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The Use of Ultraviolet Radiation in Enhancing the Shelf Life of Some Tropical Fruits and Vegetables

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ABSTRACT

Fruits and vegetables serve as vital sources of essential vitamins for the human body. However, they are susceptible to premature spoilage due to the presence of pathogenic microorganisms. Ultraviolet radiation has been employed for sterilizing food to mitigate microbial contamination. This paper explores the application of ultraviolet C (UVC) irradiation for the sterilization and shelf-life extension of locally grown tropical fruits and vegetables, specifically orange, pepper, and okra, in Benue State, Nigeria. The study investigates the UVC dose-dependent effects of UVC on shelf life and proximate composition of tropical fruits and vegetables. For irradiation, the samples were placed at the irradiation point 15 cm from the UV source of a UVC irradiator. Each group was irradiated with different UV doses. The exposure times were 15 minutes, 20 minutes, 25 minutes, and 30 minutes. An unirradiated group was used as the control. The doses for these exposures were 0 Jcm^{-2}, 2.468 Jcm^{-2}, 3.290 Jcm^{-2}, 4.113 Jcm^{-2}, and 4.936 Jcm^{-2} respectively. The optimal irradiation times for sterilization and shelf-life extension were determined to be 15 minutes for pepper and 15 minutes for orange, with an irradiation dose of 2.468 Jcm-2. These exposures extended the shelf life of pepper and orange by 12 and 15 days, respectively, without significant effects on their proximate composition. However, the sterilization doses for okra resulted in severe discolouration within 24 hours, making them unsuitable for the shelf-life extension. The findings highlight the potential of UVC irradiation as an effective method for preserving fruits and vegetables, with implications for reducing post-harvest losses and improving overall crop quality.

Keywords:
UVC Irradiation,
Sterilization,
Pathogenic microorganisms,
Postharvest losses,
UV dose.

INTRODUCTION

Fruits and vegetables are essential components of the human diet. They provide essential nutrients necessary for development and other human body processes. Orange, pepper, and Okra are tropical plants that have become staple parts of the human diet in various parts of the world. Orange provides essential dietary fibre requirement that helps in preventing high levels of blood sugar, lowering cholesterol levels, and aiding digestion (Waleed, 2019). Vitamin C from orange has been reported to enhance iron intake, as a treatment for scurvy and positively affect the evolution of many types of cancer (Economos & Clay, 1999; Martí *et al.*, 2009). Pepper is reported to be a good source of vitamins A and B, and antioxidants (Amaechi *et al.*, 2021). Okra phytochemical properties have been linked with disease reduction for type-2 diabetes, cardiovascular, and digestive diseases, as well as the antifatigue effect, and liver detoxification. Moreover, okra mucilage has been widely used in medicinal applications such as plasma replacement or blood volume expanders (Elkhalifa *et al*., 2021). Besides their nutritional and health benefits, fruits and vegetables are important sources of economic activity generating a large part of resources for farmers and other players in the value chain.

Despite the benefits and importance of fruits and vegetables, their short shelf lives and perishable nature limit their availability. They are particularly affected by pathogenic and spoilage microorganisms that lead to early spoilage (Alegbeleye *et al*., 2022; Gera & Odudu, 2022). Ultraviolet radiation has been used for sterilization of food.

Sources have reported the successful application of UV light for eliminating or reducing undesirable spoilage and pathogenic microorganisms (Araque *et al.*, 2018; Choudhary & Bandla, 2012; Koutchma, 2019). UV treatment of E. coli in apple cider juice, E. coli and Bacillus cereus endospores in raw cow milk, skimmed milk and soy milk in Choudhary & Bandla (2012), E. coli or S. senftenberg in pork skin and muscle (Wong *et al.*, 1998), L. monocytogenes in frankfurters (Sommers et al., 2010) all show the viability of UV in inactivation of microorganisms. Successful application of ultraviolet radiation for food sterilization against spoilage microorganisms will positively affect their shelf lives which will result in their longer availability for consumption.

While the shelf life may be extended, it is important to note the likelihood of irradiation significantly affecting food quality. Studies have shown that UV response depends on produce type, Cultivar, maturity stage, physiological age, harvest season, targeted pathogen, as well as other factors that are yet to be defined (Charles & Arul, 2007). Hence, the major consideration for UV irradiation in fruits and vegetables is in ascertaining individual doses for different crops that will limit spoilage without affecting quality. This will aid the development of food preservation technologies. However, to develop food preservation technologies, there is a need to address crop specificity so that for each crop, there is a balance between a low dose which stimulates a positive response versus a high dose that results in inhibition (Charles & Arul, 2007).

In this study, varying doses of UVC were used in irradiating orange, pepper, and okra samples and their effects on the proximate composition and shelf life were assessed.

MATERIALS AND METHODS

Fruits and vegetables were classified into sample groups based on exposure times. Each group was irradiated with different UV doses. The exposure times were 15 minutes, 20 minutes, 25 minutes, and 30 minutes. The doses for these exposures were 2.468 Jcm^{-2}, 3.290 Jcm^{-2}, 4.113 Jcm^{-2}, and 4.936 Jcm^{-2} respectively. For irradiation, the samples were placed at the irradiation point 15 cm from the UVC source. The UV dose for irradiation was determined from the effective decimal reduction doses for UV inactivation on spoilage microorganisms determined in another study (Kaki *et al.*, 2023). One of the sample groups with zero UV dose was used as a control. The groups were treated in duplicates with each of the groups containing ten (10) samples. Each of the different groups was assessed for quality and the effect of UV irradiation on their shelf life was evaluated. Samples were stored at ambient conditions. The temperature and humidity of the storage room during the observation period were measured and reported.

The colour, skin feel (texture), and firmness were observed over the study duration. The colour assessment was carried out. To do this, the colour of freshly exposed crops and vegetables was observed from the onset until there was a change in product colour that affected product acceptability during storage. This is important because change in colour and wrinkling of products affects consumer perception which in turn influences purchase acceptability. Firmness is also an indicator of product shelf life (Brouwer *et al.*, 2019) and a predictor of fruit decay. The skin of fruits and vegetables was observed for wrinkling, shrinking and other changes. Excessive wrinkling and shrinking of crops are indicators of spoilage.

The proximate composition was determined using the standard method of the Association of Organic and Analytic Chemists (AOAC, 2005). This was carried out at the Chemistry Department, Benue State University Makurdi. Results from these tests were subjected to One Way ANOVA and Welch ANOVA tests to determine whether there was a statistically significant difference in the quality of fruits in different treatment groups with varying UV doses in relation to the unirradiated control. The Tukey Post hoc test in combination with the Games-Howell Post hoc test was used to determine the doses whose proximate composition values varied significantly in relation to that of the control.

RESULTS AND DISCUSSION

Shelf Life

The results of the shelf-life observation for oranges are presented in Table 1 and those for peppers are presented in Table 2.

Table 1: Observed Shelf Life for Orange

S/NO	GROUP	SHELF LIFE (Days)	Extended Shelf Life (Days)
1	Control	33	-
2	15M	45	12
3	20M	48	15
4	25M	45	12
5	30M	41	8

Table 2: Observed Shelf Life for Pepper

S/NO	GROUP	SHELF LIFE (Days)	Extended Shelf-Life (Days)
1	Control	23	-
2	15M	35	12
3	20M	35	12
4	25M	40	17
5	30M	45	22

Effects of UVC Irradiation on the Shelf Life of Orange

The data presented in Table 1 shows the effects of UV-C irradiation on the shelf life of oranges. In the control group, where oranges were left unexposed to UV-C, the fruits had a shelf life of 33 days. This represents the typical rate of decay that oranges undergo when stored under regular atmospheric conditions.

When subjected to a 15-minute UV-C exposure, the oranges exhibited a significantly extended shelf life, lasting for 45 days. This 12-day increase suggests that the UV-C treatment effectively curtailed the activity of microorganisms, which are known to be responsible for fruit spoilage.

The most significant extension in shelf life occurred when the oranges were exposed to UV-C irradiation for 20 minutes, resulting in a 48-day shelf life. This 15-day enhancement points to the UV-C light's ability to target and eliminate a broader spectrum of pathogens and microorganisms, thus further delaying spoilage.

However, when the exposure time was increased to 25 minutes, the shelf life remained the same as the 15-minute group, at 45 days. This observation hints that there may be an upper threshold beyond which increasing the exposure time does not yield additional gains in shelf-life extension.

The group exposed for 30 minutes had a reduced shelf life of 41 days compared to the 20-minute group. This decrease might indicate that prolonged UV-C exposure could potentially have some adverse effects, on factors affecting the overall quality of the crop and its shelf life.

The daily measurements of the mass of oranges were taken and utilized to calculate the percentage of their initial mass remaining. Furthermore, the number of remaining fruits was recorded throughout the experiment. The significance of these results becomes particularly evident when examining the deterioration patterns in the various groups.

By day 33, a notable contrast emerged between the control group and the groups exposed to UV-C irradiation. In the control group, all the oranges had reached a state of spoilage. However, in the 15-minute exposure group, nine oranges were still in good condition, retaining 33.8% of their initial mass. The 20-minute exposure group showed a similar outcome, with nine oranges maintaining 38.3% of their initial mass. The 25-minute group had eight oranges remaining, which represented 28.4% of their initial weight. Meanwhile, the 30-minute group had only five fruits left, with 18.5% of the initial group mass intact.

On day 41, all oranges in the 30-minute exposure group had deteriorated. The contrast between the UV-C exposed groups and the control group became even more apparent. In the 15-minute group, five oranges were still in an acceptable condition, retaining 17.9% of their initial group mass. In the 20-minute group, nine fruits maintaining 25.7% of their initial mass were present. However, the 25-minute group saw a more significant decline, with only four fruits, representing 12.4% of the initial group mass.

Finally, by day 45 both the 15-minute and 25-minute exposure groups had exhausted their longevity, leaving no viable oranges. However, in the 20-minute exposed group, three oranges were still in good condition, collectively accounting for 8.4% of the initial mass.

These results underscore the potential of UV-C irradiation in prolonging the shelf life of oranges and preserving their quality. The data depicts the progression of spoilage, with the control group experiencing rapid decay while the UV-C exposed groups demonstrated a substantial delay in the deterioration process. This information is valuable for the food industry, as it provides a scientific foundation for implementing UV-C irradiation as a preservation technique, ultimately reducing food waste, and enhancing the availability of high-quality, long-lasting fruit products.

Effects of Irradiation on the Shelf Life of Pepper

The results of the findings regarding the shelf life of peppers exposed to different UV-C doses are presented in Table 2. In this study, the control sample, which received no UV-C treatment, had a shelf life of 23 days. However, the peppers exposed to UV-C irradiation exhibited notable differences in their shelf life.

The 15-minute and 20-minute exposure groups both displayed an extended shelf life of 35 days, representing a twelve-day increase when compared to the control group. The 25-minute exposure group showed an even more significant extension, with a shelf life of 40 days, marking a substantial 17-day improvement. The most notable result was observed in the 30-minute exposure group, which had a shelf life of 45 days, indicating a substantial 22-day extension.

These results underline the considerable potential of UV-C irradiation as a method for both sterilization and the extension of the shelf life of pepper.

The control group's 23-day shelf life signifies the natural rate of spoilage for peppers under standard storage conditions. The twelve-day extension observed in both the 15-minute and 20-minute exposure groups can be attributed to the UV-C treatment's effectiveness in inhibiting the growth of bacteria, moulds, and yeasts. This reduced microbial activity slows down the degradation of the peppers, enhancing their longevity.

The 17-day extension observed in the 25-minute exposure group suggests that a longer duration of UV-C exposure successfully eliminates a broader range of harmful microorganisms, further delaying spoilage. This extended shelf life is particularly significant for the preservation and quality maintenance of peppers.

The 22-day extension in the 30-minute exposure group highlights the effectiveness of prolonged UV-C exposure in sterilizing the peppers and extending their shelf life.

The daily measurements of the mass of pepper were tracked and evaluated to determine the percentage of their initial mass remaining. The significance of these results becomes apparent when considering the patterns of deterioration in the different groups.

On day 23, a significant distinction emerged between the control group and the pepper groups subjected to varying durations of UV-C exposure. In the control group, all the peppers had reached a state of spoilage. However, in the 15-minute exposure group, five peppers remained in good condition, retaining 5.5% of their initial mass. The 20-minute exposure group exhibited a similar outcome, with ten peppers maintaining 12.7% of their initial mass. Remarkably, the 30-minute exposure group had 11 peppers that still retained 14.1% of the initial group mass.

By day 36, when all peppers in the 15-minute and 20-minute groups had deteriorated, the 25-minute exposure group showcased its effectiveness. Eight peppers remained in good condition, accounting for 12.7% of the initial group mass, indicating a remarkable preservation effect. Simultaneously, the 30-minute exposure group had eleven peppers with a mass representing 10.6% of the initial group mass.

After all the peppers in the 25-minute group had spoiled by day 41, the UV-C-exposed groups continued to demonstrate their resilience. In the 30-minute group, five peppers remained in a good state, retaining 3.8% of the initial group mass.

These results underscore the substantial potential of UV-C irradiation in extending the shelf life of peppers and preserving their quality. The data clearly illustrates the progression of spoilage, with the control group experiencing rapid decay, while the UV-C exposed groups exhibited a remarkable delay in the deterioration process.

The implications of these findings are significant, as they provide a scientific basis for implementing UV-C irradiation as a preservation technique in the pepper industry. This can lead to a reduction in food waste, improved quality maintenance, and a longer shelf life for pepper products, addressing critical concerns in the food sector and benefiting both producers and consumers.

Effects of UVC Irradiation on the Shelf Life of Okra

The effects of UVC irradiation on the shelf life of Okra were quite pronounced. In particular, the Okra fruits displayed a marked and unfavourable change in their colouration, resulting in the darkening of their skin within just 24 hours of exposure to the UVC doses. This colour change is not merely an aesthetic concern; it signifies a departure from the usual appearance of the Okra, which is a critical factor in consumer appeal.

The alteration in colour, which leads to a darker, less appealing appearance, significantly reduces the desirability of the Okra fruit in the eyes of consumers. Okra is typically sought after for its vibrant green hue and fresh appearance, and any deviation from this norm can deter potential buyers. As such, this colour change represents a considerable challenge for the marketability of irradiated Okra at these doses. This is a slight departure from the results obtained by Techavuthiporn et al. (2024) who reported improved bioactive compounds for okra irradiated with lower doses between 1.5 kJm^{-2} – 3.0 kJm^{-2}.

While the UVC doses effectively achieve the sterilization of the Okra crops, ensuring they are safe for consumption in terms of pathogens, they are not suitable for the goal of extending the fruit's shelf life. The adverse impact on the fruit's visual appeal and consumer acceptance outweighs the benefits of sterilization. Therefore, alternative methods need to be explored to ensure both safety and shelf-life extension for Okra to meet consumer preferences and market demands.

Proximate Composition

The results for the proximate composition of orange, pepper, and okra have been presented in Tables 3, 4, and 5 respectively. The effects of UVC irradiation on the proximate compositions are discussed below.

Table 3: Proximate Composition of Orange

GRP	ASH	MOISTURE	FAT	CRUDE FIBRE	PROTEIN	CARB.
Control	0.725±0.092	79.09±0.196	2.863±0.053	2.462±0.005	2.367±0.058	12.471±0.396
15M	0.575±0.121	84.242±0.192	2.563±0.003	2.469±0.005	1.720±0.010	8.432±0.085
20M	0.555±0.048	86.252±0.910	2.341±0.088	2.019±0.005	1.707±0.006	7.124±0.823
25M	0.883±0.479	87.133±1.553	2.311±0.020	2.311±0.020	1.237±0.012	5.474±1.107
30M	0.663±0.061	87.133±1.553	2.471±0.110	2.471±0.110	1.017±0.012	7.700±1.474

Table 4: Proximate Composition of Pepper

GRP	ASH	MOISTURE	FAT	CRUDE FIBRE	PROTEIN	CARB.
Control	2.243±0.024	86.818±0.024	1.029±0.033	1.263±0.010	1.007±0.006	7.640±0.179
15M	1.448±0.360	86.393±0.838	0.427±0.012	1.421±0.003	0.733±0.015	9.578±0.493
20M	2.100±0.291	87.872±0.070	0.643±0.068	1.600±0.006	0.627±0.023	7.158±0.292
25M	0.942±0.028	85.933±0.188	0.413±0.010	1.374±0.013	0.583±0.047	10.76±0.240
30M	0.320±0.278	82.372±2.312	0.477±0.032	0.849±0.008	0.533±0.06	15.450±2.604

Table 5: Proximate Composition of Okra

GRP	ASH	MOISTURE	FAT	CRUDE FIBRE	PROTEIN	CARB.
CT	2.300±0.613	90.048±0.206	1.335±0.018	0.871±0.015	2.387±0.015	3.060±0.401
15M	1.895±0.718	89.667±0.424	1.951±0.013	1.302±0.006	1.643±0.006	3.542±0.614
20M	1.208±0.063	89.888±0.084	1.541±0.020	0.995±0.006	1.420±0.010	4.947±0.082
25M	1.887±0.996	88.695±0.213	1.669±0.073	1.037±0.015	1.017±0.006	5.594±0.082
30M	1.875±0.209	89.597±0.152	1.119±0.068	0.984±0.004	0.933±0.058	5.492±0.408

Effects of UVC Irradiation on Orange Proximate Composition

Levene's test was conducted within a 95% confidence interval to assess the homogeneity of variance in the mean proximate composition of oranges. The results indicated non-homogeneous variation for all aspects of orange proximate composition (P_{Fat}= 0.009, P_{Carb}= 0.042, $P_{Protein}$ = 0.002, P_{Fibre}< 0.001, $P_{Moisture}$ = 0.013 and P_{Ash} = 0.036). Subsequently, Welch's robust test was employed to determine the significance of this mean variation.

Significant variations were observed in the Fat ($P < 0.001$), Carbohydrate ($P = 0.001$), Protein ($P < 0.001$), Fiber ($P < 0.001$), and Moisture contents ($P < 0.001$) of oranges.

However, there was no significant variation in the mean ash content among the different groups of oranges (Sig = 0.219).

To identify which groups exhibited statistically significant differences in comparison to the control, the Games-Howell post hoc test was used. Notably, the fat concentration for oranges subjected to 20- ($P = 0.009$) and 25-minute ($P = 0.004$) irradiation significantly differed from the control group, while the 15- ($P = 0.021$) and 30-minute ($P = 0.048$) irradiated crops did not exhibit significant variations in comparison to the control. In terms of carbohydrate content, all the exposure groups showed statistically insignificant variation from the control mean ($P > 0.001$). For protein content, the 25-minute ($P = 0.020$) and 30-minute ($P = 0.01$) exposure groups significantly differed from the control, whereas the 15-minute ($P = 0.041$) and 20-minute ($P = 0.023$) variations were not statistically significant. As for fibre content, the mean variations were statistically significant for the 20-minute ($P < 0.001$) and 30-minute ($P = 0.001$) exposures, while the 15-minute ($P = 0.573$) and 25-minute ($P = 0.192$) exposures did not show significant variations. Moisture content exhibited statistically significant variations for the 25-minute ($P = 0.004$) exposure, while the 15-minute ($P = 0.015$), 20-minute ($P = 0.013$) and 30-minute ($P = 0.035$) exposures displayed statistically insignificant differences.

Table 6 provides a summary of the significance of the mean proximate composition of oranges.

Table 6: Significance of Variation in Mean Proximate Composition of Orange

Dose	Proximate Composition					
	Ash	**Fibre**	**Moisture**	**Protein**	**Carbohydrate**	**Fat**
15 Min	NS	NS	NS	NS	NS	NS
20 Min	NS	Sig	NS	NS	NS	NS
25 Min	NS	NS	Sig	Sig	NS	Sig
30 Min	NS	Sig	NS	Sig	NS	NS

Key: NS = Not Significant
Sig = Significant

Comparing the effect of UVC irradiation on the shelf life and proximate composition of oranges, it is observed that the application of a 15-minute UV-C irradiation to oranges yielded an extension of shelf life by 12 days compared to the control group, without inducing any notable changes in the proximate composition of the fruit. Similarly, a 20-minute irradiation prolonged the shelf life by 15 days, marking the lengthiest extension observed. However, this extended shelf life was accompanied by a significant impact on the fibre content of the oranges.

Furthermore, the 25-minute and 30-minute irradiation periods resulted in impressive shelf-life extensions of 45 and 41 days, representing increases of 12 and 8 days, respectively. Notably, the 25-minute irradiation significantly impacted the moisture, protein, and fat contents of oranges, while the 30-minute irradiation primarily affected the fibre and protein contents. This is corroborated by Fundo et al. (2021) who reported a 5-day extension of shelf life for orange juices treated with UVC and Torkamani & Niakousari, (2011) who also reported a 10-day increase in shelf life.

This comprehensive examination underscores that the optimal duration for both sterilization and shelf-life extension of oranges is a 15-minute UV-C exposure. Within this timeframe, oranges exhibit a significant increase in longevity without compromising their essential nutritional components. This finding emphasizes the delicate balance achievable through precise UV-C exposure, offering an effective means of preserving oranges for an extended period while ensuring the preservation of their nutritional integrity.

Practically, this result bears substantial implications for agricultural practices and consumer satisfaction. For farmers, adopting the 15-minute UV-C exposure method could translate into reduced post-harvest losses, increased market competitiveness, and enhanced overall yield quality. Consumers, in turn, benefit from the prolonged availability of oranges with maintained nutritional value, ensuring a consistent supply of fresh and healthy fruit.

The investigation establishes that a 15-minute UV-C irradiation emerges as the optimal strategy for both food quality and shelf-life extension of oranges. This nuanced approach ensures an extended shelf life for oranges while preserving their nutritional vitality, presenting a valuable advancement in post-harvest technology with significant advantages for both producers and consumers alike.

Effects of UVC Irradiation on Pepper Proximate Composition

Levene's test was conducted within a 95% confidence interval to assess the homogeneity of variance in means for the proximate composition of pepper. It was determined that the variations in ash ($P = 0.059$) and fibre ($P = 0.234$) content were homogenous across all groups, whereas variations in protein ($P = 0.013$), moisture ($P = 0.001$), fat ($P = 0.017$), and carbohydrate ($P = 0.001$) contents were not homogenous. Consequently, an ANOVA test was employed to evaluate the significance of variations in mean ash and fibre content. Meanwhile, the Welch Robust test was used to examine the significance of variations in protein, moisture, fat, and carbohydrate content.

The ANOVA test for pepper's fibre ($P < 0.001$) and ash ($P < 0.001$) content, indicated significant variations in these two components. To identify specific group differences, the Tukey Honest Significance Difference (HSD) post hoc test was carried out. The mean ash content in the control group, as well as the 15-minute and 20-minute exposure groups, did not significantly differ from each other. However, the mean ash content in the 25-minute and 30-minute exposure groups showed significant variation from the control. The Tukey HSD for fibre content revealed variations across all groups from the control except the 15-minute group.

The results of the Welch Robust test for equality of means for protein, fat, moisture, and carbohydrate content of pepper showed significance in mean variations ($P < 0.001$) was observed in all four proximate categories (protein, fat, moisture, and carbohydrate). To identify groups with significant differences, the Games-Howell post hoc test was employed. Specifically, protein content was found to vary significantly from the control only in the 30-minute group (P = 0.001). The 15-minute (P = 0.011), 20-minute (P = 0.023), and 25-minute (P = 0.012) groups protein content did not show statistical significance in their variation from the control. Similarly, only the fat content in the 30-minute group (P = 0.000) had significant variation from the control mean fat content. The fat content in the 15-minute (P = 0.011), 20-minute (P = 0.014), and 25-minute groups (P = 0.010) did not vary significantly from the control. Moisture content significantly differed only in the 20-minute exposure group (P = 0.002). The 15-minute (P = 0.885), 25-minute (P = 0.460), and 30-minute (P = 0.228) had no significant difference in their variations. For the carbohydrate content, the 25-minute (P < 0.001) exposure group showed significant differences from the control while the 15-minute (P = 0.045), 20-minute (P = 0.294), and 30-minute (P = 0.104) showed no significant variation from the control group.

A summary of the results for the significance of the difference in the mean proximate compositions of the irradiation groups in relation to the control for pepper is presented in Table 7.

Table 7: Significance of Variation in Proximate Composition of Pepper

Dose	**Significance of Variation in Proximate Composition in Relation to Control**					
	Fat	**Ash**	**Carbohydrate**	**Protein**	**Moisture**	**Fibre**
15 Min	NS	NS	NS	NS	NS	NS
20 Min	NS	NS	NS	NS	Sig	Sig
25 Min	Sig	Sig	NS	NS	NS	Sig
30 Min	NS	Sig	Sig	Sig	NS	Sig

Key: NS = Not Significant
Sig = Significant

Upon comparing the shelf-life and significance of the effect of UVC irradiation on the proximate composition of pepper, it is evident that irradiation for 30 minutes extended the shelf life by twenty-seven (27) days, with statistically significant effects on ash, carbohydrate, and fibre contents. Similarly, a 25-minute irradiation prolonged shelf life by twenty-two days, showing statistically significant impacts on fat, ash, and fibre content. Meanwhile, the 15-minute and 20-minute irradiation, resulted in a twelve (12) day shelf-life extension, exhibiting varying degrees of significance in their effects on pepper's proximate composition. Specifically, the 20-minute irradiation induced statistically significant changes in moisture and fibre contents, while the 15-minute exposure demonstrated no substantial impact on proximate composition.

Among the various irradiation durations investigated, the 15-minute exposure was the most favourable in terms of extending shelf life, with a noteworthy twelve (12) day extension, and yet it exhibited no statistically significant impact on the proximate composition of pepper. This implies that the 15-minute irradiation strikes a delicate balance, effectively prolonging the shelf life without significantly altering the nutritional content of the bell pepper.

The observed success of the 15-minute irradiation in extending shelf life while maintaining proximate composition stability could be attributed to a few factors. Firstly, this duration might be optimal for reducing microbial activity and decay processes, which contribute to spoilage. The controlled irradiation period likely achieves sufficient sterilization to enhance shelf life without causing substantial changes in the pepper's nutrient content. These findings are consistent with the study by (Castillejo et al., 2022), which found that applying 6 kJm^{-2} of UVC extended the shelf life of bell peppers by 4 days. Moreover, combining UVC application with cooling led to a shelf-life extension of 9 days, alongside improved firmness, and a significant reduction in weight loss ($p \leq 0.05$) over a 21-day storage period, as reported by (Jaruekdee & Promyou, 2019). Similar results were observed when using a UVC dose of 0.25 kJm^{-2} for bell peppers, as demonstrated by (Ma et al., 2021).

This result holds significant implications for both farmers and consumers. For farmers, the ability to extend the shelf life of bell peppers through a 15-minute irradiation process provides a practical and efficient means of preserving their produce. This can potentially reduce post-harvest losses and increase market viability. Additionally, the minimal impact on proximate composition suggests that the nutritional quality of the pepper remains largely intact, meeting consumer expectations for fresh and nutritious produce.

Effects of UVC Irradiation on Okra Proximate Composition

Levene's test was conducted to assess the homogeneity of variances in the proximate composition of Okra within the 95% confidence interval. The analysis revealed that the variance in Okra's fat content P = 0.154) was homogenous across the different groups. However, variations in protein (P = 0.002), fibre (P < 0.001), moisture (P = 0.013), carbohydrate (P = 0.019), and ash (P = 0.036) content were found to be non-homogenous. Consequently, the One-Way ANOVA Test was employed to determine the significance of the variations in mean fat content among the different groups. This analysis confirmed that the variation in fat content was statistically significant (P < 0.001). Subsequently, Tukey's test was used to examine the differences in fat content between the irradiated groups and the control group. It was observed that the fat content in the control group and the group exposed to 30 minutes of irradiation were similar, while the mean fat content in the other groups deviated from that of the control.

The Welch Robust test for equality of means was applied to assess the significance of variations within a 95% confidence interval in mean carbohydrate (P = 0.012), protein (P < 0.000), fibre (P < 0.001), ash (P = 0.219), and moisture (P < 0.001) content. Among these components, ash content in the irradiated samples displayed no significant variation in means when compared to the control group. In contrast, protein, fibre, carbohydrate, and moisture contents exhibited significant variations among the groups. Subsequently, the Games-Howell test was used to determine how the irradiated groups' mean protein, fibre, carbohydrate, and moisture contents differed from the mean of the control group.

The carbohydrate content of the sample exposed to 20 minutes ($P = 0.038$) of irradiation was observed to significantly differ from the control. Meanwhile, the mean carbohydrate contents of the groups exposed to 15 minutes ($P = 0.784$), 25 minutes ($P = 0.070$), and 30 minutes ($P = 0.262$) of irradiation did not significantly vary from the control mean. As for fibre content, the groups exposed to 20 minutes ($P < 0.001$) and 30 minutes ($P < 0.001$) of irradiation displayed significant differences from the mean, while the groups exposed to 15 minutes ($P < 0.001$) and 25 minutes ($P = 0.004$) did not show significant variation. Both protein and moisture content in all four irradiated groups with 15 minutes ($P = 0.007$), 20 minutes ($P = 0.007$), 25 minutes ($P= 0.007$), and 30 minutes ($P = 0.001$) significantly differed from the control mean.

A summary of the significance of proximate composition variations in irradiated okra groups is presented in Table 8. These results indicate that some aspects of the proximate composition of Okra were notably affected by exposure to UV-C light for all the irradiation groups. However, the 15-minute dose had relatively fewer effects on proximate composition in comparison to the longer exposure periods (20 minutes, 25 minutes, and 30 minutes).

Table 8: Summary of Significance of Variation in Okra Proximate Composition

Dose	Significance of Variation in Proximate Composition in Relation to Control					
	Fat	**Ash**	**Carbohydrate**	**Protein**	**Moisture**	**Fibre**
15 Min	NS	NS	NS	Sig	Sig	NS
20 Min	NS	NS	Sig	Sig	Sig	NS
25 Min	NS	NS	NS	Sig	Sig	Sig
30 Min	NS	NS	NS	Sig	Sig	Sig

Key: NS = Not Significant
Sig = Significant

A combination of the results from the effects of UVC irradiation on the shelf-life and proximate composition of okra shows that the current doses utilized for irradiation are not appropriate for sterilization of okra. This is seen from the early spoilage of irradiated samples and the consequent significance of the effect on the proximate composition of the irradiated samples from what is observed in the control.

CONCLUSION

This study has investigated the applications of UVC in the sterilization and shelf-life extension of orange, okra, and pepper locally grown in Benue State, Nigeria. The effects of UVC on shelf life and proximate composition were found to be dose dependent. The optimal irradiation dose was found to be 2.468 Jcm^{-2} for orange, pepper, and okra. These exposures extended the shelf-life of pepper and orange by twelve (12) and fifteen (15) days respectively without significant effect on the proximate composition of these crops. The sterilization doses for okra were found to be unsuitable for extending the shelf life of okra as they produced severe discolouration after twenty-four (24) hours of irradiation.

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