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Ultraviolet (UV-C) radiation: An innovative non-thermal technology for quality enhancement and shelf life extension of reef cod (*Epinephelus diacanthus*) fillets during chilled storage

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Abstract

Recently, advanced processing techniques have gained attention for mitigating spoilage in fish and fishery products. Fresh seafood quality deteriorates at various stages, including cultivation, processing, harvesting, transportation, and post-purchase storage, primarily due to microbial contamination, poor handling, inadequate packaging, suboptimal storage practices, limited on-farm facilities and adverse weather conditions. UV-C radiation has emerged as a promising method for reducing spoilage by inactivating pathogenic and spoilage microorganisms through DNA lesions and disruption of cellular enzyme activity and membrane integrity. This study evaluated the impact of UV-C radiation on the quality and shelf life of reef cod (*Epinephelus diacanthus*) fillets during chilled storage ($4\pm1^{\circ}\text{C}$). Fillets were exposed to UV-C for 20s, 40s, and 60s and stored for 15 days. Fillets treated with UV-C for 20s exhibited superior overall performance across various quality parameters. Chemical spoilage indicators such as trimethylamine nitrogen (TMA-N) and total volatile basic nitrogen (TVB-N) increased over time, with the 20s treatment group recording the lowest TVB-N value (20.3 mg/100g) on Day 10. Rancidity markers, including peroxide value (PV) and thiobarbituric acid (TBA) value, were minimized in the 20s group, with PV and TBA values of 2.5 meq O₂/kg and 0.98 mg MDA/kg, respectively, on Day 10. Microbial analysis revealed significantly lower total plate counts (TPC) in UV-C-treated samples, with the 20s treatment maintaining TPC of 5.2 log CFU/g compared to 6.5 log CFU/g in the control. Sensory and textural evaluations highlighted better acceptability and structural integrity in the 20s-treated fillets for up to 10 days. These findings demonstrate that UV-C treatment, particularly at 20s, effectively preserves seafood quality during chilled storage and holds potential for wider application in the seafood industry.

Keywords: UV-C radiation, non-ionizing radiation, microbial inactivation, fish quality, food safety

1. Introduction

Seafood, including fish, crustaceans, and mollusks, are highly valued in the food industry due to their distinctive sensory characteristics when cooked and their rich nutritional profile. Fish is considered as one of the healthiest sources of animal-derived food due to its rich protein content, well-balanced essential amino acid profile, essential n-3 polyunsaturated fatty acids (PUFAs) and abundant levels of fat-soluble vitamin (A and D), as well as essential macro and micro minerals such as selenium, phosphorus, magnesium, and iodine (Kontominas *et al.*, 2021) ^[29].

India's fish production is growing rapidly at 10.34% annually, with per capita fish consumption at 6.31 kg (HoFS, 2023) ^[22]. In 2022-23, marine product exports reached 1.73 million metric tons, valued at USD 8.09 billion, a record high (MPEDA, 2023). Global per capita seafood consumption is projected to rise from 20.7 kg in 2022 to 21.3 kg by 2032 (FAO, 2022) ^[14], reflecting increasing demand alongside a focus on sustainability. However, the seafood industry faces several issues that constrain its growth and endanger its sustainability. A major challenge for the seafood industry is food safety. Fresh fish and marine products being nutritionally rich, pose a unique challenge due to their high perishability compared to other fresh meats.

This increased perishability is attributed to high water activity, neutral pH, substantial quantities of free amino acids, autolytic enzymes, and a high percentage of unsaturated fatty acids present in fish. Spoilage microorganisms and oxidation reactions from PUFA are the main causes that accelerate spoilage during storage. Due to this, an expressive amount of fish (30-35%) is discarded from catch to final consumption worldwide (Monteiro *et al.*, 2021) [40].

Processing technologies play a critical role in preserving seafood by improving both the quality and safety of the final product through their various applications (Kulawik *et al.*, 2023) [31]. Regulating biological, chemical, and microbiological processes is vital for maintaining food security, safety, and quality. Conventional thermal pasteurization is the most basic food preservation method, achieved through the inactivation of enzymes and inactivation of microorganisms (Kaavya *et al.*, 2021) [27]. However, these techniques can negatively impact certain food components, leading to a decline in sensory quality and, consequently, a decrease in their commercial value (Niveditha *et al.*, 2021) [42].

In this context, alternative non-thermal techniques, such as high hydrostatic pressure, ozone, ultrasound, pulsed electric fields, irradiation, pulsed light, microwave, ohmic heating, and Ultraviolet (UV) light, are becoming increasingly relevant. These methods offer numerous benefits, including lower processing temperatures, effective microorganism inhibition and enzyme inactivation, reduced production losses and energy consumption, extended shelf life, and preservation of nutritional value (Delorme *et al.*, 2020) [10].

Among non-thermal technologies, UV radiation is distinguished by its cost-effectiveness, ease of deployment, ability to prevent cross-contamination, minimal environmental impact, and lack of potentially harmful chemical residues. UV radiation, especially UV-C, is regarded as a non-toxic food processing method that avoids the drawbacks associated with conventional thermal processing. UV-C light is known for its germicidal efficacy, which includes the ability to induce DNA damage in pathogenic microorganisms (Singh *et al.*, 2021) [50]. The mechanisms by which ultraviolet radiation inactivates microorganisms vary according to the specific wavelengths employed during treatment. UV-C radiation effectively inactivates microorganisms by causing damage to their nucleic acids, which are highly efficient absorbers of UV light at the 253.7 nm wavelength, leading to the disruption of their cellular functions (Cichoski *et al.*, 2015) [8]. Recent technological advancements have led to the development of new UVC-based disinfection systems with increased intensity and improved penetration into food products. Monteiro *et al.* (2017) [38] reported that low UV-C doses enhanced PUFA content and controlled pH in tilapia fillets and Santos *et al.* (2018) [48] observed reduced TVB-N levels and extended shelf life in catfish and pirarucu, respectively, although lipid oxidation increased. Lázaro *et al.* (2020) found that UV-C combined with MAP effectively reduced pathogens and prolonged the shelf life of tilapia fillets, highlighting the importance of dose optimization for enhanced quality and safety. Additionally, Ultraviolet (UV) light has been endorsed by key international regulatory agencies, such as Health Canada, the European Union, and the US Food and Drug Administration's Hazard Analysis Critical Control Point (HACCP) system, for its application

as a pathogen control method in the processing of seafood (Bernard & Scott, 2007; FDA, 2019) [5, 15].

In 2021-2022, India's marine fish landings reached 4.13 million tonnes, with demersal species contributing 0.91 million tonnes (26%) (HoFS, 2023; CMFRI, 2022) [22, 9]. Gujarat accounted for 0.50 million tonnes, including 0.14 million tonnes of demersal fish. Reef cod (*Epinephelus diacanthus*), a key species in Gujarat's demersal fishery (October-March), is highly valued in global markets, particularly in the U.S., EU, and Southeast Asia, as frozen whole fish or fillets (Verma *et al.*, 2020) [53]. In light of increasing fish production and export demands, this study evaluated the effect of UV-C radiation at varying exposure times on the quality and shelf life of *Epinephelus diacanthus* fillets during chilled storage.

2. Materials and Methods

2.1 Raw Material

Fresh reef cods (*Epinephelus diacanthus*), originally harvested from the west coast of Gujarat using trawl nets, were purchased from the Veraval landing center for experimental purposes. In the first experiment, 5 kg of fish was obtained, with an average length of 24.20±0.57 cm and weight of 555.21±2.27 g. Fish were transported in an insulated box (0-2°C) from the Veraval landing center to the Fish Processing Laboratory, KU, Veraval. Upon arrival, they were rinsed with chilled water, descaled, beheaded, gutted, and washed again to remove contaminants. After dressing, the fish were filleted, reweighed, and given a final rinse with chilled water for thorough cleaning.

2.2 Ultraviolet (UV-C) Chamber

The UV chamber used in this study, Stericab was purchased from Life Steriware, India, and is equipped with a single 8-watt UV tube operating at a wavelength of 254 nm. It features 15 trays for holding the product inside the chamber and includes a UV intensity meter displayed on the unit.

2.3 Procedure for Experiment

The first experiment aimed to determine the optimal exposure time of UV-C radiation on fish fillets. Fillet samples subjected to UV-C were categorized as UV(c), UV1, UV2, and UV3. The UV(c) sample was designated as the control and received no pre-treatment. UV1 was exposed to UV-C for approximately 20 seconds, UV2 for about 40 seconds and UV3 for around 60 seconds. After UV-C treatment, samples were packed in 200-gauge LDPE pouches and stored at chilled conditions (4±1°C). Quality assessments of the fillets were performed at 5-day intervals to monitor the effect of UV-C on fish quality and shelf life.

2.4 Quality Analysis

Standardized methods were used to analyze the physical, proximate, biochemical, rancidity, microbiological, and sensory attributes of reef cod (*Epinephelus diacanthus*). Proximate composition and pH were assessed using AOAC (2006) [1]. Biochemical parameters (TMA-N and TVB-N) were measured using Beatty and Gibbons (1937), and rancidity indices (PV, TBA) using Jacobs (1958) [2] and AOAC (2006) [1]. Microbiological analysis included TPC, *E. coli*, *S. aureus*, and psychrotrophic counts, and sensory attributes were rated on a nine-point hedonic scale (Peryan & Pilgrim, 1957) [45].

2.5 Statistical Analysis

Statistical analysis was conducted in triplicate for each sample and storage interval using ANOVA, as per Snedecor and Cochran (2014) [51]. IBM BASIC Windows Release 1.13 was used to evaluate differences among treatments and identify the optimal combination.

3. Results and Discussion

3.1 Quality attributes of raw material

Fresh reef cod (*Epinephelus diacanthus*) was used as raw material, and its physical, biochemical, microbiological, and sensory attributes were evaluated to determine composition and freshness, as shown in Table 1.

3.2 pH

The changes in pH values during storage are presented in Fig. 1. The initial pH was recorded as 5.77 ± 0.06 for the UV(c) (control) and 5.83 ± 0.06 , 5.83 ± 0.12 , and 5.87 ± 0.06 for UV1, UV2, and UV3 samples, respectively (mean $\pm$ SD). A significant interaction effect was observed between the treatments and storage periods ($p < 0.05$), with a coefficient of variation (CV) of 1.36%. Fillets exposed to short, moderate, and long UV-C treatments showed higher pH values than the control up to day 5, likely due to UV-C-induced ROS formation, which accelerates protein degradation and releases free amino acids (Chan *et al.*, 2003; Molina *et al.*, 2014) [6, 37].

After day 5, UV-C-treated samples showed significantly lower pH values ($p < 0.05$) than the control, with both groups displaying an increasing pH trend during storage (Fig. 1). Similar findings were reported by Santos *et al.* (2018) [48], Molina *et al.* (2014) [37], and Rodrigues *et al.* (2016) [47], who documented a gradual increase in pH during refrigerated storage of UV-C-treated *Arapaima gigas* (pirarucu), *Dicentrarchus labrax* fillets, and *Oncorhynchus mykiss* fillets, respectively. This pH elevation can be attributed to the accumulation of alkaline compounds, such as ammonia, trimethylamine (TMA), dimethylamine (DMA), and biogenic amines, resulting from microbial activity (Molina *et al.*, 2014; Monteiro *et al.*, 2012) [37, 39]. UV-C light is known to inhibit bacterial growth, reducing the production of alkaline compounds during storage (Molina *et al.*, 2014; Rodrigues *et al.*, 2016) [37, 47]. This may explain the lower pH values observed in the UV-C-treated samples on days 5, 10, and 15. By the 15th day of chilled storage, the UV(c) sample showed the highest pH value of 6.80 ± 0.10 , followed by UV3, UV2, and UV1, with pH values of 6.63 ± 0.06 , 6.43 ± 0.10 , and 5.83 ± 0.06 , respectively. These results align with the findings of Monteiro *et al.* (2017) [38], who reported elevated pH levels in Nile tilapia (*Oreochromis niloticus*) treated with higher doses of UV-C light compared to lower doses after the storage period. This further highlights the effectiveness of UV-C treatment as a preservation method for fish species.

4. TMA-N

The variations in TMA-N content of reef cod fillets during refrigerated storage are presented Fig. 2. Throughout the storage period, the TMA-N content in the UV(c), UV1, UV2, and UV3 samples showed a consistent upward trend. Initially, the TMA-N levels were 3.43 ± 0.22 mg/100g for UV(c), 3.15 ± 0.18 mg/100g for UV1, 3.25 ± 0.15 mg/100g for UV2, and 3.29 ± 0.23 mg/100g for UV3. A significant interaction effect between the treatment and storage duration

was observed ($p < 0.05$), with a CV of 2.55%. TMA-N levels remained stable initially in all UV-C-treated samples and were lower than the control by the end of storage. Consistent with Rodrigues *et al.* (2016) [47], UV-C treatment delayed TMA-N increase, maintaining levels within the European Community's acceptable limit (10-15 mg/100g) until day 15. On day 10, the control exceeded this range (16.92 ± 0.25 mg/100g), while UV-C-treated samples remained within limits, with values of 15.05 ± 0.32 (UV1), 15.29 ± 0.22 (UV2), and 15.77 ± 0.20 mg/100g (UV3).

4.1 TVB-N

During storage, TVB-N levels significantly increased ($p < 0.05$) in both untreated and UV-C-treated reef cod fillets, with untreated fillets showing a pronounced rise (Fig. 3). Initially, the TVB-N content was 10.48 ± 0.24 mg/100g for the UV(c) (control) and 10.15 ± 0.26 mg/100g, 10.32 ± 0.19 mg/100g, and 10.43 ± 0.29 mg/100g for UV1, UV2, and UV3, respectively (mean $\pm$ SD). However, from the 5th day onward, UV-C-treated samples showed significantly lower ($p < 0.05$) TVB-N levels compared to the control, indicating the positive impact of UV-C treatment in reducing TVB-N production during the refrigerated storage of reef cod fillets. TVB-N, comprising ammonia, trimethylamine (TMA), and dimethylamine (DMA), indicates protein degradation from microbial and enzymatic activity. By day 15, TVB-N levels were highest in the control (37.54 ± 0.16 mg/100g) and lower in UV1, UV2, and UV3 samples (34.41 ± 0.45 , 35.23 ± 0.35 , and 35.40 ± 0.50 mg/100g, respectively). UV-C treatment, known to inhibit bacterial growth by damaging DNA and compromising cell wall integrity (Rizzotti *et al.*, 2015) [46], effectively reduced spoilage, corroborating findings from prior studies (Showmer, 2015; Lázaro *et al.*, 2014; Molina *et al.*, 2014) [49, 32, 37]. The reduced TVB-N levels in UV-C-treated samples likely result from bacterial inhibition by UV-C. Similar trends in TVB-N increase have been reported in sutchi catfish steaks (Mohan *et al.*, 2008) [36], Nile tilapia fillets (Monteiro *et al.*, 2012) [39], and striped catfish.

According to European Community regulations, the acceptable range for TVB-N content in unprocessed fishery products is 25-35 mg/100g. On the 10th day of storage, the UV(c) samples exceeded this limit, reaching 28.90 ± 0.70 mg/100g. However, UV-C-treated reef cod fillets remained within the acceptable range until the 15th day, with TVB-N values of 34.41 ± 0.45 mg/100g for UV1, 35.23 ± 0.35 mg/100g for UV2, and 35.40 ± 0.50 mg/100g for UV3 (mean $\pm$ SD). UV1-treated fillets showed better quality preservation than those exposed to higher UV-C doses. Studies suggest higher UV-C doses increase carbonyl content over time in tilapia (Monteiro *et al.*, 2017) [38]. The correlation between protein and lipid oxidation (Wongwichian *et al.*, 2015; Babakhani *et al.*, 2016) [54, 2] may explain the higher TVB-N levels in reef cod fillets with prolonged UV-C treatment.

4.2 Changes in Indices of Rancidity

4.2.1 PV

Lipid oxidation is typically evaluated by measuring the formation of peroxide (primary oxidation), TBARs (secondary oxidation), and fluorescent compounds (Fr value; tertiary oxidation). Among these, the peroxide value (PV) serves as a key indicator of oxidative rancidity, representing the initial phase of lipid oxidation in food products. As shown in Fig. 4, there was a clear increasing

trend in PV across all samples as storage time progressed. The interaction effect between treatments and storage duration was statistically significant, with a CV of 5.62%. The initial PV for the UV(c) (control) was 1.42 ± 0.20 m.eq./kg, while the values for UV1, UV2, and UV3 samples were 1.20 ± 0.21 m.eq./kg, 1.28 ± 0.32 m.eq./kg, and 1.32 ± 0.22 m.eq./kg, respectively (mean $\pm$ SD). These results indicate that the oxidative stability of the fillets was impacted by both UV-C treatment and storage time, with a significant increase in peroxide formation over the storage period. The impact of UV-C treatment on PV alone has not been previously studied in food matrices. In this study, lipid oxidation during storage is attributed to lipoxygenase activity and pro-oxidants like free iron from protein degradation (Wongwichian *et al.*, 2015) [54]. Refrigeration-induced lipid oxidation is well-documented (Khalafalla *et al.*, 2015; Monteiro *et al.*, 2017; Rodrigues *et al.*, 2016) [28, 38, 47]. UV-C, a dose-dependent pro-oxidant, raised PV to 12.13 ± 0.52 m.eq./kg after 15 days at $4 \pm 1^\circ\text{C}$, exceeding the acceptable limit of 10 m.eq./kg, while UV1, UV2, and UV3 remained lower at 10.14 ± 0.35 , 10.25 ± 0.19 , and 10.40 ± 0.39 m.eq./kg. UV treatment increased ($p > 0.05$) PV but did not affect lipid oxidation ($p > 0.05$), likely due to the low fat content (1.7%). UV1, with minimal exposure, showed the lowest PV, correlating with lower TBA values compared to UV2 and UV3.

4.2.2 TBA

Lipid oxidative rancidity is a critical non-microbial factor responsible for meat spoilage, leading to significant chemical alterations that negatively impact both sensory and nutritional quality (Barriuso *et al.*, 2013) [3]. During refrigerated storage, malonaldehyde (MDA) levels progressively increased across all treatments, particularly in the UV(c) (control) as storage time progressed (Fig. 5). A significant interaction effect between treatment types and storage duration was observed, with a CV of 2.23%. Initially, the TBA values were 0.39 ± 0.01 mg MDA/kg for the UV(c), and 0.38 ± 0.01 mg MDA/kg for UV1 and UV2, with UV3 showing a similar 0.39 ± 0.01 mg MDA/kg (mean $\pm$ SD). According to Campo *et al.* (2006), 2 mg MDA/kg is considered the threshold beyond which meat is deemed unfit for human consumption. The extent of lipid oxidation increased in a dose-dependent manner with UV-C radiation. By the 15th day of storage at $4 \pm 1^\circ\text{C}$, the untreated fillets exceeded the acceptable limit, reaching 2.15 ± 0.05 mg MDA/kg. Meanwhile, reef cod fillets exposed to longer UV-C durations (UV3) displayed a higher TBA value of 1.91 ± 0.03 mg MDA/kg compared to those treated with lower UV-C doses, with UV2 and UV1 exhibiting 1.85 ± 0.04 mg MDA/kg and 1.79 ± 0.05 mg MDA/kg, respectively consistent with the findings of Monteiro *et al.* (2017) [38]. UV1 treatment did not significantly impact TBA values, indicating lower UV-C doses did not induce lipid oxidation. Variations in TBA values likely result from malondialdehyde instability and its binding to fish compounds. This trend aligns with findings in rainbow trout and Nile tilapia during refrigerated storage (Rodrigues *et al.*, 2016; Monteiro *et al.*, 2012) [47, 39].

4.2.3 Microbiological Analysis

4.2.3.1 Total Plate Count (TPC)

TPC is commonly used as an index of spoilage in fish and

seafood products, representing the number of colony-forming units (CFU) per gram of food. Changes in the TPC of reef cod fillets are presented Fig. 6. Initial TPC values for UV(c), UV1, UV2, and UV3 were 3.57 ± 0.12 , 2.80 ± 0.20 , 2.37 ± 0.13 , and 2.07 ± 0.16 log CFU/g, respectively. The interaction effect between treatment and storage period was statistically significant, with a CV of 3.79%. Fillets exposed to the longest UV-C treatment (60 s) exhibited the most significant ($p < 0.05$) reduction in microbial load, followed by those treated for 40 and 20 seconds, consistent with the findings of Molina *et al.* (2014) [37]. The efficacy of UV-C treatment in reducing microbial growth is influenced by factors such as food composition, microbial species, and density (Guerrero-Béltran & Barbosa-Cánovas, 2004) [20]. Due to its limited penetration, UV-C primarily targets surface microorganisms (Koutchma *et al.*, 2009) [30]. According to FSSAI (2017) [18], the maximum permissible microbial load in fresh fish is 5 log CFU/g. After 15 days of storage at $4 \pm 1^\circ\text{C}$, TPC levels exceeded this limit, reaching 5.90 ± 0.21 log CFU/g in the UV(c) and 5.17 ± 0.12 log CFU/g, 5.10 ± 0.20 log CFU/g, and 5.04 ± 0.21 log CFU/g in UV1, UV2, and UV3 samples, respectively. Variations in microbiota between fish species (Leroi & Joffraud, 2011) [34] and the differential susceptibility of microorganisms to UV-C, due to their capacity to repair DNA damage (Ferrario *et al.*, 2013) [17], could explain these findings. Several studies have reported the effectiveness of UV treatments in decontaminating seafood, including mackerel (Huang & Toledo, 1982) [24], shrimp (Dunn *et al.*, 1995) [11], salmon fillets (Ozer & Demirci, 2006) [43], and various fish species (Cheigh *et al.*, 2012) [7].

4.2.3.2 Total Psychotropic Counts

The changes in the total psychrotrophic count of reef cod fillets during refrigerated storage are presented in Fig. 7. The interaction effect between treatments and storage duration was statistically significant, with a CV of 3.37%. Initially, the total psychrotrophic count for UV(c) (control) was 3.33 ± 0.16 log CFU/g, while for UV1, UV2, and UV3 samples, the counts were 2.85 ± 0.2 log CFU/g, 2.59 ± 0.19 log CFU/g, and 2.47 ± 0.18 log CFU/g, respectively. After 25 days of chilled storage at $4 \pm 1^\circ\text{C}$, the psychrotrophic count in UV(c) increased to 7.84 ± 0.15 log CFU/g, exceeding the maximum permissible limit of 7 log CFU/g as per FSSAI (2017) [18]. In contrast, UV-treated samples exhibited lower counts, with UV1, UV2, and UV3 recording 7.13 ± 0.19 log CFU/g, 7.09 ± 0.17 log CFU/g, and 7.06 ± 0.17 log CFU/g, respectively. Psychrotrophic spoilage bacteria, primarily Gram-negative, are highly susceptible to UV-C radiation due to their lack of a robust outer membrane protecting their DNA (Jagger, 1983; López-Caballero *et al.*, 2002) [26, 35]. This susceptibility accounts for reduced psychrotrophic counts. However, UV-C efficacy during storage is limited by its poor penetration beyond the surface and reduced effectiveness in high-lipid and protein foods, where macromolecules absorb radiation, diminishing its antimicrobial action (Cheigh *et al.*, 2012) [7].

4.2.3.3 *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*)

Escherichia coli (*E. coli*) and *Staphylococcus aureus* (*S. aureus*) was not detected in any reef cod samples during 15 days of chilled storage period.

4.2.4 Sensory Evaluation

Appearance

Significant differences ($p < 0.05$) were noted among the samples over time, with the control group showing a sharper decline in appearance compared to UV-C treated fillets (Fig. 8 (a)). Initially, the appearance scores were 8.30 ± 0.48 for the UV(c) (control) and 8.80 ± 0.42 , 8.70 ± 0.48 , and 8.70 ± 0.48 for the UV1, UV2, and UV3 treatments, respectively. By day 15 of storage at $4 \pm 1^\circ\text{C}$, the scores had dropped to 2.90 ± 0.32 for the control and to 4.80 ± 0.42 , 3.90 ± 0.32 , and 3.60 ± 0.52 for UV1, UV2, and UV3, respectively. The control sample fell below the minimum acceptable appearance score of 4.70 ± 0.48 after 10 days, while all UV-C treated samples remained above 5 points (indicating moderate acceptance), aligning with the findings of Lee *et al.* (2016) [33].

Colour

Initial colour scores for the control (UV(c)) and UV-treated samples (UV1, UV2, UV3) were 8.50 ± 0.53 , 8.80 ± 0.42 , 8.70 ± 0.48 , and 8.60 ± 0.52 , respectively. By the 15th day, the scores declined to 2.90 ± 0.57 for the control and 4.80 ± 0.63 , 3.70 ± 0.48 , and 3.30 ± 0.48 for UV1, UV2, and UV3, respectively. The untreated control group fell below the minimum acceptable score of 4.70 ± 0.48 after 10 days, whereas all UV-treated samples maintained moderate acceptability (>5 points) throughout the storage period. UV1 demonstrated the best colour retention after 15 days (Fig. 8 (b)). These results align with findings by Holck *et al.* (2018) [23], who reported no significant changes in sensory colour attributes in UV-C-treated cold-smoked salmon.

Odour

Odour scores declined from 8.50 ± 0.71 for the control and 8.80 ± 0.42 , 8.70 ± 0.48 , and 8.60 ± 0.70 for UV1, UV2, and UV3 at the beginning of storage to 2.80 ± 0.42 , 4.80 ± 0.63 , 3.60 ± 0.52 , and 3.20 ± 0.63 , respectively, after 15 days. The control group developed a putrid odour within 5 days and

fell below the minimum acceptable score of 4.50 ± 0.53 by day 10 (Fig. 8 (c)). In contrast, UV-treated samples maintained moderate acceptability throughout storage, with UV1 consistently achieving the highest odour scores. UV-C treatments at higher doses (e.g., 60 s) resulted in an ammoniacal odour rather than a putrid scent, corroborating earlier observations by Huang and Toledo (1982) [24] and Holck *et al.* (2018) [23].

Texture

Initial texture scores were 8.60 ± 0.70 for the control and 8.80 ± 0.42 , 8.70 ± 0.48 , and 8.60 ± 0.52 for UV1, UV2, and UV3, respectively. After 15 days, the scores decreased to 3.10 ± 0.32 for the control and 4.90 ± 0.57 , 4.00 ± 0.47 , and 3.90 ± 0.74 for UV1, UV2, and UV3, respectively. The control group exhibited undesirable texture changes within 5 days and dropped below the minimum acceptable score of 4.90 ± 0.57 after 10 days. UV-treated samples, particularly UV1, retained acceptable texture (>5 points) throughout the storage period (Fig. 8 (d)). However, UV2 and UV3 demonstrated reduced texture quality by day 15, likely due to softening effects associated with higher UV-C doses, consistent with findings by Park and Ha (2015).

Overall Acceptability

Overall acceptability scores declined from 8.50 ± 0.53 (control) and 8.80 ± 0.42 , 8.70 ± 0.48 , and 8.60 ± 0.52 (UV1, UV2, UV3) to 2.90 ± 0.57 , 4.80 ± 0.63 , 3.70 ± 0.48 , and 3.30 ± 0.48 , respectively, by the end of storage. The control group dropped below the acceptable score of 4.60 ± 0.52 after 10 days, whereas UV-treated samples maintained moderate acceptability throughout the storage period. UV1 showed the highest overall acceptability among the treatments, while UV2 and UV3 exhibited a rapid decline after 10 days (Fig. 8 (e)). These observations align with previous reports on mackerel by Huang and Toledo (1982) [24] and on chicken breast by Park and Ha (2015) [44], emphasizing the efficacy of UV-C treatments in preserving sensory quality.

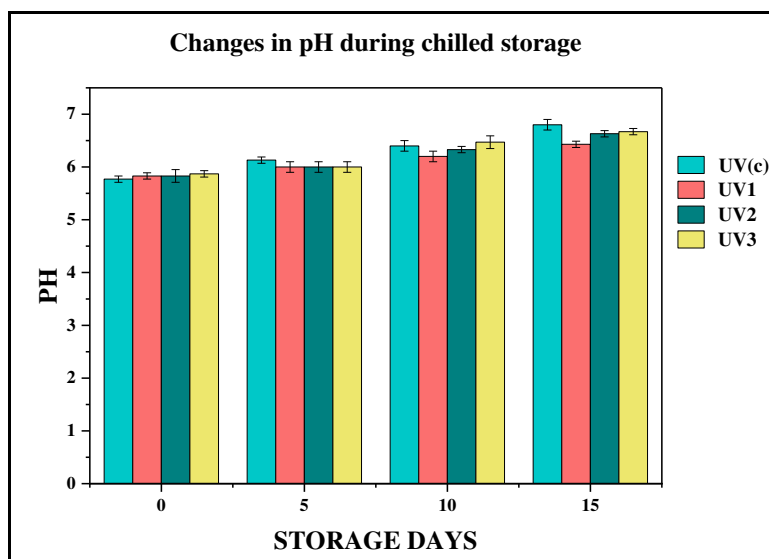


Fig 1: Variation in pH of reef cod (*E. diacanthus*) fillets throughout chilled storage

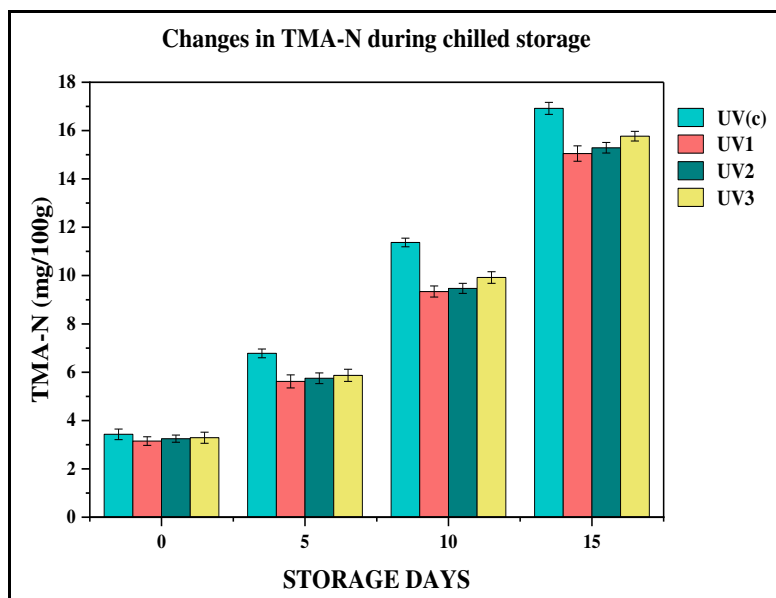


Fig 2: Variation in TMA-N concentration in reef cod (*E. diacanthus*) fillets throughout chilled storage

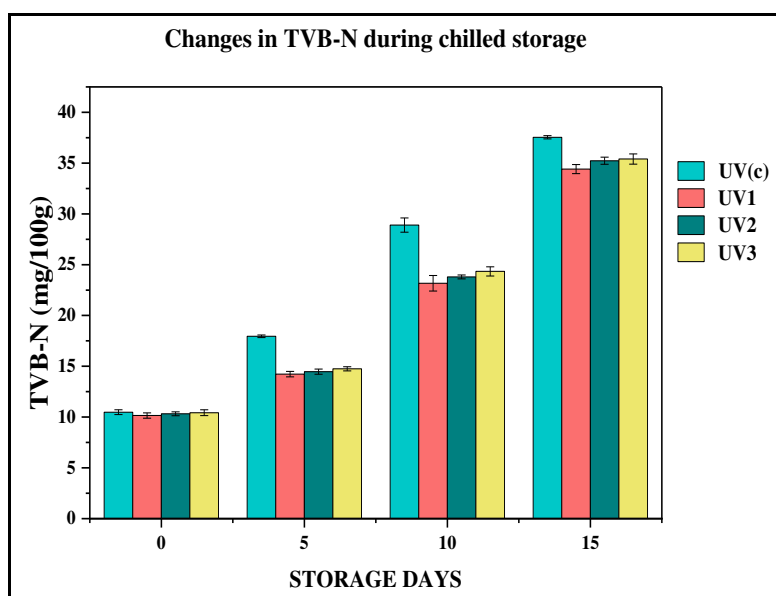


Fig 3: Variation in TVB-N concentration in reef cod (*Epinephelus diacanthus*) fillets throughout chilled storage

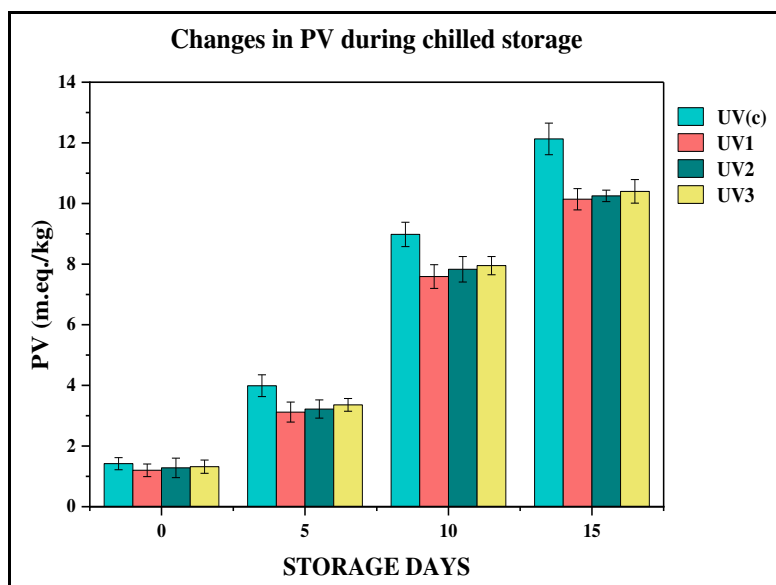


Fig 4: Variation in PV concentration in reef cod (*E. diacanthus*) fillets throughout chilled storage

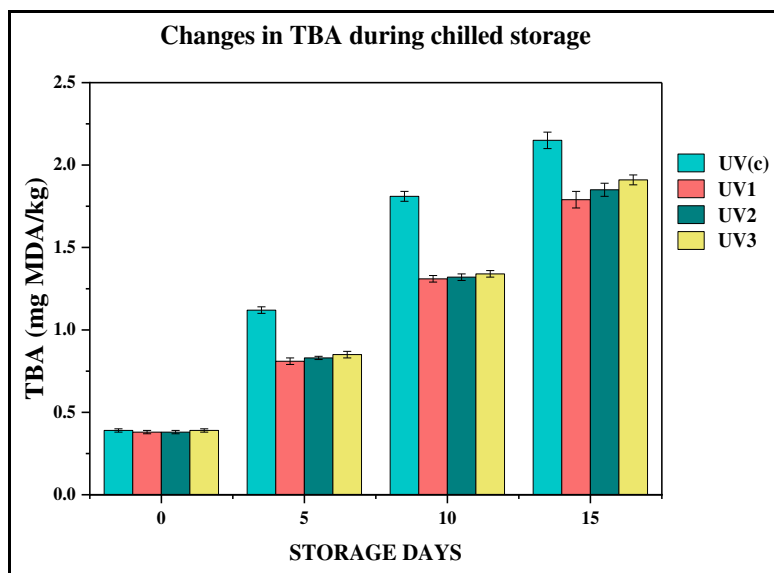


Fig 5: Variation in TBA concentration in reef cod (*E. diacanthus*) fillets throughout chilled storage

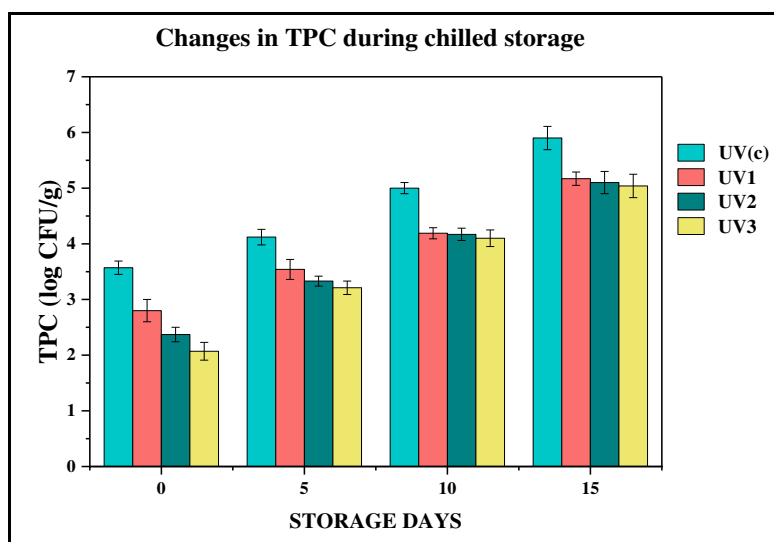


Fig 6: Variation in TPC in reef cod (*E. diacanthus*) fillets throughout chilled storage

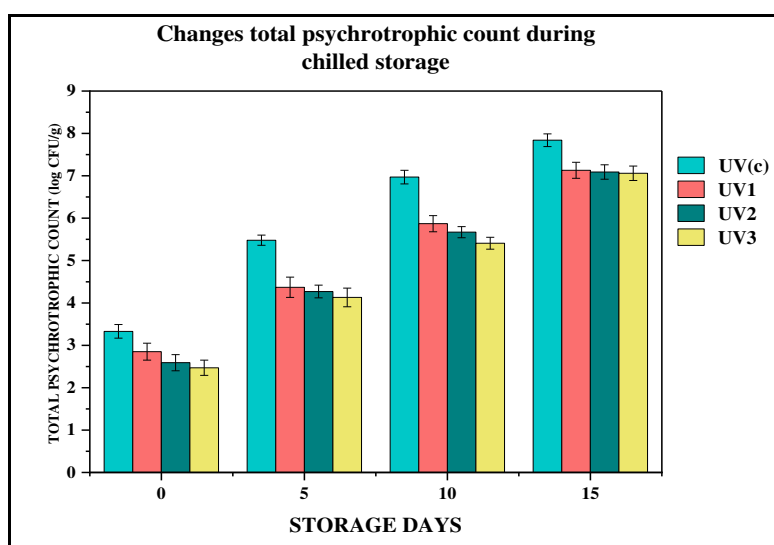
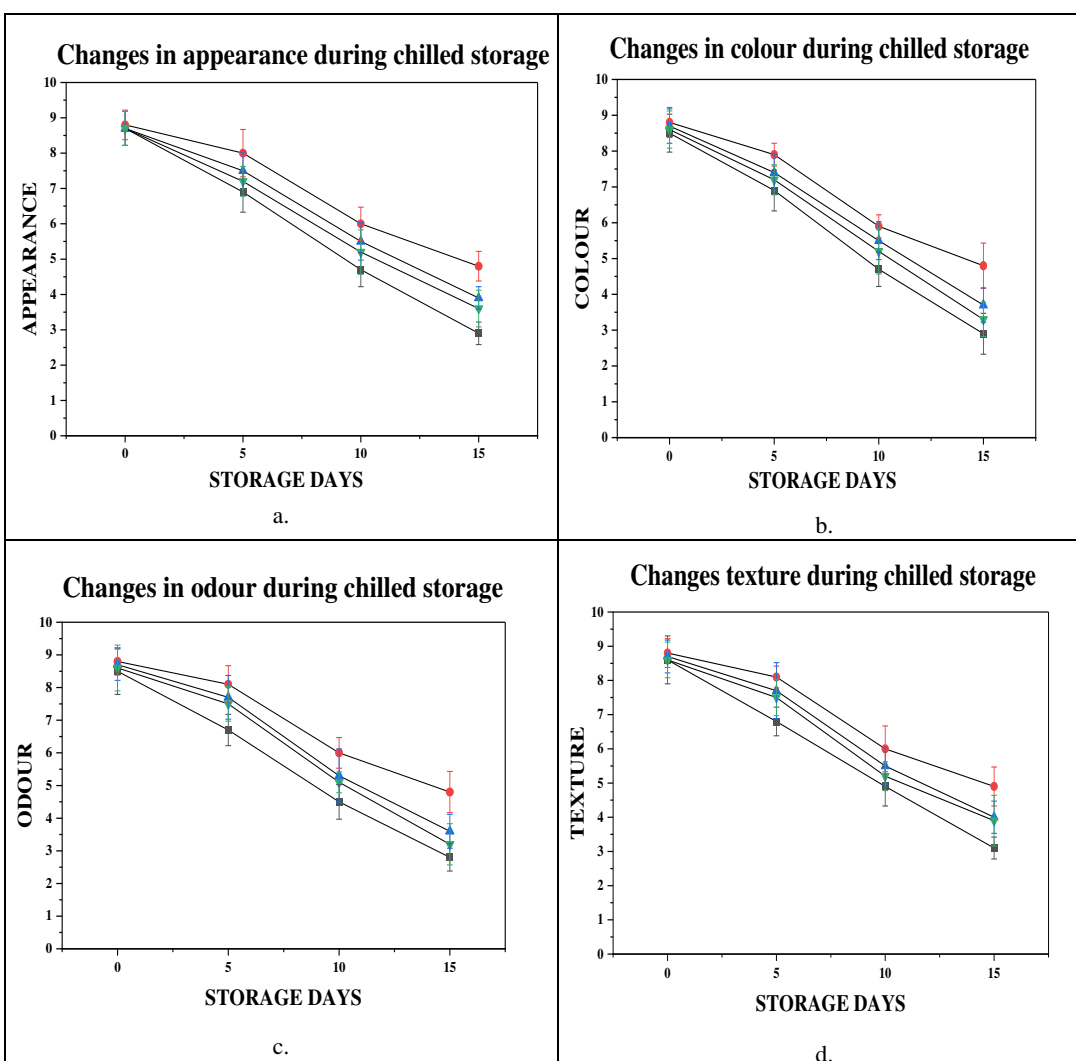


Fig 7: Variation total psychrotrophic count in reef cod (*E. diacanthus*) fillets throughout chilled storage

Table 1: Characteristics of raw reef cod (*E. diacanthus*) fish

A. Physical Characteristics			Mean $\pm$ S.D.
1	Total length (cm)		24.31 $\pm$ 2.27
2	Weight of fish (g)		555.21 $\pm$ 0.94
B. Proximate composition			
1	Moisture (%)		76.83 $\pm$ 0.45
2	Total Protein (%)		17.41 $\pm$ 0.18
3	Total Fat (%)		1.39 $\pm$ 0.08
4	Total Ash (%)		1.43 $\pm$ 0.06
C. Chemical characteristics			
1	pH		5.77 $\pm$ 0.06
2	TMA-N (mg/100g)		1.43 $\pm$ 0.22
3	TVB-N (mg/100g)		10.48 $\pm$ 0.24
4	PV (milliequivalent/Kg of fat)		1.42 $\pm$ 0.20
5	TBARS (MDA mg/kg)		0.39 $\pm$ 0.01
D. Microbiological characteristics			
1	Total Plate Count (TPC) (log CFU/g)		3.57 $\pm$ 0.12
2	Total Psychrotrophic Count (log CFU/g)		3.33 $\pm$ 0.16
3	<i>Escherichia coli</i> (cfu/g)		N.D.
4	<i>Staphylococcus aureus</i> (cfu/g)		N.D.
E. Sensory characteristics			
1	Appearance		8.70 $\pm$ 0.48
2	Colour		8.50 $\pm$ 0.53
3	Odour		8.50 $\pm$ 0.71
4	Texture		8.60 $\pm$ 0.70
5	Overall Acceptability		8.50 $\pm$ 0.53



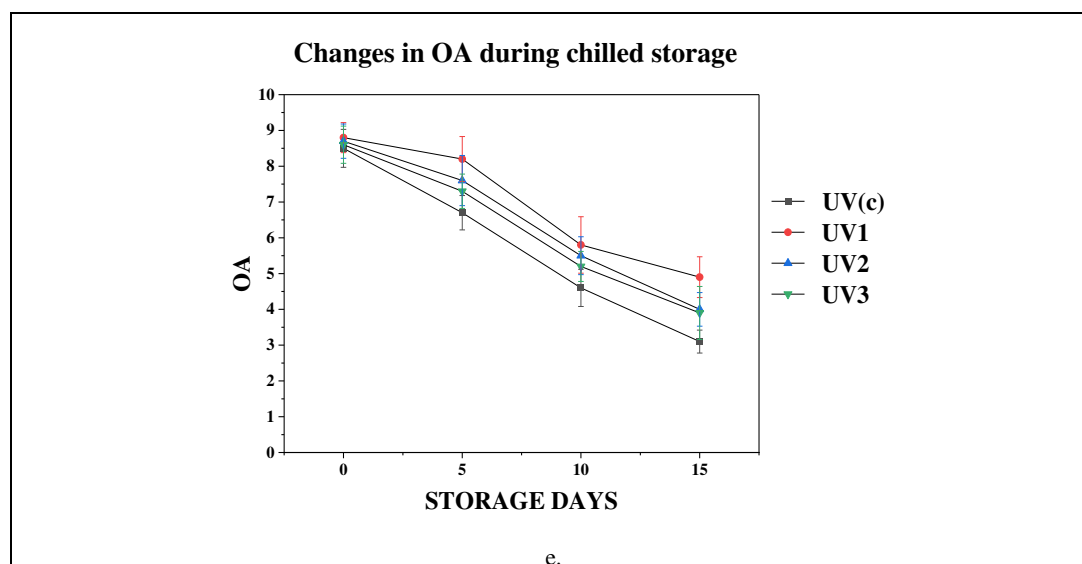


Fig 8 (a, b, c, d and e): Changes in sensory scores of reef cod (*Epinephelus diacanthus*) during chilled storage

5. Conclusion

The experiment demonstrated the effectiveness of UV-C technology in delaying spoilage indicators such as TVB-N, TMA-N, and pH while maintaining the textural integrity and sensory quality of reef cod fillets, thus extending their shelf life to approximately 10 days. UV-C's mechanism, involving the disruption of microbial DNA, significantly reduced microbial loads, including total plate counts and psychrotrophic bacteria, effectively delaying spoilage without thermal damage to the product. However, the progressive increases in oxidative markers (PV, TBA) and spoilage indicators beyond the 10-day mark revealed UV-C's limitations in providing long-term preservation, particularly concerning lipid stability and sensory degradation. This research highlights the potential of UV-C offering an advanced solution for extending seafood shelf life and quality in commercial processing.

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