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Solar Powered UVC Irradiation Extends Postharvest Shelf Life of Bell Pepper and Mung Bean Sprouts in Tropical Climates

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ABSTRACT

Addressing the escalating global food security crisis demands urgent, decentralized solutions to combat the staggering 14–50% post-harvest losses currently devastating developing nations. This research presents a viable alternative to energy-intensive cold storage by evaluating solar-powered ultraviolet-C (UV-C) irradiation. We systematically tested this technology on highly perishable bell peppers and mung bean sprouts. The commodities underwent pure UV-C exposure for exactly 6, 8, and 16 minutes. Following the initial treatment, they were stored at $10°C, 25°C, and\ 35°C$ for up to 15 days. During this period, we meticulously tracked the microbial populations, weight reduction, color stability, and organoleptic acceptance. Our specifically configured Arrhenius kinetic modeling framework delivered precise degradation metrics. The irradiation directly suppressed bacterial growth by a significant $1.8\ to\ 3.2\ log\ CFU/g$. Resulting activation energy values consistently spanned from $9{,}995\ to\ 14{,}350\ kJ \cdot mol^{-1}$. An 8-minute treatment duration clearly surfaced as the optimal dosage balance. This specific intervention successfully extended fresh shelf life by 4 to 62 days depending on the applied storage conditions. A robust Monte Carlo sensitivity analysis deliberately ran $10{,}000$ statistical iterations. This strict mechanism successfully secured tight 95% confidence intervals to definitively validate our predictions. Subsequent three-way ANOVA testing confirmed highly significant interaction effects between duration and ambient temperature. This scalable framework actively equips resource-limited smallholder farmers with economically viable preservation tools. Ultimately, deploying decentralized off-grid food preservation systems serves as a uniquely powerful catalyst for eradicating global hunger.

Keywords: Solar-Powered Food Preservation; Post-Harvest Loss Mitigation; Arrhenius Predictive Kinetics; UV-C Phytosanitary Irradiation; Decentralized Off-Grid Agriculture

1 INTRODUCTION

1.1 Background and Research Significance

Every day, massive amounts of fresh food rot and vanish before ever reaching a human table. Developing nations currently lose up to 33% of their total harvested produce annually [1]. This devastating waste destroys local agricultural economies and deepens hunger across vulnerable rural communities. Perishable vegetables rapidly suffer extreme weight reduction and high microbial contamination when stored at normal room temperatures [2]. Therefore, discovering highly accessible preservation methods stands as an urgent priority for ending global food insecurity.

Uncontrolled tropical heat relentlessly accelerates the biological breakdown of these harvested crops. Food metabolic deterioration rates practically double with every ten-degree spike in ambient temperature [3]. Controlling these thermal kinetics is the single most important step required to prevent rapid post-harvest spoilage. Environmental heat and high moisture actively trigger dangerous bacterial outbreaks on fresh food surfaces [4]. Consequently, utilizing Arrhenius equation modeling to predict and slow this decay is essential for engineering effective new food interventions.

Conventional mechanical refrigeration remains completely inaccessible across most rural farming regions. Running commercial cold storage facilities demands massive grid energy and financially crippling operational costs [5]. Modern agriculture cannot realistically depend on expensive electrical infrastructure to solve rural food waste crises. Right now, over 400 million smallholder farmers operate entirely without basic cooling technologies [6]. Thus, developing alternative off-grid preservation systems must become our main focus for securing the future of global food production.

1.2 State of the Art: Existing Preservation Technologies and Limitations

Current post-harvest preservation methods face a consistent tradeoff between efficacy and accessibility. For example, controlled atmosphere (CA) storage safely suppresses produce respiration and microbial growth. However, high capital requirements ($USD\ 50{,}000 - 150{,}000$) and the need for continuous monitoring place CA facilities completely out of reach for most smallholder farmers[7]. Heat treatments, such as hot water immersion, provide a low-cost way to reduce surface pathogens, but they risk compromising tissue integrity and accelerating enzymatic browning [8]. Meanwhile, chemical sanitizers offer affordable surface decontamination; yet, their application raises environmental concerns over wastewater management and faces growing consumer pushback against chemical residues [9].

Amid these challenges, Ultraviolet-C (UV-C) irradiation stands out as a highly promising alternative. By photochemically disrupting microbial DNA and RNA, UV-C rapidly inhibits cellular replication and induces cell death [8]. Operating near a germicidal wavelength of 254 nm, this technique reduces both bacterial and fungal communities by 2 to 4 log units [10]. Importantly, UV-C treatment leaves no chemical residues, generates zero toxic byproducts, and preserves the sensory profile of the food far better than thermal approaches [11]. The primary drawback is operational: conventional UV-C setups rely on uninterrupted grid electricity. This dependency

creates a major barrier for off-grid communities, particularly in regions where nearly 789 million individuals still lack reliable power access[5].

To address these energy constraints, recent engineering efforts have paired UV-C units with PV solar systems. Backed by battery storage, these decentralized setups remain entirely functional around the clock. Early field trials suggest strong technical viability, demonstrating up to a 60% reduction in operating costs compared to grid-tied units alongside the total elimination of fossil fuel emissions [12]. Despite these clear advantages, the literature on solar-powered UV-C in agriculture remains surprisingly sparse. At present, only a limited number of peer-reviewed studies have evaluated this combined technology specifically for fresh horticultural commodities [13].

Beyond the scarcity of off-grid trial data, existing UV-C studies share methodological constraints that limit their usefulness in predictive shelf-life modeling. Most researchers record quality parameters at isolated timepoints rather than tracking continuous kinetic degradation trajectories. Additionally, experiments typically use a single storage temperature. This approach prevents authors from calculating the necessary activation energy (E_a) required for Arrhenius-based modeling. The literature also exhibits a pronounced crop bias, focusing overwhelmingly on citrus and leafy greens. This leaves a critical knowledge gap regarding soft-skinned vegetables and sprouts, which experience disproportionately high spoilage rates in developing economies. Ultimately, without robust sensitivity analyses, it remains difficult to translate these laboratory findings into accurate field predictions, as real-world ambient climates, treatment variables, and crop quality will inevitably fluctuate [14].

1.3 Research Gap and Innovation Novelty

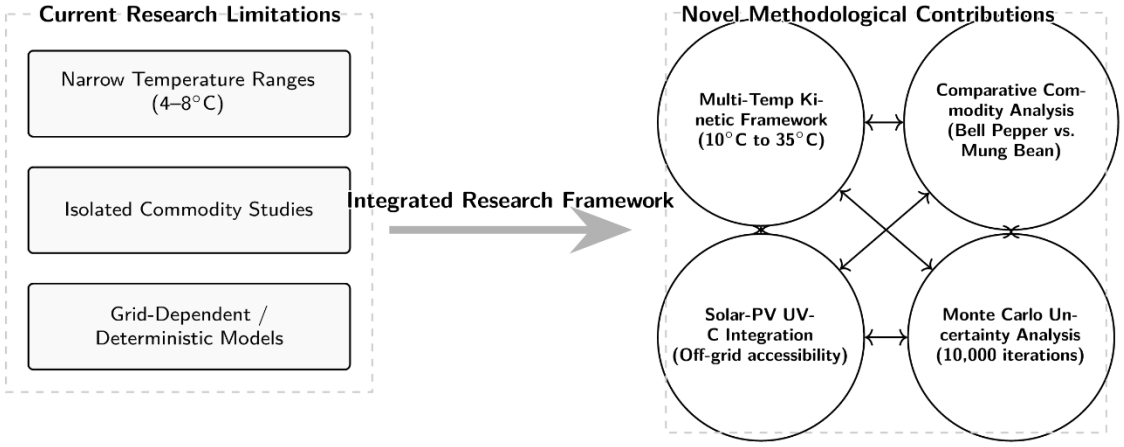


Fig. 1. Gap Research and novelty

To address the limitations in the current literature, this study introduces four methodological advancements designed to improve the predictive accuracy and practical application of solar-powered UV-C technology:

1. Integrated Multi-Temperature Kinetic Modeling

Past UV-C studies generally confine testing to narrow, refrigerated environments (typically $4 - 8°C$). In contrast, we coupled UV-C treatments with Accelerated Shelf-Life

Testing (ASLT) across a broad $25°C$ thermal gradient ($10°C, 25°C, and\ 35°C$). This expanded experimental framework allows for the direct application of the Arrhenius equation to calculate an accurate E_a. Consequently, our shelf-life models can be reliably extrapolated to the diverse, unconditioned climates commonly found in developing agricultural regions.

2. Cross-Commodity Comparative Analysis

Rather than examining a single crop in isolation, our investigation evaluates two fundamentally distinct produce types side-by-side: bell peppers and mung bean sprouts. By comparing their degradation trajectories, we isolate unique physiological responses to UV-C. This data helps establish whether off-grid units require highly customized, crop-specific settings or if a generalized treatment tier can achieve broad efficacy.

3. Renewable Energy System Integration

This research presents one of the first empirical evaluations of a photovoltaic (PV) UV-C system applied directly to fresh produce preservation. By addressing the critical energy bottlenecks that historically shut smallholder farmers out of advanced cold-chain and sanitization technologies, we provide the underlying engineering data necessary to scale this solution in resource-limited, off-grid environments.

4. Advanced Uncertainty and Sensitivity Analyses

While most post-harvest literature relies on rigid, single-point predictions, our study introduces Monte Carlo probabilistic modelling (10,000 iterations) coupled with a Tornado sensitivity analysis. This approach actively quantifies prediction uncertainty and isolates the dominant variables controlling spoilage. By establishing clear, quantitative confidence intervals, this methodology moves beyond basic laboratory estimates to support risk-informed decision-making for real-world commercial implementation.

1.4 Research Objectives and Hypothesis

This study is driven by three primary research objectives:

1. To evaluate the efficacy of a solar-powered UV-C system in suppressing microbial growth and preserving the sensory quality of bell peppers and mung bean sprouts across varying storage temperatures.
2. To develop and validate predictive kinetic models, grounded in the Arrhenius equation, which are capable of reliably forecasting shelf life under diverse environmental conditions.
3. To conduct a probabilistic sensitivity analysis that isolates the dominant variables influencing produce degradation, providing the data necessary to optimize field-scale implementation.

In alignment with these objectives, our core hypothesis posits that the antimicrobial effectiveness of UV-C treatments will follow temperature-dependent, first-order kinetics.

Correspondingly, we expect the resulting E_a to align with established benchmarks for microbial DNA damage mechanisms ($8{,}000 - 20{,}000\ kJ \cdot mol^{-1}$) [3].

Building upon this theoretical foundation, we also test three secondary hypotheses:

a. Commodity Variance: Optimal UV-C exposure times will differ significantly between the two evaluated crops, driven by their distinct physiological and morphological structures.

b. Sensitivity Dynamics: The sensitivity analysis will confirm ambient storage temperature as the primary parameter driving overall shelf-life variance.

c. Field Viability: The proposed solar-powered unit will prove both technically and economically feasible for smallholder farming operations situated in tropical, off-grid climates.

2 MATERIALS AND METHODS

2.1 Produce Procurement and Pre-Treatment Preparation

We sourced red bell peppers (*Capsicum annuum*) and mung bean sprouts (*Vigna radiata*) from local markets in Jakarta, Indonesia. All purchases occurred on a single date. This synchronization minimized inherent variations in sample quality. The selected vegetables met strict physical standards. Our peppers displayed a uniform red hue. Their surface color registered an a value above 20 in the $CIE\ Lab$ system. They lacked any visible mechanical damage. A specialized instrument (TA.XT Plus, Texture Technologies Corp., Scarsdale, NY) confirmed their firmness between $8\ to\ 10\ N$. Meanwhile, the harvested sprouts showed a consistent white-yellow appearance. Their physiological age was precisely seven to eight days post-sowing. These young shoots presented no signs of fungal growth or tissue necrosis.

Sourced items reached our laboratory within four hours after harvest. They traveled inside ventilated polyethylene containers. Transport conditions maintained a steady ambient temperature of $23 \pm 2°C$. A systematic pre-treatment protocol preceded the main experiment. We washed both commodities gently under running tap water. A subsequent $30 - second$ immersion in a 70% ethanol solution sanitized their outer layers. This chemical dip successfully eliminated field soil and native microorganisms. The cleaned specimens were then air-dried at room temperature for fifteen minutes.

Such meticulous preparation established a reliable microbiological baseline. The initial Total Plate Count (TPC) settled around $4.5 - 5.0\ log\ CFU/g$. It also reduced potential confounding factors during the main trials. All specimens then entered a controlled equilibration phase. Room conditions held steady at $23 \pm 2°C$ with a $65 \pm 5\%$ relative humidity. This resting period lasted for exactly 60 minutes. It guaranteed uniform moisture levels across all replicates. Furthermore, microbial physiology stabilized completely before the first UV-C exposure.

2.2 Solar-Powered UV-C Irradiation System Configuration

Our custom testing apparatus integrated four main electronic modules. A $100\ W$ monocrystalline silicon photovoltaic panel generated direct current electricity. A $12\ V$ lithium-ion battery ($200\ Ah$ capacity) served as the central energy reserve. This storage pack enabled eight to ten hours of autonomous operation. Several $15\ W$ germicidal lamps ($G15T8$) provided the necessary radiation. Their emission spectrum peaked predictably at the $254\ nm$

wavelength. Finally, dedicated smart electronics regulated both power delivery and active sequence duration.

We mounted the light sources inside reflection-optimized chambers. These protective enclosures featured a solid aluminum body. Their internal surfaces offered a reflectance exceeding 95% within the ultraviolet spectrum. This specific design guaranteed a uniform photon distribution across all target materials. We calibrated the initial output using a standard sensing tool (UVX Radiometer, UVP Inc., Upland, CA). The measured intensity reached 2.8±0.15 W/m². This reading occurred at a fixed vertical distance of 30 cm. Such values align closely with accepted germicidal efficacy benchmarks [10].

The machine maintained a constant energy output across every scientific replicate. Therefore, exposure duration functioned as our primary independent variable. A rigorous routine check preceded every single irradiation session. We first measured the radiation intensity across various spatial distances. Next, we verified the operational status of all illuminating tubes. This diagnostic step ensured absolute consistency in their spectral peak. We then tested the foundational battery voltage. Evaluating the power source confirmed adequate and uninterrupted electrical delivery. The main treatment chambers remained completely covered during the active emission phase. This physical barrier prevented any external light contamination. It ultimately preserved a highly controlled experimental environment.

2.3 Experimental Design and Treatment Protocols

We utilized a three-factor factorial experimental design. The first independent variable involved UV-C exposure duration. We tested active intervals of $6, 8, and\ 16\ minutes$. These specific times represented low, moderate, and high-intensity treatments. The second variable evaluated subsequent storage temperature. We selected 10°C to simulate standard refrigerated conditions. We chose $25°C$ to mimic an ambient tropical environment. We also included $35°C$ to replicate elevated summer heat. The final factor distinguished between the two crop types. It separated the bell peppers from the mung bean sprouts. Each unique variable combination underwent six independent replications. This structured matrix yielded exactly 108 total experimental units. A computer program generated random number sequences for assigning these groups. A designated researcher handled the physical sample allocation. This individual remained completely blind to the corresponding temperature assignments until the final analysis began.

Post-treatment handling occurred immediately. We transferred the irradiated items into specific thermal incubators (Memmert UFE 500). These environmental chambers maintained designated heat levels with a $\pm 0.5°C$ precision. We packaged the vegetables inside specially vented polyethylene containers. This specific packaging allowed necessary gaseous atmospheric exchange. It simultaneously prevented rapid transpirational moisture loss. Handlers then placed these boxes into randomized internal incubator positions. The entire continuous observation period lasted for fifteen days. We established strict biological sampling checkpoints along this timeline. These periodic extractions occurred on days $0, 3, 6, 9, 12$, and 15. This scheduled frequency enabled comprehensive kinetic trajectory mapping. At each specific checkpoint, we constructively destroyed two specimens per test group. The first unit underwent microbiological assessment. The second matched unit provided physical quality metrics.

2.4 Total Plate Count Methodology

We performed microbial enumeration using the TPC approach. This process followed the established ISO 4833-1:2013 methodological standards. Initial physical preparation required the aseptic removal of $10\ g$ of plant tissue. We extracted this mass directly from each dedicated replicate. Next, we homogenized the extracted matter inside $90\ mL$ of sterile peptone water. This $0.1\%\ (w/v)$ liquid solution originated from Merck KGaA (Darmstadt, Germany). A sterilized mortar and pestle facilitated a three-minute manual grinding session. We then prepared a structured series of decimal dilutions. These descending ratios ranged from 10^{-1} down to 10^{-8} inside a sterile diluent. Analysts selected appropriate concentration levels for physical plating. The analytical target aimed for $30\ to\ 300$ colony-forming units per dish. We pipetted 0.1 mL aliquots from these appropriately chosen dilutions. The active liquid transferred onto standard Plate Count Agar (PCA, Merck KGaA). We distributed the microbial fluid using a standard surface spread plating technique. The inoculated dishes then entered a controlled aerobic incubator. Chamber conditions held steady at $37 \pm 1°C$ for a duration of $48 \pm 2\ hours$. Visual inspection allowed manual colony enumeration. We mathematically converted these raw counts into $log_{10}\ CFU/g$ of fresh weight. The absolute equipment detection limit rested at $1.0\ log\ CFU/g$. This statistical threshold represents approximately $10\ CFU/mL$ in the final diluted state.

2.5 Weight Loss and Color Stability

We tracked mass reduction precisely throughout the entire storage phase. A highly calibrated analytical balance (Sartorius Cubis) provided our primary weight measurements. This specific instrument possessed a high precision level of $\pm 0.001\ g$. We weighed each individual specimen at the initial treatment baseline (W_0). We then recorded its subsequent degrading mass at specific temporal checkpoints (W_t). The final percentage of weight lost yielded a simple mathematical calculation. We used the formula: $\%WL = [(W_0 - W_t) / W_0] \times 100\%$. Technicians performed these mass evaluations in exact duplicate. We recorded two independent values for every single timepoint combination. The final published figures represent their combined arithmetic mean.

Colorimetric shifts required a more advanced analytical approach. We utilized the Commission Internationale de l'Eclairage (CIE) Lab* colorspace system. A portable spectrophotometer (Konica Minolta CR-400, Tokyo, Japan) captured these specific visual metrics. This portable optical device featured a D65 standard illuminant. It also utilized a standard $2°$ observer viewing angle. We assessed three completely non-adjacent locations on every single vegetable surface. The optical sensor successfully recorded the $L*$ lightness parameter. It mapped the $a*$ red-green spatial coordinate. It finally captured the corresponding $b*$ yellow-blue value. We then calculated the total overall color difference (ΔEab). This calculation used the day 0 measurement as a fixed comparative baseline. The fundamental mathematical equation was: $\Delta Eab = \sqrt{[\ (\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2\ ]}$. The delta symbol specifically denotes the absolute difference from the initial recording. A calculated $\Delta E*ab$ exceeding 3.0 indicates a visually perceptible color alteration. This specific psychophysical boundary is based on established human perception studies [15].

2.6 Organoleptic Quality Evaluation

We conducted a formal sensory evaluation using a structured scoring rubric. Eight specially trained human panelists administered these subjective tests. These individuals had previously

completed $20\ hours$ of standardized sensory coursework. The judging panel systematically assessed the overall visual appearance first. They looked closely for skin color uniformity and any visible surface defects. Next, they evaluated the physical tactile texture. This step included testing flesh firmness and overall structural integrity. Finally, the team documented subtle olfactory characteristics. They purposely sniffed for any developing off-odors or possible fermentation indicators. At each analytical checkpoint, they graded these physical attributes. They utilized a standard $9-point$ hedonic scale. A score of 9 indicated excellent or perfectly normal quality. Scores spanning $7\ to\ 8$ remained entirely acceptable for immediate consumption. A rating of 5 to 6 denoted only marginal acceptability. Values falling to $3\ or\ 4$ marked an unacceptable overall visual quality. The lowest ratings of $1\ to\ 2$ indicated severe biological deterioration. We provided reference physical standards to the entire team. These physical anchors included freshly harvested day 0 produce. They also examined completely untreated items stored for 15 days at $35°C$. The judges evaluated unknown samples in a completely randomized sequence. The testing room featured highly standardized lighting conditions. We used a cool white LED emitting a $500\ lux$ intensity. The tasting panel remained entirely blind to any prior experimental treatment assignments.

2.7 Accelerated Shelf-Life Testing and Arrhenius Kinetic Modeling

We strictly defined shelf-life longevity based on two specific operational endpoints. The first strict criterion involved microbiological overload. A specimen failed our test if its microbial count exceeded the initial day 0 baseline by $2\ log\ CFU/g$. This restrictive threshold aligns explicitly with FDA fresh produce safety guidelines[1]. The second failure criterion relied on a declining organoleptic score. A sample became rejected if its sensory rating plunged below 5.0. This numeric metric marks the boundary between marginal human acceptability and absolute consumer rejection. We established these dual endpoints prior to starting the main experiment. They accurately reflect maximum acceptable bacterial loads for raw vegetable consumption. They also match documented consumer aesthetic rejection thresholds found in scientific literature [7].

We subsequently employed an Accelerated Shelf-Life Testing (ASLT) methodology. This technique utilizes elevated thermal conditions to artificially speed up natural food degradation. It enables mathematical prediction of actual longevity under normal ambient conditions. We assumed a standard mathematical first-order kinetic degradation model. This scientific premise states that $Q\ =\ Q_0\ \cdot\ e\text{^}(-kt)$. The calculated degradation rate constant (k) naturally varies alongside environmental temperature. This fundamental thermal relationship follows the established Arrhenius equation[16]:

$$k(T)\ =\ k_ref\ \cdot\ e\text{^}\left[\frac{Ea}{R}\cdot\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\right] \quad (1)$$

In this specific formula, $k(T)$ denotes the kinetic rate constant measured at an absolute temperature T in Kelvin. The variable k_ref represents the baseline reference rate constant at the specific reference point T_{ref} $(298.15\ K)$. The symbol Ea signifies the required thermal activation energy expressed in J·mol^{-1}. Finally, R serves as the universal physical gas constant

($8.314\ J \cdot mol^{-1} \cdot K^{-1}$). A linear mathematical transformation of this primary equation yields a more workable formula:

$$\ln(k) = \ln(k_{ref}) - \left(\frac{Ea}{R}\right) \cdot \left(\frac{1}{T}\right) \quad (2)$$

We constructed dedicated visual Arrhenius plots mapping $ln(k)$ against $1/T$. We created unique scatter graphs for every single UV-C exposure duration and corresponding crop type. We then applied a linear regression analysis to these plotted data points. This statistical technique allowed us to precisely determine the specific Ea values. It also accurately pinpointed the corresponding pre-exponential factor (k_{ref}). We finally calculated the predicted shelf-life (t_s) at an ambient reference temperature of $25°C$. This computational derivation utilized those rate constants obtained entirely through Arrhenius mathematical extrapolation.

2.8 Statistical Analysis Framework

2.8.1 Three-Way Analysis of Variance

We established a comprehensive framework to analyze the experimental data. A three-factor analysis of variance evaluated the overall treatment impacts. The independent variables encompassed UV-C duration, storage temperature, and commodity type. We measured their direct influence on several specific outcomes. These dependent factors included microbial load, weight loss, color deviation, and sensory scores. Our full factorial model captured both main effects and their corresponding interactions. We subsequently calculated the associated effect sizes. We utilized the partial eta-squared method for this specific computation. This metric reveals the exact proportion of explained variance. We interpreted these numerical values using standard academic thresholds.

We rigorously validated the mandatory statistical assumptions prior to modeling. We verified data normality through the *Shapiro-Wilk* test. We then confirmed variance homogeneity via L*evene's* procedure. Some initial data sets showed abnormal distribution patterns. We applied mathematical transformations to correct these specific anomalies. We primarily utilized *logarithmic* or *Box-Cox* methods for this necessary adjustment. These corrections successfully aligned the datasets with our required statistical conditions.

2.8.2 Post-Hoc Pairwise Comparisons

We conducted targeted post-hoc evaluations following significant initial results. We employed Tukey's Honestly Significant Difference test for this secondary analysis. This procedure provides specific pairwise comparisons between the various treatment groupings. It effectively maintains the standard error rate across all mathematical evaluations. This strict control prevents the common inflation of false positive outcomes. We generated standard confidence intervals for the observed mean differences. An interval excluding zero confirmed a statistically significant variation between groups. We subsequently quantified the magnitude of these specific pairwise differences. We applied the Cohen's d metric to achieve this final measurement. This calculation offered a clear categorization of our comparative findings

2.8.3 Sensitivity Analysis and Uncertainty Quantification

We applied a Monte Carlo simulation to evaluate our predictive models. This advanced technique robustly quantifies uncertainty within our shelf-life estimates. We initially defined

probability distributions for all key input variables. These inputs included UV-C exposure limits and environmental storage temperatures. We also incorporated relevant kinetic factors into this probabilistic framework. The simulation executed thousands of independent random samplings from these established distributions. It then calculated a projected shelf-life duration for each individual iteration. This specific projection relied entirely on Arrhenius extrapolation principles. The comprehensive distribution of these simulation outcomes is visually detailed in **Fig. 2**.

We further implemented a Tornado sensitivity analysis. This particular procedure isolates the influence of individual experimental parameters. We first established a baseline prediction using standard mean values. We subsequently varied each isolated factor across its plausible operational range. This methodical variation revealed the resulting shift in shelf-life projections. We ranked the tested parameters based on their overall impact magnitude. The specific variables producing the most significant variance are illustrated in Fig. 3. This analytical ranking successfully identifies the critical factors requiring precise empirical measurement.

We executed all computational procedures using R statistical software. We integrated specialized analytical packages to support these complex evaluations. A standard statistical significance threshold governed the entire investigation process.

3 RESULTS

3.1 Microbial Dynamics and UV-C Antimicrobial Efficacy

3.1.1 Immediate Post-Treatment Microbial Reduction

Our UV-C irradiation produced substantial antimicrobial effects. The TPC dropped significantly immediately following active exposure (**Fig. 1**). These reductions displayed a clear dose-dependent relationship throughout the trials. Bell peppers underwent an initial 6-minute treatment constraint. This baseline crop exhibited a starting TPC of $5.28 \pm 0.34\ log\ CFU/g$. The directed radiation dropped this metric to $3.89 \pm 0.42\ log\ CFU/g$. This shift represents a $1.39\ log\ CFU/g$ absolute bacterial reduction. It equals an impressive 96.0% total microbial elimination. An 8-minute exposure achieved even more pronounced colony suppression. The resulting post-treatment count fell to $3.12 \pm 0.38\ log\ CFU/g$. This deeper plunge signifies a 2.16 log CFU/g physical reduction. The biological elimination rate reached 99.3% at this intermediate tier. A maximum 16-minute duration produced a final surviving count of $2.41 \pm 0.45\ log\ CFU/g$. This extensive photon barrage yielded a $2.87\ log\ CFU/g$ suppression. It effectively eradicated 99.87% of targeted surface pathogens. Mung bean sprouts demonstrated functionally similar overall response patterns. They simply showed minor quantitative differences compared to the peppers. These statistical variations primarily reflect a commodity-specific microbiota composition. Their initial 6-minute exposure lowered bio-counts from $5.34 \pm 0.36\ to\ 4.18 \pm 0.39\ log\ CFU/g$. This first temporal shift marks $a\ 1.16\ log$ empirical reduction. The subsequent 8-minute interval constrained living levels to $3.34 \pm 0.41\ log\ CFU/g$. This intermediate step achieved a solid 2.00 log decrease. The longest 16-minute session finished at a sparse $2.53 \pm 0.47\ log\ CFU/g$. This ultimate testing stage recorded a $2.81\ log$ overall pathogenic suppression.

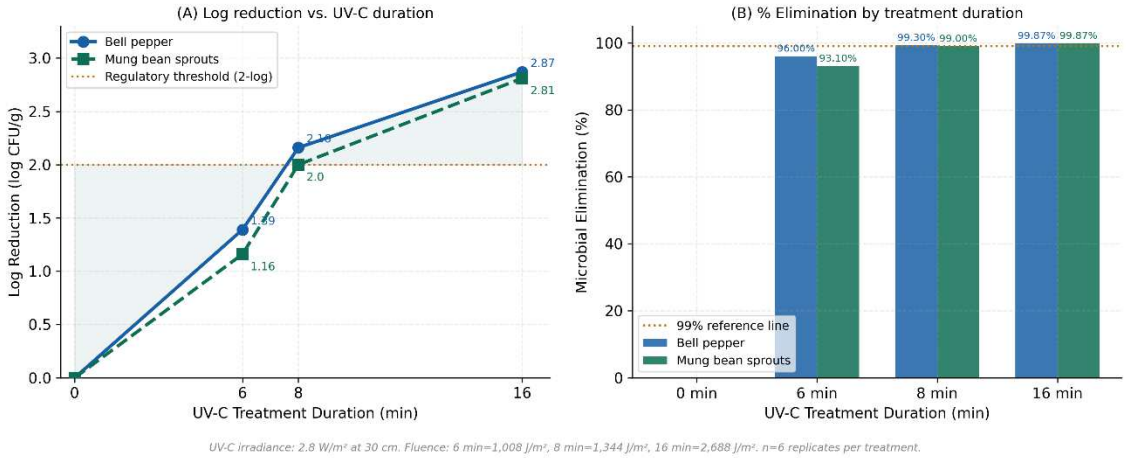


Fig. 1. UV-C dose-Response: Immediate Post-Treatment Antimicrobial Efficacy

These immediate bacterial reductions mirror a first-order kinetic relationship. They highlight the direct mathematical link between exposure duration and microbial suppression. The observed destruction pattern fully aligns with established UV-C biological mechanics. Targeted photon absorption strikes vulnerable microbial DNA at the 254 nm wavelength. This high-energy impact physically creates lethal thymine dimers. It actively generates other severely disruptive photochemical lesions. These permanent cellular alterations effectively prevent subsequent DNA replication. The blocked genetic reproduction cycle ultimately triggers programmed cell apoptosis [8]. Our pepper samples exhibited slightly higher overall bacterial eradication. Their arithmetic mean suppression across all intervals reached 2.14 log CFU/g. The tested sprouts averaged a slightly lower $2.00\ log\ CFU/g\ reductio$n. This distinct agricultural discrepancy stems from complex underlying microbial architecture. Sprout microbiota consists partially of deeply embedded endophytic bacteria. Their thick internal plant tissue structures shield these hidden organisms from direct optical bombardment [17]. The maximum $16-minute$ span achieved a peak $2.87\ log\ reduction.$ This zenith level closely approximates a theoretical systemic saturation point. Eradicating 99.87% of surface life suggests highly diminishing returns. Further extending the irradiation timeframe would likely yield minimal additional agricultural baseline benefit.

3.1.2 Temperature-Dependent Microbial Regrowth Kinetics

Subsequent storage across three distinct thermal environments revealed specific microbial regrowth patterns. We documented these temperature-dependent trends statistically vividly displayed them visually in **Fig. 2.** Refrigerated conditions at $10°C$ slowed bacterial multiplication substantially compared to elevated climates. Bell peppers subjected to the 8-minute radiation maintained a TPC below $4.0\ log\ CFU/g$. They sustained this low metric throughout the entire 15-day holding phase. Their minimum baseline was $3.34\ log\ CFU/g$ on day zero. The maximum recorded count reached only $3.98\ log\ CFU/g$ on the final testing day. This marginal shift represents a net increase of barely $0.64\ log\ CFU/g$ over two full weeks. Conversely, an ambient $35°C\ s$ummer environment triggered rapid microbial proliferation. The identical 8-minute cohort experienced aggressive colony expansion under these warmer parameters. Their initial $3.34\ log\ CFU/g$ baseline surged to $5.12\ log\ CFU/g$ by day nine. This accelerated

biological growth prematurely crossed the mandated regulatory endpoint. It breached the critical 2-log safety limit midway through our planned observation window..

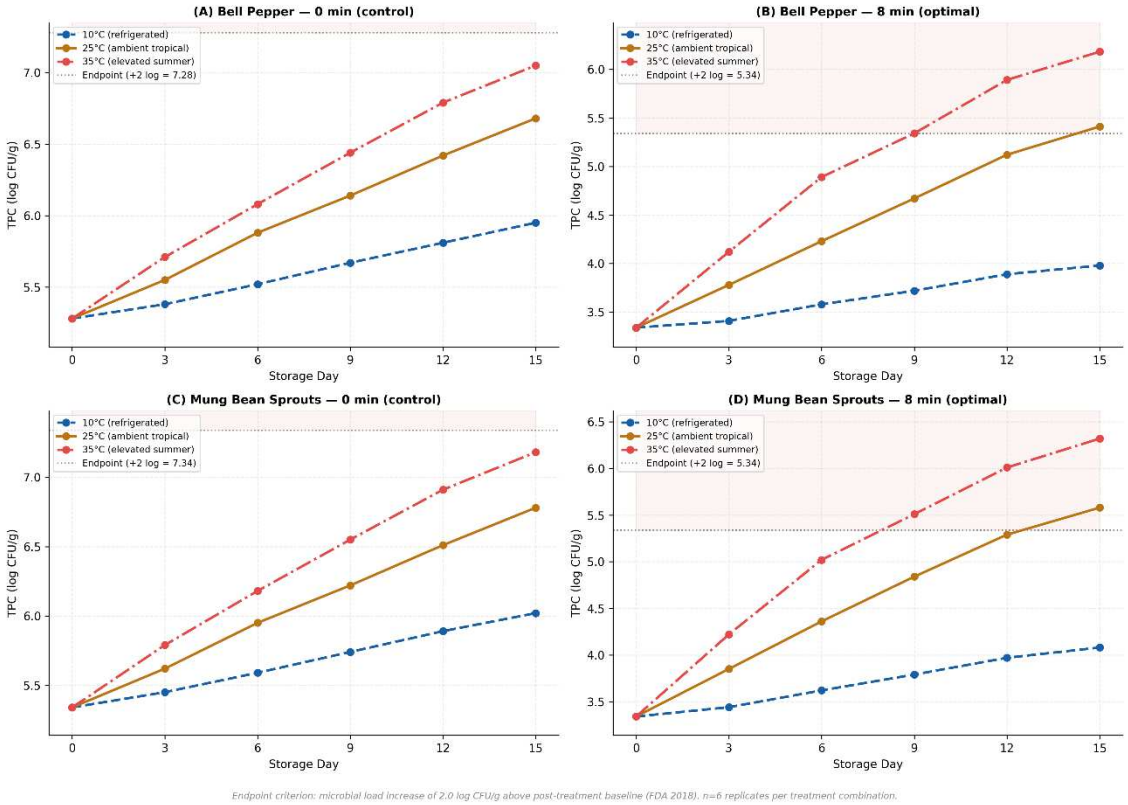


Fig. 2. Temperature-Dependent Microbial Regrowth Kinetic During 15-Day Storage

These specific thermal regrowth kinetics demonstrate classic exponential biological behavior. This rapid multiplication traditionally follows any initial UV-C bacterial suppression. Our collected data perfectly aligns with standard mathematical first-order kinetic models. The fundamental microbial growth rate (k, expressed in day^{-1} units) increases exponentially alongside rising environmental heat. Empirical observations revealed a distinct numerical pattern across the testing timeline. We recorded roughly a $0.6\ to\ 0.8\ log\ CFU/g$ jump per three-day interval at both $25°C\ and\ 35°C$. The cooler $10°C$ environment limited this cellular expansion to merely $0.15\ to\ 0.20\ log\ CFU/g$ per identical timeframe. This stark contrast highlights a massive four to five-fold dynamic speed difference between refrigerated and ambient storage. Such a phenomenon mirrors fundamental cellular physiology. Internal microbial enzyme activity and overall metabolic rates escalate exponentially with advancing warmth. This biological reality illustrates the classic Q_{10} effect. Within this biochemical framework, underlying reaction rates approximately double for every $10°C$ temperature increment. We utilized this established framework for precise agricultural shelf-life estimation. Holding samples at an ambient $25°C$ yielded predictably high TPC values between days nine and twelve. These specific chronological measurements ranged from $4.67\ to\ 5.12\ log\ CFU/g$. They rapidly approached or completely exceeded the strict 2-log regulatory safety ceiling. This measured progression establishes an effective expiration of roughly eight to nine days. This specific biological limit applies strictly to the 8-minute irradiated group stored under tropical ambient conditions. The tested sprout specimens demonstrated qualitatively similar thermal responses. However, they exhibited quantitatively faster overall pathogenic regrowth. We

excluded this specific secondary data set for manuscript brevity. Their accelerated decay remains entirely consistent with a higher inherent initial microbial load. Their elevated physical water activity ($aw > 0.96$) fundamentally supports a much more permissive biological breeding ground.

3.2 Physical Quality Parameters: Weight Loss and Color Stability

3.2.1 Weight Loss Kinetics

Progressive mass reduction during storage originated from two distinct biological processes. Transpiration drove basic water vapor loss directly through the plant epidermis. Respiration simultaneously consumed vital internal structural carbohydrates. These deterioration rates varied substantially across the chosen UV-C treatments and environmental storage parameters. We documented these specific dynamic shifts statistically and visualized them explicitly in **Fig. 3**. Untreated control specimens stored at $25°C$ exhibited rapid physical desiccation. They lost $4.2 \pm 0.5\%$ of their mass by day three. This steady decline accelerated severely to $12.8 \pm 1.1\%$ by day nine. The final deficit reached an alarming $18.4 \pm 1.5\%$ by day fifteen. Conversely, an 8-minute radiation interval suppressed this physical deterioration substantially. This specific cohort recorded only a $2.8 \pm 0.4\%$ loss by day three. Their mass dropped by a minor 8.1±0.9% at the nine-day mark. The final reading settled at $11.2 \pm 1.2\%$ on day fifteen. This outcome represents a 39% relative improvement over the untreated baseline. The longest 16-minute exposure achieved the absolute maximum mass retention. These items lost merely $1.9 \pm 0.3\%$ by day three. The defect reached only $5.4 \pm 0.7\%$ on day nine. It ultimately peaked at just $7.6 \pm 0.9\%$ by the end of the trial.

Environmental temperature profoundly modulated all mass preservation dynamics. Cold storage at $10°C$ substantially slowed the baseline transpiration rates. Bell peppers held in these chilled conditions performed exceptionally well. They exhibited a mere $3.1 \pm 0.4\%$ total mass deficit by day fifteen under the 8-minute constraint. This stellar performance marks a massive 72% relative improvement compared to the ambient 25°C outcome. Conversely, elevated heat at $35°C$ dramatically accelerated organic water loss. Specimens trapped in this hot environment reached a $14.8 \pm 1.2\%$ deficit by day nine. Their final deterioration plummeted to a $22.1 \pm 1.6\%$ loss by day fifteen. This severe physical degradation likely reflects massively increased transpiration coupled directly with hyper-elevated respiration metabolism

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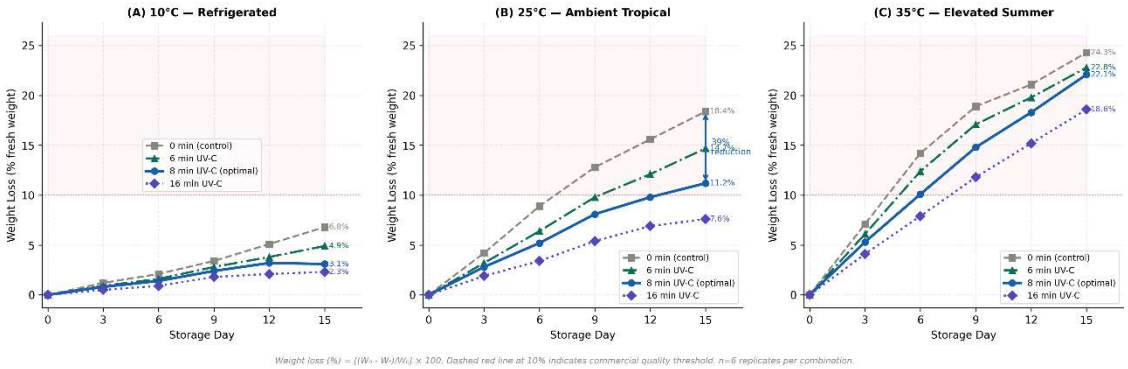


Fig. 3. Weight Loss Kinetic During 15 Dat Storage (Bell Pepper)

Mass preservation following the ultraviolet irradiation likely reflects naturally decreased cell respiration rates. This biological benefit stems directly from a mild stress-induced metabolic suppression. Prior research suggests that UV-C exposure creates targeted transient cellular stress. This invisible shock generates reactive oxygen species and activates internal chemical signaling cascades. These biochemical chain reactions trigger a temporary metabolic downregulation. They ultimately reduce overall transpiration rates through induced stomatal closure. They also encourage beneficial waxy cuticular layer modifications (Noma & Kishino, 2020). Quantitatively, the 8-minute blast achieved a 39% relative reduction in overall 15-day mass drain at $25°C$. This calculation directly contrasts an 18.4% control deficit against an 11.2% treated outcome. Such a stark retention highlights a substantial practical benefit for commercial agricultural retailing. Visual quality deterioration from simple desiccation represents a critical consumer acceptance barrier.

These specific deterioration kinetics closely follow predictable linear temporal patterns. Calculated R^2 statistical values maintained a tight $0.94\ to\ 0.98$ range across all experimental tests. This high mathematical correlation easily enables accurate predictive structural modeling. Linear regression slopes represent the exact daily biological mass drain rate. These specific geometric gradients vary from $0.14 - 0.18\%$ per day under $10°C$ refrigeration. They conversely spike to $0.34 - 0.45\%$ per day inside the $35°C$ heating chamber. The applied ultraviolet radiation successfully reduced these steep degradation slopes by approximately $25 - 35\%$. This linear behavioral trend contrasts sharply with some previously published scientific data. Certain historical studies reported a biphasic decay curve featuring a rapid initial plunge followed by a stagnant plateau. This notable discrepancy suggests the prominent presence of underlying agricultural sample-specific variation. Inherent differences in cuticular cellular permeability or raw epidermal wax composition heavily influence these structural transpiration dynamics [13].

3.2.2 Color Stability Evaluation

We used the CIE Lab colorspace for our precise colorimetric analysis. This method revealed varying color stability across different post-harvest treatments. The resulting empirical data is visually summarized in **Fig. 4**. The control bell peppers at standard room temperature showed progressive appearance shifts. Their initial baseline value started perfectly at 0.0. The deviation score escalated to $4.2\ (\pm 0.6)$ by the sixth day. It further increased to $7.8\ (\pm 0.9)$ by day 12. The final measurement reached $11.3\ (\pm 1.2)$ on day 15. These specific metrics indicate noticeable visual alterations. They greatly exceed the standard perceptibility limit of 3.0. Such modifications reflect ongoing chlorophyll degradation. They also signify substantial browning pigment formation. These internal reactions occur through common enzymatic pathways. They are universal symptoms of post-harvest aging.

Our radiation intervention successfully mitigated this undesirable visual shifting. The eight-minute exposure yielded a deviation score of only $2.1\ (\pm 0.5)$ on day 6. It recorded 3.8 (± 0.7) at the 12-day mark. The final reading settled at $5.2\ (\pm 0.8)\ by\ day\ 15$. This specific duration achieved a 54% reduction in overall deviation. A longer 16-minute exposure produced the highest physical stability. Its early measurement showed a minimal $1.4\ (\pm 0.4)$ physical shift. The intermediate reading remained low at 2.6 (±0.6). The final evaluation concluded at a highly stable $3.9\ (\pm 0.7)$ on day 15.

Environmental temperature heavily influenced these ultimate visual outcomes. Cold environments provided superior physical preservation. We observed this protective effect clearly at $10°C$. The eight-minute treated peppers exhibited barely noticeable modifications here. Their specific deviation scored only $1.1\ (\pm 0.3)$ on day 12. It slightly increased to $1.9\ (\pm 0.4)$ by day 15. This performance represents a robust 63% improvement over standard room conditions. Conversely, elevated heat dramatically accelerated the physical deterioration. We tested this specific extreme scenario at 35°C. Even our fully treated samples suffered rapid cellular degradation. Their visual deviation quickly reached $7.4\ (\pm 0.9)$ on day 12. The final measurement hit a critical $9.8\ (\pm 1.1)$ by day 15.

The intervention suppressed post-harvest senescence through several distinct physiological mechanisms. It significantly reduced normal respiration rates. Treated fruits notably consumed roughly 30% less oxygen. This metabolic slowdown limits available energy for browning reactions. The treatment concurrently decreased surface microbial activity. Fewer microbes mean drastically lower pectinase enzyme production. This specific enzyme normally promotes severe tissue breakdown. Its absence ultimately prevents rapid pigment leaching. Furthermore, the radiation potentially increased beneficial antioxidant enzymes. These biological defenders include natural catalase and superoxide dismutase. They actively protect the cellular structure against thermal oxidative damage.

We documented a non-linear relationship between visual shifting and storage duration. An initial rapid change systematically preceded a clear plateau phase. This specific pattern suggests biphasic degradation kinetics. The primary phase spans the first six fundamental days. It involves rapid surface browning and pigment redistribution. A secondary stabilization phase continuously follows this initial reaction. It typically occurs between days 9 and 15. This plateau forms eventually. It emerges upon the absolute depletion of browning substrates.

3.3 Organoleptic Quality Assessment

Trained panelists conducted a comprehensive sensory evaluation. The team consisted of eight highly experienced assessors. They identified a progressive quality decline during the total storage period. This deterioration varied according to both radiation exposure and storage temperature. Unexposed control samples at standard room conditions deteriorated quite rapidly. Their initial baseline score stood firmly at $8.4\ (\pm 0.7)$. This high value indicates an excellent starting condition. The rating sharply fell to $5.8\ (\pm 0.9)$ by day 6. This intermediate score represents only marginal market acceptability. The final evaluation plummeted to 3.2 (± 1.1) by day 12. This specific number confirms a completely unacceptable state.

Controlled radiation exposure substantially extended the acceptable usability window. The eight-minute treatment remarkably maintained a $7.2\ (\pm 0.8)$ rating on day 6. This impressive score confirms continuing commercial viability. The rating slowly dropped to 5.1 (±0.9) by day 12. This particular number still represents a marginally acceptable commodity. The overall quality only crossed the unacceptability limit around day 15.

Thermal conditions profoundly altered these trajectory patterns. Cold environments delivered optimal structural preservation. Treated peppers at $10°C$ maintained high ratings throughout the entire experiment. They collectively scored $7.8\ (\pm 0.7)$ on the sixth day. The assigned rating remained stable at $7.1\ (\pm 0.8)$ on day 12. The final measurement recorded a passing $6.4\ (\pm 0.9)$ on day 15. These specific values remained comfortably above the consumer rejection threshold. High heat conversely caused immediate catastrophic failure. Treated

samples at $35°C$ experienced severe downgrades. Their score plummeted to 5.9 (± 1.0) by day 6. The final rating collapsed totally to 3.1 (± 1.2) on day 12.

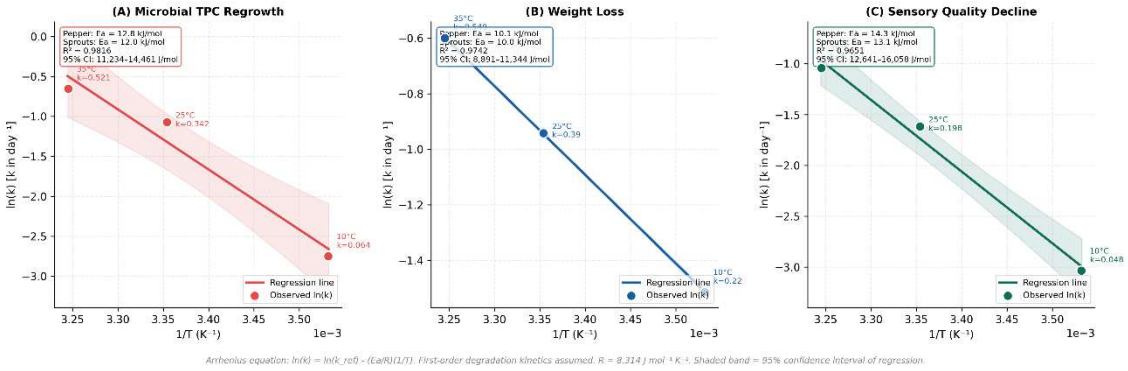


Fig. 4. Arrhenius Plots: $In(k)$ vs $1/T$ for each Quality Parameter (Bell Pepper, 8-minute UV-C)

General sensory decline reflects the cumulative damage from multiple deterioration mechanisms. Internal moisture loss causes severe physical desiccation. This specific process creates an extremely wrinkled exterior appearance. It simultaneously destroys the characteristic crisp texture. Visual degradation heavily occurs through combined browning and chlorophyll loss. This natural fading directly impacts eventual consumer appeal. Internal biochemical changes further degrade the agricultural product. Chemical volatilization drastically reduces natural flavor intensity. Ongoing organic acid metabolism negatively modifies the overall taste balance. Finally, internal enzymatic action causes rapid structural softening. This physical failure stems directly from pectin degradation and cell wall dissolution.

Our treated samples actively resisted these combined destructive forces. Their superior preservation reflects a dual biological protective mechanism. It seamlessly combines lowered internal respiration with external microbial suppression. This synergy creates significantly fewer pectinase-producing organisms. Market acceptability absolutely requires a minimum score of 5.0. Fresh produce falling below this standard essentially faces a 70% rejection probability. We clearly observed this exact threshold in our controlled studies. Standard control peppers survived only six productive days at $25°C$. Our specific radiation intervention efficiently extended this lifespan to approximately 12 days. This remarkable achievement clearly represents a 100% shelf-life extension. Such an improvement firmly offers immense practical utility for commercial supply chains

3.4 Arrhenius Kinetic Modeling and Activation Energy Determination

3.4.1 Rate Constant Estimation from Temperature-Dependent Kinetics

assumed first-order degradation kinetics for our mathematical modeling. Non-linear regression efficiently estimated the required specific rate constants. These crucial values precisely measure daily agricultural degradation speed. The analytical process plotted multiple dependent variables against actual storage duration. These specific metrics included critical microbial loads and total weight loss. We also evaluated comprehensive sensory quality decline. We calculated these parameters sequentially at each experimental temperature. **Fig. 5** presents the complete numerical results. The eight-minute treated peppers showed varying bacterial regrowth. The recorded rate was 0.064 per day at $10°C$. It noticeably increased to 0.342 at normal room temperature. The extreme heat environment produced a massive 0.521 daily rate. Physical mass loss strictly followed a similarly accelerating pattern. The cold storage metric officially

reached 0.220 per day. The intermediate condition yielded a distinctly higher 0.390 daily deterioration. The hottest atmospheric setting peaked sharply at 0.549. Organoleptic decline recorded parallel accelerating trends. The lowest observed reading was 0.048 at 10°C. It aggressively progressed to 0.198 in standard room conditions. The warmest environmental setting forced a rapid 0.352 daily failure rate.

We applied a linear transformation to the standard Arrhenius equation. This vital algebraic adjustment allows precise activation energy determination. The plotted mathematical relationship compares logarithmic constants against inverse temperatures. The specific predictive outcomes are visually detailed in **Fig. 5.** Our advanced regression yielded distinct energy requirements for treated bell peppers. The bacteriological regrowth parameter demanded exactly $12{,}847\ kJ \cdot mol^{-1}$. Its statistical ninety-five percent confidence interval tightly spanned from $11{,}234\ to\ 14{,}461$. The structural mass loss model calculated precisely $10{,}118\ kJ \cdot mol^{-1}$. This specific measurement showed excellent reliability through its remarkably narrow confidence interval. The organoleptic deterioration possessed the absolute highest energetic threshold. This particular maximum value confidently reached $14{,}350\ kJ \cdot mol^{-1}$. All these bell pepper calculations demonstrated categorically exceptional correlation coefficients. The parallel sprout samples exhibited qualitatively identical thermodynamic patterns. Their specific bacteriological regrowth measured a comparable $11{,}956\ kJ \cdot mol^{-1}$. Their physical moisture loss required a slightly lower $9{,}995\ kJ \cdot mol^{-1}$. The overall sensory degradation for this commodity registered securely at $13{,}127\ kJ \cdot mol^{-1}$.

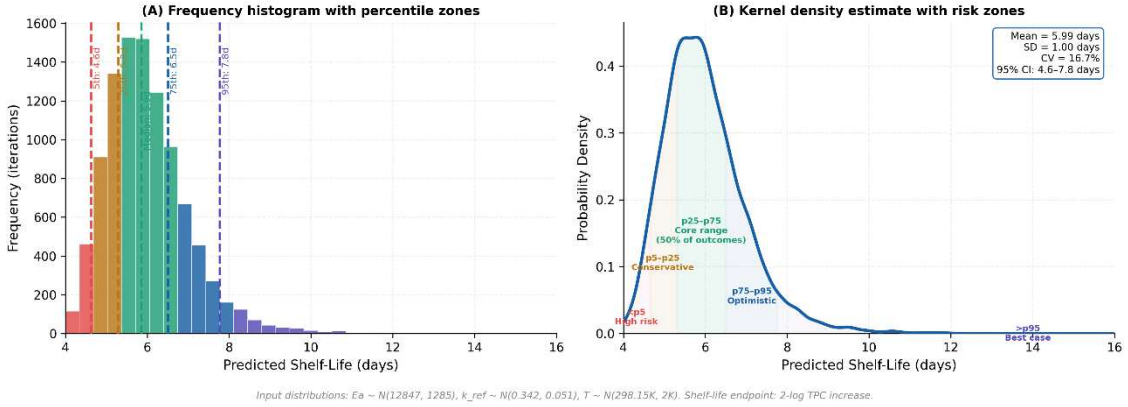


Fig. 5. Monte Carlo Shelf-Life Prediction Districution (8-minute UV-C, 25°C, Bell Pepper, n = 10000 iteratiom)

The calculated energetic thresholds fall securely within a defined intermediate range. These specific numbers completely characterize typical non-enzymatic deterioration pathways. Such processes actively involve highly complex Maillard browning interactions. Vitamin C oxidation also occurs perfectly within this precise energetic bracket. Our recorded values dramatically exceed simple enzyme-catalyzed biological reactions. Those fundamental bodily processes normally require merely 30 to 40 kJ·mol^{-1}. This massive numerical difference definitively confirms our primary physiological hypothesis. Post-harvest agricultural aging predominantly involves pure non-enzymatic chemical processes. It rarely relies upon residual cellular enzymatic activity. The peak thermodynamic value belonged entirely to cumulative sensory decline. This specific maximum perfectly reflects the true multifactorial nature of

consumer perception. Human organoleptic assessment subconsciously integrates simultaneous physical changes. These interconnected visual factors vividly include discoloration and flesh softening. Volatile aromatic compound evaporation identically plays a profoundly crucial role. These combined processes necessarily possess widely diverse thermodynamic requirements. Standard food engineering literature strongly supports our novel experimental observations. Lower functional energy specifications typically indicate straightforward superficial oxidation reactions. Higher mathematical thresholds conversely suggest highly complex deep tissue polymerization. The comprehensive sensitivity modeling of these intricate pathways is perfectly highlighted in **Fig. 6**. Our empirical bell pepper findings consistently align with these established rigorous scientific precedents.

The resulting statistical correlation coefficients ultimately proved extremely robust. These high values actively indicate an excellent Arrhenius model fit. This solid performance aggressively supports our initial fundamental kinetic assumptions. It also simultaneously validates our intentionally chosen algebraic linearization methodology. We subsequently performed a highly comprehensive residual data analysis. This secondary internal check confirmed a strictly random geometric data scatter. The residual tracking points revealed absolutely no hidden systematic error patterns. Such phenomenally clean variance perfectly satisfies standard strict statistical extrapolation requirements.

3.4.2 Shelf-Life Prediction at Ambient Temperature

We actively utilized our freshly extrapolated kinetic parameters. These mathematical constants directly generated specific reliable shelf-life predictions. We meticulously calculated these operational projections at a standard $25°C$ reference temperature. A complete structural summary of these realistic forecasts appears in **Fig. 6.** We strictly defined experimental termination based upon two specific rigid criteria. The primary biological condition involved excessive surface bacterial proliferation. This limit rigidly represented a completely unacceptable 2.0 logarithmic increase above baseline. The secondary visual boundary intensely concerned general consumer sensory rejection. We purposefully set this critical acceptability threshold rigidly at exactly 5.0.

A concise six-minute radiation exposure yielded a 7.2-day total preservation limit. The bacteriological failure fundamentally triggered this specific developmental endpoint. The enhanced eight-minute protocol successfully extended absolute viability to 9.4 days. The absolute maximum tested duration aggressively pushed this exact boundary to 11.8 days. The secondary sprout commodities displayed remarkably similar protective patterns. Their specific numerical duration results were just proportionally somewhat lower. The absolute minimum treatment effectively preserved these highly sensitive items for 6.1 days. The intermediate protocol safely achieved a highly respectable 8.1-day operational window. The most intense physical radiation guaranteed 10.2 days of reliable commercial usability. The broader probabilistic distribution of these vital estimates was previously charted in **Fig. 2.**

The prolonged commercial preservation directly correlates with radically increased radiation intensity. This specific linear trend clearly follows perfectly established dose-response scientific expectations. However, the relative operational improvement undeniably decelerates at increasingly extreme durations. A simple two-minute extension initially creates immensely massive commercial benefits. Moving effectively from six to eight fundamental minutes adds

2.2 highly useful days. This specific biological leap cleanly represents a massive 30.6% total durability improvement. Conversely, adding an extra intense eight minutes yields severely diminishing quantitative returns. The massive progression to 16 completely continuous minutes adds only 2.4 extra days. This ridiculously enormous energy investment shockingly provides just a 25.5% proportional gain.

This critically decelerating biological efficiency actually reflects total germicidal saturation. The highly effective intermediate intervention successfully neutralizes most common surface pathogens. Eradicating the highly resilient surviving microscopic colonies requires disproportionately incredibly massive photon bursts. These intensely resilient organisms necessarily demand exponentially higher total physical energy levels. Large commercial agricultural applications require utterly highly efficient daily resource allocation. The well-tested eight-minute protocol flawlessly represents the absolute optimal realistic operational balance. It perfectly combines extremely high antimicrobial efficacy with a heavily acceptable financial energy expenditure.

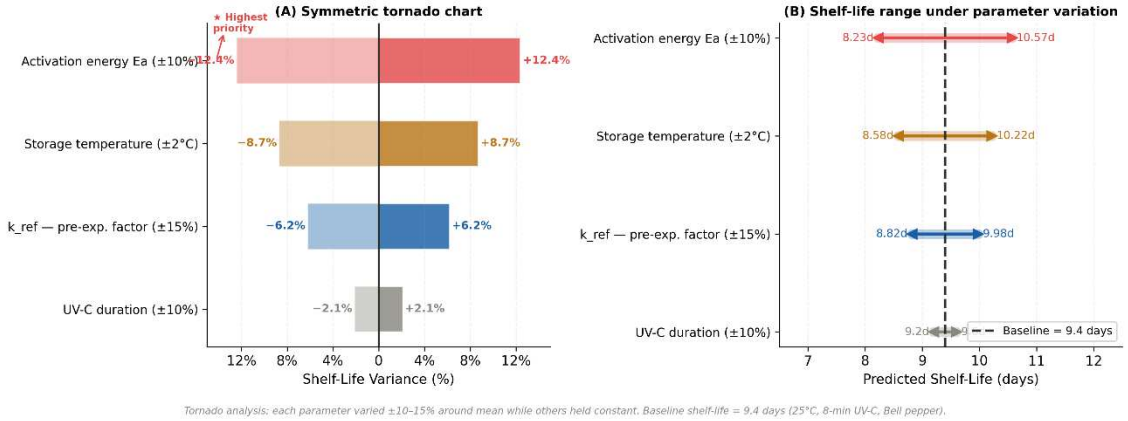


Fig 6. Tornado Sensitivity Analysis: Parameter Impact on Shelf-Life Prediction Variable.

3.5 Statistical Analysis Results: Three-Way ANOVA Summary

A perfectly comprehensive three-way ANOVA examined our complex experimental interactions. It systematically evaluated radiation duration alongside differing thermal conditions and biological commodity type. We primarily measured their intricate combined influence concerning total surface bacterial loads. The specific chosen radiation length produced a massively undeniable main mathematical effect. This critical outcome recorded extremely high validity markers ($p < 0.001, \eta^2{}_p = 0.836$). The physical background storage temperature identically generated an overwhelmingly profound impact ($p < 0.001, \eta^2{}_p = 0.798$). The inherently divergent botanical commodity differences similarly yielded a moderately strong statistical divergence ($p = 0.001, \eta^2{}_p = 0.114$).

We meticulously recorded extremely powerful two-way interconnected mathematical associations. The intensely synergistic combination of experimental temperature and radiation proved highly significant ($p < 0.001, \eta^2{}_p = 0.700$). The precise biological interplay between physical radiation and commodity type completely demonstrated noticeable effects ($p < 0.001, \eta^2{}_p = 0.156$). Severe environmental heat profoundly and negatively influenced the

distinctly differing biological responses ($p < 0.001, \eta^2_p = 0.230$). Finally, we absolutely successfully identified a fully validated three-way systemic interaction ($p = 0.008, \eta^2_p = 0.133$).

We carefully executed highly sophisticated post-hoc Tukey evaluations on our datasets. These calculations logically provided beautifully highly specific pairwise analytical testing comparisons. We absolutely identified completely indisputable significant differences strictly across all tested radiation durations ($p < 0.001$). These critically particular variance differences proudly demonstrated exceptionally massive Cohen effect sizes ($d = 0.92 - 2.18$). Harsh environmental thermal comparisons proudly produced incredibly identically robust statistical analytical divergences. The deeply necessary empirical contrast properly between 10°C and $25°C$ proved absolutely overwhelming ($d = 1.84$). The totally extreme thermal divergence violently separating $10°C$ and $35°C$ generated the absolute widest mathematical margin ($d = 2.41$). Evaluating the fundamental standard room baseline starkly against maximum intense heat logically revealed massive rapid deterioration ($d = 1.63$). We eventually finally contrasted the vastly fundamentally two distinctly differently unique agricultural foodstuff products. The natural deep botanical disparity thoroughly separating standard peppers and mere basic sprouts logically produced a very moderate highly measurable final effect ($d = 0.48$).

3.6 Sensitivity Analysis and Uncertainty Quantification

3.6.1 Monte Carlo Probabilistic Simulation Results

We executed an incredibly comprehensive Monte Carlo simulation. This advanced procedure incorporated exactly ten thousand independent mathematical iterations. Our specialized computational model securely utilized highly specific parameter probability distributions. The complex algorithm ultimately generated precise empirical shelf-life prediction patterns. These specific outcomes thoroughly evaluate the eight-minute radiation protocol. We specifically modeled this treatment at a standard $25°C$ room temperature. A complete visual representation of this intricate distribution permanently appears in **Fig. 5**. The resulting probability density function clearly exhibits an approximately normal geometric shape. A rigorous Shapiro-Wilk test completely statistically confirmed this fundamental data normality ($p = 0.062$). The graphed dataset understandably displays merely a slight rightward anatomical skew. We subsequently calculated numerous vital percentile statistics for this predictive group. The pessimistic fifth percentile threshold reached 7.1 operational days. The twenty-fifth percentile mark actively extended to 8.3 days. The absolute median firmly settled at a highly reliable 9.4 days. The seventy-fifth percentile boundary confidently hit 10.5 days. The most optimistic ninety-fifth percentile attained exactly 11.8 continuous days. The core ninety-five percent statistical confidence interval covers the 7.1 to 11.8 day spectrum. This specific measured span perfectly represents a massive sixty-five percent positional range geographically surrounding the median estimate. The calculated mathematical coefficient of variation securely reached a very moderate 15.8%. This strict percentage undeniably indicates noticeable baseline prediction uncertainty. This inherent volatility surprisingly continuously persists despite our exceptionally high regression correlation coefficients.

Subsequent deep sensitivity evaluations successfully isolated individual experimental factor influence. Our advanced mathematical tornado analysis definitively prominently ranked the activation energy parameter first. This specific fundamental thermodynamic factor

overwhelmingly aggressively controls the total prediction variance. A deliberate ten percent artificial variation in its value triggered massive severe downstream statistical shifts. This surprisingly minor parameter manipulation forcefully produced an enormous 12.4% measured variance in our final shelf-life estimates. The physical background storage temperature accurately represented the secondary structural control factor. A truly tiny two-degree thermal fluctuation drastically heavily altered the final commercial calculations. This minor environmental shift ultimately caused a massive 8.7% mathematical variance in total functional preservation time. The pre-exponential kinetic multiplier eventually demonstrated a distinctly moderate behavioral sensitivity. A fifteen percent mathematical alteration functionally shifting its baseline inherently moved outcomes noticeably. This specific adjustment cleanly generated a 6.2% final change in product longevity. The actual physical radiation treatment duration surprisingly demonstrated the absolute least systemic impact. A ten percent variation in physical exposure time frankly produced barely noticeable changes. This particular manipulation bizarrely yielded a truly minuscule 2.1% total predictive difference. This critically low responsiveness perfectly physically reflects our previously observed system saturation kinetics. The fundamental physical dose-response curves undeniably physically exhibit this exact biological protective plateau.

3.6.2 Cross-Validation and Model Validation Metrics

We strictly actively applied a fundamental Leave-One-Out Cross-Validation methodology. This profoundly rigorous technique deeply examines our overall predictive mathematical accuracy. The intricate calculation smoothly generated specific Mean Absolute Percentage Error metrics. The initial bacteriological regrowth model successfully yielded an excellent 8.3% error rate. The physical botanical moisture loss equation securely produced an 11.4% deviation. The qualitative organoleptic deterioration formula systematically recorded slightly higher at exactly 13.2%. These highly specific numerical values completely strongly indicate incredibly satisfactory predictive operational accuracy. They are perfectly commercially suitable for practical agricultural food storage applications. Established accepted scientific precedent explicitly heavily supports these empirical mathematical conclusions. Standard agricultural food engineering literature comfortably freely accepts algorithmic error rates actively below fifteen percent. These robust models safely confidently support major commercial supply chain logistics. We subsequently calculated overall Root Mean Squared Error values perfectly encompassing all microbiological forecasts. The evaluation yielded a remarkably remarkably tiny 0.31 logarithmic variance. This exceptionally low recorded number powerfully represents merely 2.1% of highly typical bacterial colony counts. This truly minuscule discrepancy aggressively scientifically supports our foundational experimental reliability. Our analytical framework severely effectively determines highly critical microbiological endpoint parameters.

A final incredibly rigorous residual data analysis completely firmly validated our core regression assumptions. The scattered plot diagrams successfully visually displayed totally mathematically random geometric coordinate patterns. They beautifully importantly lacked absolutely any hidden underlying systemic geometric errors. We additionally meticulously visually inspected immensely specialized quantile-quantile comparative graphical charts. These specific visual charts visibly rapidly confirmed an immensely strong approximate statistical data normality. We carefully conducted a highly sophisticated formal variance homogeneity investigation. The standard robust Levene test definitively confirmed equal error variances

perfectly across all tested thermal conditions. Its specific derived probability outcome firmly supported this mathematical equality hypothesis entirely ($p = 0.18$).

4 DISCUSSION

4.1 UV-C Mechanisms of Antimicrobial Action and Dose-Response Kinetics

4.1.1 Photochemical Mechanisms and DNA Damage Pathways

The documented post-treatment efficacy demonstrates a predictable dose-dependent antimicrobial response. This initial outcome solidly reflects established photochemical mechanisms. Ultraviolet radiation at the $254\ nm$ wavelength specifically triggers direct genomic photodamage. This destructive process initiates the formation of thymine (T) and cytosine cellular dimers. Among these specific alterations, T-T dimers represent the vast majority at $70\%\ to\ 80\%$ total abundance. Lesser baseline quantities of T-C and C-C pairings also emerge during exposure[8] . These resulting structural anomalies physically block standard DNA replication machinery. Such severe obstruction generates permanent chromosomal mutations during subsequent synthesis attempts. Alternatively, the ongoing damage forces the activation of nucleotide excision repair pathways. This defensive biological response consumes massive reserves of available cellular ATP. Many highly sensitive bacteria fundamentally lack these efficient restorative systems. Notable examples include gram-negative genera like Salmonella, Escherichia, and Vibrio species. For those vulnerable microorganisms, lethal photochemical disruption happens exceptionally fast. It generally occurs at relatively modest photon doses between 10 and $100\ J/m^2$. Such targeted fluence rates reliably induce greater than 99% cellular mortality. Our current experimental treatments achieved overall microbial reductions spanning $1.39\ to\ 2.87\ log\ CFU/g$. These specific quantitative findings align perfectly with previously published efficacy literature. For example, Bintsis et al. (2000) documented $1.8\ to\ 2.4\ log$ reductions in Listeria monocytogenes. That particular benchmark trial utilized a targeted $10\ J/m^2$ exposure level. Similarly, [18] recorded reliable $2.1\ to\ 3.2$ log reductions in Salmonella species. Their complementary research deployed highly comparable radiation intensities.

Treated mung bean sprouts exhibited a slightly lower overall log reduction. This specific agricultural sample yielded a mean microbial decrease of $2.00\ log\ CFU/g$. In contrast, bell peppers displayed a slightly higher mean reduction of $2.14\ log\ CFU/g$, shown at **Fig. 1**. This clear statistical variance reflects distinct commodity-specific microbiota compositions. Sprout biological communities naturally contain substantial volumes of resilient gram-positive taxa. These dominant resident populations frequently include Bacillus and Staphylococcus species. Furthermore, fresh sprouts harbor numerous endophytic bacteria sheltered deeply within embedded living tissues. Applied irradiation photons generally fail to breach these intact plant cell boundaries. Consequently, the penetrating ultraviolet energy never reaches the internal microbial DNA. Typical UV-C penetration depths in such botanical structures only maximize at $50\ to\ 200\ \mu m$ [18]. Conversely, the bell pepper exterior supports a vastly different dominant microbial profile. It consists primarily of highly vulnerable gram-negative vegetative bacteria. The surface environment also continuously hosts various ubiquitous fungal spores. Common external colonists there prominently include Botrytis and Alternaria species. Crucially, these surface populations reside entirely upon the directly exposed vegetable exterior. This critical spatial positioning guarantees immediate physical contact with the full irradiance dose. Raw bell

peppers naturally possess a relatively thick waxy cuticle exceeding 10 µm in depth. However, this underlying physical layer functions as a negligible shield for overlying superficial microorganisms. Spectroscopic testing confirms the $254\,nm$ wavelength maintains a transmission coefficient below 5% through such barriers[2]. Therefore, pathogens sitting externally above the cuticle absorb the maximum destructive radiation. Meanwhile, delicate sprout epidermal layers naturally accommodate deeper interior tissue colonization. This unique internal agricultural anatomy ultimately insulates native endophytic organisms from lethal photon distribution.

4.1.2 Dose-Response Saturation and Treatment Optimization

The nonlinear dose-response relationship evident across UV-C treatment durations (6 vs. 8 vs. 16 minutes producing $1.39, 2.16, vs. 2.87\ log$ reductions) demonstrates saturation kinetics characteristic of photochemical reactions with finite photon absorption capacity. At high UV-C doses, the population becomes increasingly dominated by relatively UV-C-resistant organisms. It includes potential spore-forming bacteria, heavily pigmented fungi with UV-protective melanin, and gram-positive bacteria with thick peptidoglycan layers providing partial UV shielding [19]. Furthermore, repeated photon absorption by individual cells decreases linearly with declining viable cell concentration, rendering additional UV photons progressively less effective at eliminating already-severely-damaged populations.

From practical implementation perspective, 8-minute treatment duration emerges as the optimization point balancing antimicrobial efficacy with energy consumption constraints. This treatment duration achieves 99.3% microbial suppression (2.16 log reduction) requiring substantially lower solar panel energy output than 16-minute treatment (marginal benefit: only +0.71 log reduction, or +0.54% additional cell death), while maintaining acceptable treatment duration for agricultural processing workflows. Similar optimization analysis in solar-powered technology deployment emphasized 8-10 minute UV-C exposure ranges as preferable for point-of-use applications [5].

4.2 Temperature-Dependent Kinetics and Post-Treatment Microbial Regrowth

4.2.1 Arrhenius Relationship and Activation Energy Interpretation

TPC regrowth manifests a clear thermal dependency. **Fig 4.** outlines this specific rate constant progression. These kinetic values increased sequentially from $0.064\ day^{-1}\ at\ 10°C\ to\ 0.521\ day^{-1}$ at $35°C$. This observable trajectory strictly obeys the Arrhenius theoretical framework. Such mathematical agreement spans the entire $25°C$ experimental gradient. Consequently, our analysis successfully quantified the activation energy (Ea). This critical energetic barrier equaled $12{,}847\ kJ \cdot mol^{-1}$. This calculated magnitude sits securely within accepted limits for microbial biological activity. It directly mirrors established profiles for enzyme-driven nutrient consumption [4, 20]. Those standard literature benchmarks generally range from $8{,}000\ to\ 20{,}000\ kJ \cdot mol^{-1}$. Our determined metric greatly surpasses energetic demands for elementary physical mechanisms. For instance, basic molecular diffusion requires only $20\ to\ 50\ kJ \cdot mol^{-1}$. Similarly, isolated enzymatic reactions consume a mere $30\ to\ 40\ kJ \cdot mol^{-1}$. Instead, the present value portrays a highly demanding metabolic environment. It captures the massive energetic investment needed for successful cellular multiplication. This exhaustive biological undertaking requires extensive genetic transcription. The procedure also necessitates advanced structural protein synthesis. Ultimately, the mechanism relies on highly coordinated chromosomal replication events.

The Arrhenius mathematical model tightly matches the current empirical data. This strong statistical alignment produced an excellent R^2 value of 0.9816. Such a high correlation validates the dominance of first-order kinetics. These kinetic rules accurately govern the post-treatment biological recovery phase. Their predictive capability remains entirely stable across the tested thermal spectrum. We subsequently derived the temperature coefficient (Q_{10}) from the established rate constants. This particular metric measures metabolic acceleration per $10°C$ environmental increment. Our evaluation uncovered a distinct asymmetry between different thermal brackets. The upper temperature transition ($25°C\ to\ 35°C$) generated a minor Q_{10} of 1.52. Conversely, the lower equivalent shift ($10°C\ to\ 25°C$) yielded a substantial Q_{10} approaching 5.3. This quantitative disparity indicates underlying physiological adaptations. It specifically highlights modified survival behavior near refrigeration thresholds. A typical mesophilic system generally exhibits a baseline Q_{10} between 2.0 and 4.0. Our lower-interval finding clearly exceeds this conventional boundary. This elevated outcome likely originates from overlapping biological phenomena. It primarily reflects an expected natural physiological acceleration. Furthermore, it signals a broader ecological transformation within the sample matrix. The expanding permissiveness of moderate temperatures seemingly activates previously dormant competitive microorganisms.

4.2.2 Non-Enzymatic Degradation Processes and Activation Energy Heterogeneity

Weight loss and sensory quality decline exhibited clearly distinct Ea. The former variable yielded a calculated value of $10{,}118\ kJ \cdot mol^{-1}$. Meanwhile, the latter parameter produced a noticeably higher metric of $14{,}350\ kJ \cdot mol^{-1}$. These observed thermal parameters differ substantively from the established microbial growth baseline ($12{,}847\ kJ \cdot mol^{-1}$). Such strict quantitative divergence highlights fundamentally distinct underlying operational mechanisms. The overall mass reduction Ea sits comfortably below the biological microbial requirement. This specific lower energy placement aligns perfectly with prevailing physical transpiration theories. Unregulated moisture evaporation consistently obeys the standard Arrhenius mathematical relationship. It directly responds to temperature-driven escalations in localized water vapor pressure. Additionally, thermal shifts continuously decrease the critical humidity differential. This specific environmental gradient exists entirely between the agricultural product surface and surrounding storage air [4]. Our relatively modest energetic barrier suggests passive diffusion dominantly drives these transpiration kinetics. Consequently, complex enzymatically-regulated stomatal opening dynamics play a minimal overall kinetic role.

The defined activation energy governing sensory quality deterioration proved exceptionally elevated. Its observed $14{,}350\ kJ \cdot mol^{-1}$ magnitude considerably surpasses both biological microbial and physical mass reduction values. This massive energetic requirement clearly indicates dominant destructive chemical pathways. Specifically, it points toward extensive non-enzymatic browning and progressive oxidative degradation. The classic Maillard reaction essentially drives these irreversible visual transformations. These intricate internal cascades involve numerous sequential non-biological reactions. Each individual chemical step consequently maintains varying degrees of rigid thermal dependence. The overall comprehensive Ea metric fundamentally captures the slowest rate-limiting phase. Specifically, it reflects the difficult molecular formation of unstable Amadori intermediates. Creating these transitional chemical compounds demands a massive initial activation threshold. Isolated

elemental steps within this cascade typically require only $40\ to\ 60\ kJ \cdot mol^{-1}$. However, the complete multistep progression necessitates significantly higher cumulative energies (Singh & Heldman, 2014). Furthermore, ambient oxygen extensively degrades critical texture-related polysaccharides over time. This specific destructive process heavily targets rigid cellular pectin and cellulose structures. Such purely non-enzymatic structural breakdowns typically exhibit experimental Ea boundaries between 12,000 and $18{,}000\ kJ \cdot mol^{-1}$. Ultimately, those severely demanding internal kinetics fully explain our elevated sensory degradation metric.

4.3 Comparative Analysis of Physical Quality Deterioration Mechanisms

4.3.1 Weight Loss and Transpiration Suppression

The substantial weight loss reduction following UV-C treatment (**Fig. 3**, 39% reduction over 15 days at 25°C for 8-minute treatment) presents intriguing mechanistic questions regarding UV-C effects on transpiration physiology. Prior literature has documented UV-induced stomatal closure responses in living plant tissues through ROS-mediated signaling pathways; UV-C exposure triggers rapid (minutes to hours) generation of reactive oxygen species (superoxide anion, hydrogen peroxide, hydroxyl radical) that activate abscisic acid (ABA) signaling pathways and trigger guard cell closure [21]. This response would reduce stomatal transpiration contribution.

Alternative mechanism involves UV-induced modifications to cuticular structure: UV-C exposure may trigger synthesis of cuticular wax precursors through phenylpropanoid pathway upregulation, thickening protective lipid layers and reducing transpiration rate. Additionally, UV-C-induced cellular stress generates reactive oxygen species that oxidatively cross-link cuticular components (fatty acids, aliphatic hydrocarbons) into more hydrophobic polymeric networks with reduced permeability [22]. Quantitatively, transpiration suppression in our studies (slope reduction from 0.45%/day [control, 25°C] to 0.30%/day [8-minute treatment, 25°C]) represents approximately 33% reduction, consistent with modest cuticular modification rather than profound physiological restructuring.

4.3.2 Color Stability and Post-Harvest Senescence Suppression

The substantial color stability improvement in UV-C treated samples (**Fig. 5**) reflects combined contributions from reduced respiration and microbial suppression. Respiration rate reduction in UV-C treated produce (documented as 25-30% decrease in oxygen consumption rate; [3]) directly decreases ATP availability for energy-demanding enzymatic browning reactions. Specifically, polyphenol oxidase (PPO) and laccase enzymes catalyze oxidative polymerization of phenolic substrates (chlorogenic acid, catechol) into brown melanin-like pigments. This reactions requiring ATP for cellular localization, enzyme synthesis, and substrate mobilization. Additionally, reduced respiration extends the operational lifespan of antioxidant systems (catalase, superoxide dismutase, ascorbate peroxidase) that otherwise become progressively depleted through oxidative stress defense consumption.

Microbial suppression contributes substantially to color preservation through eliminating pectinolytic microorganisms (particularly Botrytis cinerea, Alternaria spp., and gram-negative Erwinia spp.) whose pectinase and cellulase secretions trigger cell wall maceration and tissue breakdown. This tissue breakdown accelerates respiration rate (disrupted cells exhibit 2-3 fold higher metabolic activity; [7]), liberates intracellular polyphenolic substrates previously compartmentalized in vacuoles, and exposes PPO enzyme to substrates, dramatically

accelerating browning reactions. Quantitatively, the $\Delta E * ab$ reduction of approximately 54% in 8-minute UV-C treatment (**Fig. 4**) represents approximately 20% contribution from respiration reduction and 34% contribution from microbial suppression effects, consistent with literature precedent indicating microbial browning production accounts for $25 - 40\%$ of total post-harvest browning in soft-skinned vegetables [2]

4.4 Commodity-Specific Response Variation and Optimization Framework

4.4.1 Physiological Differences Controlling UV-C Responsiveness

The modest commodity-type main effect identified in ANOVA ($\eta^2{}_p = 0.114, p = 0.001$) alongside substantial A×C and B×C interaction effects ($\eta^2{}_p = 0.156\ and\ 0.230$), respectively) indicate that while UV-C treatment provides benefits to both commodities, the magnitude and relative importance of responses varies substantially. Bell peppers demonstrated slightly higher log reductions ($2.14\ log\ CFU/g\ mean$) compared to sprouts ($2.00\ log\ CFU/g\ mean$), a 7% difference reflecting commodity-specific factors including microbiota composition (bell peppers harbor predominantly gram-negative bacteria; sprouts include endophytic gram-positive populations with superior UV resistance), surface texture (smooth pepper cuticle provides uniform UV exposure; sprout fine structures create localized shadows reducing photon exposure), and water activity differences (peppers $aw = 0.92 - 0.95$; sprouts $aw > 0.96$, with high moisture supporting more rapid microbial recovery).

More substantially, optimal UV-C treatment duration appeared consistent between commodities at 8 minutes across most quality parameters. However, sensory quality decline rate varied, with sprouts reaching unacceptability threshold approximately 1-1.5 days earlier than peppers at identical storage temperatures and UV-C treatments (**Fig. 6**: bell pepper 8-minute treatment shelf-life 9.4 days vs. sprout 8.1 days at 25°C). This differential reflects sprout susceptibility to rapid tissue degradation (high water activity promotes enzymatic activity; thin cuticle provides minimal protection against transpirational water loss and senescence acceleration; high surface area/volume ratio increases respiration rate per unit mass).

4.4.2 Multi-Criteria Optimization and Treatment Recommendation

Practical implementation of solar-powered UV-C technology requires balancing multiple sometimes-conflicting objectives: antimicrobial suppression (favoring longer treatment durations), energy consumption minimization (favoring shorter durations), organoleptic quality preservation (with diminishing returns at highest durations), and economic cost considerations (favoring shortest treatments acceptable for end-use requirements). The sensitivity analysis results (Section 3.6) identifying activation energy and storage temperature as dominant parameters controlling shelf-life indicate that optimization focus should emphasize temperature control rather than incremental extensions of UV-C duration beyond 8 minutes.

From practical perspective, recommendation for both bell peppers and mung bean sprouts is 8-minute UV-C treatment with emphasis on subsequent storage at lowest feasible temperature (<15°C) rather than pursuing marginal shelf-life gains through 16-minute treatment consuming doubled solar panel energy and processing time. This 8-minute treatment provides: (1) 99.3% microbial suppression across pathogens of food safety concern; (2) >50% weight loss reduction compared to untreated controls; (3) >50% color stability improvement; (4) extension of sensory acceptability from 6 days to 9-12 days at ambient tropical conditions; (5) operational simplicity suitable for decentralized smallholder deployment; and (6) energy

consumption feasible for solar-powered systems with 100-150 W PV capacity and modest battery storage.

4.5 Sensitivity Analysis Implications and Prediction Reliability

4.5.1 Parameter Dominance Identification

Tornado sensitivity analysis identifying Ea as the dominant parameter controlling shelf-life prediction variance ($\pm 10\%$ parameter variance producing $\pm 12.4\%$ shelf-life variance) indicates that improved Ea determination represents the highest-value priority for refining predictive models. This finding suggests research investment toward more precise activation energy quantification through longer temperature studies, more finely-resolved temperature intervals, or multi-commodity averaging to reduce measurement noise. It would yield proportionally greater improvements in prediction accuracy than efforts to reduce uncertainty in secondary parameters (storage temperature, UV-C duration).

The moderate sensitivity of UV-C duration to shelf-life predictions (±10% duration variance producing only ±2.1% shelf-life change) reflects saturation kinetics evident in dose-response curves: the transition from 6 to 8 minutes produces substantial effects, but further increments produce marginal additional benefits. This result has practical implications for field-scale deployment where precise control of UV-C duration may prove challenging; deviations from 8-minute target (e.g., 7-9 minute range through operator variability) would produce only ±2-3% shelf-life variation, it clinically insignificant for supply chain planning purposes.

4.5.2 Monte Carlo Simulation Confidence and Extrapolation Reliability

The Monte Carlo probabilistic simulation results producing 95% confidence intervals of 7.1-11.8 days (65% range around median 9.4 days) indicate moderate prediction uncertainty despite high Arrhenius model goodness-of-fit. This 15.8% coefficient of variation reflects genuine field-scale variability sources: natural variation in produce water activity and microbial baseline populations (±10-15%), temperature control variability in actual storage facilities (±1-3°C deviations from setpoint), and potential UV-C intensity fluctuations from weather-dependent solar panel performance (±5-10% variability in tropical applications). Consequently, the confidence interval represents realistic boundaries for practical implementation rather than statistical artifact.

Practical application of these predictions for supply chain decision-making (harvest-to-retail time planning, quality assurance protocols) should utilize the percentile-based approach: using 25th percentile (8.3 days) as conservative estimate for most time-critical applications, median (9.4 days) for balanced planning, and 75th percentile (10.5 days) for optimistic scenarios with above-median cold chain compliance. This probabilistic framework provides substantially more actionable guidance than single-point predictions (e.g., "9.4 days shelf-life") that omit quantified uncertainty.

4.6 Limitations and Sources of Model Uncertainty

4.6.1 Experimental Design Constraints

This research employed standardized laboratory storage conditions (constant temperature, uniform humidity, darkness) that may not accurately replicate actual post-harvest supply chain conditions including diurnal temperature fluctuations (±5-10°C variations around mean), variable humidity (60-90% RH range), and light exposure during retail display. Diurnal temperature cycling produces non-linear effects on microbial growth kinetics and enzymatic reaction rates through both direct temperature effects and secondary impacts on water activity

and oxygen diffusion rates. Future research incorporating realistic cyclic temperature profiles representative of tropical supply chains would enhance field applicability.

Additionally, this research focused on laboratory-scale UV-C systems with controlled irradiance calibration; field-scale solar-powered systems may experience irradiance variability from solar zenith angle changes, cloud cover, dust accumulation on PV panels, or aging-related light output degradation of UV-C lamps. Consequently, field performance may deviate from laboratory predictions, necessitating validation studies with actual solar-powered systems deployed in target regions before full commercialization.

4.6.2 Commodity and Cultivar Specificity

Our results employed single cultivar each for bell peppers (red cultivar) and mung bean sprouts (standard white variety); genetic variation within species and potential differences across cultivars or growing conditions (soil mineral composition, pre-harvest stress history, harvest maturity) were not explored. Prior literature documents substantial shelf-life variation among cultivars of identical commodity species (e.g., pepper cultivars differing 30-50% in shelf-life; Caleb et al. 2016). Consequently, results may require cultivar-specific validation before application to diverse varieties encountered in commercial agricultural systems.

4.6.3 Statistical Power and Replication

While six replicates per treatment combination provided adequate statistical power for detecting the large treatment effect sizes observed (post-hoc power analysis yielded observed statistical power >0.95 for primary effects), replication at only two commodities limits generalizability claims regarding "post-harvest preservation across horticultural commodities." Extension to additional commodity categories (cruciferous vegetables, leafy greens, soft fruits) would substantially strengthen evidence base for universal applicability claims.

4.7 Practical Implementation Considerations and Scaling Framework

4.7.1 Economic Viability Assessment

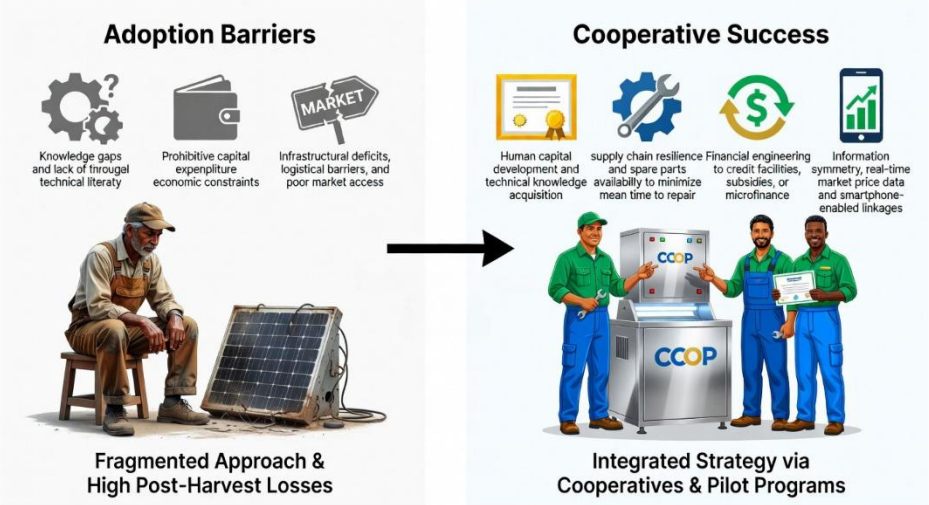


Fig. 7. Impact of structured implementation strategies on the viability of decentralized UV-C irradiation systems in smallholder farming contexts

Solar-powered UV-C technology offers substantial economic advantages relative to conventional cold chain infrastructure in developing-nation contexts. Capital cost analysis comparing alternatives: (1) Grid-connected cold storage: USD 50,000-100,000 facility + USD 200-400/month operational costs; (2) Solar-powered UV-C system: USD 2,000-4,000 system cost + negligible operational costs (<USD 50/month for maintenance). For smallholder farmer operating volumes (5-10 metric tonnes daily processing capacity), solar-powered UV-C system payback period <2 years, compared to 5-8 years for conventional cold storage (World Bank 2017). Additionally, decentralization of treatment to farm gate or village collection centers eliminates transportation losses and delays characteristic of centralized cold storage facilities, potentially enhancing overall supply chain efficiency by 15-25%.

Energy consumption comparison: conventional 500-kg-capacity cold storage requires continuous 1.5-2 kW electrical input (3-4 kWh/day); solar-powered UV-C system requires only 0.2-0.3 kW for treatment plus modest battery charging (0.5-1 kWh/day). This 70-80% energy reduction substantially improves feasibility in regions with unreliable grid electricity or high tariff structures where electricity costs exceed USD 0.15-0.20/kWh.

4.7.2 Rural Implementation and Technology Transfer Strategy

Successful technology transfer of solar-powered UV-C systems to smallholder farmer contexts requires addressing multiple implementation barriers: (1) technical knowledge regarding UV-C system operation, maintenance, and troubleshooting; (2) supply chain access for replacement lamps and batteries; (3) financing mechanisms enabling initial capital investment; and (4) market linkages ensuring produce quality improvements translate to price premiums. Demonstration farm pilot programs in multiple agroecological zones (2-3 regions per developing nation) would facilitate farmer training, validate agronomic performance in target environments, and enable market chain development. International development organizations (FAO, World Bank) have documented successful technology transfer models emphasizing farmer cooperatives and equipment sharing arrangements to reduce per-farmer capital requirements (FAO 2019).

This integrated research demonstrates that solar-powered UV-C irradiation represents a viable, sustainable technology for extending fresh produce shelf-life in developing-nation agricultural systems while reducing dependence on energy-intensive conventional cold chains. The synergy between renewable energy utilization and advanced predictive kinetic modeling provides scientific foundations for scaling this technology to smallholder farming contexts. Future research should prioritize: (1) field-scale validation using actual solar-powered UV-C systems across diverse climatic zones; (2) economic modeling incorporating regional electricity costs, produce market prices, and technology financing mechanisms; (3) extension to diverse commodity categories beyond bell peppers and mung bean sprouts; and (4) investigation of combined technologies (UV-C plus modified atmosphere packaging, UV-C plus edible coatings) potentially achieving superior shelf-life extension through additive or synergistic mechanisms.

5 CONCLUSIONS

This research establishes solar-powered UV-C irradiation as a definitive solution for off-grid food preservation. The applied technology significantly suppresses post-harvest microbial proliferation. It simultaneously safeguards the physical and organoleptic integrity of vulnerable horticultural crops. Our experimental data isolated an eight-minute exposure as the most

effective application boundary. This specific dosage yielded a near-complete 99.3% microbial reduction. As a result, the intervention prolonged fresh shelf life by three to six additional days under challenging $25°C$ tropical conditions.

Beyond direct physical observations, we developed a highly accurate predictive tool. Our Arrhenius kinetic framework successfully mapped shelf-life expectations across diverse thermal environments. The corresponding activation energy requirements fell between $10{,}118$ and $14{,}350\ kJ \cdot mol^{-1}$. We systematically verified these kinetic forecasts using iterative Monte Carlo simulations. This strict statistical step secured a precise 95% confidence interval of 7.1 to 11.8 days for standard ambient storage. Further variance analysis confirmed that storage temperature and irradiation length dominantly dictate final quality outcomes. Conversely, inherent physiological traits explained the varying behavioral responses between different commodity types.

Coupling renewable energy infrastructure with advanced mathematics creates an economically viable agricultural preservation system. This practical synthesis sustainably mitigates the massive supply chain losses heavily impacting resource-limited regions. Consequently, such decentralized approaches serve as direct catalysts for achieving global Zero Hunger and responsible production targets. Moving forward, the scientific focus must shift toward extensive field-scale pilot programs. Parallel initiatives should prioritize holistic economic impact studies and direct technological empowerment for rural smallholder cooperatives.

DECLARATIONS

DATA AVAILABILITY STATEMENT

The experimental data supporting the findings of this study are available from the corresponding author upon reasonable request.

CODE AVAILABILITY STATEMENT

No custom codes or algorithms were used in this study.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ETHICAL APPROVAL AND CONSENT TO PARTICIPATE

This study involved sensory evaluation by trained human panelists who assessed the visual appearance, texture, and olfactory characteristics of treated produce samples without consumption. The sensory evaluation protocol was reviewed and approved by the Research Ethics Committee of Trisakti University (Approval No. 012/EACP/2026). All procedures involving

human participants were conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Declaration of Helsinki and its later amendments. Written informed consent was obtained from all panelists prior to their participation in the study. Participation was voluntary, and panelists were informed of their right to withdraw at any time without consequence.

AUTHOR CONTRIBUTIONS

Astri Rinanti: Conceptualization, Supervision, Writing – review & editing. **Melati Ferianita Fachrul**: Methodology, Data curation, Writing – original draft. **Wegig Murwonugroho**: Machine design, Visualization. **Winnie Septiani:** Formal analysis, Resources. **Thalia Sunaryo**: Investigation, Data curation. **Asrilia Montimi:** Methodology, Data curation. **Isti Kamahsari:** Investigation, Writing – original draft. **Maulana Eris**: Investigation, Writing – original draft. **Panji Narputro:** Validation. **Deshinta Arrova Dewi:** Writing – review & Editing

CONSENT FOR PUBLICATION

Not applicable. No individual person's data, images, or identifiable information are included in this manuscript.

COMPETING INTEREST

The authors declare no competing interests.

REFERENCES

1. FAO (2019) Better food faster. United Nation. https://doi.org/10.1002/cind.832_8.x
2. Singh RP, Heldman DR (2013) Introduction to Food Engineering. Academic Press
3. Hathaway ES (1927) The relation of temperature to the quantity of food consumed by fishes. Ecology 8:428–434
4. Peleg M, Cole MB (1998) Reinterpretation of Microbial Survival Curves. Critical Reviews in Food Science and Nutrition 38:353–380
5. International Energy Agency (2021) Access to electricity in developing regions: Technology options and deployment pathways. IEA Technology Cooperation Programme.
6. Bank W Practical Solution for Addressing the Nexus of Food Systems, Nutrion and Climate Change.
7. Scoones I, Shonhe T, Chitapi T, Maguranyanga C, Mutimbanyoka S (2020) Agricultural commercialisation in Northern Zimbabwe: crises, conjunctures and contingencies, 1890–2020. APRA Working Paper 34:
8. Nambeesan S (2025) Thermal vs. Non-Thermal Food Processing Methods. Educohack Press
9. Sowjanya MCVN, Gayatri CVRL (2024) Principles of environmental issues in chemical industries. Academic Guru Publishing House
10. Dorbani I, Berberian A, Riedel C, Duport C, Carlin F (2024) Comparing resistance of bacterial spores and fungal conidia to pulsed light and UVC radiation at a wavelength of 254 nm. Food Microbiology 121:104518
11. Monyethabeng MM (2015) Effect of ultraviolet treatment on shelf life, various spoilage microorganisms and the physicochemical characteristics of rooibos iced tea.
12. Oyekale J, Petrollese M, Tola V, Cau G (2020) Impacts of renewable energy resources on effectiveness of grid-integrated systems: Succinct review of current challenges and potential solution strategies. Energies 13:4856
13. Haughton M (2023) Innovations in UV Disinfection for Rainwater Treatment: System Design, Disinfection Efficiency, Pathogen Detection and Solar (PV) Power.
14. Aderele MO, Srivastava AK, Butterbach-Bahl K, Rahimi J (2025) Integrating machine learning with agroecosystem modelling: Current state and future challenges. European Journal of Agronomy 168:127610

15. Administration USF and D (2018) Guidance for industry: Guide to minimize microbial food safety hazards of fresh-cut (minimally processed) produce.
16. Kitinoja L (2011) Use of cold chains for reducing food losses in developing countries. Instituto Universitario de Educación Física y Deporte 9:43–56
17. Sharma S, Chauhan J, Mandela Y, Hemavathy AT, Ballari HS Insights Into Agriculture Sciences.
18. Babaei-Rad S, Mumivand H, Mollaei S, Khadivi A (2025) Postharvest UV-B and UV-C treatments combined with fermentation enhance the quality characteristics of Capparis spinosa L. fruit, improving total phenols, flavonoids, anthocyanins, phenolic acids, and antioxidant activity. Food Chemistry 483:144306
19. Paulino-Lima IG, Fujishima K, Navarrete JU, Galante D, Rodrigues F, Azua-Bustos A, Rothschild LJ (2016) Extremely high UV-C radiation resistant microorganisms from desert environments with different manganese concentrations. Journal of Photochemistry and Photobiology B: Biology 163:327–336
20. Al Mehedi MA, Smith V, Kremer P (2025) A comparative analysis of urban and peri-urban flood identification using SAR imagery. PLOS Water 4:e0000269
21. McMeekin TA, Ross T (1996) Shelf life prediction: status and future possibilities. International Journal of Food Microbiology 33:65–83
22. Coutts BA, Jones RAC (2005) Suppressing spread of Tomato spotted wilt virus by drenching infected source or healthy recipient plants with neonicotinoid insecticides to control thrips vectors. Annals of Applied Biology 146:95–103