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Application of Gamma Irradiated Edible Coating in Extending Shelf Life of Fresh Cucumber

Mohamed A. Abdelaleem[1], Entsar N. Mohamed[2], Amira G.M. Darwish[3,4] and Abeer M.F. Elbaz[2]

[1]Food Irradiation Unit, Plant Research Department, Radioisotopes Application Division, Egyptian Atomic Energy Authority (EAEA), Cairo, Egypt.
[2]Food Engineering and Packaging Research Department, Food Technology Research Institute, Agriculture Research Center, Cairo, Egypt.
[3]Food Industry Technology Program, Faculty of Industrial and Energy Technology, Borg Al Arab Technological University (BATU), Alexandria, Egypt.
[4]Department of Food Technology, Arid Lands Cultivation Research Institute (ALCRI), City of Scientific Research and Technological Applications (SRTA-City), Alexandria, Egypt.

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ABSTRACT

This study investigates the enhancement of carboxymethyl cellulose (CMC)/glycerol (Glyc) edible coatings through gamma irradiation (0, 1, 2, and 3 kGy) to extend the shelf life of fresh cucumbers. Analytical characterization using Fourier Transform Infrared (FTIR) confirmed that the primary functional groups of the CMC matrix remained stable following irradiation. Thermal evaluations via Thermogravimetric Analysis (TGA), Differential scanning calorimetry (DSC), and Thermomechanical Analysis (TMA) revealed that a 2 kGy dose provided an optimal for thermal stability due to radiation-induced cross-linking. Physicochemical results showed that irradiated coatings (3 kGy) significantly outperformed unirradiated controls in preserving quality throughout a 28-day storage period. Rheological analysis indicated that irradiation reduced the apparent viscosity of the CMC/Glyc solutions due to the cleavage of glycosidic bonds, which improved application characteristics. Furthermore, microbiological testing demonstrated that the 3 kGy irradiated coating acted as a potent antimicrobial agent.

Introduction

Edible films serve several critical functions in food preservation, including acting as a barrier to the migration of moisture, oxygen, carbon dioxide, and volatile aromas. Furthermore, these films can function as active packaging by incorporating essential additives like antioxidants, antimicrobials, and flavoring agents, while simultaneously enhancing the structural integrity and handling of the food product (Zhu *et al.*, 2011).

As a globally significant crop, the cucumber (*Cucumis sativus* L.) is highly valued for its crisp texture and nutritional profile. Despite its popularity, its high-water content makes

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*Corresponding author.
E-mail address: mdabdelrazek.md@gmail.com, Abdelrazek_MD@yahoo.com
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it extremely perishable and difficult to store for extended periods, even under refrigeration. Storage challenges are primarily driven by rapid respiration rates, chlorophyll degradation (yellowing), and significant moisture loss, which results in shriveling and increased susceptibility to microbial spoilage (Olawuyi and Lee, 2019).

Carboxymethyl cellulose (CMC) is an anionic polysaccharide synthesized through the alkalization of cellulose and a subsequent reaction with chloroacetate. This process introduces carboxymethyl groups at the C2, C3, or C6 positions of the glucose monomers, resulting in a molecular framework rich in hydroxyl groups that facilitate efficient water binding and absorption. The functional characteristics of the resulting polymer—such as its superior film-forming ability and moisture regulation—are primarily governed by its molecular weight, the degree of carboxylation per anhydroglucose unit, and the specific distribution pattern of carboxyl groups along the cellulose backbone (Ali *et al*., 2015). Due to its inherent biodegradability and non-toxicity, CMC is widely adopted for edible coatings, where it plays a pivotal role in maintaining the textural integrity of various food systems while supporting environmental sustainability (Li *et al*., 2008; Nie *et al*., 2004) and (Singh *et al*., 2019).

While radiation-processing technologies are well-established in various commercial sectors, their application in enhancing the functional properties of edible polymers—such as proteins and carbohydrates—remains an emerging field (Nelida Lucia del, 2016). Gamma irradiation is effectively utilized to induce the controlled degradation of bio-resources like chitosan, alginate, and cellulose, which aids in recycling and environmental mitigation. Once degraded by radiation, these carbohydrates exhibit significant biological activities, including antimicrobial properties and plant growth promotion, and can even serve as immune-boosting additives in animal and aquaculture feed (Makuuchi and Cheng, 2012).

The literature suggests that the synergistic use of edible coatings and gamma irradiation can significantly enhance the preservation of fresh produce. Building on this, the primary objectives of the current work were to evaluate the effects of a CMC/Glyc coating, modified by gamma irradiation, on the thermal behavior, physicochemical characteristics, rheological properties, and microbiological stability of fresh cucumbers, thereby extending their shelf life.

Materials and Methods

Materials

High-viscosity laboratory-grade Carboxymethyl Cellulose (CMC; 1500 cp at 20°C) and 99.5% pure glycerol (Mw = 92.09 g/mol) were purchased from the El Gomhouria Company for Drugs and Chemicals, Cairo, Egypt. Fresh cucumber fruits were obtained from a local Egyptian market one day post-harvest and were immediately transferred to ambient storage conditions (27 ± 3°C) for the duration of the study.

Preparation of CMC/Glycerol coating

To prepare the edible coating, a CMC/Glycerol bioblend was formulated by dissolving 0.4 g of carboxymethyl cellulose in 20 ml of distilled water under continuous stirring at 80 °C. Glycerol was subsequently incorporated at 1% (v/v) to achieve a 2:1 (vol %) composition, selected for its optimized physical properties. The resulting solution was divided into four distinct groups (SR0, SR1, SR2, and SR3) and maintained in a liquid state. These groups were then subjected to gamma irradiation at doses of 0, 1, 2, and 3 kGy, respectively, following the methodology established by (Abdel-Ghaffar and Ali, 2022).

Gamma Irradiation process

The CMC/Glyc solutions were subjected to gamma irradiation at doses of 0, 1, 2, and 3 kGy. This process was conducted using a ^{60}Co Russian gamma chamber with a consistent dose rate of 395.1 Gy/h. The treatment was performed at the Cyclotron Project facility, housed within the Nuclear Research Center of the Egyptian Atomic Energy Authority (EAEA).

Application of CMC/Glyc as surface coating food Preservation

During the homogenization of the CMC/Glyc mixtures, the solutions were applied to the fresh cucumbers via surface coating, ensuring uniform and complete coverage of the fruit's exterior. These coated specimens were then evaluated alongside a control group of untreated (uncoated) cucumbers. All samples were stored at ambient temperature for a storage study lasting 28 days (Fernández *et al*., 2010).

Fourier Transform Infrared (FTIR)

Fourier-Transform Infrared (FTIR) spectroscopy was employed to analyze the chemical structure of the films using a Jasco FTIR - 4100 spectrophotometer (Japan). Spectra were recorded across a wavenumber range of 400–4000 cm^{-1}.

Thermal Analyses

Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) was performed on a TA Instruments Q50 (New Castle, DE, USA). The experimental procedure involved heating the samples to 491°C at 10°C/min within an atmospheric air environment (nitrogen purge, 80 mL/min) (Grande Tovar *et al*., 2019).

Differential scanning calorimetry (DSC)

Differential scanning calorimetry (DSC2A-00181, TA Instruments, USA) was employed to determine the fusion temperature (Tm). The protocol included a heating-cooling cycle between 25 and 500°C, with the Tm data extracted from the 10°C/min heating scan (Grande Tovar *et al.*, 2020).

Thermomechanical Analysis (TMA)

Thermomechanical analysis (TMA) was conducted using a Waters TMA 450 system operating in film tension mode. Samples with dimensions of 30 mm in length, 2 mm in width, and 50-micron in thickness were preconditioned at 25°C and 60% relative humidity (RH) for a minimum of 48 hours before testing. The thermal program involved heating from -50°C to 180°C at a rate of 2°C/min, utilizing a static strain of 0.67% and a 20-micron amplitude at a frequency of 1 Hz.

Physicochemical and Microbiological Properties

Vitamin C content

Ascorbic acid concentrations in both coated and uncoated cucumbers were determined using the 2,6-dichlorophenolindophenol (DCPIP) titration method. Briefly, 2 mL of centrifuged fruit juice was combined with 5 mL of 4% (w/v) oxalic acid and 2 mL of distilled water. After vortexing, the mixture was titrated against a DCPIP solution (0.24 mg/mL) until a stable pink endpoint was achieved. A fresh ascorbic acid standard (0.2 mg/mL) was prepared daily to calibrate the vitamin C factor. Results were calculated as milligrams of ascorbic acid per milliliter of juice, with all measurements performed in duplicate (Ballesteros *et al.*, 2022).

Weight loss

Weight loss was monitored weekly by recording the difference between the initial weight of the fresh cucumbers at day zero and their weight at subsequent intervals throughout the storage period (Ezz-eldeen, 2012). Measurements were performed using an electronic analytical balance with a sensitivity of 0.01 g.

pH

The pH of both coated and uncoated cucumber samples was determined using a digital pH meter (Hanna Instruments HI 2221, Szeged, Hungary). The electrode was directly immersed into a 15–20 g portion of fresh cucumber homogenate for each measurement. To ensure accuracy and reproducibility, the analysis was conducted in duplicate for every homogenate, following the protocol described by (Ballesteros *et al.*, 2022).

Total Soluble Solid (TSS)

The Total Soluble Solids (TSS) of both coated and uncoated cucumber samples were evaluated using a digital refractometer (Hanna Instruments HI 96801, Hungary). Following the procedure of, 2 g of fruit homogenate was centrifuged at 1792 xg for 5 minutes. Subsequently, 200 µL of the resulting supernatant was analyzed, with results expressed as °Brix (g fructose/100 g juice). To ensure statistical precision, three replicates were recorded for each sample (Ballesteros *et al.*, 2022).

Firmness

The firmness of the fresh cucumbers was monitored over a 21-day storage period using a TAXT2i texture analyzer (Stable Micro Systems Ltd., UK). Penetration tests were conducted using a 2 mm diameter stainless steel cylindrical probe equipped with a 5 kg load cell. The crosshead speed was maintained at 0.5 mm^{-1} and the maximum peak force recorded during the penetration was defined as the fruit's firmness (Rocculi *et al.*, 2009).

Rheological analysis

Rheological characterization was conducted using an AR2000 controlled stress rheometer (TA Instruments) with a 40 mm, 0.034-radian cone-and-plate geometry. Measurements were maintained at a precise temperature of 20 ± 0.1 °C. To account for the shear sensitivity of the CMC domain structure, solutions were stirred gently for one hour before being carefully loaded with a spatula. The measuring cone was lowered at a minimal speed to avoid structural disruption, followed by a 10-minute rest period. Evaporation was mitigated using a solvent trap geometry to ensure a saturated environment during testing (Benchabane and Bekkour, 2008).

Microbiological Analysis

To assess microbial content, coated and uncoated samples were combined with 24 ml of 0.1% buffered peptone water (BPW; Difco, Sparks, MD, USA) and homogenized for 2 minutes using a Seward 400 Circulator stomacher. Following homogenization, serial dilutions in BPW were performed, and samples were spread-plated in duplicate. Total bacterial counts (TBC) were determined using Tryptic Soy Agar (TSA; Difco) incubated at 37°C for 24 hours. For the enumeration of yeasts and molds (YM), samples were plated on Dichloran Rose Bengal Chloramphenicol Agar (DRBC) and maintained at 25°C for 48 hours.

Statistical analysis

Statistical analysis was conducted using SPSS software (version 18.0; SPSS Inc., Chicago, IL, USA). All experiments were performed in triplicate, with data expressed as the mean ± standard deviation. To evaluate differences between groups, a one-way analysis of variance (ANOVA) was employed, followed by Duncan's post-hoc test for mean comparisons. Statistical significance was defined at a threshold of $p < 0.05$ (SPSS., 2009).

Results and Discussions

Edible coatings represent a versatile preservation strategy for fresh produce, functioning as a protective, semi-permeable membrane that modulates the internal microenvironment of the fruit or vegetable. By acting as a selective barrier, these coatings regulate the exchange of moisture, oxygen (O_2), and carbon dioxide (CO_2), which effectively slows the rates of respiration and dehydration. This physiological control is essential for maintaining structural and textural integrity, retaining aromatic volatile compounds, and inhibiting microbial proliferation, ultimately extending the shelf-life of the produce by defending against multiple forms of degradation (Lee *et al.*, 2003).

Fourier Transform Infrared (FT-IR) Spectral analysis of CMC/Glyc solution

FTIR spectral analysis - in the range between 4,000 and 450 cm^{-1} of nonirradiated and irradiated CMC/Glyc solution is shown in **Figure 1 (A, B, C and D)**. Where (A), (B), (C) and (D) are irradiated CMC/Glyc solutions at doses 0, 1, 2 and 3 kGy, respectively. Unirradiated peak of CMC/Glyc illustrated around 3282 cm^{-1} corresponding the hydrogen bonding O-H stretching region (Zaïdi *et al.*, 2011) (Gad *et al.*, 2021), the small hump around 2928 and 2880 cm^{-1} belonging to the C-H stretching vibration. The sharp peak observed at 1591 cm^{-1} confirms the presence of COO- is assigned to stretching of the carboxyl group (Su *et al.*, 2010) (Vidal *et al.*, 2020). The band around 1412 cm^{-1} and 1320 cm^{-1} are assigned to O-H stretching in-plane and C-H stretching in symmetric of CMC/Glyc (Abou Taleb *et al.*, 2009) (Gupta *et al.*, 2019). The FTIR spectrum of CMC/Glyc showed the bands at 1105 cm^{-1} and 1028 cm^{-1} were characteristic of the C-O stretching on polysaccharide skeleton (Chai and Isa, 2013).

The overall FTIR spectral profile of the irradiated CMC/Glyc solutions remained largely unchanged after gamma exposure, with no new absorption bands emergent, indicating that the key functional groups were preserved following ionizing radiation. These findings are consistent with the results of (Choi *et al.*, 2009), who also reported that the functional groups of CMC were not altered by irradiation. As with other polysaccharides, however, CMC can still undergo chemical modification when subjected to radiation (von Sonntag, 2003). Thus, the FTIR data confirms that the irradiated solutions retain their primary functional groups (-OH, -CH, and C-O). However, the subtle shifts in the peaks between samples A, B, C, and D suggest that the irradiation treatment likely caused minor changes in the molecular environment or hydrogen bonding intensity within the solution matrix.

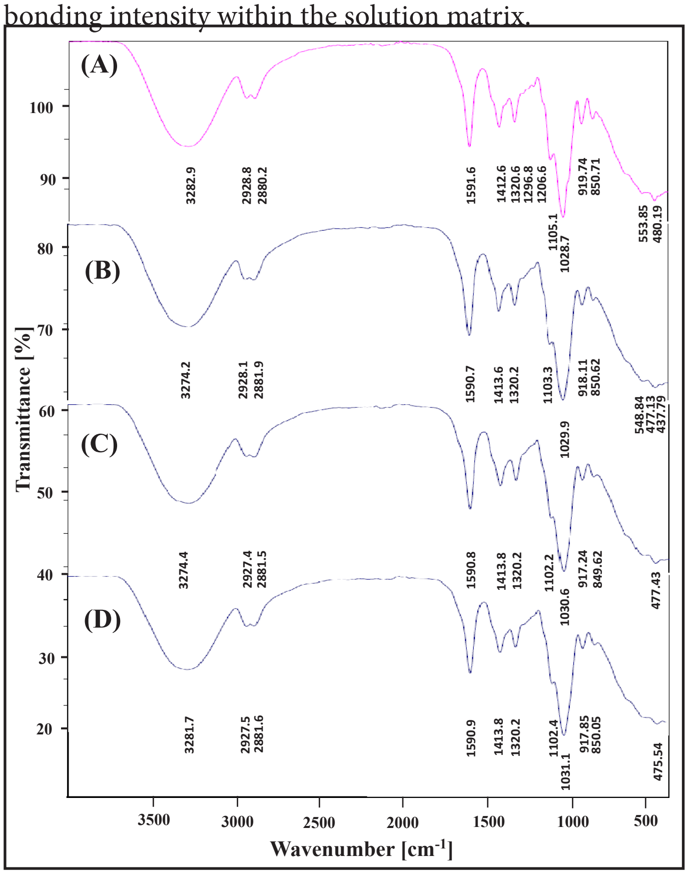

Figure (1): FTIR spectra of irradiated CMC (A = 0 kGy, B = 1 kGy, C = 2 kGy, and D = 3 kGy)

Thermal properties of CMC/Glyc solution

Thermogravimetric analysis (TGA) is an essential tool in materials science for evaluating sample purity and thermal endurance. In this study, primary TGA thermograms were analyzed to calculate key kinetic parameters, including the reaction order and activation energy of thermal decomposition. Furthermore, TGA was employed to experimentally assess the thermal stability of CMC/Glyc blends. The initial TGA thermograms for CMC/Glyc solutions, both before and after irradiation, are presented in **Figure (2-A)**. Based on the weight-loss percentages recorded up to 491°C **(Table 1)**, the irradiated samples exhibited greater thermal resistance than the unirradiated controls, particularly above 300°C. in addition, the control samples (0 kGy) showed superior stability below 100°C, samples irradiated at 2 kGy show a stabilizing effect compared to the other irradiated doses. At 400°C and 491°C, the 2 kGy sample retains the most residual mass (25.5% remaining, or 74.5% loss). This suggests that at this specific dose, radiation-induced cross-linking may predominate over chain scission, creating a slightly more robust charred residue that resists further breakdown. In addition, enhanced thermal resistance at elevated temperatures (up to 491°C) and reinforce the polymer matrix against high-heat decomposition and irradiation treatments strengthen the material's structure. In the other hand, 3 kGy dose consistently exhibits the highest weight loss across all temperature levels (e.g., 72.55% at 300°C and 81.69% at 491°C). This indicates that higher levels of radiation likely induce chain scission within the polymer, breaking down the molecular weight and making the material more susceptible to thermal degradation. These findings align with previous research by (Abdel Ghaffar *et al.*, 2019), (Abdel-Ghaffar and Ali, 2022), which indicated that thermal stability typically increases in correlation with higher irradiation doses.

Furthermore, (Ali *et al.*, 2015) found that the thermal stability of bioblend CMC/TiO_2 increased with increasing the irradiation dose up to (10 kGy). A sort of crosslinking process occurred after irradiation treatment of CMC, that increase thermal stability in pure CMC (Senna *et al.*, 2000), (Ibrahim *et al.*, 2013) and (Ibrahim *et al.*, 2014). Differential scanning calorimetry (DSC) technique is one of the convenient methods for investigating the compatibility of polymer blend. **Figure (2-B)** show the DSC thermograms for CMC/Glyc at different gamma irradiation doses (1, 2 and 3 kGy). The DSC curve shows two endothermic (water removal) peaks; at 57.03, 60.31, 59.22 and 63.81°C for 0, 1, 2 and 3kGy, respectively which are ascribed to moisture evaporation, and another endothermic peaks; at 307 °C (from 251.5 to 362.5 °C), 298.95 °C (from 261.27 to 336.63 °C), 300.06 °C (from 271.37 to 328.75 °C) and 296.44 °C (from 266.35 to 326.53 °C) for 0, 1, 2 and 3 kGy, respectively which is attributed to the dehydration/decomposition of CMC. This behavior is associated to the complete decomposition of CMC, leading to a minute solid residue (El-Sherbiny *et al.*, 2009). Moreover, as shown in **Figure (2-B)**, the 2 kGy dose shows a unique profile, where the exothermic (decomposition) peak appears slightly broader and less sharp than the 1 kGy dose. This likely reflects the "sweet spot" identified in the TGA analysis, where a balance of radiation-induced cross-linking provides a more stable thermal response before further degradation occurs at higher doses. On the contrary, at 3 kGy, the exothermic peak begins to flatten and shift slightly to the left (lower temperature). This is indicative of polymer chain scission, where the radiation has broken enough glycosidic bonds to lower the thermal threshold required for decomposition, leading to the lower thermal stability observed at the highest dose. Our finding is in agreement with (El-Sakhawy *et al.*, 2019) who found that CMC have two endothermic curves. In the contrast with unirradiated CMC/Glyc, the maximum melting temperature (T_m) 307 °C, shifted slightly to the left after irradiation treatment. Where T_m values were 298.95, 300.06 and 296.44 °C for 1, 2 and 3 kGy, respectively. Irradiation of CMC/Glyc shows a narrow endothermic band, probably attributed to the higher thermal stability of CMC.

Table 1. Effect of irradiation dose on thermogravimetric properties of CMC/Glyc

Temperature (°C)	Weight Loss (%)			
	0 kGy	**1 kGy**	**2 kGy**	**3 kGy**
100	8.236	15.71	13.61	15.44
200	22.89	27.04	23.44	28.61
300	67.97	66.25	66.6	72.55
400	78.09	74.05	71.39	78.63
491	81.83	76.81	74.5	81.69

Thermomechanical Analysis (TMA) in **Figure (2-C)** revealed that irradiation doses up to 3 kGy significantly impact dimensional stability. The consistent decrease in sample thickness (μm) during heating suggests that thermal energy triggers internal stress relaxation or further structural reorganization, such as cross-linking, across all irradiation levels (García *et al.*, 2009) and (James, 2017). Based on the thermograms provided, the dimensional changes of all samples under a constant load of -5.0 g across a temperature range of roughly 25°C to 125°C, can be observed. Across all four irradiation doses (0, 1, 2, and 3 kGy), the curves exhibit a consistent downward trend, indicating compression or softening of the material as temperature increases. Sample irradiated with 3 kGy, shows the largest displacement (53 μm), which could indicate that higher doses are inducing chain scission, leading to a more "relaxed" or softer matrix that compresses more easily. On the other hand, lowest irradiation dose (1kGy) shows the smallest total displacement (28 μm), suggesting that low-dose irradiation might have enhanced the structural rigidity, possibly through localized cross-linking.

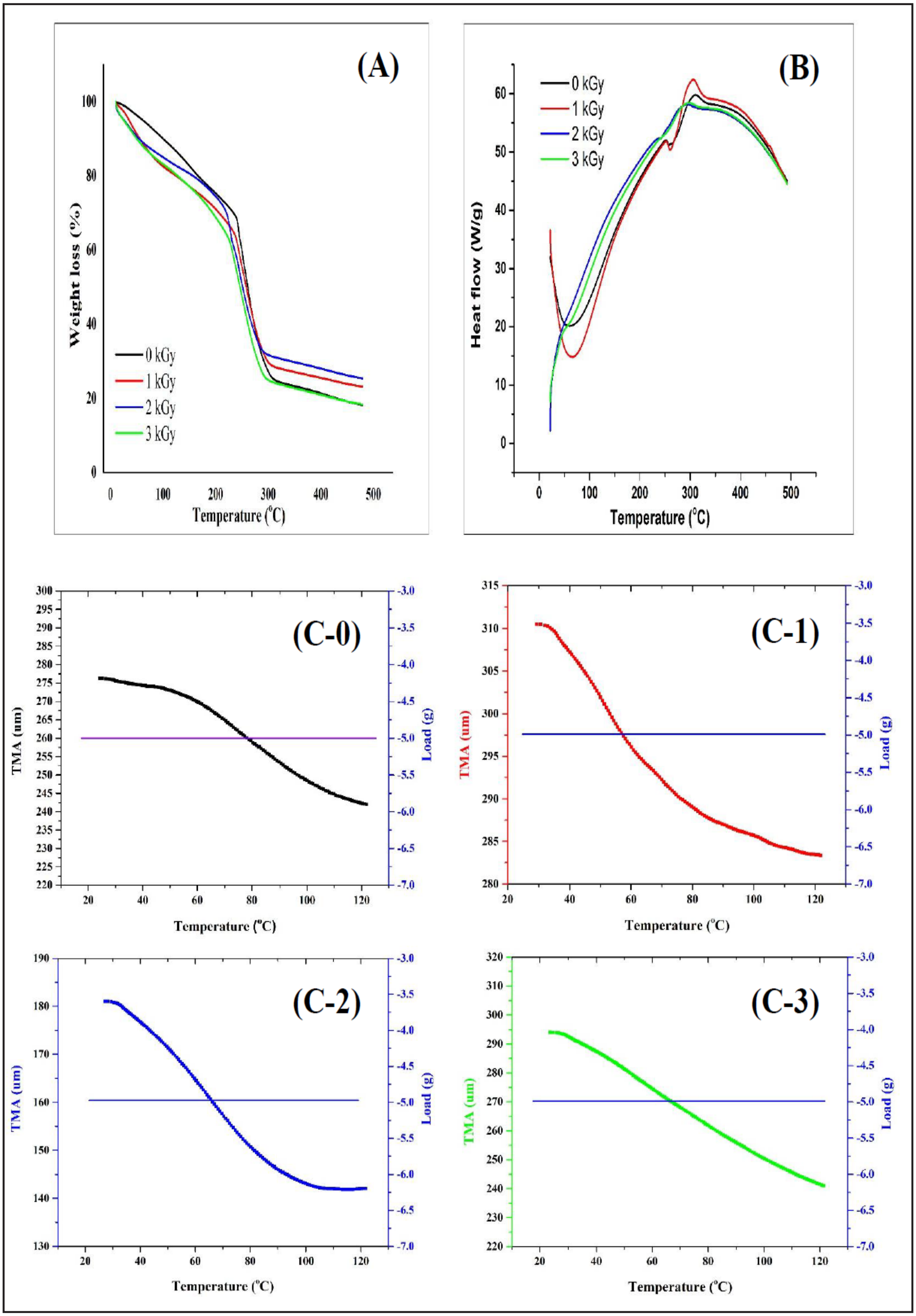

Figure (2): (A) Thermogravimetric analysis (TGA), (B) Differential scanning calorimetry analysis (DSC) and (C) Thermomechanical Analysis (TMA); (C-0) 0 kGy, (C-1) 1 kGy, (C-2) 2 kGy and (C-3) 3 kGy.

Physicochemical and Microbiological Properties

Vitamin C content

Vitamin C is a vital water-soluble antioxidant that mitigates damage from reactive oxygen species in various produce, including citrus, guava, and cucumber (Lester, 2006). **Figure (3-A)** illustrates the fluctuations in Vitamin C concentration throughout the storage period. Our findings indicate a significant interaction ($p \leq 0.05$) between storage duration and the type of edible coating applied. Specifically, cucumber coated with unirradiated CMC/Glyc showed a rapid loss of Vitamin C, whereas those treated with irradiated coatings exhibited a more gradual decline. Overall, the irradiated coatings significantly improved Vitamin C retention, with the 3 kGy treatment proving most effective across all samples.

Weight loss

Weight loss, a critical indicator of post-harvest quality loss in fruits and vegetables, is driven largely by metabolic respiration and moisture transpiration. Our results **(Figure, 3-B)** demonstrate a consistent and progressive reduction in weight across all cucumber samples over the duration of the storage trials. Over the 20-day storage duration, significant differences in weight loss were observed between the control group (unirradiated CMC/Glyc coating) and the cucumbers treated with irradiated solutions (1, 2, and 3 kGy). Beginning on day 4 and continuing throughout the study, weight loss was significantly higher ($P \leq 0.05$) in the unirradiated samples compared to those treated with irradiated coatings. Interestingly, among the irradiated groups, weight loss increased in correlation with the irradiation dose. This overall reduction in weight loss can be attributed to the synergistic effect of the treatments on reducing respiration rates and delaying the onset of senescence.

Gamma radiation enhances the coating's effectiveness by inducing a cross-linking network that restricts the outward evaporation of moisture (Amarante *et al*., 2001). As a result, these coatings provide a robust physical barrier that significantly retards dehydration. This process is essential for maintaining fruit turgor and preventing the onset of shriveling during storage (Almenar *et al*., 2006) (Feranmi, 2024).

pH

The pH values for uncoated and coated fresh cucumber stored at room temperature are presented in **Figure (3–C)**. Non-significant differences in all samples coated with irradiated CMC/Glyc solution during storage period. A slight non-significant decrease in pH values showed in all irradiated samples after 12 days of storage. The observed decrease in pH may be attributed to the semi-permeable CMC/Glyc film formed on the fruit's surface. This barrier likely modified the internal atmosphere by altering endogenous CO_2 and O_2 concentrations, which subsequently delayed the ripening process. Conversely, Oluwaseun *et al*. (2013) reported a slight increase in the pH of cucumbers coated with CMC/Glyc by the conclusion of a seven-week storage period.

Total soluble solids (TSS)

The results revealed that total soluble solids (TSS) remained statistically similar ($P \geq 0.05$) across all treatments, including the control, during the initial seven days of storage. However, following this period, samples coated with the unirradiated CMC/Glyc solution experienced a significant decline ($P \geq 0.05$) in TSS levels. In contrast, cucumbers treated with irradiated coatings (1, 2, and 3 kGy) maintained more stable TSS concentrations throughout the remainder of the study **(Fig, 3–D)**. In the control samples (unirradiated CMC/Glyc), total soluble solids (TSS) declined to 8% by day 14, reaching a minimum of 7.6% by the end of the 21-day period. While a general reduction in TSS was observed across all treatments as storage progressed, the decrease was notably less pronounced in samples treated with irradiated CMC coatings. This preservation of soluble solids is likely due to the synergistic effect of irradiation and CMC, which delays fungal proliferation and slows physiological processes such as respiration, transpiration, and senescence (Vachon *et al*., 2003). These findings align with (Dong and Wang, 2017), who noted that stable TSS levels in coated cucumbers result from the inhibition of respiratory and metabolic activities.

In contrast, (Özden *et al*., 2002) noted that a decline in soluble solids during storage is a natural phenomenon. This occurs because sugars—the fundamental component of a product's soluble solid content—are gradually depleted through respiration and the ongoing metabolic requirements of the cucumber samples.

Firmness

The firmness of all the coated cucumber decreased gradually during the 21 days of storage **(Figure, 3–E)**. In all irradiated CMC/Glyc-coated samples a slight decrease of firmness was observed during the duration of storage - which was similar to the above results for weight loss - compared to control samples. This phenomenon can be attributed to the interaction between storage duration and the application of irradiated coatings. A parallel trend was noted in mass loss, where cucumbers treated with these specific solutions showed minimal fluctuations. It is suggested that the limitation of moisture loss was the primary mechanism allowing coated samples to maintain greater firmness compared to the control. This reasoning aligns with the findings of (Aguirre-Joya *et al*., 2017), who established that moisture loss is directly correlated not only with mass reduction but also with the rate of fruit softening.

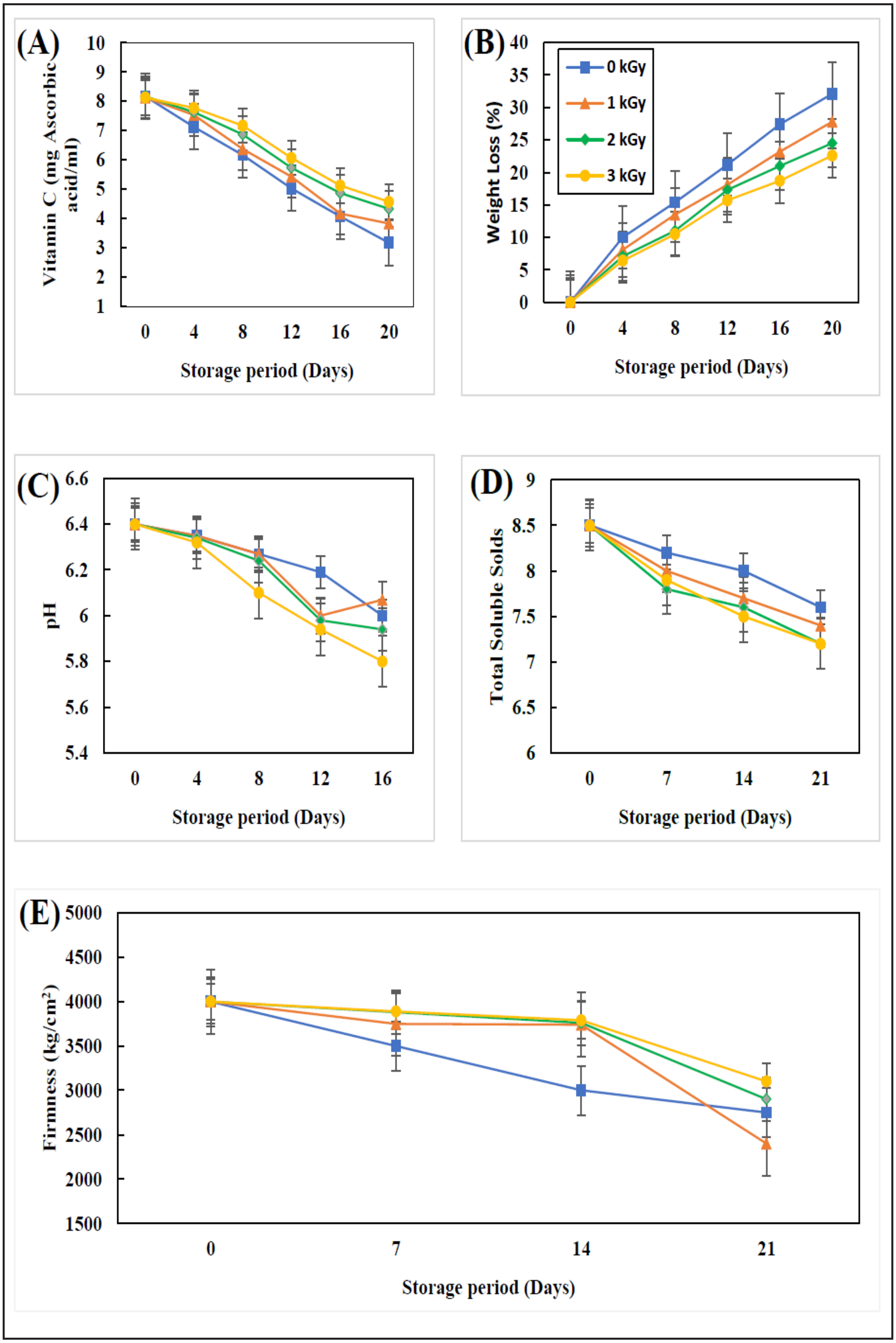

Figure (3): Physical and chemical changes of Coated fresh cucumber during storage at room temperature.

Rheological Characteristics of edible coating

Figure (4) presents the flow and viscosity curves for all evaluated samples. The flow behavior, illustrated in **Figure (4-A)**, depicts shear stress as a function of the shear rate. As the shear rate increases, a corresponding continuous rise in shear stress is observed for the CMC/Glyc solution. Notably, the curves for the upward and downward shear rate sweeps almost entirely overlap, indicating that the CMC/Glyc system possesses excellent structural recovery under external mechanical stress. Furthermore, a progressive increase in irradiation dosage results in a gradual reduction in the shear stress of the solution.

Flow behaviour shown in **Figure (4–B)** represents the impacts of irradiation treatment on the apparent viscosity of CMC/Glyc solution as a function of shear rate, where apparent viscosity initially decreased rapidly as the share rate increased and then stabilized in all samples. Rheological properties of CMC/Glyc suspensions exhibit viscoplastic behaviour (Jankowska *et al.*, 2023) (Salehi *et al.*, 2023).

Exposing the CMC/Glyc solution to irradiation results in a reduction in viscosity. To enhance the flexibility of the resulting edible films, glycerol is incorporated as a stable, non-toxic plasticizer. These plasticizers are essential for reducing stiffness and increasing film elasticity; however, they can also elevate the water vapor permeability of the material (Sobral *et al.*, 2001).

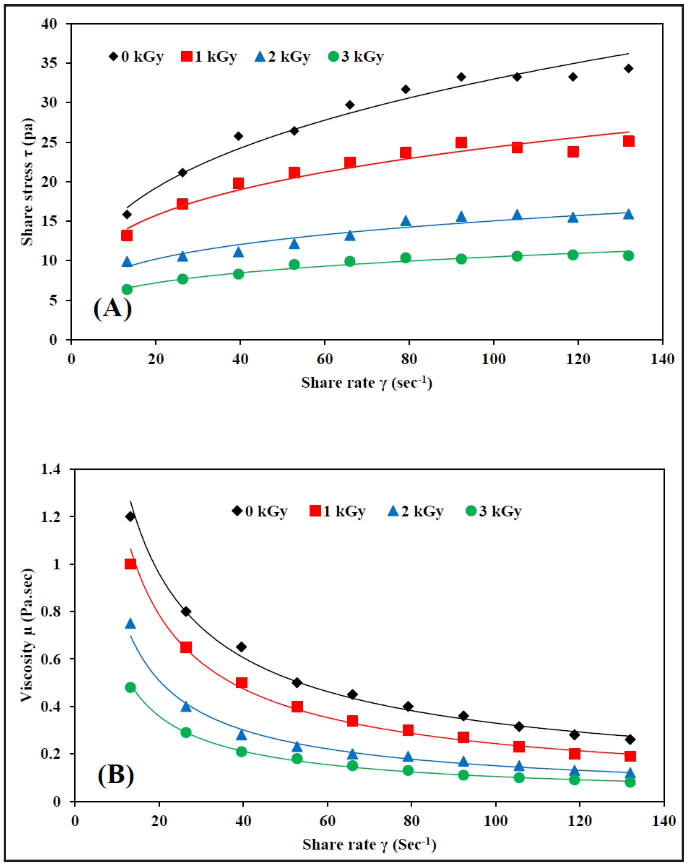

Figure (4): Rheological Characteristics of edible solution, A) Flow behaviour, B) Viscosity.

The reduction of viscosity behaviour was observed at all dose levels leading to a greater reduction in the viscosity. The results demonstrated that the average apparent viscosity of CMC/Glyc solution decreased from 1.2 to 0.26 Pa.sec in control samples (0 kGy). While the values of viscosity of irradiated samples at doses from 1 - 3 kGy decreased from 1 to 0.19 Pa.sec, 0.75 to 0.12 Pa.sec and 0.48 to 0.08 Pa.sec, respectively.

The observed modifications in viscosity following irradiation can be attributed to the cleavage of glycosidic bonds within the cellulose backbone. Importantly, this structural degradation occurs without altering other functional groups (Suljovrujić *et al.*, 2007) (Choi *et al.*, 2008). Radiation processing is a common technique for synthesizing CMC-based hydrogels (Fei *et al.*, 2000). Research suggests that radiation-induced cross-linking in CMC is often more efficient than traditional chemical methods, though achieving high cross-linking density may require substantial radiation doses. It is critical to note that in all irradiated materials, cross-linking and degradation occur simultaneously as competing mechanisms (Wach *et al.*, 2003).

Microbiological Analysis

The fluctuations in total bacterial count (TBC) and mold and yeast count (MYC) for both coated and uncoated cucumbers are illustrated in **Figure 5 (A and B).** During the first week of storage, the initial bacterial load in the control samples (unirradiated CMC/Glyc) was 6.2 log CFU/g, whereas samples treated with the 3 kGy irradiated coating exhibited a significantly lower load of 2.71 log CFU/g. This trend is consistent with findings reported by Olarte *et al.* (2009) regarding broccoli. By the third week, the TBC for control cucumbers reached 9.84 log CFU/g, while the irradiated treatment limited bacterial growth to 6.23 log CFU/g. These data demonstrate that the irradiated CMC/Glyc solution functions effectively as both an edible coating and a potent antimicrobial agent.

The enumeration of yeasts and molds is a critical quality indicator for fresh produce, as fungal decay represents a primary factor limiting shelf life and commercial distribution. As shown in **Figure (5)**, the application of CMC/Glyc coatings significantly reduced ($p < 0.05$) microbial populations compared to uncoated controls. Specifically, the initial mold and yeast count (MYC) in control samples was 4.53 log CFU/g during the first week, whereas samples treated with 3 kGy irradiated coatings exhibited a reduced load of 2.82 log CFU/g. Throughout the storage period, the irradiated CMC/Glyc coating successfully inhibited fungal proliferation, maintaining a final count of 7.34 log CFU/g compared to the significantly higher 9.62 log CFU/g observed in control samples. The effectiveness of the CMC/Glyc coating in controlling spoilage is likely due to its ability to act as a gas barrier, thereby establishing a modified atmosphere that preserves the fruit's integrity (Dutta *et al.*, 2009).

Furthermore, the decrease of microbial count in coating with irradiated CMC/Glyc solution is probably due to antimicrobial effect of degradable biological compounds after irradiation treatments where, (Makuuchi and Cheng, 2012) found that irradiation of carbohydrates polymers like CMC, present biological compounds that have antimicrobial activity.

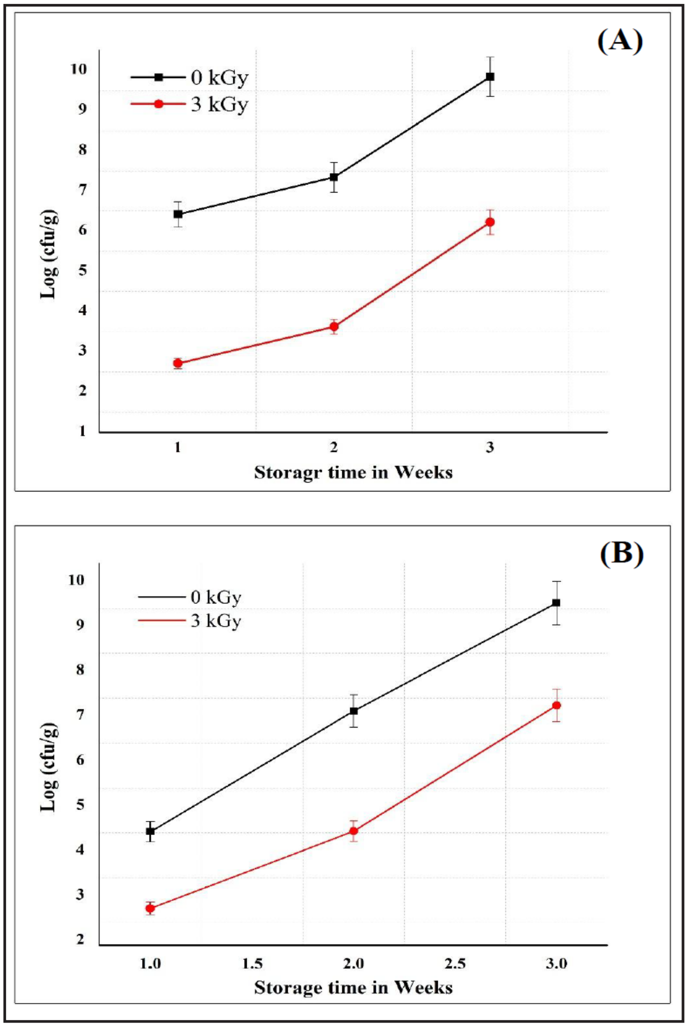

Figure (5): Effect of coating with irradiated CMC/Glyc solution at dose 3 kGy on A) the total bacterial count (TBC) and B) mold & yeast count (MYC) during storage period.

Conclusions

In conclusion, this study demonstrates that gamma irradiation significantly enhances the functional performance of CMC/Glyc edible coatings for cucumber preservation. This modified coating effectively establishes a semi-permeable atmosphere that suppresses respiration, minimizes weight loss, and maintains total soluble solids. Most notably, the 3 kGy treatment provided the most robust antimicrobial defense, significantly reducing both bacterial and fungal proliferation. While, thermal analysis (TGA and DSC) identified 2 kGy as the optimal dose for enhancing thermal stability, likely due to radiation-induced cross-linking that outweighs chain scission at this specific level. Collectively, these findings suggest that irradiated CMC/Glyc coatings offer a synergistic approach to extending the shelf-life and maintaining the post-harvest quality of fresh produce.

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