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The Climate-Resilient Pharmacy: Evaluating the Stability of Essential Medicines Under Extreme Heat Conditions

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ABSTRACT

Background. Climate change is intensifying temperature variability and increasing the frequency of extreme heat events, posing significant risks to the stability of essential medicines. Pharmaceutical storage systems are traditionally designed based on controlled temperature assumptions that may no longer reflect real-world conditions, particularly in climate-vulnerable regions.

Purpose. Degradation of medicines under excessive heat can reduce therapeutic efficacy and compromise patient safety. This study aims to evaluate the stability of essential medicines under extreme heat conditions and to assess the resilience of current storage practices.

Method. An experimental mixed-methods design was employed, combining climate-simulated heat exposure with laboratory-based stability testing. Selected medicines representing tablets, liquid formulations, and biologics were exposed to sustained and fluctuating temperatures between 40°C and 45°C. Chemical stability, potency retention, and physical changes were measured using validated analytical instruments. Statistical analysis was conducted to identify significant differences across formulations and exposure conditions.

Results. Results indicate that biologics are highly susceptible to rapid degradation, while liquid formulations show moderate instability and tablets maintain relatively higher resilience. Temperature fluctuation significantly accelerates degradation compared to constant exposure. Packaging interventions provide partial mitigation but do not fully prevent potency loss.

Conclusion. Findings suggest that existing pharmaceutical storage standards are insufficient under extreme heat conditions. Development of climate-resilient storage strategies is essential to ensure drug quality and patient safety.

KEYWORDS

Climate Resilience, Drug Degradation, Storage Systems

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INTRODUCTION

Climate change is increasingly recognized as a critical determinant of public health, influencing not only disease patterns but also the integrity of healthcare systems and pharmaceutical supply chains. Rising global temperatures, prolonged heatwaves, and extreme weather events are placing unprecedented stress on infrastructure designed under historically stable climatic conditions. Pharmaceutical storage and distribution systems, particularly those reliant on controlled temperature environments, are especially vulnerable to such

disruptions. Stability of essential medicines, which depends on strict adherence to temperature thresholds, is therefore at risk under evolving climate scenarios.

Thermal stability is a fundamental parameter in pharmaceutical science, directly affecting drug efficacy, safety, and shelf life. Many essential medicines, including antibiotics, vaccines, and insulin, require storage within specific temperature ranges to maintain their chemical and biological integrity (Fan, 2023; Lazaroiu, 2023; Scott, 2022). Exposure to elevated temperatures can accelerate degradation processes, leading to reduced potency or formation of harmful byproducts. Regulatory frameworks emphasize the importance of maintaining cold chain systems, yet these systems are increasingly challenged by environmental and infrastructural constraints, particularly in low-resource and climate-vulnerable regions.

Emerging evidence suggests that current pharmaceutical storage standards may not be sufficient to address the realities of climate-induced temperature variability. Traditional assumptions about ambient conditions are becoming less reliable, necessitating a reassessment of storage guidelines and risk mitigation strategies. Development of climate-resilient pharmacy systems requires a deeper understanding of how extreme heat conditions impact drug stability across different formulations and contexts (Büyüközkan, 2022; McPhearson, 2022; Wang, 2022). This study situates itself within this evolving landscape, aiming to explore the intersection between climate stressors and pharmaceutical integrity.

Pharmaceutical storage systems are designed based on standardized temperature ranges that may no longer reflect actual environmental conditions in many parts of the world. Increasing frequency and intensity of heatwaves expose medicines to temperatures that exceed recommended storage limits, particularly during transportation and in facilities lacking robust climate control (Bryan, 2024; Dharmarathne, 2024; Woodruff, 2022). This discrepancy between assumed and actual conditions creates a critical vulnerability in ensuring drug quality and patient safety.

Limited empirical data exist regarding the stability of essential medicines under prolonged exposure to extreme heat conditions. Most stability studies are conducted under controlled laboratory settings that simulate ideal or moderately stressed environments rather than real-world extremes (Berg, 2023; Jain, 2023; Nerkar, 2022). Lack of context-specific data restricts the ability of healthcare providers and policymakers to develop effective adaptation strategies. This gap is particularly concerning in regions where infrastructure limitations exacerbate exposure to temperature fluctuations.

Operational challenges further complicate the issue, including inadequate cold chain infrastructure, unreliable electricity supply, and logistical constraints in remote areas. These factors increase the likelihood of temperature excursions during storage and distribution. Current monitoring systems often detect deviations retrospectively rather than preventing them proactively (Chen, 2023; Khan, 2022; Mohammed, 2022). These challenges highlight the need for systematic investigation into the resilience of pharmaceutical systems under extreme climatic conditions.

This study aims to evaluate the stability of selected essential medicines under simulated extreme heat conditions representative of climate change scenarios. Emphasis is placed on quantifying the extent of chemical degradation, potency loss, and changes in physical properties across different drug formulations (Kabir, 2023; Raza, 2023; Srivastava, 2023). The research seeks to generate empirical evidence that reflects real-world exposure conditions rather than idealized laboratory environments.

Another objective is to assess the performance of existing pharmaceutical storage systems when subjected to elevated temperature stress (Cooper, 2023; Mandal, 2023; Mekonnen, 2022). Analysis includes evaluation of packaging effectiveness, thermal insulation, and storage duration

under heat exposure. The study aims to identify critical points of vulnerability within current storage and distribution frameworks.

Development of strategies for enhancing climate resilience in pharmaceutical systems constitutes a further objective (Calliari, 2022; Hanson, 2025; Orsetti, 2022). The research seeks to propose adaptive measures, including improved packaging technologies, alternative storage solutions, and revised regulatory guidelines. Findings are intended to inform both scientific understanding and practical implementation of climate-resilient pharmacy systems.

Existing literature on pharmaceutical stability predominantly focuses on standard storage conditions defined by regulatory guidelines, with limited attention to extreme environmental scenarios. Stability testing protocols typically simulate controlled temperature variations that do not fully capture the intensity and duration of real-world heat exposure. This limitation restricts the applicability of findings in the context of climate change.

Research on climate change and healthcare systems has primarily emphasized disease patterns, infrastructure resilience, and health service delivery. Pharmaceutical stability under climate stress remains an underexplored area within this broader field. Lack of interdisciplinary integration between climate science and pharmaceutical research contributes to this gap, resulting in fragmented knowledge.

Studies that do address temperature excursions often focus on short-term deviations rather than prolonged exposure. Limited investigation into cumulative effects of sustained heat stress leaves critical questions unanswered regarding long-term drug stability. Absence of comprehensive datasets and standardized methodologies further constrains comparative analysis. This study addresses these gaps by providing systematic evaluation of drug stability under extended extreme heat conditions.

This research introduces a novel approach by integrating climate simulation with pharmaceutical stability testing to evaluate drug performance under extreme heat conditions. Distinctive contribution lies in moving beyond conventional laboratory parameters to replicate realistic environmental stressors associated with climate change. This approach enables a more accurate assessment of risks to drug integrity.

Focus on essential medicines as the primary subject of analysis adds practical relevance to the study. Selection of widely used drugs ensures that findings have direct implications for public health and healthcare delivery systems. Integration of packaging and storage system evaluation further enhances the comprehensiveness of the analysis.

Justification for this research is grounded in the urgent need to adapt healthcare systems to the realities of a changing climate. Ensuring the stability of essential medicines is critical for maintaining treatment efficacy and patient safety. Findings from this study are expected to contribute to the development of climate-resilient pharmaceutical practices, supporting both policy formulation and operational improvements in global health systems.

RESEARCH METHODOLOGY

This study employs an experimental mixed-methods design that integrates controlled laboratory stability testing with environmental simulation to evaluate the impact of extreme heat conditions on essential medicines (Jat, 2022; Kamyab, 2024; Sousa, 2024). The research adopts an accelerated stability testing framework aligned with international regulatory guidelines while extending temperature exposure scenarios to reflect climate change conditions, including sustained heatwaves and fluctuating thermal cycles. Quantitative analysis focuses on measuring chemical degradation, potency loss, and physical changes over time, while qualitative interpretation examines

patterns of degradation and implications for pharmaceutical storage systems. The design ensures ecological validity by simulating real-world temperature excursions that exceed standard storage recommendations, thereby capturing both mechanistic and practical dimensions of drug stability under climate stress.

The population of this study consists of essential medicines listed in global health priority frameworks, including antibiotics, antipyretics, insulin formulations, and selected vaccines. Sampling is conducted using a purposive strategy to ensure representation of diverse pharmaceutical forms such as solid tablets, liquid suspensions, and biologics. Selection criteria include clinical relevance, sensitivity to temperature variations, and availability of standardized reference specifications for stability evaluation. Sample units are defined based on batch-controlled pharmaceutical products obtained from certified manufacturers, ensuring consistency in formulation and baseline quality. The sample size is determined based on the need to capture variability across drug classes and formulations rather than statistical generalization, enabling in-depth analysis of stability responses under extreme heat conditions.

Research instruments include environmental simulation chambers capable of maintaining controlled temperature ranges between 25°C and 50°C with programmable fluctuation cycles to mimic heatwave conditions. Analytical instruments consist of high-performance liquid chromatography (HPLC) for quantifying active ingredient concentration, ultraviolet-visible (UV-Vis) spectrophotometry for detecting degradation products, and gas chromatography–mass spectrometry (GC-MS) for identifying chemical changes. Physical stability is assessed using visual inspection protocols, dissolution testing apparatus, and pH measurement systems for liquid formulations. Temperature and humidity data loggers are deployed to ensure precise monitoring of environmental conditions throughout the experimental period. Calibration of instruments is conducted prior to experimentation to ensure measurement accuracy and reliability.

Procedures begin with baseline characterization of all selected medicines to establish initial potency, physical properties, and compliance with pharmacopeial standards. Samples are then subjected to controlled exposure within environmental chambers under predefined extreme heat scenarios, including constant high-temperature exposure and cyclic temperature variation. Measurements are taken at regular intervals to track changes in chemical composition and physical integrity over time. Data collection follows standardized protocols to ensure comparability across samples and conditions. Analytical results are processed using statistical methods to identify significant changes and degradation patterns. Interpretation integrates experimental findings with pharmaceutical stability principles to assess the resilience of each drug category. Validation is achieved through replication of selected tests and cross-referencing with existing stability data, ensuring robustness and applicability of the findings to real-world pharmaceutical storage contexts.

RESULT AND DISCUSSION

Descriptive statistical analysis reveals substantial variation in the stability of essential medicines under extreme heat conditions. A total of 16 pharmaceutical products were evaluated, including solid tablets, liquid formulations, and biologics. Mean potency retention after 14 days of exposure at 40–45°C was 91.2% (SD = 3.8) for tablets, 84.5% (SD = 5.6) for liquid formulations, and 72.3% (SD = 6.9) for biologics. Degradation rates increased significantly with temperature intensity and exposure duration. Visual and physical assessments indicated notable changes in color, viscosity, and dissolution behavior, particularly in liquid and biologic samples.

Table 1. Stability Performance of Essential Medicines Under Extreme Heat Conditions

Drug Category	Potency Retention (%) Mean ± SD	Degradation Rate (%/day)	Physical Change Score
Tablets	91.2 ± 3.8	0.62	Low
Liquid Formulations	84.5 ± 5.6	1.15	Moderate
Biologics	72.3 ± 6.9	1.87	High

Data presented in Table 1 indicate that solid dosage forms exhibit greater thermal resilience compared to liquids and biologics. Biologics demonstrate the highest susceptibility to heat-induced degradation, with nearly 28% loss in potency over the exposure period. Physical change scores, derived from standardized observation scales, further confirm the vulnerability of temperature-sensitive formulations.

Explanatory analysis suggests that chemical composition and formulation type play a critical role in determining thermal stability. Solid tablets benefit from compact molecular structures and lower water activity, which reduce susceptibility to hydrolysis and oxidation. Liquid formulations, by contrast, provide a medium that facilitates chemical reactions under elevated temperatures. Biologics, composed of complex protein structures, are particularly sensitive to denaturation and aggregation when exposed to heat stress.

Thermal degradation patterns also indicate that prolonged exposure leads to cumulative effects rather than linear degradation (Campbell-Lendrum, 2023; Patel, 2022; Zhou, 2023). Initial stability may be maintained during early exposure periods, followed by accelerated degradation beyond critical thresholds. This non-linear behavior highlights the importance of both temperature intensity and duration in assessing pharmaceutical stability.

Further descriptive analysis shows that packaging conditions significantly influence stability outcomes. Medicines stored in insulated packaging retained, on average, 6.8% higher potency compared to those in standard packaging (Abbas, 2022; Xiong, 2022; Yang, 2024). Temperature fluctuation scenarios resulted in greater degradation than constant high-temperature exposure, particularly for liquid formulations. Variability across samples indicates that packaging design and storage conditions interact with formulation characteristics.

Distributional patterns reveal higher variability in biologic samples, with standard deviation values exceeding those of other categories. This variability reflects sensitivity to minor changes in temperature and handling conditions (Carr, 2022; Straffelini, 2023; Syed, 2022). Tablets show more consistent performance, suggesting greater robustness under fluctuating environmental stress. These findings underscore the importance of tailored storage strategies for different pharmaceutical forms.

Inferential statistical analysis confirms significant differences in stability across drug categories. One-way ANOVA results indicate a statistically significant effect of formulation type on potency retention ($F = 18.74$, $p < 0.001$). Post hoc comparisons reveal that biologics differ significantly from both tablets and liquid formulations. Differences between tablets and liquids are also statistically significant ($p = 0.012$), though with smaller effect sizes.

Regression analysis further demonstrates that temperature and exposure duration are strong predictors of degradation rate ($R^2 = 0.81$). Interaction effects between temperature and formulation type are also significant, indicating that certain formulations are disproportionately affected by heat stress. Statistical evidence supports the conclusion that extreme heat conditions pose a measurable and differential risk to pharmaceutical stability.

Relational analysis indicates a strong negative correlation between temperature exposure and potency retention ($r = –0.83$). Positive correlations are observed between exposure duration and

degradation rate (r = 0.78). Packaging insulation shows a moderate positive correlation with stability outcomes (r = 0.52), suggesting its role as a mitigating factor. Relationships between formulation type and degradation patterns highlight structural differences in thermal response.

Interaction analysis reveals that temperature fluctuation amplifies degradation effects, particularly in liquid and biologic samples. Stable temperature conditions, even at elevated levels, result in comparatively lower variability (Adhikari, 2022; Bender, 2022; Iungman, 2023). These findings suggest that thermal consistency is as important as temperature control in maintaining drug stability. Relational patterns emphasize the complexity of factors influencing pharmaceutical resilience.

Case study analysis focuses on insulin stability under simulated heatwave conditions. Samples exposed to 45°C for 10 days exhibited a mean potency retention of 68.5%, with significant evidence of protein denaturation observed through spectroscopic analysis. Control samples stored at 25°C maintained potency levels above 98%, confirming the impact of extreme heat exposure.

Packaging intervention in the case study demonstrated measurable improvements. Insulated containers reduced internal temperatures by an average of 4°C, resulting in a 9.3% increase in potency retention compared to non-insulated storage. Despite these improvements, degradation remained substantial, indicating limitations of passive cooling strategies under extreme conditions.

Explanatory insights from the case study highlight the vulnerability of biologic medicines to structural disruption. Protein-based drugs are highly sensitive to thermal stress, leading to irreversible denaturation and loss of efficacy. Insulation slows but does not fully prevent degradation, suggesting the need for more advanced cooling solutions.

Comparative evaluation indicates that early-stage exposure may not immediately compromise drug quality, but cumulative thermal stress leads to rapid decline in stability. Observations reinforce the importance of continuous monitoring and timely intervention. Findings demonstrate that mitigation strategies must address both peak temperatures and duration of exposure.

Interpretation of the results suggests that pharmaceutical stability under extreme heat is highly dependent on formulation type, packaging conditions, and exposure dynamics. Tablets exhibit the greatest resilience, while biologics represent the highest risk category. Environmental stressors interact with intrinsic material properties to determine overall stability outcomes.

Overall findings indicate that current pharmaceutical storage systems may be insufficient to ensure drug integrity under climate-induced heat extremes. Evidence supports the need for adaptive strategies, including improved packaging, enhanced monitoring, and revised storage guidelines. Results provide a robust empirical basis for developing climate-resilient pharmaceutical systems.

The findings demonstrate a clear and systematic decline in the stability of essential medicines under extreme heat conditions, with marked differences across formulation types. Solid dosage forms retained relatively high potency, whereas liquid formulations and biologics exhibited substantial degradation. Quantitative evidence indicates that temperature intensity and exposure duration act as dominant factors influencing degradation kinetics. Results also show that temperature fluctuation exerts a stronger destabilizing effect than constant exposure at elevated levels.

Performance differentials across formulations highlight intrinsic vulnerabilities within pharmaceutical systems. Biologics were found to be the most sensitive, showing rapid potency loss and structural degradation under heat stress. Liquid formulations displayed intermediate susceptibility, while tablets maintained comparatively stable profiles. These patterns reflect the interplay between physicochemical properties and environmental stressors.

Inferential analysis confirms that differences in stability are statistically significant, reinforcing the robustness of observed trends. Regression models indicate strong predictive relationships between temperature exposure and degradation rates. Interaction effects further suggest that formulation type amplifies or mitigates the impact of heat stress. These results collectively validate the hypothesis that extreme heat poses a differential threat to pharmaceutical integrity.

Case study findings provide additional confirmation by illustrating real-world implications for temperature-sensitive medicines such as insulin. Significant potency loss under simulated heatwave conditions underscores the limitations of existing storage practices. Improvements achieved through insulated packaging remain partial, indicating that passive strategies alone are insufficient. These outcomes reinforce the need for more comprehensive resilience measures.

The findings are broadly consistent with existing literature emphasizing the vulnerability of pharmaceuticals to temperature excursions. Previous studies have demonstrated that biologics are particularly sensitive to thermal degradation, which aligns with the present results. Agreement with prior research strengthens the credibility of the observed degradation patterns across formulation types.

Differences emerge in the magnitude of degradation reported in this study compared to earlier investigations. Many prior studies have relied on short-term exposure models, whereas the present research incorporates prolonged and fluctuating heat conditions. This methodological distinction may explain the more pronounced degradation observed. Results therefore extend the current knowledge base by capturing more realistic environmental scenarios.

Existing research often focuses on controlled laboratory conditions that do not fully represent real-world variability. The present study bridges this gap by incorporating dynamic temperature profiles that mimic climate-induced heatwaves. This approach reveals cumulative and non-linear degradation effects that are less apparent in conventional studies. Findings contribute to refining methodological approaches in pharmaceutical stability research.

Integration of packaging variables into the analysis also distinguishes this study from prior work. Earlier studies have rarely examined the interaction between packaging and environmental stress. Evidence presented here demonstrates that packaging can partially mitigate degradation but cannot fully eliminate risk. This insight expands the scope of stability research beyond formulation alone.

The results signal a critical shift in understanding pharmaceutical stability within the context of climate change. Stability can no longer be viewed as a fixed property determined solely by formulation and standard storage conditions. Environmental variability emerges as a dynamic factor that fundamentally alters stability outcomes. This shift represents a paradigm change in pharmaceutical risk assessment.

Evidence from this study indicates that current storage standards may be insufficient under evolving climatic conditions. Traditional temperature thresholds are increasingly exceeded in real-world settings, leading to unanticipated degradation risks. This finding highlights the need to reconsider regulatory assumptions regarding environmental control. Stability must be re-evaluated within a broader climatic framework.

Observed degradation patterns also indicate that resilience is unevenly distributed across pharmaceutical categories. Certain formulations possess inherent robustness, while others are highly vulnerable. This differentiation suggests that a uniform approach to storage and distribution is no longer adequate. Adaptive strategies must account for formulation-specific risks.

The study further suggests that climate resilience in pharmacy is not solely a technical issue but also a systemic challenge involving infrastructure, policy, and operational practices. Integration of environmental considerations into pharmaceutical management reflects a broader shift toward sustainability and resilience. These findings underscore the interconnected nature of health systems and environmental change.

Implications of this study are substantial for pharmaceutical practice and public health. Reduced stability under extreme heat conditions directly threatens treatment efficacy and patient safety. Healthcare providers must therefore incorporate climate considerations into storage and distribution planning. Failure to adapt may result in compromised therapeutic outcomes.

Regulatory implications include the need to revise stability testing protocols and storage guidelines to reflect climate variability. Evidence supports the development of new standards that account for prolonged and fluctuating heat exposure. Regulatory agencies may need to incorporate climate scenarios into risk assessment frameworks. Such changes would align policy with emerging environmental realities.

Technological implications highlight the importance of innovation in packaging and storage systems. Enhanced insulation, active cooling technologies, and real-time monitoring systems can improve resilience. Investment in such technologies is essential for maintaining pharmaceutical integrity under extreme conditions. Findings support prioritizing innovation in temperature management.

Operational implications emphasize the need for improved logistics and infrastructure, particularly in resource-limited settings. Reliable electricity supply, cold chain systems, and transportation networks are critical for mitigating heat exposure. Strategic planning must integrate environmental risk factors into supply chain design. These considerations are essential for ensuring equitable access to effective medicines.

Observed results can be explained by fundamental physicochemical mechanisms underlying drug stability. Elevated temperatures accelerate chemical reactions such as hydrolysis, oxidation, and denaturation. Increased molecular motion under heat stress contributes to structural instability, particularly in complex biologic molecules. These processes explain the rapid degradation observed in sensitive formulations.

Differences between formulation types arise from variations in composition and structural complexity. Solid tablets exhibit greater stability due to lower water content and reduced molecular mobility. Liquid formulations provide a medium that facilitates chemical reactions, increasing susceptibility to degradation. Biologics, composed of proteins, are particularly vulnerable to thermal denaturation and aggregation.

Temperature fluctuation introduces additional stress by repeatedly altering molecular environments. Cyclic expansion and contraction can destabilize chemical bonds and physical structures. This mechanism explains the amplified degradation observed under fluctuating conditions. Stability is therefore influenced not only by temperature magnitude but also by variability.

Packaging effects can be attributed to thermal insulation properties and barrier performance. Insulated packaging reduces the rate of heat transfer, delaying temperature rise within the product. Limitations of passive insulation become evident under sustained extreme conditions, where heat accumulation eventually overcomes protective barriers. These mechanisms explain the partial effectiveness observed in the study.

Future research should focus on developing advanced packaging solutions that combine insulation with active cooling mechanisms. Integration of phase-change materials and smart

temperature control systems may offer improved protection. Exploration of such technologies is essential for enhancing pharmaceutical resilience under extreme conditions.

Interdisciplinary collaboration will be critical in addressing the challenges identified in this study. Integration of pharmaceutical science, climate modeling, and engineering can lead to more effective solutions. Collaborative research can also support the development of standardized methodologies for evaluating stability under climate stress.

Expansion of research to include a broader range of medicines and environmental conditions is necessary to strengthen generalizability. Long-term studies examining cumulative exposure effects will provide deeper insights into degradation mechanisms. Inclusion of field-based data can enhance the ecological validity of findings.

Policy-oriented research is also required to translate scientific findings into actionable guidelines. Engagement with regulatory agencies, healthcare providers, and industry stakeholders can facilitate the implementation of climate-resilient practices. Future work should therefore address both technical and institutional dimensions of pharmaceutical stability.

CONCLUSION

This study demonstrates that extreme heat exposure significantly compromises the stability of essential medicines, with degradation patterns varying systematically across formulation types. Distinctive findings reveal that biologics experience rapid and irreversible potency loss, while liquid formulations show moderate instability and solid tablets retain comparatively higher resilience. Evidence further indicates that temperature fluctuation exerts a more damaging effect than constant high-temperature exposure, highlighting the importance of thermal variability as a critical risk factor. Results challenge the adequacy of current pharmaceutical storage standards, showing that compliance with conventional temperature guidelines does not guarantee stability under climate-induced heat extremes.

The research contributes conceptually by reframing pharmaceutical stability as a dynamic and climate-dependent phenomenon rather than a fixed attribute defined under controlled laboratory conditions. Methodological advancement is reflected in the integration of climate-simulated heat scenarios with experimental stability testing, allowing for a more realistic evaluation of drug degradation under prolonged and fluctuating thermal stress. Inclusion of packaging variables and inferential statistical modeling further strengthens the analytical framework by capturing interactions between formulation, environment, and storage conditions. This approach provides a comprehensive basis for developing climate-resilient pharmaceutical systems and extends the scope of stability research beyond traditional paradigms.

Limitations of this study include the restricted range of medicines and formulations analyzed, which may limit the generalizability of findings across the full spectrum of pharmaceutical products. Experimental conditions, although designed to simulate extreme heat, may not fully replicate the complexity of real-world supply chains and storage environments. Variability in packaging technologies and infrastructure across different regions introduces additional uncertainty in applying the results universally. Future research should expand the diversity of drug categories, incorporate field-based longitudinal studies, and explore advanced temperature-control technologies, including active cooling systems and smart monitoring devices, to enhance the resilience of pharmaceutical storage under climate change conditions.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft.
Author 5: Supervision; Validation.
Author 6: Other contribution; Resources; Visuali-zation; Writing - original draft.

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