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Microbial Inactivation and Shelf-Life Extension of Vegetables Using Hybrid UV-A/UV-C Assisted Dehydration

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Abstract

Post-harvest losses of perishable vegetables remain a major food security challenge in sub-Saharan Africa, where inadequate preservation technologies accelerate microbial spoilage and quality deterioration. This study evaluated a fabricated hybrid UV-C/UV-A–assisted dehydrator for microbial inactivation and shelf-life extension of onion (Allium cepa), okra (Abelmoschus esculentus), and tomato (Solanum lycopersicum). Vegetables were subjected to UV-C (570 mJ cm^{-2}) and UV-A (8100 mJ cm^{-2}) during dehydration and stored under ambient conditions for 48 days. Total viable count (TVC), moisture reabsorption, and microbial growth kinetics were assessed and statistically analyzed using $\log_{10}$-transformed ANOVA ($p < 0.05$). UV-treated samples exhibited an immediate microbial reduction of approximately one log cycle and maintained significantly lower microbial loads throughout storage compared with controls. By Day 48, UV-treated vegetables remained within acceptable microbiological limits, while control samples approached or exceeded safety thresholds. Additionally, UV-treated samples showed up to 7% lower moisture reabsorption, contributing to suppressed microbial proliferation. The findings demonstrate that hybrid UV-C/UV-A dehydration provides a synergistic non-thermal preservation mechanism combining microbial inactivation and moisture control. This approach offers a scalable, energy-efficient solution for reducing post-harvest vegetable losses under tropical storage conditions.

Keywords: Hybrid UV dehydration; UV-C/UV-A irradiation; microbial inactivation; shelf-life extension; non-thermal preservation

Introduction

Post-harvest losses remain a major constraint to food security in sub-Saharan Africa, where approximately 30–40% of total agricultural production is lost before consumption (FAO, 2019; Sheahan & Barrett, 2017). In Nigeria, perishable vegetables such as onion (*Allium cepa*), okra (*Abelmoschus esculentus*), and tomato (*Solanum lycopersicum*) are particularly vulnerable due to high moisture content, inadequate storage infrastructure, and tropical climatic conditions. Despite large-scale production in northern Nigeria and

expanding cultivation in Benue State (National Bureau of Statistics, 2020), substantial quantities spoil before reaching consumers, resulting in economic losses and reduced food availability (Olayemi, Kareem & Olayinka, 2019).

These vegetables are nutritionally important, providing vitamin C, vitamin B6, potassium, dietary fiber, and bioactive compounds such as quercetin with antioxidant and anti-inflammatory properties (Corzo-Martínez & Villamiel, 2007; Griffiths et al., 2002). However, their high intrinsic moisture content (≈85–90%) promotes rapid microbial growth and enzymatic degradation under ambient storage conditions (Zhou, Zhang & Fang, 2018). Effective preservation strategies must therefore reduce microbial load and moisture while minimizing nutrient degradation.

Conventional methods such as refrigeration, curing, and thermal dehydration offer partial solutions but present notable limitations. High-temperature drying can degrade thermolabile nutrients—particularly vitamin C—and alter sensory characteristics including colour, flavour, and texture (Ratti, 2012; Kaya & Demirkol, 2021). Open sun and natural air drying remain common in tropical regions due to low technological requirements, yet these methods are slow, weather-dependent, and susceptible to contamination (Smith & Castro, 2007; Ojiya & Tyona, 2021). Consequently, there is increasing interest in non-thermal preservation technologies capable of enhancing microbial safety while preserving nutritional quality (Mujumdar, 2014).

Ultraviolet (UV) radiation has emerged as a promising non-thermal intervention. UV-C (200–280 nm) inactivates microorganisms by inducing DNA damage that prevents replication (Guerrero-Beltrán & Barbosa-Cánovas, 2004; Koutchma, 2009), while UV-A (320–400 nm) contributes to oxidative microbial suppression (Cadet et al., 2003). Integrating UV radiation into dehydration systems offers a dual-function mechanism: microbial inactivation coupled with moisture reduction under moderate thermal conditions. Such hybrid systems may extend shelf life while limiting nutrient loss associated with conventional high-temperature drying.

However, limited data exist on the combined application of UV-C and UV-A within a dehydration framework for tropical vegetables stored under ambient conditions. In particular, quantitative evaluation of microbial suppression, growth kinetics during storage, and moisture reabsorption behaviour is needed to validate practical effectiveness.

This study therefore evaluates a fabricated hybrid UV-C/UV-A–assisted dehydrator for microbial inactivation and shelf-life extension of onion, okra, and tomato. Immediate microbial reduction, storage stability over 48 days, and moisture reabsorption characteristics were assessed, and treatment effects were statistically validated. The findings aim to support the development of an energy-efficient, scalable preservation strategy capable of reducing post-harvest losses in Nigeria and similar tropical environments.

Materials and Methods

Raw Materials and Experimental Design

Fresh onion (*Allium cepa*), okra (*Abelmoschus esculentus*), and tomato (*Solanum lycopersicum*) were procured from a local market in Benue State, Nigeria. Samples were sorted to eliminate defects, washed with potable water, and sliced uniformly (3–5 mm thickness) to ensure consistent radiation exposure and drying kinetics.

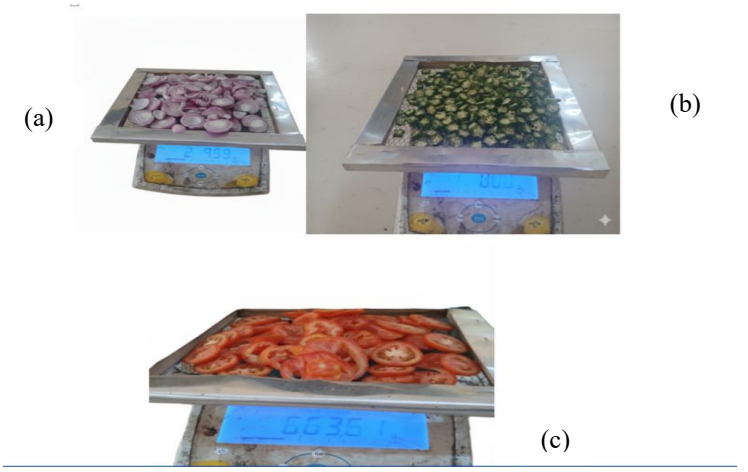

Plate 1: (a). Initial weight of the sliced fresh onion sample (b) Initial weight of the sliced fresh okra sample (c) Initial weight of the sliced fresh tomato sample

A completely randomized design was employed with two treatments:

(i) conventional dehydration (control) and

(ii) hybrid UV-C/UV-A–assisted dehydration. All experiments were conducted in triplicate.

Hybrid UV-C/UV-A Dehydration

Dehydration was performed using a fabricated chamber equipped with low-pressure mercury UV-C lamps (254 nm) and UV-A lamps (365 nm) arranged to ensure uniform irradiance distribution. Radiation intensity was measured using a calibrated UV radiometer, and exposure time was adjusted to achieve target doses of **570 mJ cm^{-2} (UV-C)** and **8100 mJ cm^{-2} (UV-A).**

Drying was conducted under moderate chamber temperatures to maintain a non-thermal processing regime. Dehydration continued until constant mass was attained. Final dried samples were cooled to ambient temperature and packaged in sterile polyethylene pouches for storage studies.

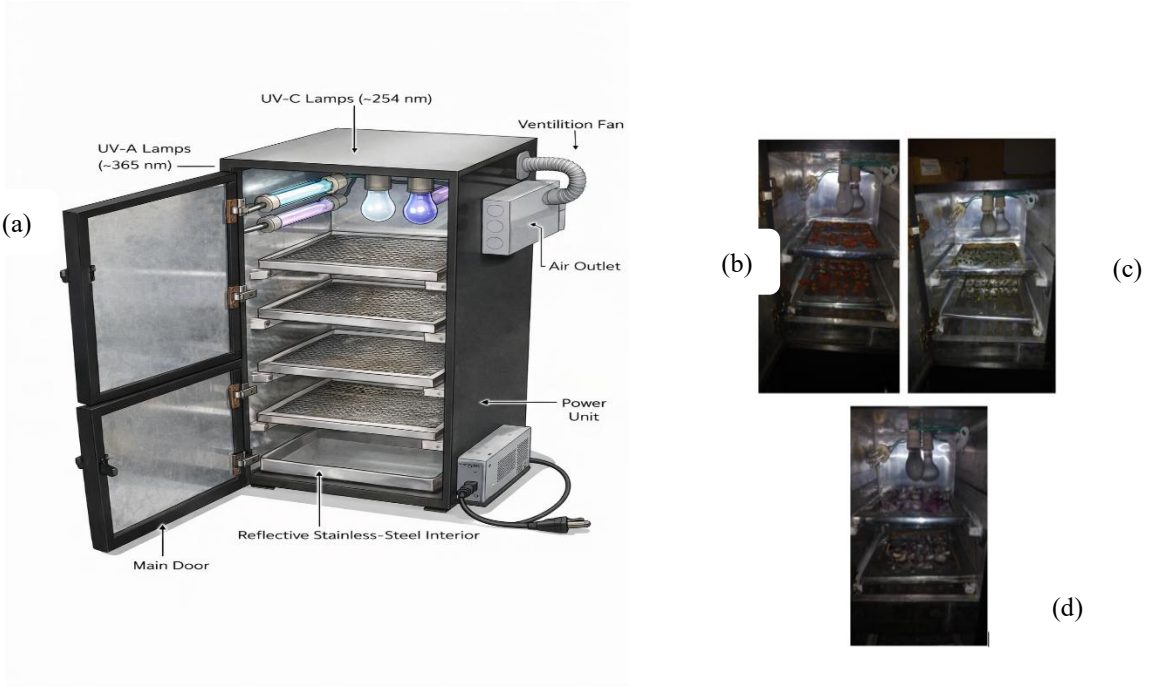

Figure 1 (a) Fabricated hybrid UV-C/UV-A dehydrator, (b), (c), (d) Photograph of the Fabricated UV-dehydrator during characterization of Tomatoes, Okra and Onions respectively

Storage Study

Packaged samples were stored at ambient laboratory conditions (27 ± 2°C; relative humidity 60–70%) for 48 days. Analyses were conducted at Day 0 (post-drying), Day 28, and Day 48 to monitor microbial load and moisture reabsorption.

Microbial Analysis

Total viable count (TVC) was determined using the standard plate count method. One gram of sample was aseptically homogenized in 9 mL sterile peptone water and serially diluted. Aliquots were plated on nutrient agar using the pour plate technique and incubated at 37°C for 24–48 h. Colony-forming units were enumerated and expressed as CFU g^{-1}.

Yeast and mold counts were assessed using selective media under appropriate incubation conditions. All microbiological determinations were performed in triplicate.

Moisture Content Determination

Moisture content was determined gravimetrically by oven-drying approximately 5 g of sample at 105°C to constant weight. Moisture (%) was calculated as the percentage mass loss relative to initial weight. Measurements were conducted in triplicate.

Statistical Analysis

Microbial counts were $\log_{10}$-transformed prior to analysis to normalize variance and meet parametric assumptions. One-way analysis of variance (ANOVA) was performed separately for each crop to evaluate treatment effects (control vs UV-treated). The F-statistic was computed as the ratio of between-treatment mean square to within-group mean square.

Statistical significance was determined at $p < 0.05$. Where significant differences were observed, reductions were attributed to the UV-C/UV-A intervention. Data are presented as mean ± standard deviation of triplicate determinations.

Results and Discussion

Immediate Microbial Reduction Following UV-C/UV-A Dehydration

Hybrid UV-C/UV-A dehydration produced an immediate reduction in surface microbial load across all vegetables. At Day 0, UV-treated onion, okra, and tomato recorded lower total viable counts (TVC) compared with conventionally dehydrated controls (Table 1), corresponding to an initial reduction of approximately 0.3–0.5 log cycles. This confirms the immediate germicidal action of ultraviolet irradiation.

The reduction is primarily attributed to UV-C–induced DNA damage (Koutchma, 2009), while UV-A contributes through oxidative stress mechanisms that inhibit microbial repair (Guerrero-Beltrán & Barbosa-Cánovas, 2004; Kim & Kang, 2020). These findings establish the combined UV treatment as an effective pre-storage microbial control step.

Microbial Growth Kinetics During Ambient Storage

Microbial populations increased progressively in all samples during 48 days of ambient storage; however, growth rates differed significantly between treatments (Table 1). Control samples exhibited steeper exponential growth after Day 21, whereas UV-treated samples showed markedly slower proliferation.

By Day 48, control onion, okra, and tomato reached 2.6×10^4, 3.7×10^4, and 1.8×10^4 CFU g^{-1}, respectively, exceeding or approaching recommended microbiological limits (AOAC, 2019). In contrast, UV-treated samples remained within acceptable safety thresholds at 2.3×10^3, 3.4×10^3, and 1.9×10^3 CFU g^{-1}. Across all crops, UV-treated samples maintained approximately one log-cycle lower microbial counts throughout storage, demonstrating more than a two-fold extension of microbiological shelf life.

Yeast and mold counts followed similar trends (data not shown), with UV-treated samples exhibiting 85–90% lower fungal loads at Day 48. The antifungal efficacy of UV radiation has been widely documented (Bintsis et al., 2000; Koutchma, 2009).

Table 1. Total Viable Count (TVC) of Dehydrated Vegetables During 48-Day Storage

Crop	Treatment	Day 0 (CFU g^{-1})	Day 28 (CFU g^{-1})	Day 48 (CFU g^{-1})
Onion	Control	2.8×10^2	3.4×10^3	2.6×10^4
Onion	UV-C/UV-A	1.1×10^2	8.2×10^2	2.3×10^3
Okra	Control	3.5×10^2	5.6×10^3	3.7×10^4
Okra	UV-C/UV-A	1.4×10^2	1.3×10^3	3.4×10^3
Tomato	Control	2.2×10^2	2.7×10^3	1.8×10^4
Tomato	UV-C/UV-A	9.0×10^1	6.9×10^2	1.9×10^3

UV-treated samples consistently maintained approximately one log-cycle lower microbial counts compared to controls.

Moisture Reabsorption and Its Role in Shelf-Life Extension

Moisture content increased steadily in all samples during storage but was consistently lower in UV-treated vegetables (Table 2). By Day 48, control samples reached moisture contents of 19.6% (onion), 25.4% (okra), and 20.4% (tomato), whereas UV-treated samples recorded 15.5%, 18.3%, and 15.9%, respectively.

Because microbial growth is strongly influenced by water activity (Fellows, 2017), the reduced hygroscopic behavior of UV-treated samples played a central role in suppressing microbial metabolism. The slower moisture uptake may be associated with ultraviolet-induced surface modifications that reduce water vapor adsorption (Onwuka, 2018). Shelf-life extension therefore resulted from synergistic microbial inactivation and moisture control.

Table 2. Moisture Content (%) of Dehydrated Vegetables During Storage.

Crop	Treatment	Day 0 (%)	Day 48 (%)
Onion	Control	8.4	19.6
Onion	UV-C/UV-A	8.2	15.5
Okra	Control	9.6	25.4
Okra	UV-C/UV-A	9.4	18.3
Tomato	Control	7.9	20.4
Tomato	UV-C/UV-A	7.8	15.9

UV-treated samples exhibited up to 7% lower moisture reabsorption compared to controls.

Statistical Validation of Treatment Effect

One-way ANOVA conducted on $\log_{10}$-transformed total viable count (TVC) data confirmed statistically significant differences between UV-treated and control samples across all vegetables (Table 3). Logarithmic transformation was applied to normalize variance and satisfy assumptions of parametric analysis, consistent with standard microbiological statistical practice (AOAC, 2019; Ratti, 2012).

Treatment effects were highly significant for onion ($F = 18.42$, $p = 0.003$), okra ($F = 21.67$, $p = 0.002$), and tomato ($F = 14.35$, $p = 0.006$). Among the three crops, okra exhibited the strongest treatment response, indicating greater sensitivity to microbial suppression under hybrid UV exposure.

These statistically significant differences confirm that the observed microbial reductions and slower growth kinetics were directly attributable to the combined UV-C/UV-A intervention rather than random variation.

Table 3. Summary of One-Way ANOVA for $\mathbf{Log_{10}}$ TVC.

Crop	F-value	p-value	Significance
Onion	18.42	0.003	Significant
Okra	21.67	0.002	Significant
Tomato	14.35	0.006	Significant

Differences significant at $p < 0.05$.

Overall Implications for Shelf Stability

The combined microbial, moisture, and statistical evidence confirms that hybrid UV-C/UV-A dehydration significantly improves ambient shelf stability of onion, okra, and tomato. The treatment produced an immediate reduction in surface microbial load (~1 log cycle) and sustained suppression of microbial growth over 48 days of storage. Importantly, UV-treated samples remained within acceptable microbiological limits, whereas control samples approached or exceeded safety thresholds, indicating more than a two-fold extension of shelf life.

The observed stability resulted from a dual mechanism: direct UV-C–induced microbial DNA damage and reduced moisture reabsorption, which limited water activity and microbial proliferation. This synergistic effect aligns with established non-thermal preservation principles (Syamaladevi et al., 2019; Garcia et al., 2021).

Collectively, these findings validate the fabricated UV-C/UV-A dehydrator as an effective, energy-efficient alternative to conventional thermal drying for enhancing microbial safety and extending shelf life under tropical storage conditions.

Conclusion

This study demonstrated that hybrid UV-C/UV-A–assisted dehydration is an effective non-thermal preservation strategy for improving the microbial safety and shelf stability of onion, okra, and tomato. The combined ultraviolet treatment achieved an immediate reduction in surface microbial load and maintained approximately one log-cycle lower total viable counts throughout 48 days of ambient storage compared with conventionally dehydrated controls.

UV-treated samples remained within acceptable microbiological limits at the end of storage, whereas control samples approached or exceeded recommended thresholds. The extended shelf life was further supported by significantly reduced moisture reabsorption, with UV-treated vegetables exhibiting up to 7% lower moisture uptake. This moisture control, coupled with sustained microbial suppression, confirms a synergistic preservation mechanism involving both ultraviolet inactivation and reduced water activity.

Statistical analysis verified that treatment effects were significant across all crops ($p < 0.05$), confirming that the observed improvements were directly attributable to the combined UV-C/UV-A intervention

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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