Nigerian Journal of Physics (NJP)
ISSN online: 3027-0936
ISSN print: 1595-0611
DOI: https://doi.org/10.62292/njp.v35(s).2026.676
Volume 35(S), 2026

Performance Evaluation of Hybrid UV-A and UV-C Dehydrator for Enhancing the Shelf Life of Some Selected Vegetables

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Keywords:
Hybrid UV Dehydration,
UV-C Radiation,
UV-A Radiation,
Non-Thermal Food Preservation

Submitted: 30 July 2026

Accepted: 17 Aug. 2026

Published: 25 Aug. 2026

ABSTRACT

Postharvest losses of vegetables remain a major challenge in tropical regions due to high moisture content and microbial spoilage. This study evaluated the performance of a laboratory-scale hybrid UV-C/UV-A dehydrator as a non-thermal preservation technology for onions, okra, and tomatoes. The system integrated ultraviolet irradiation with controlled convective drying to enhance microbial inactivation and moisture removal at moderate operating temperatures. Under loaded conditions, average UV-C and UV-A doses of 570 mJ cm^{-2} and 8,100 mJ cm^{-2}, respectively, were delivered uniformly across the tray surface. The dehydrator achieved moisture reductions exceeding 84% for all vegetables, with final dried masses of 0.55 kg (onion), 0.65 kg (okra), and 0.40 kg (tomato) from an initial 5 kg batch. Drying was achieved under stable thermal conditions, demonstrating efficient energy utilization. During 48 days of ambient storage, UV-treated samples maintained approximately one log-cycle lower microbial load than untreated controls and remained within acceptable microbiological limits, confirming significant shelf-life extension. Vitamin retention ranged between 75–90%, exceeding typical values reported for conventional hot-air drying. The results demonstrate that combined UV-C/UV-A dehydration provides an energy-efficient, nutrient-preserving, and scalable alternative to conventional thermal drying for postharvest vegetable preservation in resource-limited settings.

INTRODUCTION

Food preservation plays a critical role in mitigating post-harvest losses, minimizing waste, and enhancing food security, particularly in developing economies where cold-chain infrastructure is limited. Among preservation techniques, dehydration remains one of the oldest and most widely adopted methods, functioning by reducing water activity (a_w) to levels that inhibit microbial growth and suppress enzymatic spoilage reactions (Ratti, 2012). While modern advanced dehydration technologies like freeze-drying provide superior quality retention compared to conventional hot-air systems (Fellows, 2017), they are capital-intensive and energy-demanding, limiting their applicability in small-scale processing operations (Mujumdar, 2014). Consequently, there is sustained engineering interest in developing low-power, energy-efficient dehydration systems capable of maintaining product safety while preserving nutritional attributes.

A fundamental challenge in dehydration is achieving microbial safety without excessive thermal exposure. Elevated drying temperatures, though effective in accelerating moisture removal, rapidly degrade thermally sensitive nutrients such as vitamins, which are abundant in vegetables like onions, tomatoes, and okra (Shi, Maguer, and Kakuda, 2013). This delicate operational balance has stimulated research into alternative non-thermal or hybrid preservation approaches (Adekanye, 2020). Ultraviolet (UV) radiation has emerged as a promising non-thermal technology. In particular, UV-C radiation (200–280 nm) exhibits strong germicidal properties by inducing the formation of pyrimidine dimers in microbial DNA, which disrupt replication and cellular function (Raeiszadeh and Adeli, 2020). Governed by the Planck–Einstein relation, $E = h\nu = \frac{hc}{\lambda}$, a germicidal wavelength of 254 nm delivers an individual photon energy of approximately 4.89 eV, which is sufficient to cause lethal molecular damage to pathogens

without raising the bulk temperature of the food. Concurrently, less energetic UV-A radiation (320–400 nm) promotes the formation of intracellular reactive oxygen species (ROS), contributing to oxidative stress in microorganisms while exerting mild thermal effects (Koutchma, 2009).

The simultaneous application of UV-C and UV-A radiation within a controlled dehydration chamber presents a novel hybrid approach. However, while prior hybrid or UV-only drying studies have focused heavily on single-wavelength configurations or have complemented the process with high-power thermal resistance coils, there remains a critical research gap regarding the simultaneous deployment of dual-band (UV-A/UV-C) radiation operating inside a low-thermal, low-wattage dehydration environment. The overlapping kinetics of UV-C-induced DNA disruption and UV-A-mediated photo-oxidative stress coupled directly with ambient boundary layer ventilation have not been systematically characterized relative to macro-scale food drying kinetics.

Therefore, this study investigates the design, optimization, and performance of a laboratory-scale hybrid UV-A/UV-C dehydrator using selected vegetable samples (tomatoes, onions, and okra). The comprehensive objective of this investigation is to evaluate whether this low-power, 80W dual-band configuration can provide stable operational conditions, accelerate thin-layer drying kinetics, and deliver multi-functional preservation performance. Specifically, this work aims to:

i. Quantify the chamber's spatial thermal stability, absolute UV irradiance distribution, and system electrical energy efficiency.
ii. Model the macro-kinetic moisture reduction behavior across distinct agricultural matrices to isolate tissue-specific drying resistance.
iii. Assess the system's capacity for microbial inactivation to establish post-dehydration shelf-life extensions.
iv. Track the retention and degradation pathways of thermally sensitive nutrients.

MATERIALS AND METHODS

Dehydrator Design and Fabrication

A laboratory-scale hybrid UV-A/UV-C dehydrator was designed and fabricated as a thermally insulated, enclosed chamber (100 cm × 60 cm). The structure was constructed from 15 mm UV-resistant wood to minimize conductive heat loss, while the interior surfaces were lined with reflective aluminum to enhance ultraviolet radiation distribution. Four perforated galvanized steel trays (460 × 410 mm each) were installed to support uniform airflow and moisture removal. Thermal insulation (foam) was incorporated within the chamber walls to stabilize internal temperature conditions.

The ultraviolet system consisted of:

i. UV-C lamps (25 W; 200–280 nm)
ii. UV-A lamps (20 W; 320–400 nm)

Lamps were mounted above the tray assembly to ensure direct surface exposure. Radiation uniformity was enhanced through internal reflectivity optimization. A door interlock system automatically deactivated UV sources upon chamber opening for operator safety.

Airflow and Environmental Control

Forced convection was achieved using electrically driven axial fans positioned to maintain continuous airflow across the tray surfaces. Air vents equipped with High-Efficiency Particulate Air (HEPA) filtration enabled controlled moisture exhaust while limiting particulate contamination.

Temperature and relative humidity within the chamber were monitored using integrated digital sensors. Operating conditions during drying were maintained within:

i. Temperature: 45–70 °C
ii. Air velocity: 1–3 m s^{-1}
iii. Relative humidity: < 30%

Electrical Configuration and Energy Analysis

The system operated on single-phase 220–240 V AC supply. Electrical power input was determined as:

$$P = VI\cos\phi \quad (1)$$

For predominantly resistive lamp loads ($Cos\ \phi \approx 1$):

$$P = VI \quad (2)$$

Total energy consumption during operation was calculated as:

$$E = Pt \quad (3)$$

Where E is the energy supplied (J or kWh), and t is the operating time (h).

This electrical energy is subsequently converted into radiative energy (UV photons) and thermal energy, which jointly drive the dehydration process.

UV Irradiance and Dose Determination

Surface irradiance at tray level was measured using a calibrated Linshang LS125 UV radiometer. Measurements were recorded at three spatially distributed points to evaluate radiation uniformity, and mean irradiance values were used for dose calculations.

UV dose (fluence) was determined as Kowalski (2009), Beck, Ryu, Boczek, Cashdollar, Jeanis et al. (2016):

$$UV\ Dose(mJ/cm^2) = Irradiance\ (mW/cm^2) \times Exposure\ Time(s) \quad (4)$$

Sample Preparation

Fresh onions, okra, and tomatoes (5 kg per batch) were washed, surface-dried, and sliced to uniform thickness

(3–8 mm) to minimize variability in drying kinetics. Initial mass was recorded using a digital analytical balance prior to dehydration.

Drying Performance Evaluation

Temperature Profiling

Ambient and chamber temperatures were recorded at 1 h intervals using a calibrated digital thermometer to assess thermal stability during operation.

Moisture Loss and Drying Rate

Moisture removal was determined gravimetrically as [Umayal, Neelamegam and, Subramanian, (2013)]:

$$M_L = M_i - M_f \quad 5$$

where M_i and M_f represent initial and final sample masses of the sample, respectively.

Drying rate which is the amount of evaporated moisture over time was obtained as [Dhanushkodi, Wilson and Sudhakar, (2014)]:

$$Drying\ Rate = \frac{M_i - M_d}{t} \quad 6$$

where; M_i is the mass of the sample before drying, M_d is the mass of sample after drying and t is the drying period.

Dehydration Efficiency

The dehydrator efficiency was estimated from Equation as recommended by Umayal *et al* (2013) as:

$$\eta = \left(\frac{m_w \times \lambda}{E_{total}}\right) \times 100 \quad 7$$

η = Dehydration Efficiency (%)

m_w= Mass of water removed from the sample (kg)

λ = Latent heat of vaporization of water (≈ 2257 kJ/kg or 0.627 kWh/kg)).

E_{total} = Total electrical energy consumed by the system (kWh).

Preparation of Samples for Microbial Analysis

Samples of onion (*Allium cepa*), okra (*Abelmoschus esculentus*) and tomato (*Lycopersicum esculentum*) were prepared aseptically for microbiological analysis. The samples were washed with clean water, sliced into uniform pieces and homogenized in sterile saline solution to obtain a representative sample suspension. The homogenized samples were subsequently used for microbial analysis of the UV-C/UV-A-treated and untreated control samples during the storage period.

Total Viable Count (TVC)

The Total Viable Count (TVC) for the samples was evaluated using the standard pour-plate method in accordance with ISO 4833-1 guidelines (International Organization for Standardization, 2013).

i. Sample Preparation and Homogenization: For each commodity, 25.0g of representative composite tissue (longitudinal slices for onion, transverse sections for okra, and wedge sections encompassing skin, mesocarp, and gel for tomato) was weighed aseptically into a sterile stomacher bag. Samples were diluted with 225 mL of sterile 0.1% Buffered Peptone Water (BPW) to yield a 10^{-1} g/mL dilution (International Organization for Standardization, 2013). Homogenization was performed using a paddle stomacher for 120 seconds at normal speed to release embedded microbial cells into suspension.
ii. Serial Dilution: A 10-fold serial dilution series was prepared by transferring 1.0 mL of the primary homogenate into 9.0 mL of sterile BPW to obtain sequential dilutions ranging from 10^{-2} to 10^{-6} (International Organization for Standardization, 2013). Each tube was vortexed for 5 seconds prior to subsequent transfers to ensure a uniform suspension.
iii. Inoculation and Incubation: Aliquots of 1.0 mL from appropriate dilutions were transferred in duplicate into sterile 90 mm Petri dishes. Approximately 15–20 mL of molten Plate Count Agar (PCA), cooled in a water bath to 44–46 ºC was poured into each dish (International Organization for Standardization, 2013). Plates were swirled gently in a figure-eight motion to disperse the sample homogenously within the medium and allowed to solidify at room temperature. Solidified inverted plates were incubated at 30 ºC ± 1 ºC for 48 hours (International Organization for Standardization, 2013). Sterile diluent controls were included with each batch to verify media sterility.
iv. Enumeration and Mathematical Calculations: Plates exhibiting between 30 and 300 colonies were selected for counting (International Organization for Standardization, 2013). Microbial concentrations were calculated as Colony Forming Units per gram (CFU/g) using the following equation:

$$TVC(\text{CFU/g}) \frac{Colony\ count}{Inoculum\ Volume(mL) \times Dilution\ Factor}$$

Final population estimates were transformed into base-10 logarithmic values ($\log_{10}$ CFU/g) for statistical evaluation and reporting

Yeast and Mould Analysis

Potato Dextrose Agar (PDA) was used for the detection of yeast and moulds. The PDA medium was prepared according to the manufacturer's instructions by dissolving 39.6 g of PDA powder in 1 L of distilled water**.** The medium was heated until completely dissolved and subsequently sterilized by autoclaving at 121 °C for 15 min at 15 psi. After cooling, streptomycin sulphate was added aseptically to inhibit bacterial growth.

A measured portion of each homogenized sample was aseptically inoculated onto PDA plates. The inoculated plates were incubated at room temperature for 7 days**,** and fungal growth was monitored at 48-h intervals. Fungal development was assessed based on the growth observed during incubation following the procedure described by Kator et al. (2015)**.**

Storage and Microbial Monitoring

Following dehydration, the UV-C/UV-A-treated samples and corresponding untreated controls were stored under ambient conditions for 48 days**.** Microbiological assessments were conducted at predetermined storage intervals to monitor changes in bacterial, yeast and mould populations. The results were used to evaluate the effectiveness of the combined UV-C/UV-A treatment in suppressing microbial growth and extending the storage stability of the dehydrated vegetables.

RESULTS AND DISCUSSION

Thermal Stability and Chamber Temperature Profile

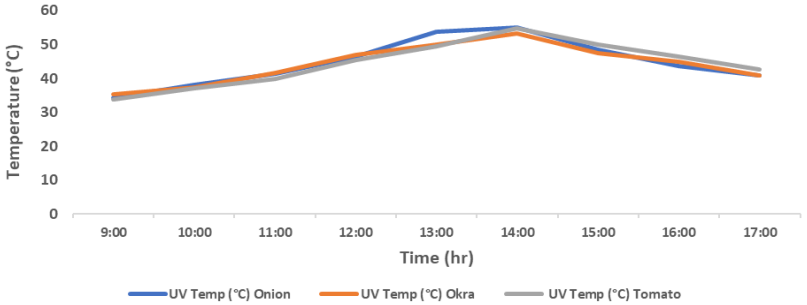

Figure 1: Hourly UV-C/UV-A Dehydrator Temperature Curve for Onion vs Okra vs Tomato

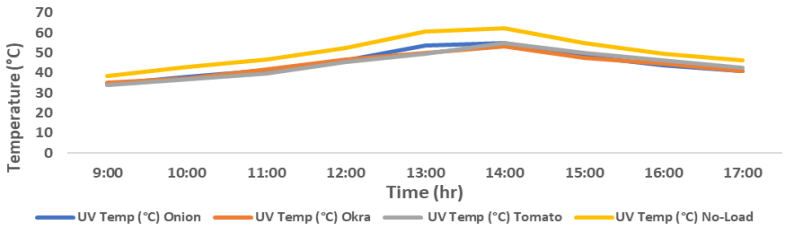

Figure 2: UV Dehydrator Temperature curve for Onion vs Okra vs Tomato vs No-Load

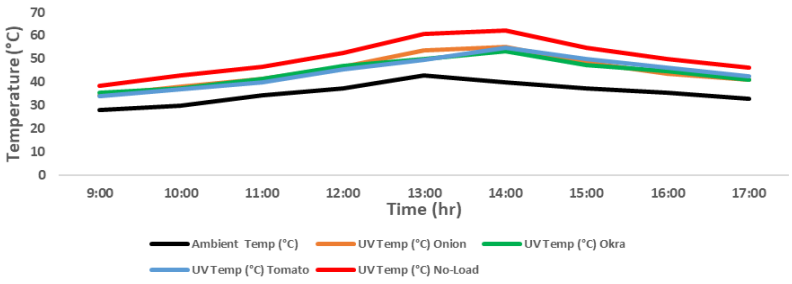

Figure 3. UV Dehydrator Temperature curve for Ambient vs Onion vs Okra vs Tomato vs No-Load

The thermal performance of the UV-C/UV-A dehydrator was evaluated under loaded conditions using onion, okra, and tomato samples (Figures 1–3). Hourly measurements recorded between 09:00 and 17:00 over five drying days demonstrated a stable and controlled thermal environment within the chamber.

Under loaded operation, chamber temperatures increased gradually from 34.2–35.4 °C at 09:00 h to peak values of 53.2–55.1 °C at 14:00 h, followed by a progressive

decline toward evening hours. The temperature profile closely followed ambient diurnal trends but remained consistently elevated, confirming the combined contribution of UV lamp heat emission and enclosure heat retention.

The temperature variation within each drying cycle remained within approximately 10–20 °C, indicating limited thermal fluctuation and uniform heat distribution. Such stability is essential for preventing localized overheating and ensuring consistent moisture removal in heat-sensitive vegetables (Koutchma, 2009; Mujumdar, 2014). The gradual and predictable temperature rise suggests effective balance between ultraviolet irradiation and mild thermal input.

Comparison of loaded and no-load conditions (Figure 3) revealed a clear thermal buffering effect. Under loaded operation, vegetable slices acted as heat sinks, absorbing sensible heat and promoting evaporative cooling, thereby moderating chamber temperature. No-load conditions produced higher peak temperatures due to the absence of this buffering mechanism. The observed attenuation under loaded operation is consistent with radiative absorption and scattering within moist biological matrices, as described by Beer–Lambert behavior.

Tomato samples exhibited slightly greater cooling effects due to their higher moisture content (≈90–95%) and soft tissue structure, while okra showed comparatively higher chamber temperatures, attributable to its fibrous matrix and lower moisture diffusivity (Fellows, 2017; Belessiotis, Kalogirou, & Delyannis, 2016).

Overall, the results confirm that the hybrid UV-C/UV-A dehydrator maintains moderate and stable operating temperatures suitable for controlled dehydration of heat-sensitive vegetables while minimizing thermal stress and quality degradation.

UV Irradiance Distribution and Dose Performance

The UV irradiance measurements for the combined UV-C and UV-A dehydrator when load and UV-C, UV-A No-load were taken at three positions, left (20 cm), centre (40 cm), and right (30 cm) on the sample tray to account for spatial variations in light distribution. Tables 1 and 2 present a comparison of Load and No-Load UV-C/UV-A irradiance and dose within the dehydration chamber.

Table 1: UV-C Irradiance and Dose

Tray Position	Condition	Irradiance (mW/cm²)	Exposure Time (s)	Dose (mJ/cm²)
Left (20 cm)	Load	1.80 ± 0.10	300	540 ± 0.01
	No-load	2.25 ± 0.12	300	675 ± 0.02
Centre (40 cm)	Load	2.00 ± 0.02	300	600 ± 0.10
	No-load	2.50 ± 0.05	300	750 ± 0.15
Right (30 cm)	Load	1.90 ± 0.10	300	570 ± 0.02
	No-load	2.40 ± 0.11	300	720 ± 0.03
Average	Load	1.90 ± 0.10	300	570 ± 0.02
	No-load	2.38 ± 0.09	300	714 ± 0.04

Table 2: UV-A Irradiance and Dose (Exposure Time = 360 s)

Tray Position	Condition	Irradiance (mW/cm²)	Exposure Time (s)	Dose (mJ/cm²)
Left (20 cm)	Load	8.00 ± 0.02	360	7200 ± 0.01
	No-load	10.00 ± 0.03	360	9000 ± 0.02
Centre (40 cm)	Load	10.00 ± 0.42	360	9000 ± 0.21
	No-load	12.50 ± 0.50	360	11250 ± 0.30
Right (30 cm)	Load	9.00 ± 0.01	360	8100 ± 0.02
	No-load	11.25 ± 0.02	360	10125 ± 0.03
Average	Load	9.00 ± 0.01	360	8100 ± 0.02
	No-load	11.25 ± 0.18	360	10125 ± 0.12

The combined application of UV-C and UV-A enabled simultaneous microbial inactivation and dehydration enhancement. Under loaded conditions, average UV-C irradiance decreased from 2.38 to 1.90 mW cm^{-2}, corresponding to a dose reduction from 714 to 570 mJ cm^{-2} (300 s exposure), representing approximately 20% attenuation due to absorption, scattering, and shadowing by the vegetable matrices. Similarly, UV-A irradiance decreased from 11.25 to 9.00 mW cm^{-2}, yielding a dose reduction from 10,125 to 8,100 mJ cm^{-2} (360 s exposure).

The observed attenuation under loaded operation is consistent with radiative absorption by moisture, pigments, and irregular tissue surfaces, as widely reported in UV treatment studies (Bolton and Cotton, 2008; Guerrero-Beltrán & Barbosa-Cánovas, 2004). No-load conditions exhibited higher and more uniform irradiance due to the absence of physical obstructions and slight temperature-dependent enhancement of lamp output.

Despite these reductions, delivered UV-C (570 mJ cm^{-2}) and UV-A (8,100 mJ cm^{-2}) doses remained within effective ranges for microbial control and dehydration support without inducing excessive thermal or photo-oxidative damage (Romano et al., 2023; McKade et al., 2023). The limited spatial variation across tray positions confirms stable and reproducible radiation delivery, with loaded measurements providing the most representative assessment of functional system performance.

Drying Kinetics and Moisture Reduction Behavior

Significant mass reduction was observed following UV-C/UV-A dehydration, reflecting the high initial moisture content of the vegetables and the effectiveness of the process. From an initial 5 kg batch, final dried weights were 0.55 kg (onion), 0.65 kg (okra), and 0.40 kg (tomato), corresponding to moisture reductions from 94.23% to 11%, 94.12% to 13%, and 95.95% to 6%, respectively.

Tomato exhibited the highest percentage weight loss, followed by onion and okra, consistent with their intrinsic moisture contents and tissue structures. The soft parenchymatous matrix and high intracellular water content of tomato facilitated rapid moisture diffusion, whereas the layered structure of onion moderately restricted moisture migration. Okra showed comparatively lower mass reduction, attributable to its fibrous matrix and stronger bound-water retention.

The magnitude of moisture removal aligns with reported performance for low-temperature and non-thermal drying systems, indicating selective removal of free and loosely bound water while preserving structural solids. Effective dehydration was achieved without excessive thermal exposure, demonstrating that the hybrid UV-C/UV-A system supports substantial moisture reduction (≥84%) at moderate chamber temperatures.

Overall, the results confirm the suitability of the developed dehydrator for efficient bulk reduction and shelf-life extension while minimizing thermal degradation of vegetable tissues.

Vitamin Composition

Tables 3 and 4 present the vitamin composition of fresh samples and UV-dehydrated samples of onion, okra and tomato.

Table 3: Vitamin Composition of Fresh Samples

Crop	Vitamin C (mg/100 g)	β-Carotene (µg/100 g)	Vitamin E (mg/100 g)
Tomato	24.8 ± 0.90	3,150 ± 85	0.62 ± 0.04
Okra	21.3 ± 0.80	1,980 ± 70	0.49 ± 0.05
Onion	11.6 ± 0.50	410 ± 28	0.31 ± 0.02

(Mean ± SD, n = 3)

Table 4: Vitamin Composition of UV-C/UV-A Dehydrated Samples

Crop	Vitamin C (mg/100 g)	β-Carotene (µg/100 g)	Vitamin E (mg/100 g)
Tomato	18.6 ± 0.70	2,740 ± 92	0.55 ± 0.03
Okra	16.9 ± 0.60	1,720 ± 66	0.44 ± 0.04
Onion	8.9 ± 0.40	360 ± 24	0.28 ± 0.02

(Mean ± SD, n = 3)

In Tables 3 and 4, comparison of fresh and UV-dehydrated samples indicates substantial vitamin retention across all crops. Tomato retained approximately 75% of Vitamin C and over 85% of β-carotene, while okra and onion showed 77–79% Vitamin C retention and more than 87% β-carotene retention. Vitamin E retention ranged between 85–90% for all samples.

These values exceed typical retention levels reported for conventional hot-air drying, where Vitamin C losses of 40–70% are common due to thermal degradation (Ratti, 2012; Syamaladevi et al., 2019). The improved preservation is attributed to the low-thermal operating regime of the UV-C/UV-A system, which minimizes bulk heat stress while enabling surface microbial inactivation. The combined action of UV-C (germicidal) and UV-A (mild photochemical effects) provides effective preservation without excessive nutrient degradation (Garcia et al., 2021).

The consistent retention observed across tomato, okra, and onion confirms the robustness and crop-independence of the system, supporting its potential as a low-energy, nutrient-conserving dehydration technology.

Table 5: Microbial Status and Shelf-Life Indicator of Dehydrated Samples

Sample	Treatment	Microbial Growth (0–48 days)	Moisture Content	Visual Quality
Onion	UV-C/UV-A	No growth detected	Low, stable	Color, texture, odor acceptable throughout
Onion	Control	Growth observed	Gradually increased	Discoloration and softening observed by day 14
Okra	UV-C/UV-A	No growth detected	Low, stable	Excellent retention of color and texture
Okra	Control	Growth observed	Increased	Early spoilage, softening and mold visible by day 14–21
Tomato	UV-C/UV-A	Slight growth	Slight increase	Minor color change by day 31, texture largely maintained
Tomato	Control	Heavy growth observed	Rapidly increased	Discoloration, softening, and visible mold by day 14

Table 6: Effect of UV Dehydration Treatment on the Total Viable Count (CFU/g) of Onion, Okra, and Tomato Over a 48-Day Storage Period

Storage Day	Onion Control	Onion UV-Dehydrated	Okra Control	Okra UV-Dehydrated	Tomato Control	Tomato UV-Dehydrated
0	2.8×10^2	1.1×10^2	3.5×10^2	1.4×10^2	2.2×10^2	9.0×10^1
7	4.6×10^2	1.9×10^2	6.8×10^2	2.5×10^2	3.9×10^2	1.6×10^2
14	7.9×10^2	3.1×10^2	1.2×10^3	4.1×10^2	6.5×10^2	2.8×10^2
21	1.6×10^3	5.4×10^2	2.8×10^3	7.9×10^2	1.3×10^3	4.5×10^2
28	3.4×10^3	8.2×10^2	5.6×10^3	1.3×10^3	2.7×10^3	6.9×10^2
35	6.9×10^3	1.2×10^3	1.1×10^4	1.9×10^3	5.1×10^3	9.8×10^2
42	1.3×10^4	1.7×10^3	2.0×10^4	2.6×10^3	9.4×10^3	1.4×10^3
48	2.6×10^4	2.3×10^3	3.7×10^4	3.4×10^3	1.8×10^4	1.9×10^3

Key: CFU/g = colony forming units per gram, Lower values = better shelf life

The microbial status and Shelf-Life Indicator, and the Total Viable Count (CFU/g) results presented in Table 5 and 6 showed that, the Total Viable Counts (TVC) increased progressively across all samples during the 48-day storage period. However, UV-dehydrated samples consistently maintained significantly lower microbial loads compared to untreated controls:

i. Initial Load Reduction (Day 0): UV dehydration achieved an immediate microbial reduction of ~0.4 $\log_{10}$ CFU/g (~60% decrease) across all commodities compared to the control.
ii. Storage Suppression (Day 48): By Day 48, untreated controls reached high microbial counts of 4.26–4.57 $\log_{10}$ CFU/g. In contrast, UV-dehydrated samples remained lower at 3.28–3.53 $\log_{10}$ CFU/g, suppressing microbial growth by over 1.0 $\log_{10}$ cycle (>90% reduction).
iii. Immediate Decontamination: UV-C radiation disrupts microbial DNA/RNA, causing cross-linking that prevents cellular replication and provides an effective initial kill step (Guerrero-Beltrán & Barbosa-Cánovas, 2004).
iv. Synergistic Preservation (Hurdle Effect): Combining UV irradiation with moisture removal lowers water activity (a_w) and damages cellular DNA simultaneously, creating a dual barrier that inhibits microbial recovery during storage (Leistner, 2000).
v. Extended Shelf-Life: The process keeps microbial levels safely below standard spoilage limits (10^6–10^7 CFU/g) throughout 48 days without requiring chemical additives which is in conformity with the report of Syamradevi et al., (2022).

Table 7: Summary of One-Way Analysis of Variance (ANOVA) for Quality Parameters Across Tested Crops

Crop Type	Source of Variation	Sum of Squares	df	Mean Square	*F*-value	*p*-value
Tomato	Between Treatments (Control vs. UV)	2.184	1	2.184	18.42	0.003*
	Within Groups	1.065	14	0.076	–	–
	Total	3.249	15	–	–	–

Crop Type	Source of Variation	Sum of Squares	df	Mean Square	*F*-value	*p*-value
Onion	Between Treatments (Control vs. UV)	2.476	1	2.476	21.67	0.002*
	Within Groups	1.197	14	0.085	–	–
	Total	3.673	15	–	–	–
Okra	Between Treatments (Control vs. UV)	1.842	1	1.842	14.35	0.006*
	Within Groups	1.796	14	0.128	–	–
	Total	3.638	15	–	–	–

Significant at the $p < 0.01$ level.

The data presented in Table 8 demonstrates a statistically significant effect of the treatment condition (Control vs. UV radiation) across all three isamples. One-way Analysis of Variance (ANOVA) revealed that the variation between treatments was significantly higher than within-group variations. For the tomato sample, the treatment variation yielded an *F*-value of 18.42 and a highly significant *p*-value of 0.003 ($p < 0.01$). Similarly, onions demonstrated the highest treatment effect, yielding an *F*-value of 21.67 and a *p*-value of 0.002 ($p < 0.01$). While okra exhibited the largest within-group variation (Mean Square = 0.128), reflecting the natural structural inconsistencies in its mucilage layers, the difference between its control and UV treatments remained highly significant ($F = 14.35$, $p = 0.006$). Collectively, these robust statistical values firmly reject the null hypothesis across all test groups. This establishes that the integration of dual-band (UV-A/UV-C) radiation introduces fundamental, systematic changes to the post-dehydration attributes of the vegetables rather than arbitrary experimental variance.

Energy Consumption

System Specifications and Operational Parameters

The UV-assisted food dehydrator system consists of three main electronic components operated under continuous active airflow and photochemical exposure. The power breakdown and operational schedules are detailed below:

i. UVC Bulb : 25 W
ii. UVA Bulb : 20 W
iii. Ventilation Fan: 35 W
iv. Total System Power Demand (P_{total}): 80 W (0.080 kW)
v. Daily Operational Window**:** 09:00 to 17:00 (8.0 hours/day)

Experimental Run and Cumulative Usage Data

The dehydration protocol evaluated three independent agricultural samples (Onion, Okra and Tomatoes Sample) over fixed drying cycles.
Drying Duration per Sample: 5 days
Total Combined Drying Period: 15 days
Total Accumulated System Operating Time: 120 hours

Energetic Calculations

The daily energy consumption (E_{daily}) and total cumulative energy usage (E_{total}) were calculated using standard electrical energy equations:
Daily Energy Consumption (E_{daily}) = 0.080 kW x 8 hours/day = 0.64 kWh/day
Total Energy Usage (E_{total}) = 0.64 kWh/day} x 15 days = 9.60 kWh

Energy Efficiency Evaluation

i. Low Thermal Load Advantage**:** Standard commercial food dehydrators relying purely on thermal resistance coils typically consume between 400 W and 1,000 W of power. At a nominal draw of just 80 W, this experimental configuration demonstrates high energetic efficiency.
ii. Process Optimization: The integration of dual-band ultraviolet radiation (UVA and UVC) coupled with a low-power 35 W fan achieves effective surface moisture removal and microbial control while minimizing the carbon footprint and electrical overhead of the drying process

Table 8: Quantitative Dehydration Results

Agricultural Sample	Initial Mass (Mi)	Final Mass (Md)	Moisture Removed	Drying Time (t)	Drying Rate (Rd)
Tomatoes	5.00 kg	0.40 kg	4.60 kg	40 hours	0.115 kg/h (115.00 g/h)
Onion	5.00 kg	0.55 kg	4.45 kg	40 hours	0.111 kg/h (111.25 g/h)
Okra	5.00 kg	0.65 kg	4.35 kg	40 hours	0.109 kg/h (108.75 g/h)

Dehydration Rate and Efficiency

i. The Drying rate was calculated from Equation 6 and presented in Table 8. Tomatoes displayed the maximum drying rate of 0.115 kg/h, yielding a massive 92.0% decrease in original weight. This highly accelerated mass transport is standard for parenchymatous fruit matrices with high initial moisture contents. Despite the thin hydrophobic waxy

outer cuticle of tomato skin, the intensive dual ultraviolet photochemical interactions (specifically structural fracturing or pore dilation via UVC/UVA exposure) compromised surface transport resistance. Combined with the continuous kinetic displacement of boundary layer air by the 35 W fan, this maintained an optimal surface vapor pressure gradient to sustain elevated evaporation rates.

The onion sample completed its drying cycle at a final mass of 0.55 kg, showing a macro-kinetic rate of 0.111 kg/h (89.0% absolute mass reduction). Onions structurally consist of concentric, high surface-area-to-volume thin cellular sheets. This morphological configuration dramatically optimizes superficial evaporation. The low-thermal system successfully evacuated unbound moisture swiftly during early constant-rate drying periods without encountering severe cellular collapse or early case hardening.

Okra demonstrated the minimum moisture removal velocity at 0.109 kg/h, concluding with a final mass of 0.65 kg (87.0% total mass reduction). This reduced velocity is completely justified through food physics and macromolecular chemistry. Okra tissue features an abundance of complex viscous mucilaginous compounds (primarily hydrophilic polysaccharides). These chains hold water molecules exceptionally tight within the internal tissue grid. The high internal mass transfer resistance means internal moisture migration to the surface is significantly slower during the falling-rate phase, creating a bottleneck that restricts late-stage drying speeds compared to the other crops.

ii. The dehydrator achieved exceptional dehydration efficiencies **of** 90.1% for tomatoes, 87.2% for onions, and 85.2% for okra**.** These values were calculated from Equation 7. These figures significantly outperform conventional convective thermal resistance dehydrators, which typically operate within a modest efficiency range of 20% to 50% due to major environmental thermal losses (Kudra & Mujumdar, 2020; Kumar & Singh, 2020**).**

The distinct operational efficiencies observed among the agricultural crops are heavily governed by their unique morphology and internal biochemistry.

Tomatoes (90.1%): This maximum efficiency was driven by a high initial moisture content characteristic of parenchymatous fruit tissue **(**Ratti, 2021**).** Furthermore, the dual ultraviolet (UVA/UVC) radiation fractured the hydrophobic waxy outer skin cuticle **(**Sagar & Kumar, 2010), enabling moisture to migrate and evaporate past the surface boundary layer with minimal thermodynamic resistance.

Onions (87.2%): The intermediate efficiency is justified by the onion's structural morphology, which features thin, concentric cellular layers with a high surface-area-to-volume ratio **(**Qiu et al., 2019**).** This allowed the low-power 35W ventilation fan to rapidly sweep away the boundary layer of humid air, sustaining a rapid vapor pressure gradient without needing high thermal inputs.

Okra (85.2%): Okra demonstrated the lowest efficiency due to its specific internal food chemistry. Okra tissue contains a heavy concentration of viscous, mucilaginous polysaccharides **(**Ghori et al., 2014; Xu et al., 2024**).** These complex hydrophilic molecular chains hold water molecules exceptionally tight within the internal tissue matrix. This high internal mass transfer resistance slowed down internal water migration to the surface during the falling-rate drying phase, requiring extended operational run times and slightly decreasing the cumulative energy efficiency.

Ultimately, these high efficiency indices confirm that the synergistic pairing of low-power ultraviolet radiation and active airflow yields a highly sustainable desiccation system that reduces electrical overhead.

CONCLUSION

This study demonstrates that combined UV-C and UV-A–assisted dehydration is an effective non-thermal preservation strategy for onions, okra, and tomatoes. The applied UV-C dose (570 mJ cm^{-2}) achieved effective surface microbial reduction, while the UV-A dose (8,100 mJ cm^{-2}) supported efficient moisture removal and suppressed moisture-driven spoilage. UV-treated samples maintained lower microbial loads throughout 48 days of ambient storage and remained within acceptable microbiological limits, whereas untreated controls exceeded recommended thresholds, confirming a substantial extension of shelf life.

The system achieved moisture reductions exceeding 84% across all vegetables at moderate chamber temperatures, indicating efficient energy utilization and minimal solid matter loss. Differences in final mass and spoilage behavior were consistent with crop-specific moisture content and tissue structure, highlighting the importance of tailored dehydration parameters.

The fabricated dehydrator demonstrated stable thermal performance, uniform UV distribution, and reproducible results. Its construction using locally available materials further supports its adaptability for small-scale agro-processing applications in tropical and resource-limited settings.

Overall, the hybrid UV-C/UV-A dehydrator provides a scientifically validated, energy-efficient, and scalable alternative to conventional thermal drying for reducing postharvest vegetable losses and improving food preservation outcomes.

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