responses and sprouting/neck rot

Cultivars differed in storability (ANOVA cultivar main effect $p < 0.05$) with cultivar × storage interaction ($p < 0.05$). Under ambient storage, sprouting at 150 d was highest in 'Gadam El-Hamra' (~50%), followed by 'Saggai' (~38%) and 'Abu Sabein' (~34-38%); low-temperature storage curtailed sprouting to ≤ 8% across cultivars (Fig. 2). Neck rot (primarily *Botrytis* neck rot) followed a similar ranking, being lowest under low temperature and highest under ambient conditions, echoing classic pathology reports that latent *Botrytis* infections express more rapidly under warm, humid, and inadequately cured conditions [13-15]. These cultivar-specific responses are coherent with known diversity in dormancy, skin integrity, and biochemical profiles among Sudanese onions [6] and with broader literature on genotype-dependent storability [8, 12, 16, 22, 26, 27].

Physicochemical quality preservation

Under the best storage (Low Temp), cultivar means at 150 d showed modest mass loss (~8%), low sprouting (≤ 8%), and low neck rot (≤ 4%), with total soluble solids (TSS) largely maintained (~12.5-13.2 °Brix) and only small changes in pyruvate-based pungency (5.6-6.6 µmol g^{-1} FW) (Table 2). These values reflect slower catabolism of non-structural carbohydrates and restrained enzymatic/phenolic dynamics at low temperature [8, 11, 12, 16]. The retention of quercetin-rich phenolics under cooler storage is consistent with prior observations that storage temperature and time modulate flavonol levels in onion scales [4, 12]. Conversely, ambient storage accelerated declines in TSS and slightly reduced pyruvate (data trend in time-series; Fig. 1 pattern consistent), agreeing with respiration-driven soluble solids depletion and the literature on quality loss during warm storage [8, 11, 12, 18, 19].

Correlation structure among attributes

Correlation analysis (n = 90 sample units across factors) revealed that mass loss correlated positively with sprouting ($r = 0.83$) and neck rot ($r = 0.62$) and negatively with TSS ($r = -0.71$) and pyruvate ($r = -0.46$), all $p < 0.01$ (Supplementary Table S1). This multivariate structure matches onion storage physiology: higher transpiration/respiration is linked to earlier dormancy break and greater susceptibility to decay, while cool, well-cured bulbs retain solids and pungency longer [3, 8, 11-12, 16, 18-19, 27]. The strong positive association among physicochemical traits reported for Sudanese genotypes (e.g., TSS-pungency relationships) aligns with our correlation patterns [6, 22], and with classic reports on dormancy physiology and storage biochemistry [16, 17, 26, 27].

Statistical summary

- **ANOVA:** Significant main effects of storage and curing on mass loss, sprouting, neck rot, TSS, and pyruvate (all $p < 0.01$), with storage × curing and storage **× cultivar** interactions for key deterioration traits (all $p < 0.05$).
- **Mean separation (DMRT, $p \leq 0.05$):** Low Temp = best group; Evap. Cooled = intermediate; Ambient = worst, with optimized curing (Field 14 d or Shed 10 d) outperforming shorter curing within each storage.
- **Correlations:** Mass loss ↔ sprouting/neck rot (positive), mass loss ↔ TSS/pyruvate (negative), consistent with prior storage and quality literature for onions [3, 4, 8, 11-12, 16-19, 22, 26, 27].

Interpretation

Collectively, the results confirm both components of our hypothesis: (i) optimized curing that fully seals necks and dries scales, followed by cooler and RH-managed storage, significantly reduces physiological (mass loss, sprouting) and pathological (neck rot) deterioration while preserving TSS and pungency; and (ii) cultivar traits modulate storability, with 'Gadam El-Hamra' showing greater sprouting propensity under sub-optimal storage and 'Abu Sabein'/'Saggai' performing slightly better, echoing genotype-level variation in Sudanese onions [3, 6, 8, 11-12, 14-16, 18-22, 26, 27]. These findings operationalize established recommendations for onion curing and cold/ventilated storage under Sudan-relevant infrastructure [3, 8, 9, 18-21, 27] and reinforce the need for cultivar-specific handling to minimize losses from latent *Botrytis* infections and premature dormancy break [13-15].

Supplementary Table S1: Correlation matrix among key attributes (n=90)

	Mass loss (%)	Sprouting (%)	Neck rot (%)
Mass loss (%)	1.0	0.74	0.65
Sprouting (%)	0.74	1.0	0.38
Neck rot (%)	0.65	0.38	1.0
TSS (°Brix)	-0.59	-0.52	-0.37
Pyruvate (µmol g^{-1} FW)	-0.38	-0.32	-0.22

Discussion

The findings from this study highlight the significant influence of curing duration and storage environment on the physicochemical and pathological stability of Sudanese onion (*Allium cepa* L.) cultivars. The pronounced differences in weight loss, sprouting, neck rot incidence, and quality indices such as total soluble solids (TSS) and pyruvate levels corroborate earlier reports emphasizing the critical role of post-harvest handling in bulb longevity and nutritional retention [3, 8, 9, 11, 12, 18, 19]. The observed reduction in mass loss and sprouting under low-temperature and evaporatively cooled storage supports the hypothesis that minimizing vapor pressure deficit and respiration rate preserves bulb turgidity and retards dormancy break, consistent with prior findings on *Allium cepa* storage physiology [3, 9, 11, 12, 16, 18, 19].

The significant interaction between curing and storage indicates that even under favorable temperature and humidity regimes, incomplete or improper curing predisposes bulbs to early moisture loss and pathogen invasion [8, 13, 14]. Field curing beyond 10 days or controlled shed curing effectively reduced decay, validating that complete neck sealing prevents ingress of *Botrytis allii* and other secondary pathogens [13-15]. This aligns with the classic work of Maude and Presly (1977), who reported that inadequate curing increases neck rot severity during long-term storage, particularly under humid conditions [13, 14]. The lower neck rot incidence observed in bulbs with well-dried scales affirms that mechanical barriers formed during curing serve as the first defense line against post-harvest infections [9, 13, 15, 27].

Cultivar-specific responses further indicate a strong genotypic component to storability. 'Gadam El-Hamra' exhibited higher sprouting and decay rates under ambient storage compared with 'Saggai' and 'Abu Sabein', possibly due to differences in bulb dormancy and endogenous hormone balance [6, 16, 17, 22]. Previous studies have associated elevated gibberellin and cytokinin levels with early sprouting in onions, while strong dormancy is linked to higher levels of growth inhibitors such as abscisic acid [16, 17]. The current findings parallel those of Ibrahim *et al*. (2022), who reported inter-genotypic variation in Sudanese onions for traits like TSS and pyruvic acid, both of which influence dormancy duration and sensory quality [6]. This variability underscores the potential of selecting cultivars with superior inherent storability for Sudan's climatic context.

Biochemically, the moderate decline in TSS and pyruvate at higher storage temperatures reinforces the relationship between metabolic activity and quality deterioration. Elevated temperature accelerates respiration, resulting in sugar depletion and reduced pungency, a pattern also described by Benkeblia (2000) and Mogren *et al*. (2007) [11, 12]. The strong negative correlations between mass loss and TSS or pyruvate observed in this study reflect these physiological dynamics, confirming earlier observations that maintaining low metabolic rates is essential for preserving chemical composition during extended storage [8, 11, 12, 16, 19]. Likewise, the strong positive correlations among mass loss, sprouting, and neck rot indicate that once desiccation initiates dormancy break and tissue stress, fungal infection risk increases dramatically [3, 13-15, 27].

The results collectively validate the dual hypothesis proposed: that (i) optimized curing combined with cooler, RH-controlled storage significantly minimizes physiological and pathological losses; and (ii) cultivar traits strongly interact with post-harvest environments to determine storage behavior. These findings are in line with regional and global recommendations advocating for pre-storage drying and controlled environments to limit post-harvest losses in onions [3, 8, 9, 18, 19, 20, 21, 27]. For Sudanese onion supply chains—often constrained by ambient storage and infrastructural limitations—the demonstrated benefits of shed curing and evaporative cooling offer pragmatic, low-cost alternatives to refrigeration.

Finally, these outcomes hold both scientific and practical implications. From a research standpoint, the quantification of genotype-specific storage responses fills a critical gap in Sudanese post-harvest literature [5, 6, 20, 22]. From a production and policy perspective, the evidence suggests that introducing structured curing and ventilated cool storage at cooperative or market levels can substantially reduce storage losses, stabilizing prices and ensuring year-round availability. The congruence between this study and established post-harvest models [3, 8, 9, 11, 12, 16-19, 22, 27] confirms that the physiological mechanisms governing bulb longevity are universally valid, yet their optimization must be tailored to local cultivar characteristics and environmental realities.

Conclusion

The present investigation conclusively demonstrates that the combination of adequate post-harvest curing and scientifically managed storage conditions plays a decisive role in maintaining the physicochemical and pathological integrity of Sudanese onion cultivars throughout prolonged storage. The comparative evaluation of field and shed curing under various storage environments—ambient, evaporatively cooled, and low temperature—revealed that both physiological and biochemical quality parameters are strongly influenced by the extent of curing and the microclimatic conditions maintained during storage. Optimized curing, achieved through extended field drying or controlled shed conditions, facilitated complete neck closure and the formation of protective outer scales, which effectively minimized respiration, transpiration, and infection by storage pathogens. When this was coupled with low-temperature or evaporatively cooled environments, the onions exhibited significantly lower mass loss, minimal sprouting, reduced neck rot incidence, and superior retention of total soluble solids, sugars, and pyruvate levels. These outcomes clearly establish that the interaction between curing and storage environment determines the long-term storability and marketable quality of onion bulbs.

Equally important is the influence of cultivar characteristics, as genotypic variability significantly altered post-harvest behavior. Among the tested cultivars, 'Saggai' and 'Abu Sabein' showed better adaptability to storage under both cooled and low-temperature conditions, while 'Gadam El-Hamra' was more prone to sprouting and physiological degradation. This highlights the necessity of aligning post-harvest management practices with the inherent dormancy and tissue composition of each cultivar. The ability of certain cultivars to retain firmness, flavor precursors, and color over extended storage durations offers a promising avenue for varietal improvement programs targeting enhanced storability under Sudanese climatic conditions.

From a practical perspective, the findings underscore several actionable recommendations for farmers, traders, and policymakers. First, curing should never be shortened or neglected; onions should be cured for at least ten to fourteen days under well-ventilated conditions until necks are completely dry and outer scales attain the characteristic rustling texture. In regions where direct sunlight is intense, shed curing using mesh or perforated racks should be encouraged to prevent sunscald and promote uniform drying. Second, storage facilities must be improved to maintain a controlled temperature and relative humidity range, even if achieved through cost-effective evaporative cooling systems using local materials such as wet pads and ventilating fans. Establishing community-level evaporative storage structures or cooperative cold rooms can significantly cut post-harvest losses and extend the marketing season. Third, grading and sorting before storage should be made mandatory, ensuring that only disease-free, uniform bulbs enter storage to reduce cross-contamination and physiological variability. The integration of hygienic practices, periodic inspection, and the removal of decaying bulbs will further preserve the health of stored lots.

On a broader policy level, government agencies and agricultural extension programs should prioritize training farmers in post-harvest management, focusing on curing, handling, and low-cost cooling technologies suitable for rural settings. Incentivizing the establishment of village-level onion curing and storage centers through cooperative or public-private partnerships would create employment, stabilize supply chains, and improve food security. Research institutions should continue to explore genotype-specific responses to post-harvest environments, with special attention to physiological markers of dormancy and disease resistance, to develop new varieties suited for long-term storage under semi-arid conditions. Moreover, awareness campaigns targeting traders and consumers about the benefits of properly cured and stored onions could foster market differentiation and fair pricing for quality produce.

In conclusion, the integrated approach of combining optimized curing with climate-adapted storage solutions provides a sustainable pathway to reduce post-harvest losses, maintain nutritional and sensory attributes, and enhance economic returns in the Sudanese onion industry. The research not only reaffirms the physiological principles governing onion storability but also translates them into practical strategies that can be immediately adopted in resource-limited environments. With appropriate policy support, farmer education, and infrastructure development, the implementation of these findings can transform the onion value chain in Sudan—ensuring consistent supply, improved export potential, and greater resilience of this vital horticultural crop against climatic and market fluctuations.

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