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Comparative Shelf-Life Predictions of Packaged Paddy Using Water Mass-Transfer Modelling and Quality-Deterioration Kinetics Under Different Controlled Relative Humidities

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ABSTRACT

Even when paddy is sufficiently dry at the start of storage, its quality may deteriorate if humid storage air drives ongoing moisture exchange among the grain, the package, and the environment. This study evaluated the Inpari 32 paddy variety packed in woven polypropylene mini-sacks and stored for 90 days at 30 °C under relative humidity (RH) levels of 50%, 70%, and 90%. Shelf life was estimated from two endpoints: moisture change predicted with a water mass-transfer model and damaged-grain development predicted with first-order quality kinetics using Indonesian National Standard (SNI) 224:2023 limits (National Standardization Agency of Indonesia, 2023). After 90 days, moisture content was 12.7166% wb at RH 50%, 13.3864% wb at RH 70%, and 15.5008% wb at RH 90%, indicating net water loss under the driest condition and marked humidification at high RH. The fitted apparent transfer capacities (P) were 0.0880, 0.0062, and 0.0335, whereas the apparent water-transfer rate constant (Q) increased from 0.0020 to 0.0092 and 0.0212 day^{-1} as RH increased. Model fit was high (R^2 = 0.9913-0.9990; RMSE = 2.69×10^{-4}-8.64×10^{-4} g H_2O g^{-1} dry solid). Damaged-grain rate constants likewise increased with RH, from 0.0068 to 0.0127 and 0.0213 day^{-1}. Moisture-based shelf lives were 312, 176, and 105 days, whereas the Medium I damaged-grain endpoint gave 296, 159, and 95 days. Thus, physical-quality failure was predicted 5.1-9.7% earlier than the moisture endpoint. The results show that RH control, rather than initial moisture content alone, should guide paddy-storage decisions in humid tropical systems.

Keywords: Damaged grain, paddy, relative humidity, shelf life, storage, water mass transfer

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INTRODUCTION

Rice is the staple food for more than 90% of Indonesia's population and is central to the country's food and economic systems (Ansari et al., 2023; Santosa et al., 2024). Although rice supply is often discussed in terms of field yield, much of its final value is determined after harvest. Across the rice supply chain, postharvest management determines grain quality until milling and distribution (Atungulu et al., 2019; Tong et al., 2019). In Indonesia, paddy commonly enters storage near 13-14% moisture content (wet basis), below or close to the 14% maximum specified by SNI 224:2023 for Premium and Medium I paddy, while warehouse air may remain warm and humid for prolonged periods. Under these conditions, paddy continues to exchange water vapour with the surrounding air, and lot quality changes during storage, transport, and waiting time before milling (Atungulu et al., 2019; Müller et al., 2022; Tong et al., 2019). Shelf life should therefore be treated as condition-dependent rather than as a fixed calendar period.

Moisture exchange is a primary process governing storage stability. Paddy kernels and husks are hygroscopic: they release water when the surrounding air is dry and absorb water when it is humid. As moisture content rises, the risks of increased water activity, respiration, fungal activity, structural weakening, and visible grain defects also increase (El-Mesery et al., 2025; Garofalo et al., 2024; Wang et al., 2022). Consequently, two paddy lots with similar initial moisture contents can behave differently when exposed to different relative humidity (RH) levels. In humid equatorial regions, RH can determine whether an initially acceptable lot remains stable.

Moisture-based models quantify the environmental pressure on stored paddy. The P-Q water-transfer model proposed by Rahayoe et al. (2025), for example, represents storage behaviour through an apparent transfer capacity (P) and an apparent transfer-rate constant (Q). It is operationally simple because it does not require every input used in classical package shelf-life calculations, such as film permeability, exposed area, vapour-pressure difference, and a complete moisture-sorption isotherm. Moisture is nevertheless not the sole basis for market acceptance: a lot can exceed the permitted damaged-grain limit before reaching the selected moisture endpoint.

Classical packaged-food shelf-life models usually combine a moisture-sorption isotherm, often the Guggenheim-Anderson-de Boer (GAB) model, with package water-vapour permeability, exposed area, product mass, external vapour pressure, and a critical moisture content (Labuza & Altunakar, 2020; Robertson, 2005; Robertson & Lee, 2021; Lee & Robertson, 2022). These mechanistic approaches explicitly represent equilibrium sorption and package resistance, but predictions can be sensitive to isotherm selection and require material- and geometry-specific inputs; multidomain products may require additional transfer terms (Roca et al., 2008). In contrast, the empirical P-Q formulation estimates capacity and rate directly for the observed packaged paddy system. It was selected

here as a parsimonious method for comparing controlled RH treatments, not as a universal replacement for isotherm-based models. P and Q must be recalibrated when the variety, packaging, temperature, or humidity regime changes.

The present work, therefore, treated paddy storage life as a two-endpoint problem. The water-transfer endpoint described water gained or lost by the packaged grain, whereas the damaged-grain endpoint represented the visible quality limits in SNI 224:2023. The objectives were to (i) characterise moisture content and water mass transfer in the selected paddy variety at 30 °C and RH 50%, 70%, and 90%; (ii) estimate and validate P and Q in the water-transfer model and the damaged-grain deterioration-rate constant; and (iii) compare the two predicted endpoints and use the earlier one for a conservative storage recommendation.

MATERIALS AND METHODS

Material Packaging and Quality Endpoints

Inpari 32, an inbred paddy variety commonly cultivated in Indonesia, was obtained from Sekaran Village, Wonosari District, Klaten Regency, Central Java, Indonesia. Its initial moisture content was 13.0903 ± 0.1217% wet basis (wb). Samples were placed in woven polypropylene (PP) mini-sacks, a permeable package commonly used for paddy handling in Indonesia. Storage was conducted for 90 days at 30 °C under controlled RH levels of 50%, 70%, and 90%. The 30 °C subset was selected from the larger thesis dataset to isolate the effect of RH without adding temperature as a source of variation. Moisture content and physical-quality attributes were monitored during storage. Shelf life was defined as the predicted time required for a selected variable to reach a critical limit. The water-transfer calculation used a moisture-related limit, whereas the quality-kinetic calculation used the damaged-grain limit. Table 1 lists the SNI 224:2023 thresholds. The Medium I damaged-grain limit of 1.5% was the principal commercial endpoint; the Premium and Medium II limits were included for sensitivity analysis.

Three independent 52-L storage boxes were used per RH treatment (n = 3). Each box contained 15 mini-sacks, each holding 200 g of paddy. Three mini-sacks per box were weighed every 5 days for 90 days and averaged into a single box-level trajectory. One mini-

Table 1
Maximum SNI 224:2023 quality limits used as shelf-life endpoints for dry milled paddy

Quality component	Unit	Premium	Medium I	Medium II
Moisture content, maximum	% wb	14.0	14.0	15.0
Empty grains, maximum	%	1.0	2.0	3.0
Damaged grains, maximum	%	0.5	1.5	3.0
Foreign matter, maximum	%	0.01	0.05	0.10

sack per box was sampled every ten days for quality evaluation. The storage box, not the individual mini-sack, was the experimental unit. The mini-sacks were woven polypropylene (10 × 17 cm); thus, 45 mini-sacks were allocated to each RH treatment. Moisture content was measured thermogravimetrically on a single 5-g portion at day 0, day 90, and at 10-day intervals for quality classification. At each 10-day quality evaluation, a single 100-g portion from the sampled mini-sack was sorted visually into empty grains, damaged grains, and foreign matter. Mini-sacks within a box were therefore sampling units (subsamples), whereas the three storage boxes provided independent replicates for each RH treatment.

Moisture Content, Mass Balance, and Water-Transfer Model

Throughout this manuscript, moisture content denotes the mass fraction of water in paddy on a wet basis, whereas water mass transfer denotes the mass of water gained or lost by the packaged sample. For each RH treatment, the total sample mass, initial water mass, dry-solid mass, target water mass, and the transferred water target were calculated before fitting the P-Q model. Wet-basis moisture content was calculated as in Equation 1.

$$MC_{wb} = \left(\frac{M_w}{M_t} \times 100\right) \quad [1]$$

where MC_{wb} is moisture content on a wet basis (% wb), Mw is water mass (g), and M_t is total sample mass (g). Initial water mass and dry-solid mass were calculated as in Equations 2 and 3.

$$M_{w,0} = \left(M_t \times \frac{M_{C0}}{100}\right) \quad [2]$$

$$M_d = M_t - M_{w,0} \quad [3]$$

where $M_{w,0}$ is initial water mass (g), M_{C0} is initial moisture content (% wb), and M_d is dry-solid mass (g). For a selected target moisture content (M_{Ct}), the target water mass was calculated as Equation 4.

$$M_{w,t} = M_d \times \frac{M_{Ct}}{(100 - M_{Ct})} \quad [4]$$

The magnitude of water transferred per unit dry solid was then calculated as in Equation 5.

$$X_A, X_{A,t} = \frac{|M_{w,t} - M_{w,0}|}{M_d} \quad [5]$$

where $X_{A,t}$ is the target transferred-water magnitude (g H_2O g^{-1} dry solid). Its absolute value was used in the shelf-life equation, while the physical direction was determined from the measured moisture trajectory. Thus, RH 50% represented net desorption and RH 90% represented net adsorption.

Water mass transfer was modelled using the P-Q formulation of Rahayoe et al. (2025). The model describes cumulative transferred water per unit dry solid as an exponential approach to an apparent transfer capacity as in Equation 6.

$$X_A = P - P\,(\exp^{-Q.t}) \quad [6]$$

where $X_A(t)$ is the transferred water at storage time t (g H_2O g^{-1} dry solid), P is the apparent transfer capacity (g H_2O g^{-1} dry solid), and Q is the apparent transfer-rate constant (day^{-1}). P and Q were estimated by minimising the squared differences between observed and predicted X_A values.

Equation 7 was used to estimate moisture-based shelf life. Under net desorption, the calculated time represented the period required to reach the selected moisture-related endpoint through water loss; under net adsorption, it represented movement toward a moisture limit through water gain.

$$t_{water} = -\frac{1}{Q} ln\left[1 - \frac{X_{A,t}}{P}\right] \quad [7]$$

Damaged-Grain Deterioration Kinetics

Damaged grains were used as the physical-quality endpoint because this attribute is specified directly in SNI 224:2023 and is readily evaluated during postharvest inspection. The change in damaged-grain percentage during storage was fitted with a first-order expression as in Equation 8.

$$BR_{(t)} = BR_0 \times exp^{(kBR_t)} \quad [8]$$

where $BR_{(t)}$ is damaged-grain content at time t (%), BR0 is the initial damaged-grain content (%), and kBR is the deterioration-rate constant (day^{-1}). The time required to reach a selected damaged-grain limit was calculated as in Equation 9.

$$t_{quality} = \frac{ln\left(\frac{BR_{crit}}{BR_0}\right)}{k_{BR}} \quad [9]$$

where BR_{crit} is the SNI damaged-grain threshold for the selected class. The principal endpoint was BR_{crit} = 1.5% for Medium I; Premium (0.5%) and Medium II (3.0%) limits were sensitivity endpoints. The initial damaged-grain value was BR0 = 0.20%.

Model Validation, Cross-Validation and Decision Rule

Model performance was evaluated using the sum of squared errors (SSE), root mean square error (RMSE), and coefficient of determination (R^2). For observed values yi and predicted values ŷi, the indices were calculated as follows (Equations 10 to 12).

$$SSE = \sum(y_i - \hat{y}_i)^2 \quad [10]$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad [11]$$

$$R^2 = 1 - \left[\frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y}_i)^2}\right] \quad [12]$$

where ȳ is the mean of the observed values and n is the number of observations in each model fit. The two shelf-life approaches were compared using absolute and relative differences. The final recommendation followed the conservative rule as in Equation 13:

$$t_{integrated} = min(t_{water}, t_{quality}) \quad [13]$$

Statistical Analysis

Descriptive results are reported as mean ± standard deviation. Differences among RH treatments were evaluated for final moisture content, P, Q, kBR, and validation indices. Analysis of variance (ANOVA) was applied at $\alpha = 0.05$, followed by Tukey's honestly significant difference (HSD) test when the RH effect was significant. Normality and homogeneity of variance were assessed before ANOVA. When assumptions were not satisfied, Welch's ANOVA or the Kruskal-Wallis test was used as a robustness check. Shelf-life values are model-derived predictions and were therefore compared descriptively rather than treated as independent experimental observations.

RESULTS AND DISCUSSION

Moisture Response and Direction of Water Transfer

The three RH environments produced distinct moisture responses (Figure 1). Paddy began at 13.0903 ± 0.1217% wb. After 90 days, moisture content decreased to 12.7166 ± 0.0076% wb at RH 50%, increased slightly to 13.3864 ± 0.0102% wb at RH 70%, and reached 15.5008 ± 0.0092% wb at RH 90%. Thus, the same initial paddy lot followed three storage trajectories: drying at RH 50%, near-equilibrium behaviour at RH 70%, and marked humidification at RH 90%.

The equilibrium moisture content (EMC) values at 30 °C explain these trajectories. EMC was 8.50%, 13.54%, and 15.74% wb at RH 50%, 70%, and 90%, respectively.

At RH 50%, final moisture remained above EMC, so desorption would probably continue during longer storage. At RH 70%, final moisture was close to EMC, indicating near-equilibrium conditions. At RH 90%, final moisture approached the high EMC and exceeded the 15% wb Medium II limit. Table 2 expresses these changes as transferred-water targets for the model. The target X_A values were 0.0408, 0.0050, and 0.0299 g H_2O g^{-1} dry solid at RH 50%, 70%, and 90%, respectively. Because $X_{A,t}$ was used as an absolute magnitude in Equation 7, its direction must be inferred from the measured moisture trajectory:

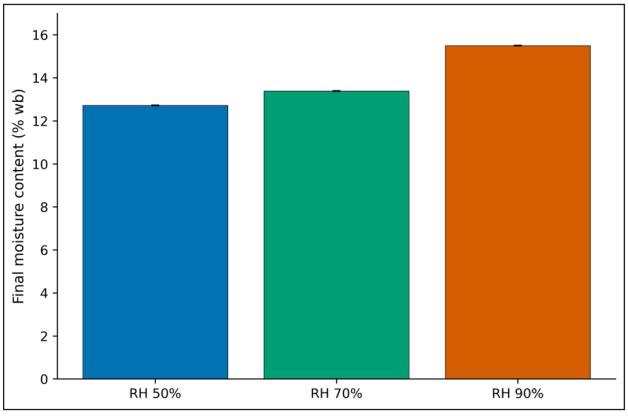

Figure 1. Final moisture content of packaged Inpari 32 paddy after 90 days at 30 °C under RH 50%, 70%, and 90%. Bars show means, and error bars show standard deviations

Table 2
Mass-balance inputs and moisture-transfer targets for packaged Inpari 32 paddy stored at 30 °C

Parameter	RH 50%	RH 70%	RH 90%
Final moisture after 90 days (% wb)	12.7166 ± 0.0076a	13.3864 ± 0.0102b	15.5008 ± 0.0092c
EMC at 30 °C (% wb)	8.50	13.54	15.74
Final moisture minus EMC (percentage points)	+4.2166	-0.1536	-0.2392
Moisture-rate constant, kM (day^{-1})	0.0038 ± 0.0001	0.0109 ± 0.0005	0.0176 ± 0.0002
Sample mass, M_t (g)	173.9836	174.2849	174.0705
Initial moisture, M_{C0} (% wb)	13.0903	13.0903	13.0903
Initial water mass, M_{w0} (g)	22.7749	22.8144	22.7863
Dry solid mass, M_d (g)	151.2087	151.4705	151.2842
Target moisture, M_{Ct} (% wb)	9.8954	13.4643	15.2896
Target water mass, M_{wt} (g)	16.6060	23.5676	27.3058
Water transfer magnitude, M_{wa} (g)	6.1690	0.7532	4.5195
Target X_A (g water g^{-1} dry solid)	0.0408	0.0050	0.0299

Note. Within the final-moisture row, means followed by different superscript letters differ significantly among RH treatments (Tukey HSD, $p < 0.05$). M_{wa} is the magnitude used in the shelf-life calculation; transfer direction is determined from the measured moisture trajectory

net water loss at RH 50%, only slight water gain at RH 70%, and marked water gain at RH 90%. This distinction is operationally important. Acceptable initial moisture content alone does not ensure safe storage when humid air continues to supply water vapour; RH control is therefore a primary barrier against increased water activity and subsequent physical deterioration (Carvalho et al., 2019; Garofalo et al., 2024; Müller et al., 2022).

Fitted P and Q Constants

The fitted constants describe the response of the tested paddy-package system to RH (Figure 2; Table 3). P was highest at RH 50% (0.0880 ± 0.0008), lowest at RH 70% (0.0062 ± 0.0002), and higher again at RH 90% (0.0335 ± 0.0001). P represents the apparent transfer capacity for the specific grain, package, temperature, RH, and model endpoint; it is not a universal material constant.

The Q parameter increased monotonically with RH, from 0.0020 ± 0.0000 day^{-1} at RH 50% to 0.0092 ± 0.0008 day^{-1} at RH 70% and 0.0212 ± 0.0004 day^{-1} at RH 90%. Thus, Q at RH 90% was approximately 10.6 times its value at RH 50%, indicating a much faster

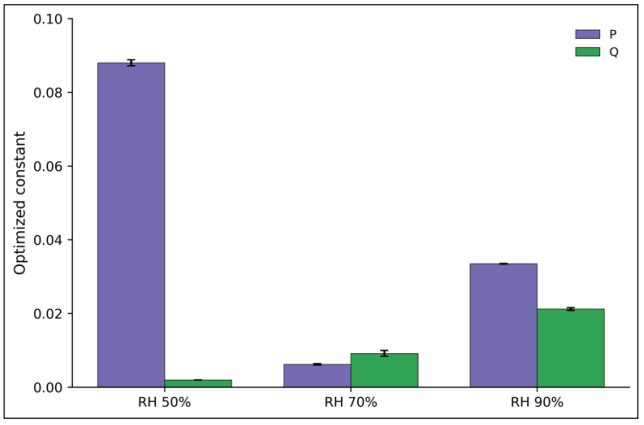

Figure 2. Optimised apparent transfer capacity (P) and transfer-rate constant (Q) for packaged Inpari 32 paddy stored at 30 °C under RH 50%, 70%, and 90%. Bars show means, and error bars show standard deviations

Table 3
Optimised P and Q constants and moisture-based shelf-life predictions for packaged Inpari 32 paddy at 30°C

RH (%)	P	Q (day^{-1})	Water-Transfer Shelf Life (days)
50	0.0880 ± 0.0008	0.0020 ± 0.0000	312
70	0.0062 ± 0.0002	0.0092 ± 0.0008	176
90	0.0335 ± 0.0001	0.0212 ± 0.0004	105

Note. P and Q were optimized from observed and predicted XA values and are specific to the tested variety, packaging, temperature, and RH

approach to the system-specific transfer asymptote. This pattern is physically consistent with a stronger water-vapour driving force under humidification. The broader temperature-RH dataset showed the same trend, with mean Q increasing from 0.0024 ± 0.0013 day^{-1} at RH 50% to 0.0242 ± 0.0110 day^{-1} at RH 90%. RH, therefore, affected both the apparent amount of water transferred and the rate of transfer.

Validation of the Water-Transfer Model

The water-transfer model closely fitted the observed X_A data during the 90-day experiment (Figure 3 and Table 4). R^2 was 0.9913 ± 0.0042 at RH 50%, 0.9928 ± 0.0016 at RH 70%, and 0.9990 ± 0.0003 at RH 90%. Together with the low error values, these results show that predicted transferred-water magnitudes tracked the observations within the calibration period. They support using Equation 7 for endpoint projection, while predictions beyond 90 days remain extrapolations.

RMSE ranged from 2.69×10^{-4} to 8.64×10^{-4} g H_2O g^{-1} dry solid, which was small relative to the transferred-water magnitudes used for shelf-life calculation. Goodness of fit does not represent storage safety. RH 90% yielded the highest R^2 because its strong,

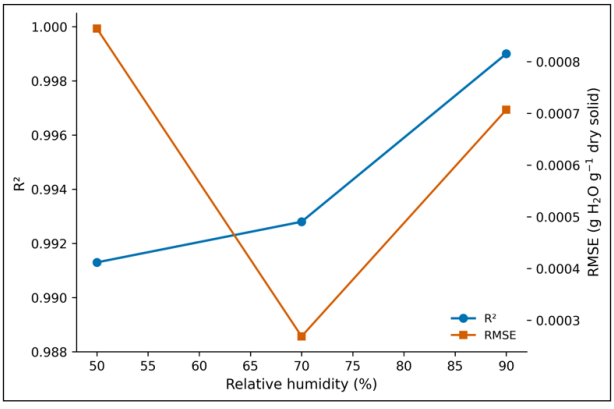

Figure 3. Goodness-of-fit statistics for the water mass-transfer model at 30 °C under RH 50%, 70%, and 90%. R^2 is the coefficient of determination, and RMSE is the root mean square error

Table 4
Validation statistics for the water mass-transfer model of packaged Inpari 32 paddy at 30 °C

RH (%)	R^2	SSE	RMSE (g H_2O g^{-1} dry solid)
50	0.9913 ± 0.0042	2.36×10^{-6}	8.64×10^{-4}
70	0.9928 ± 0.0016	2.22×10^{-8}	2.69×10^{-4}
90	0.9990 ± 0.0003	1.54×10^{-6}	7.07×10^{-4}

Note. RH = relative humidity; R^2 = coefficient of determination; SSE = sum of squared errors; RMSE = root mean square error. Statistics were calculated from observed and predicted X_A values

monotonic water-uptake signal was fitted consistently; nevertheless, the condition was hazardous because the moisture content exceeded the Medium II limit. The high fit quality at RH 90%, therefore, quantifies the hazardous trajectory rather than endorsing the storage condition.

Damaged-Grain Kinetics as a Quality Endpoint

Moisture transfer describes environmental pressure on the stored grain, whereas market decisions are often based on physical quality. Damaged grains were therefore modelled separately. The first-order rate constant kBR increased from 0.0068 ± 0.0001 day^{-1} at RH 50% to 0.0127 ± 0.0002 day^{-1} at RH 70% and 0.0213 ± 0.0002 day^{-1} at RH 90% (Figure 4A). The approximately threefold increase from RH 50% to RH 90% indicates much faster accumulation of visible defects and helps explain the reduction in Medium I quality-based shelf life from 296 to 95 days.

The selected SNI quality class strongly affected the predicted endpoint (Figure 4B). Under SNI 224:2023, Premium, Medium I, and Medium II paddy permit maximum damaged-grain contents of 0.5%, 1.5%, and 3.0%, respectively. The stricter Premium threshold was therefore reached much earlier than the Medium I and Medium II thresholds. Using the principal Medium I limit, predicted shelf life decreased from 296 days at RH 50% to 159 days at RH 70% and 95 days at RH 90%. Humid storage thus shortened shelf life by increasing both moisture content and the rate at which visible defects accumulated.

The RH effect on damaged grains is consistent with established storage behaviour. Moisture uptake can soften and stress the kernel structure, increase susceptibility to cracking, and create local wet zones within a bag. Such spatial variation may be obscured by a single mean moisture value but can appear as damaged grains during inspection.

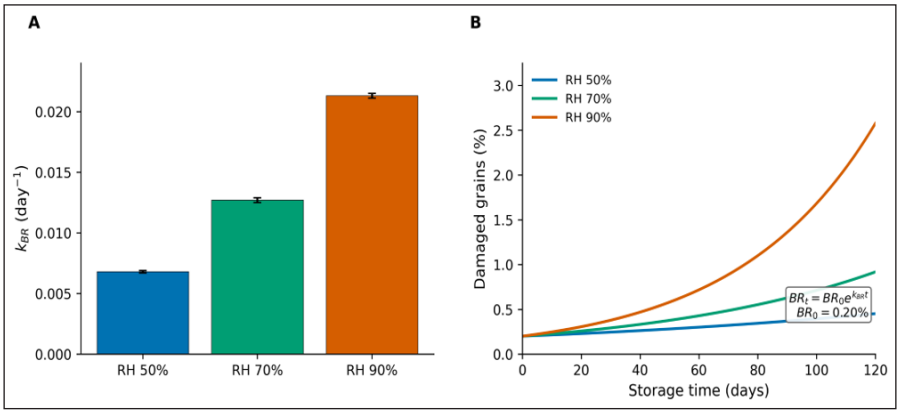

Figure 4. Damaged-grain deterioration of packaged Inpari 32 paddy at 30 °C. (A) First-order deterioration-rate constants (kBR), with error bars showing standard deviations; (B) model-predicted damaged-grain trajectories from BR0 = 0.20% under RH 50%, 70%, and 90%

Controlled-condition studies have likewise reported humidity-related physicochemical deterioration in stored rice (Garofalo et al., 2024), while work with polypropylene grain bags has shown that package and interstitial RH influence seed quality and pest risk (Rizwan et al., 2022). These studies support the direction of the present response, although numerical shelf lives are not directly comparable because commodities, packages, temperatures, and failure criteria differ.

The damaged-grain model also fitted acceptably, although less tightly at RH 90% than the water-transfer model. R^2 was 0.9913 ± 0.0065, 0.9872 ± 0.0066, and 0.9737 ± 0.0126 at RH 50%, 70%, and 90%, respectively. The larger error at RH 90% is plausible because physical defects vary among kernels depending on husk condition, local moisture exposure, and resistance to breakage, particularly during humid storage. Table 5 summarises the fitted damaged-grain kinetic constants, model-fit statistics, and predicted times to the Premium, Medium I, and Medium II quality endpoints for each RH treatment.

Comparison of Moisture and Quality-Based Endpoints

Both modelling routes ranked the RH treatments in the same order but yielded different endpoints. The water-transfer model predicted shelf lives of 312, 176, and 105 days at RH 50%, 70%, and 90%, respectively. The Medium I damaged-grain model yielded shorter predictions of 296, 159, and 95 days (Figure 5A). The differences were 16, 17, and 10 days, corresponding to reductions of 5.13%, 9.66%, and 9.52%, respectively, relative to the moisture-based predictions.

This difference is not contradictory because the models answer different questions. The P-Q model estimates when grain reaches a moisture-related endpoint, whereas the damaged-grain model estimates when a lot no longer meets a physical-quality limit. Their agreement in RH ranking strengthens the storage-risk interpretation, and the earlier damaged-grain

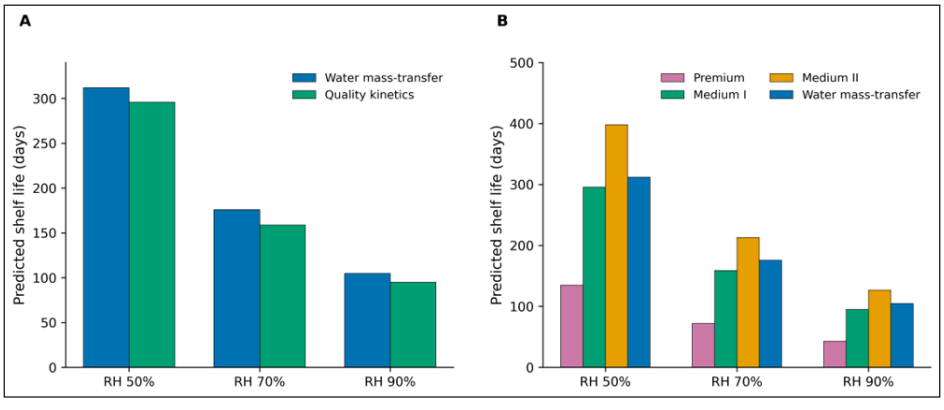

Figure 5. Shelf-life prediction and endpoint sensitivity for packaged Inpari 32 paddy at 30 °C. (A) Comparison of water mass-transfer and Medium I quality-kinetic shelf life; (B) sensitivity to the SNI 224:2023 Premium, Medium I, and Medium II damaged-grain endpoints

Table 5
Damaged-grain kinetic constants, validation statistics, and quality-based shelf-life predictions at 30 °C

RH (%)	kBR (day^{-1})	R^2	SSE	RMSE	Premium Endpoint (days)	Medium I Endpoint (days)	Medium II Endpoint (days)
50	0.0068 ± 0.0001	0.9913 ± 0.0065	0.0009 ± 0.0005	0.0077 ± 0.0059	135	296	398
70	0.0127 ± 0.0002	0.9872 ± 0.0066	0.0079 ± 0.0031	0.0217 ± 0.0181	72	159	213
90	0.0213 ± 0.0002	0.9737 ± 0.0126	0.1210 ± 0.0568	0.0686 ± 0.0875	43	95	127

Note. Shelf life was calculated from BR0 = 0.20% using SNI 224:2023 damaged-grain limits of 0.5%, 1.5%, and 3.0% for Premium, Medium I, and Medium II, respectively. RH = relative humidity; kBR = damaged-grain deterioration-rate constant; SSE = sum of squared errors; RMSE = root mean square error

endpoint provides a more conservative operational decision for Medium I paddy. Endpoint sensitivity reinforces this conclusion (Figure 5B): Premium quality required much shorter shelf lives, whereas the less restrictive Medium II limit permitted longer storage and made the water-transfer endpoint limiting in all three treatments. Shelf-life predictions should therefore always be reported with the intended market grade and failure criterion.

This dual-endpoint result also aligns with broader shelf-life research. Isotherm-based predictions for packaged dry foods vary with the selected sorption equation (Lee & Robertson, 2022; Robertson & Lee, 2021), while kinetic and time-to-failure approaches can yield different dates because they define failure differently (Kosegarten et al., 2022). The 5.13-9.66% differences observed here therefore quantify endpoint sensitivity for this paddy-package system rather than model disagreement.

Table 6 presents the absolute and relative differences between the water-transfer and Medium I damaged-grain endpoints and identifies the earlier endpoint used for the integrated storage decision

The integrated decision matrix in Figure 6 translates the model comparison into storage guidance. Damaged-grain kinetics was limiting for Premium and Medium I targets at every RH, whereas the water-transfer endpoint was limiting for Medium II because its

Table 6
Direct comparison of water-transfer and Medium I damaged-grain shelf-life predictions

RH (%)	Water-transfer Shelf Life (days)	Quality-kinetic Shelf Life (days)	Absolute Difference (days)	Quality Endpoint Earlier by (%)	Integrated Medium I Decision
50	312	296	16	5.13	296 days
70	176	159	17	9.66	159 days
90	105	95	10	9.52	95 days

Note. The integrated decision is the earlier predicted endpoint. Percentages are relative to the water-transfer prediction

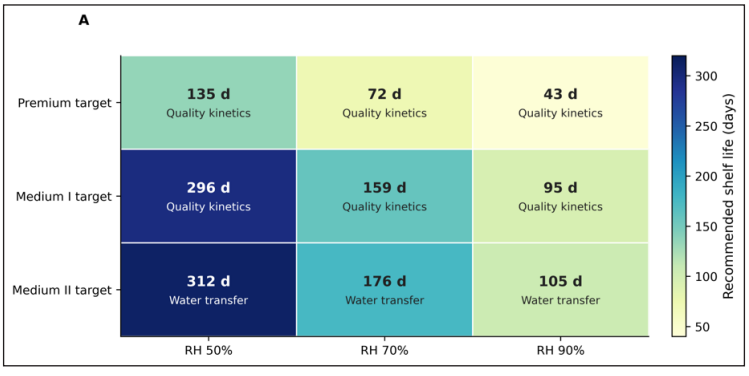

Figure 6. Integrated conservative shelf-life decision for packaged Inpari 32 paddy at 30 °C across RH levels and SNI quality targets. Each cell gives the earlier predicted shelf life and the limiting model

damaged-grain threshold was less restrictive. For Medium I paddy at 30 °C in woven PP sacks, recommended shelf lives were 296 days at RH 50%, 159 days at RH 70%, and 95 days at RH 90%. Lowering RH from 90% to 70% increased the predicted safe period by 64 days (67%), and lowering it from 70% to 50% added 137 days (86%); overall, RH 50% provided more than three times the predicted safe period at RH 90%. These differences directly affect inspection frequency, stock rotation, and decisions on drying, dehumidification, or improved barrier packaging.

RH-based P-Q Interpolation and Storage Decision Support

For decision support, P and Q were expressed as empirical RH interpolation equations over the tested range. These equations are scenario tools, not independently validated predictive models. They should not be applied outside RH 50-90% or to other varieties, packages, or temperatures without recalibration and validation, as in Equations 14 and 15.

$$P = 0.000136RH^2 - 0.020454RH + 0.769787 \quad [14]$$

$$Q = 5.982 \times 10^{-6}RH^2 - 0.000358RH + 0.004952 \quad [15]$$

where RH is expressed as a percentage. Figure 7 shows the interpolating curves. P reached a minimum near RH 70%, whereas Q increased over the tested range, indicating that RH affected both the apparent transfer capacity and the transfer rate. Because a quadratic curve was passed through only three RH levels, the reported $R^2 = 1.000$ reflects exact interpolation rather than independent evidence of predictive performance.

A simple example illustrates the interpolation. Paddy entering storage at 14% wb is already at the Premium and Medium I moisture limit and has only a small margin before the 15% wb

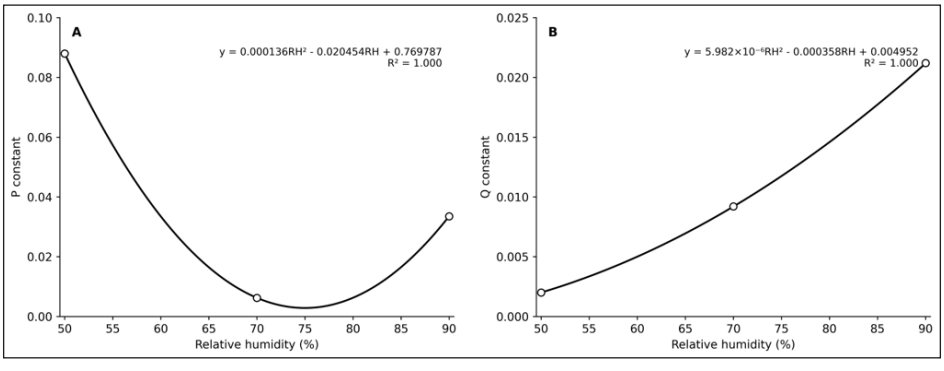

Figure 7. Empirical RH-dependent interpolation of water mass-transfer constants at 30 °C. (A) Apparent transfer capacity P; (B) apparent transfer-rate constant Q
Note. Open circles are fitted values at RH 50%, 70%, and 90%; solid curves are quadratic interpolations for scenario exploration only within the calibrated RH range

Medium II limit. Increasing from 14% to 15% wb requires approximately 0.0137 g H_2O g^{-1} dry solid. At RH 90%, Equation 7, with the fitted P and Q values, predicts this gain in approximately 25 days. At RH 70%, P is lower than the required increase, so the model does not predict that 15% wb will be reached within its calibrated asymptote; paddy beginning at 14% wb nevertheless requires close monitoring. At RH 50%, the observed direction was desorption, so movement toward a higher moisture limit was not applicable. Table 7 summarises the RH-specific moisture-transfer scenarios, predicted implications of the 15% wb endpoint, and corresponding storage-management actions for paddy entering storage at 14% wb.

Overall, RH 50% was the safest condition tested; RH 70% was a transition condition requiring routine inspection; and RH 90% was unsuitable for long-term storage. Paddy should preferably enter storage below 14% wb; lots near this value should be dried further or stored only under well-controlled humidity.

Assumptions, Scope, and Limitations

The models assume constant temperature and RH, time-invariant P, Q, and kBR values, a spatially averaged moisture state, first-order damaged-grain development from BR0 = 0.20%, and unchanged package properties. The experiment evaluated one paddy variety, one permeable mini-sack format, one temperature, and three fixed RH levels.

Table 7
Scenario-based interpretation for packaged paddy entering storage at 14% wb and 30 °C

Storage RH (%)	P	Q (day^{-1})	Moisture Endpoint Considered	Predicted Interpretation	Recommended Action
50	0.0880	0.0020	15% wb	Not applicable for moisture gain because the observed transfer direction was desorption.	Moisture risk is low, but damaged grains should still be monitored for long storage.
70	0.0062	0.0092	15% wb	The fitted P value is lower than the water increase required to reach 15% wb; the model therefore does not predict reaching 15% wb within the calibrated asymptote.	Acceptable only with monitoring because 14% wb is already the Premium/ Medium I moisture limit.
90	0.0335	0.0212	15% wb	Approximately 25 days from 14% to 15% wb.	Avoid prolonged storage; use rapid drying, RH control, stock rotation, or improved barrier packaging.

Note. The scenario uses Equation 7 and the P-Q interpolation equations at 30 °C. It addresses moisture transfer only and does not replace damaged-grain monitoring

It did not explicitly represent moisture gradients within sacks, fungi, insects, germination, sensory quality, mechanical handling, or interactions among these failure modes.

Model fit was evaluated within 90 days, but several shelf-life endpoints extend to 95-312 days and are therefore extrapolations. The RH interpolation is also based on only three levels, so its quadratic form is descriptive rather than independently validated. The numerical predictions should consequently be applied only to the tested Inpari 32-PP-sack-30 °C system and with an operational safety margin. Future work should use longer trials, independent validation data, commercial sack sizes, multiple cultivars and packaging barriers, and fluctuating warehouse temperature-RH profiles.

CONCLUSION

This study linked moisture- and quality-based shelf-life endpoints for Inpari 32 paddy in woven PP sacks at 30 °C. RH 50% produced net desorption, RH 70% produced a near-equilibrium response, and RH 90% increased moisture content to 15.5008% wb within 90 days. The P-Q model closely fitted the observed 90-day moisture data (R^2 = 0.9913-0.9990), and Q increased from 0.0020 to 0.0212 day^{-1} between RH 50% and RH 90%. Damaged-grain deterioration also accelerated, with kBR increasing from 0.0068 to 0.0213 day^{-1}. At the Medium I endpoint, quality kinetics predicted shelf lives of 296, 159, and 95 days, compared with 312, 176, and 105 days from the water-transfer model. Moisture-only prediction can therefore overestimate the commercially acceptable period. For paddy near 14% wb, RH 90% may reduce the margin to 15% wb to approximately 25 days. Operationally, paddy should be dried below 14% wb, prolonged exposure to RH 90% should be avoided, and RH and damaged grains should be monitored during stock rotation. Because several predicted endpoints extend beyond the 90-day experiment, commercial decisions should apply a safety margin until the model has been validated under longer, fluctuating warehouse conditions and across varieties and packaging systems.

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DATA AVAILABILITY

The data used in this study are available from the corresponding author upon reasonable request.

DECLARATION

Ethics approval and consent to participate: Not applicable.

CONFLICTS OF INTEREST

The authors declare no competing interests.

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