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Preparation and Characterization of Edible Carboxymethyl Cellulose Films Treated by Gamma Irradiation

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

[1]Food Engineering and Packaging Research Department, Food Technology Research Institute, Agriculture Research Center, Cairo, Egypt.
[2]Food Irradiation Unit, Plant Research Department, Radioisotopes Application Division, Egyptian Atomic Energy Authority (EAEA), 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 aimed to develop and optimize edible food packaging films based on a carboxymethyl cellulose (CMC) and glycerol (Glyc) bioblend by utilizing gamma irradiation as a modification technique. CMC/Glyc films were fabricated via the solvent casting method and subsequently exposed to low-dose gamma irradiation (0, 1, 2, and 3 kGy). The resulting films were characterized using Fourier-Transform Infrared (FTIR) spectroscopy, mechanical testing (Tensile Strength and Elongation at Break), and comprehensive thermal analyses, including Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), and Thermomechanical Analysis (TMA). Additionally, barrier properties were evaluated through Water Vapor Transmission Rate (WVTR) and gas (O_2 and CO_2) transmission rates. The results demonstrated that low-dose irradiation (up to 3 kGy) significantly enhanced the functional properties of the films. Tensile strength increased from 32.33 MPa at 0 kGy to 34.24 MPa at 3 kGy, alongside a slight improvement in elongation. Irradiation promoted molecular cross-linking, which led to a denser polymer matrix, effectively reducing WVTR and gas permeability for both O_2 and CO_2. Thermal stability was also improved, with irradiated samples exhibiting higher residual char at 491°C compared to the control. Furthermore, optical transparency increased with the irradiation dose, reaching a maximum value of 2.79 at 3 kGy.

*Corresponding author.
E-mail address: mdabdelrazek.md@gmail.com, Abdelrazek_MD@yahoo.com
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Introduction

Biodegradable packaging has witnessed a notable surge in popularity in recent years (Robertson, , 2012). Global demand for materials was forecasted to reach 884,000 tons by the year 2020 (Cerqueira *et al*., 2012).

Cellulose hardly mixes freely in typical solvents because of intramolecular and intermolecular -OH bonds as well as, due to higher molecular weight and linear shape. The processes of etherification (monochloroacetic acid) and mercerization (sodium hydroxide) produce CMC, a highly water-soluble polymer (Gulati *et al*., 2014) and (Gupta *et al*., 2019). According to (Mei *et al*., 2021), CMC is a white powder that is free-flowing, odorless, tasteless, non-toxic, biodegradable, biocompatible, hydrophilic, and an effective film-forming agent (Mondal *et al*., 2015), (Singh *et al*., 2013), and (Su *et al*., 2010).

Due to its linear chain configuration, CMC finds widespread application in diverse sectors such as oil detergents and exploration, paper manufacturing, cosmetics, textiles, and the food industry (Joshi *et al*., 2015), (Mohkami and Talaeipour, 2014), and (Toğrul and Arslan, 2003). Mercerization and etherification processes improve the mechanical properties of biodegradable films by increasing ionic and chemical crosslinking (Ma *et al*., 2008); (Yadav *et al*., 2014). These treatments also enhance the film's barrier effectiveness against oxygen, carbon dioxide, and lipids (Hu *et al*., 2016). Additionally, they contribute to higher viscosity and tensile strength, though elongation percentage tends to decrease (Tongdeesoontorn *et al*., 2012).

Glycerol is hydrophilic, decreases intermolecular forces between plasticizer and increases the movement of polymer chains, a procedure mostly used to increase the flexibility and extensibility of biodegradable films (Jouki *et al*., 2013).

The chemical principles governing the pyrolysis of cellulose are well-documented in existing literature. Thermogravimetric analysis (TGA) serves as a primary tool for monitoring mass reduction as a function of temperature under specific heating conditions and an inert environment. From this data, differential thermogravimetric (DTG) curves are derived to assess the kinetic parameters of biomass pyrolysis—a process involving the thermal breakdown of organic material without oxygen to produce char, bio-oil, and synthesis gas. Furthermore, differential scanning calorimetry (DSC) is utilized to identify critical thermal transitions (El-Sakhawy *et al*., 2019) and (Cozzolino *et al*., 2007).

Gamma irradiation is currently one of the most widely employed techniques in industrial processing. When polymers are exposed to gamma rays, the applied dose determines whether the material undergoes degradation or is modified through cross-linking (Abdel Ghaffar and Ali, 2016), (Abdel Ghaffar *et al*., 2018), (Abdel Ghaffar *et al*., 2019) and (Ali and Abdel Ghaffar, 2017). For certain polymers, gamma irradiation can alter the molecular structure based on their chemical composition, generating non-metabolized products that negatively impact biocompatibility and bioresorption rate (Marois, Zhang *et al*., 1999).

The main objective of this work was to determine the effect of gamma irradiation on inducing further modifications in the properties of the prepared selected bioblend CMC/Glyc film.

Materials and Methods

Materials

Laboratory grade Carboxymethyl Cellulose (CMC) with viscosity 1500 cp / 20 °C and glycerol 99.5%, (Mwt = 92.09) were purchased from El Gomhoria Compony for Drugs and chemicals, Cairo, Egypt.

Methods

Preparation of CMC/Glycerol film

To prepare the CMC films **(Figure, 1)**, 2g batches of CMC were dissolved in 100ml of distilled water under stirring at 80 °C. Glycerol (1% v/v) was incorporated into the solution as a plasticizer to enhance film properties. The resulting mixture was cast into Petri dishes and dried in a 40 °C hot air oven until a constant weight was achieved. Following a 48-hour stabilization period at room temperature, the peeled films were exposed to gamma radiation at doses of 0, 1, 2, and 3 kGy (Abdel-Ghaffar and Ali, 2022).

Gamma Irradiation process

The irradiation process (0, 1, 2 and 3 kGy) was performed using a ^{60}Co Russian gamma chamber (dose rate: 395.1 Gy/h) at the Cyclotron Project, Nuclear Research Center, Egyptian Atomic Energy Authority, Egypt.

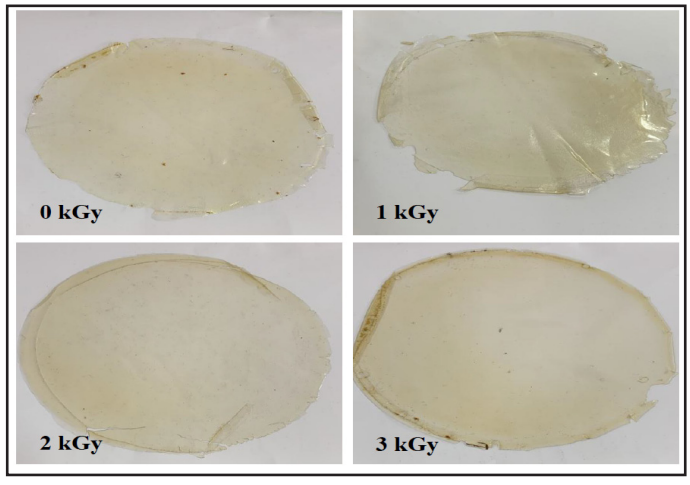

Figure (1): Visual appearance of CMC/Glyc film subjected to gamma irradiated

Physiochemical characterization of irradiated CMC/Glyc film

Film Thickness and Transparency

The thickness of the CMC films was determined using a hand-held micrometer (Mitsutoyo Co., Kanagawa, Japan), which had a 0.001 mm precision. Six random positions around each film were measured (10 specimens).

The following equation was utilized to calculate the transparency value of the CMC films (Han *et al*., 1997) by utilizing a UV-Vis spectrophotometer (Biochrome, Libra S60, B, Cambridge, England) to measure light transmittance at 600 nm.,

$$\textbf{Transparency} = -\log T600x$$

Where, x is the film thickness (mm) and T600 is the fractional transmittance at 600 nm.

Mechanical Properties

Tensile strength (TS) and % Elongation

Mechanical properties were performed in accordance with ASTM D 882-02 (2010) guidelines using Brookfield texture analyzer (CT3) with a 5-kg load cell. Films specimens (20 x 50 mm) were fixed on grips (50 mm apart) and subjected to a tensile speed of 5 mm/min. The relationship between the load and the film's initial cross-sectional area determines the stress at break. TS value was calculated using the following formula (Properties, 1995):

$$TS\ (MPa) = \frac{Maximum\ force}{Film\ thickness \times Film\ width}$$

$$Elongation\ (\%) = \frac{Length\ after\ breaking - Intial\ Length}{Intial\ Length} \times 100$$

Fourier Transform Infrared (FTIR) spectroscopy:

Fourier-Transform Infrared (FTIR) analysis was performed using a Jasco FTIR-4100 spectrophotometer (Japan) across a spectral range of 400 - 4000 cm^{-1}.

Thermal properties of irradiated films

Thermogravimetric analysis (TGA) was conducted using a TA Instruments Q50 V20.13. Samples were heated to a maximum temperature of 491°C at a constant ramp rate of 10°C/min under a nitrogen purge (80 mL/min). Differential scanning calorimetry (DSC) was conducted using a DSC2A-00181 unit. The thermal cycle consisted of a heating phase from 25 to 500 °C at a rate of 10 °C/min, followed by a cooling phase back to 25 °C. The melting temperature (Tm) was identified from the resulting DSC heating thermogram. All data acquired from both TGA and DSC measurements were processed using TA Instruments' Universal Analysis software (Grande Tovar *et al*., 2019) (Grande Tovar *et al*., 2020). Thermomechanical analysis (TMA) was performed using a TMA 450 (Waters) in film tension mode. Samples with dimensions of 30 mm × 2 mm × 50 µm were analyzed. The testing protocol involved heating from -50 °C to 180 °C at a constant rate of 2 °C/min. Dynamic parameters included a static strain of 0.67% and a 20-micron amplitude at a frequency of 1 Hz. Before testing, all specimens were preconditioned at 25 °C and 60% relative humidity (RH) for at least of 48 hours.

Barrier properties of the CMC/Glyc film

Water vapor (WV), O_2 and CO_2 transmission rate

WVTR of CMC films was measured gravimetrically according to the standard method of ASTM E96-92 method (ASTM, 1995) and (Guillard *et al*., 2003). The films (20 cm diameter), free of physical defects, were sealed on the top of Al cup containing 10 ml distilled water, and placed in a desiccator containing 80 g of calcium chloride (0 %, RH). The cups were weighed every 1 h for 5 h, and again after 24 h. The weight loss of the permeation cell was used to calculate the amount of water vapour that was adsorbed by the desiccant and transferred through the film. A tiny fan inside the desiccator maintained continuous air circulation outside the test cup, thereby ensuring a steady, uniform water pressure. Using linear regression, the slope of the weight loss versus time curve was determined (McHugh *et al*., 1993) and WVTR was calculated and expressed as (g H_2O/hr.cm^2.d). All samples were investigated at 25 °C under inside humidity of 90 %. Oxygen and Carbon dioxide Transmission Rate (O_2TR, CO_2TR)

O_2TR and CO_2TR was measured with Gas Permeability Tester G103H within measuring range from 0.01 to 50,000 cm^3/m^2·day, at temperature of 25 °C and humidity 90 % (ASTM, 2015) and (ASTM *et al*., 2016)

Statistical Analysis

Statistical analysis was performed using SPSS software, version 18.0 (SPSS Inc., Chicago, IL, USA). All experiments were conducted in triplicate, with results expressed as the mean ± standard error. Data were subjected to a one-way analysis of variance (ANOVA), followed by Duncan's post-hoc test for mean comparisons. Statistical significance was determined at a 95% confidence level ($p < 0.05$) (SPSS., 2009).

Results and Discussions

Film thickness and transparency

Table (1) includes the measured values for thickness and transparency of the film samples. The thickness of CMC films was in the range of 0.0124 to 0.0127mm, which is in the range of film thickness reported for industrial plastic and represents a suitable application field in food packag-

ing aspects. No significant differences were found between irradiated and non-irradiated CMC films. Transparency is a crucial characteristic, particularly when the film is used for see through packaging. Transparency of control CMC film was 2.45 **(Table 1)** and it was increased to 2.79 for 3 KG irradiated films, which means that low dose irradiation slightly increases transparency of the CMC films, which agrees with the results reported by (Algethami and Sciences, 2025).

Mechanical Properties

CMC films were subjected to tensile test and results are given in **Table (1)**, the CMC irradiated films samples (3 kGy) have a higher tensile strength film it reached to (34.2 MPa) compared with than that control films (32.3MPa). After gamma irradiation of polymers or composite films, two competing processes typically occur: cross-linking and chain scission. In our data, as shown in **Table (1)**, cross-linking is the dominant mechanism due to the low irradiation dose. At the low dose range shown (1 to 3 kGy), the beneficial effects of cross-linking outweigh any potential "chain scission" (the breaking of polymer backbones). If the dose were excessively high (10 kGy and above), the tensile strength would eventually decrease as the molecular weight of the polymer drops due to degradation (Abdel Ghaffar and Ali, 2016). These data are in agreement with (Abdel Ghaffar and Ali, 2016), who mentioned that there were a decrease in both tensile strength and elongation at break with increasing irradiation dose (> 10 kGy). Moreover, in the presence of glycerol, irradiation may also facilitate better integration between the plasticizer and the polymer matrix, reducing the «free volume» and increasing resistance to longitudinal stress (Ciesla *et al*., 2008). In a CMC/Glycerol blend, glycerol acts as both a plasticizer and a radiolysis mediator (Fei *et al*., 2000), because glycerol has three hydroxyl (–OH) groups, it can help bridge the gap between CMC chains (Buathongvong *et al*., 2026).

The results in **Table (1)** showed the change in the percentage of elongation of the irradiated and unirradiated CMC films prepared using 1% concentrations of glycerol. The highest percentage of elongation was 9.5% at irradiation dose 3 kGy compared to control sample where EB % was 8.5%. Thickness of the film was illustrated in **Table (1)**, where it is ranged from 0.0124 to0.0127 mm.

It has been stated that gamma irradiation is a physical technique used to improve the characteristics of polysaccharides (Hassan *et al*., 2018) and (Vinod *et al*., 2020) It has been documented that gamma irradiation of biodegradable films can change their properties, leading to an improvement in their mechanical and barrier qualities (Hakke *et al*., 2020). According to reports in the literature, biodegradable films required to be exposed to radiation in order to potentially cause a crosslink of the macromolecules (Salehi and nutrition, 2019). Glycerol (Glyc) has been identified as an effective plasticizer that enhances the mechanical, thermal, and water resistance properties of bioblend matrices through the formation of hydrogen bonds (Abdel-Ghaffar and Ali, 2022).

Table 1. Transparency, thickness and mechanical properties of irradiated CMC/Glyc films at different dose levels

Irradiation treatments	Transparency	Thickness (mm)	Mechanical properties	
			Elongation at break (EB, %)	Tensile strength (TS, Mpa)
0 kGy	2.45 ± 0.009^{d}	0.0124 ± 0.0008^{a}	8.5 ± 0.009^{d}	32.33 ± 0.011^{d}
1 kGy	2.56 ± 0.008^{c}	0.0125 ± 0.0008^{a}	8.9 ± 0.012^{c}	32.84 ± 0.012^{c}
2 kGy	2.74 ± 0.009^{b}	0.0125 ± 0.0008^{a}	9.2 ± 0.008^{b}	33.53 ± 0.018^{b}
3 kGy	2.79 ± 0.009^{a}	0.0127 ± 0.0008^{a}	9.5 ± 0.009^{a}	34.24 ± 0.015^{a}

Values are means ± standard error of triplicate determinations. Means with different letters in the same column are significantly different at $p < 0.05$.

For many food applications, film transparency is a crucial characteristic, particularly when the film is used for see-through packaging. Thus, as shown in **Table (1)**, low-dose gamma irradiation is an effective tool for improving the optical properties of CMC-based edible films, making them more transparent and potentially more appealing for food packaging applications where visibility of the product is essential. The CMC increases the viscosity of the film solution and causes greater flexibility in the polymer structure by preventing the formation of hydrogen bonds between the polymer chains and reducing molecular movement, which allows the strings to move more freely and with greater flexibility (Tongdeesoontorn *et al*., 2011).

FT-IR Spectral analysis of CMC/Glyc

FTIR spectral analysis - in the range between 4,000 and 450 cm^{-1} - of nonirradiated and irradiated CMC/Glyc films at doses 1, 2 and 3 kGy are shown in **Figure 2 (a and b)**.

Nonirradiated peak of CMC/Glyc illustrated around 3282 cm^{-1} corresponding the hydrogen bonding O-H stretching region (Zaïdi *et al*., 2011), the small hump around 2928 and 2880 cm^{-1} belongs 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). The bands around 1412 cm^{-1} and 1320 cm^{-1} are assigned to O-H stretching in-plane and C-H stretching in the symmetric mode of CMC/Glyc (Abou Taleb *et al*., 2009). The FTIR spectrum of CMC/Glyc showed that the bands at 1105 cm^{-1} and 1028 cm^{-1} which were characteristic of the C-O stretching on polysaccharide skeleton (Chai and Isa, 2013).

As illustrated, the overall spectral profiles of the sample films remained unchanged following gamma irradiation, with no emergence of new characteristic bands. This stability confirms that the primary functional groups were preserved despite exposure to ionizing radiation. These observations align with the findings of (Choi *et al*., 2009), who previously noted that the functional integrity of CMC is maintained under irradiation.

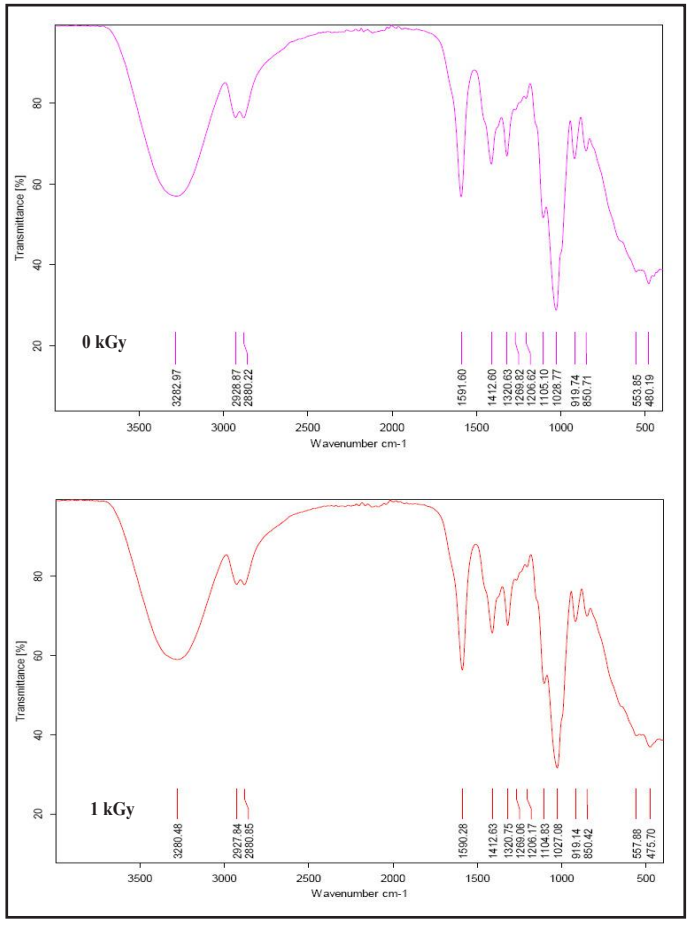

Figure (2a): FTIR of irradiated CMC/Glyc edible films at different irradiation doses (0 and 1 kGy)

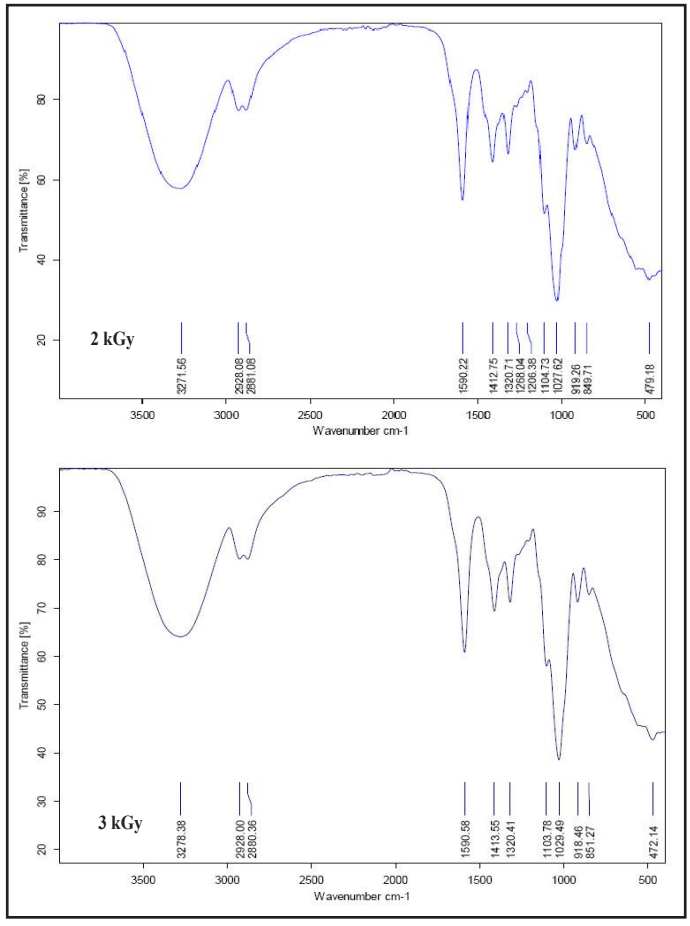

Figure (2b): FTIR of irradiated CMC/Glyc edible films at different irradiation doses (2 and 3 kGy)

Thermal properties of CMC/Glyc edible films

Thermogravimetric Analysis (TGA)

All materials display characteristic thermal degradation temperature profiles. TGA analysis offers essential information about material purity and heat tolerance, making it indispensable in materials research. **Figure 3 (a and b)** show the thermal decomposition behavior of edible films before and after irradiation treatment. The thermogravimetric profile of the control sample film **(Figure, 3a)** exhibited an initial weight loss of 30.08% as temperatures reached 246.61°C, a phase primarily attributed to the evaporation of absorbed water. Upon reaching 323.43°C, the cumulative weight loss increased to 44.84%. By the conclusion of the thermal heating at 491.26°C, the final recorded weight loss reached 6.858%. The extended dehydration phase observed in glycerol-containing films may be due to the formation of a surface oily layer, which acts as a barrier to moisture loss, as previously suggested by (Atta *et al*., 2022).

As shown in **Figure 3 (a and b),** irradiation treatments at different dose of 1, 2, and 3 kGy showed many different stages of thermal degradation phases. In the case of 1 kGy there were for thermal degradation phases started from

120.96 °C where the weight loss was 16.12% and the second phase at 251.05 °C and weight loss was 15.48%. while the last phase was 490.81 °C and the weight loss was 5.68%. like 1 kGy, 2 and 3 kGy showed different stage of thermal degradation phases, where 2 kGy started from 64.57 °C in the first stage and ended with 489.93 °C where the weight losses were 3.4% and 7.7%, respectively. And 3 kGy started from 67.68 °C and ended with 489.48 °C.

The results illustrated that irradiated CMC/Glyc is thermally stable than unirradiated one. So, our obtained data are in agreement with those in previous studies (Abdel Ghaffar *et al*., 2019), (Abdel-Ghaffar and Ali, 2022) who found that increasing thermal stability is accompanied with increasing of irradiation dose levels. 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 compared with CMC (Senna *et al*., 2000), (Ibrahim *et al*., 2013) and (Ibrahim *et al*., 2014).

One of the most notable differences is the residue left at 491°C **(Figure 3, a and b)**. The unirradiated sample (0kGy) has the lowest thermal stability in terms of final mass, leaving only about 18.4% of its weight. All irradiated samples (1, 2, and 3 kGy) show a higher residual mass (between 24% and 26%). This indicates that irradiation promotes the formation of a more thermally stable carbonaceous char, which is a common effect of gamma irradiation on polysaccharide derivatives. However, The TGA data suggests that while low-dose irradiation (1–3 kGy) does not drastically change the primary decomposition temperature of your CMC films, it does improve the overall thermal stability at high temperatures by increasing the residual char.

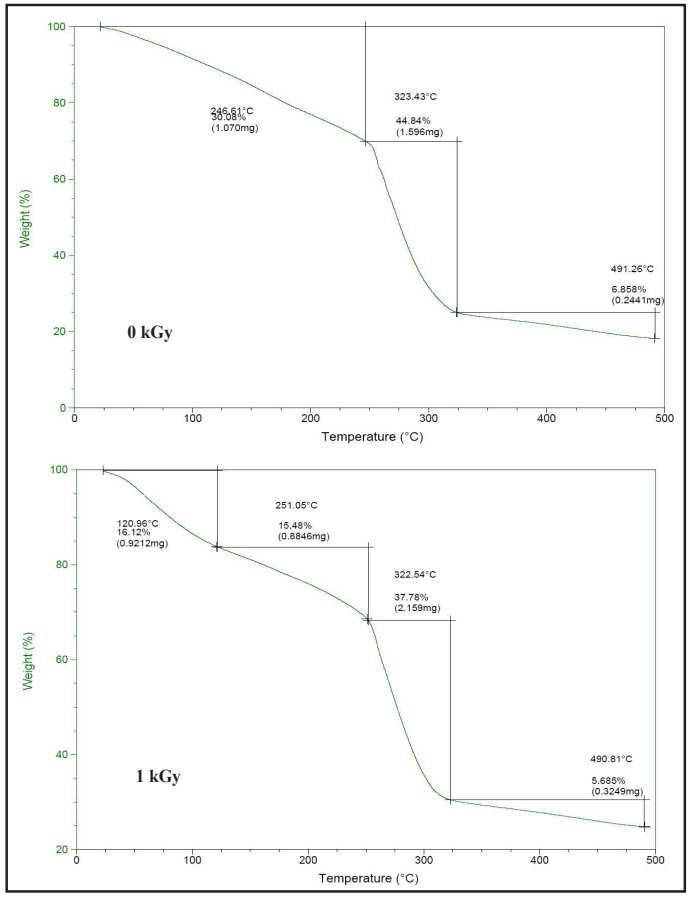

Figure (3a): Thermogravimetric analysis (TGA) of irradiated CMC/Glyc film (0 and 1 kGy)

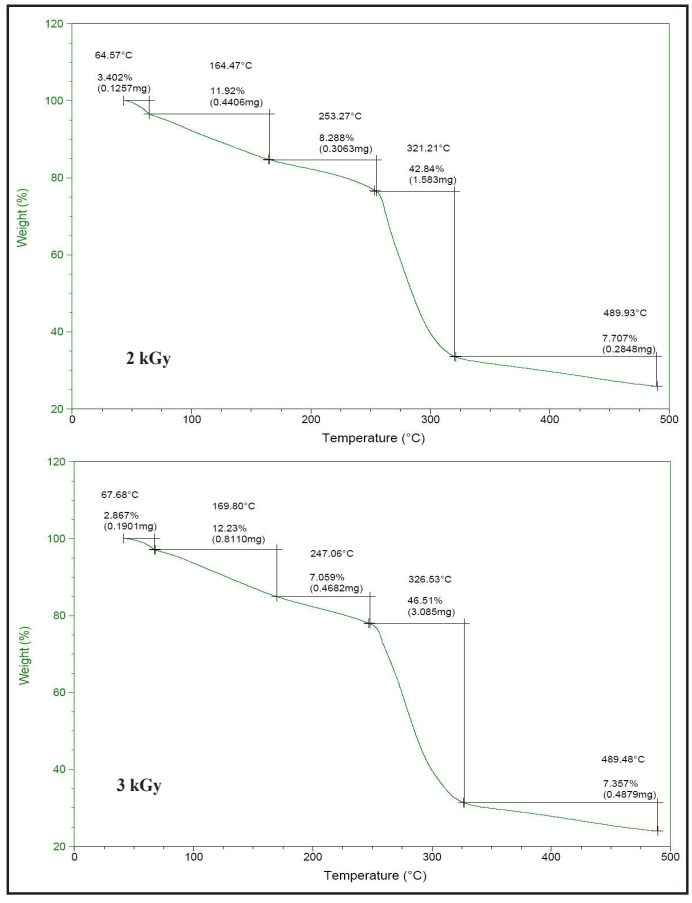

Figure (3b): Thermogravimetric analysis (TGA) of irradiated CMC/Glyc film (2 and 3 kGy)

Differential Scanning Calorimetry (DSC)

Differential scanning colometry (DSC) curves were plotted for CMC/Glyc before and after gamma irradiation to different doses as shown in **Figure 4 (a and b)**. These curves track the heat flow of both irradiated and unirradiated samples as they are heated from room temperature to nearly 500°C. Since the "Exo Up" indicator is present, peaks pointing upward represent exothermic events (releasing heat), while dips represent endothermic events (absorbing heat, such as melting).

The DSC curve shows endothermic peaks; at 307 °C (from 251.5 to 362.5 °C), 306.11 °C (from 253.27 to 358.95 °C),

303.00 °C (from 254.61 to 351.39 °C) and 307.44 °C (from 250.17 to 364.71 °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). Our finding is in agreement with (El-Sakhawy *et al*., 2019) who found that CMC have two endothermic curves.

Furthermore, increasing the dose to 2 kGy slightly increases this temperature (from 251.50 °C to 254.61°C), suggesting that moderate irradiation may slightly stabilize the crystalline structure. However, at 3 kGy, this temperature drops back down to 250.17 °C, which might indicate the onset of polymer degradation or "chain scission" outweighing the benefits of cross-linking. Compared to 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. Additionally, the enthalpy change (ΔH) significantly decreases from the Control (614.7 mJ) to the 2 kGy sample (421.1 mJ). This suggests that the 2 kGy irradiation has already "pre-cured" or cross-linked the material, leaving less residual reactive energy to be released during the DSC scan.

There is a sharp rebound in enthalpy at 3 kGy (594.4 mJ). This often indicates that the higher radiation dose has broken polymer chains (degradation), creating new reactive sites that release more energy when heated.

The combined TGA and DSC results indicate a 'dual-mode' transition within the CMC/glycerol matrix following 1–3 kGy irradiation. While thermal analysis highlights the fragmentation and scission of the polymer backbone, the mechanical behavior is primarily governed by the reorganization and cross-linking of these fragments into a more rigid, albeit thermally susceptible, network. This simultaneous occurrence of structural degradation and the formation of a more brittle architecture is a recognized characteristic of irradiated polysaccharides (Mahmud *et al*., 2026).

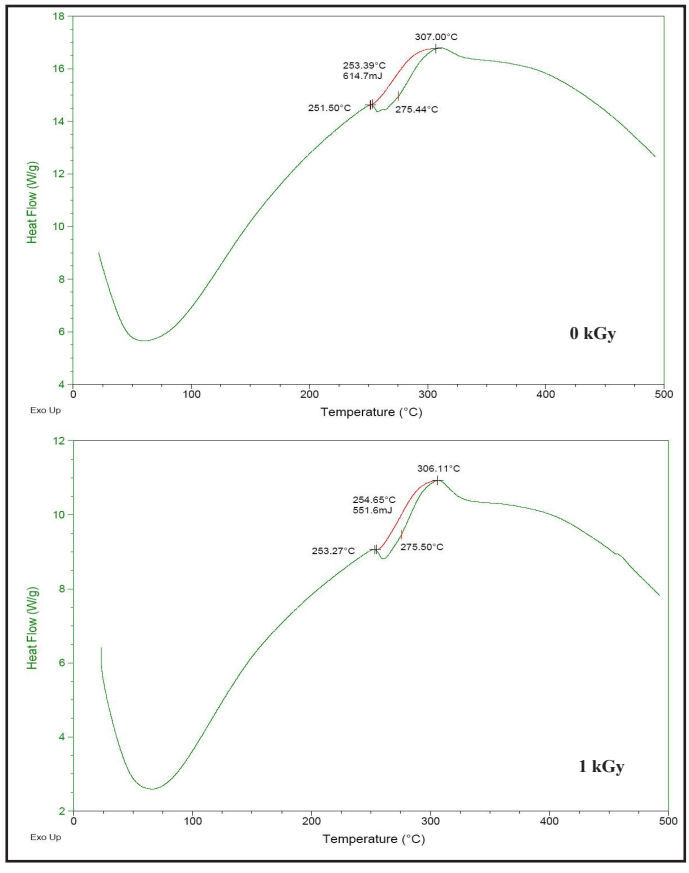

Figure (4a): Differential scanning calorimetry (DSC) analysis of irradiated CMC/Glyc film (0 and 1 kGy)

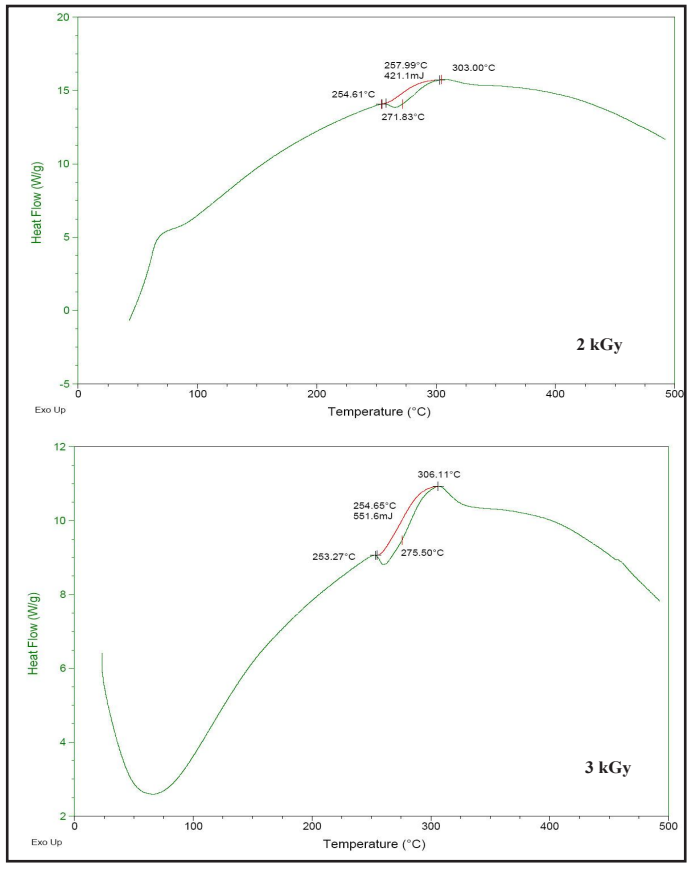

Figure (4b): Differential scanning calorimetry (DSC) analysis of irradiated CMC/Glyc film (2 and 3 kGy)

Thermomechanical Analysis (TMA)

By using TMA method for CMC-Glycerol films, the thermal fingerprint of the films expresses the film stability under the influence of heat and ionizing radiation. Thermomechanical analysis (TMA) involves placing a sample in a furnace under constant stress (compression, tension, or flexure) while systematically changing its temperature. The technique detects any deformation that occurs at specific temperatures,

making it especially useful for characterizing viscoelastic materials like organic polymers, including CMC. Such materials display both viscous and elastic behavior, which governs their mechanical response under stress.

Based on the Thermomechanical Analysis (TMA) shown in **Figure (5)**, irradiation doses (from 0 kGy to 3 kGy) influence the dimensional stability of the sample as a function of temperature. Regarding low doses, often show the highest structural stability. In mechanical testing, this is where the material shows the smallest displacement, meaning it is more resistant to deformation. A common trend across all samples is a contraction (dimensional change) as temperature increases, which is characteristic of materials with internal stresses or those undergoing a specific phase transitions/cross-linking effect. The "slope, rate of dimensional change" or the rate of contraction changes at specific temperature intervals, often indicating a softening point. Control sample shows a very gradual, smooth contraction starting around 40 °C and accelerating until 100 °C, however irradiated films at dose 1 kGy showed a much sharper initial drop between 30 °C and 50 °C, then stabilizes significantly compared to the 0 kGy sample (James, 2017).

On the other hand, samples irradiated at doses 2 kGy and 3 kGy show a more linear, steady rate of contraction. Interestingly, the 3 kGy sample shows a slight upward turn (expansion) after 100°C, which suggests the irradiation might have induced enough cross-linking to provide some structural "spring-back, effect of the cross-linked network resisting the thermal collapse of the polymer chains" or thermal expansion once the initial contraction phase is over. Films irradiated at dose 1 kGy, seem to be stabilize more rapidly. After the initial drop, the curve is flatter between 60 °C and 120 °C than the 0 kGy control.

Irradiation usually does one of two things: it creates cross-links (strengthening) or causes chain scission (weakening). The transition in the 3 kGy plot - where it stops contracting and starts slightly expanding at high heat - is a strong indicator of an increased cross-link density. In addition, in viscoelastic materials, gradually increasing temperature leads to changes in properties such as shrinkage, expansion, swelling, and softening. This restricts the polymer chains from collapsing further. Thus, Irradiation appears to be shifting the onset of dimensional change. While the 0 kGy sample begins its major descent around 50°C, the irradiated samples (especially 1 kGy) show earlier sensitivity but reach a "plateau" sooner. (Bhattacharya, 2000).

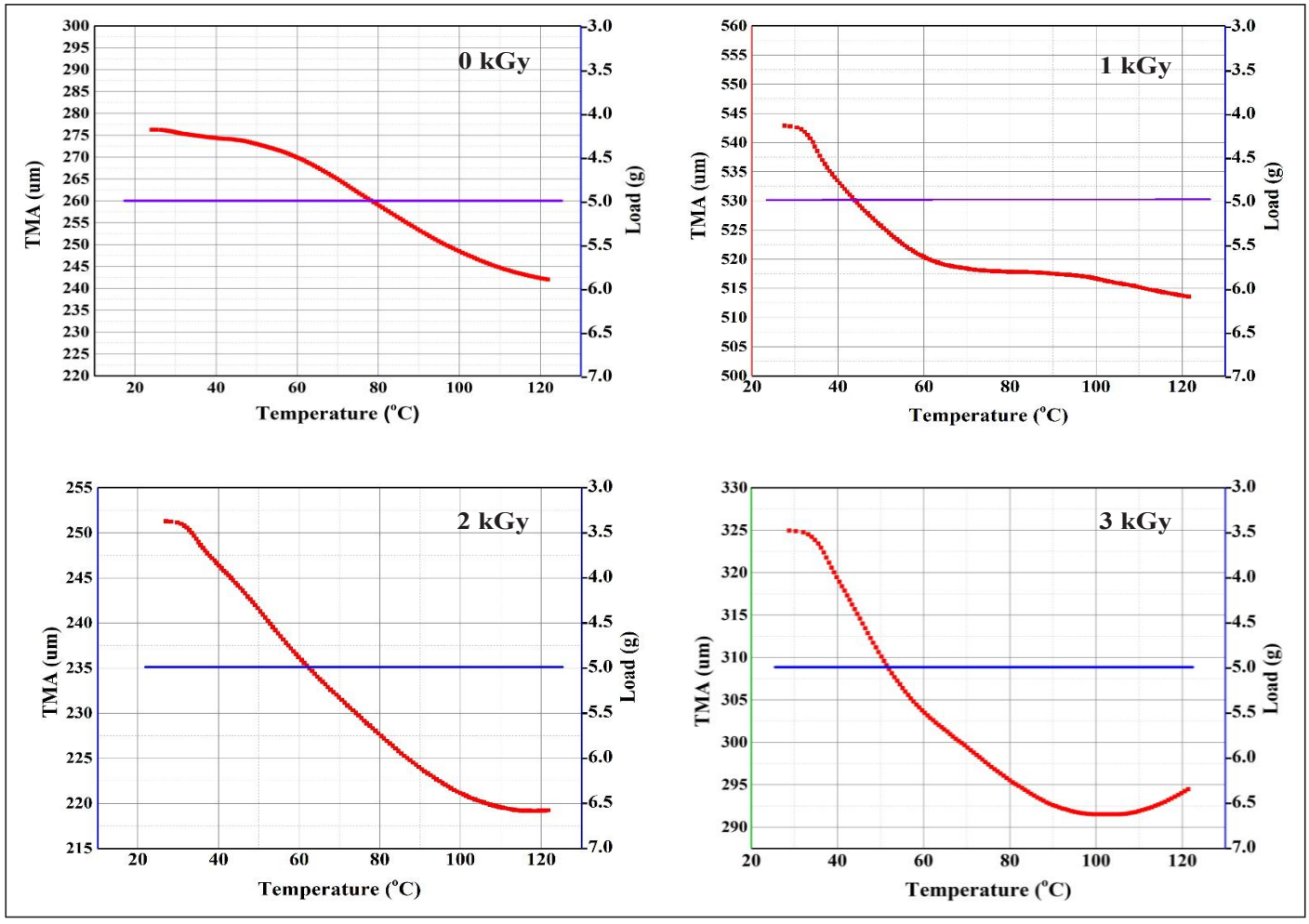

Figure (5): Thermomechanical Analysis (TMA) of irradiated CMC/Glyc edible films at different irradiation doses

Barrier properties

To extend the shelf life of food products, the barrier properties of packaging films are essential. These properties are measured by water vapor and gas permeability, which depend on the film's internal structure—specifically the amorphous regions where permeation occurs. Additives like plasticizers play a dual role; they modify the film's molecular chain mobility and diffusion coefficients, thereby impacting both its protective capabilities and its physical durability (García *et al*., 2009).

Water vapor rate transmission (WVTR)

The rate of water vapor transmission (WVTR) is a crucial property of edible films. The results for WVRT values are illustrated in **Figure (6–B)**. At a radiation dose of 1 kGy, the treatment did not yield significant differences in the WVTR of irradiated CMC/Glyc films. However, at doses of 2 and 3 kGy, there was a notable decrease in WVTR compared to the control. Furthermore, CMC/Glyc films can help prolong the shelf life of fresh foods by reducing dehydration, oxidative rancidity, and surface browning. Consequently, low gamma irradiation dose reduces the WVTR because the new cross-links create a denser "mesh" that molecules can't easily pass through (Beghetto *et al*., 2026) and (Mahmud *et al*., 2026). Nevertheless, their hydrophilic nature limits their effectiveness as barriers against water vapor (Nelida Lucia del, 2016). Therefore, The transmission of water vapor through a film typically takes place via its hydrophilic portions, with the rate dependent on the balance between hydrophilic and hydrophobic components within the film (Rojas-Graü *et al*., 2007).

Although CMC is inherently hydrophilic, its incorporation into blend films unexpectedly reduced the water vapor transmission rate. This phenomenon in CMC/Glyc films can be attributed to: (1) the robust intermolecular interactions between CMC and glycerol create tighter molecular packing and greater film compactness, and (2) the crystalline regions of CMC force water molecules to navigate around insoluble crystals, slowing their diffusion through the matrix (Zivanovic *et al*., 2007).

Oxygen and carbon dioxide permeability

Assessing the permeability of films or coatings to CO_2 and O_2 is vital for evaluating the physiological quality of coated fruits during storage. Researchers often simplify this measurement by testing isolated films rather than the coated food products themselves. This approach is supported by the findings of (Garcia *et al*., 2006), which demonstrate that water vapor permeability (WVP) values remain consistent between standalone films and applied coatings. The design of protective coatings must be tailored to the specific needs of the food item. For fresh produce, a coating should provide a strong water vapor barrier to maintain texture while allowing for moderate CO_2 and O_2 exchange to support natural respiration. In contrast, for dried fruits and nuts, the priority shifts to a strict barrier against both moisture (to preserve crispness) and oxygen (to prevent lipid oxidation) (Nelida Lucia del, 2016). Maintaining gas barrier properties is fundamental to preventing food degradation. Specifically, regulating O_2 and CO_2 levels is critical for managing respiration and oxidation without triggering anaerobic spoilage or excessive gas buildup. Beyond these functional traits, an ideal coating should preserve the fresh quality of produce, enhance its visual gloss without creating off-flavors, and remain both low-viscosity and cost-effective for commercial application (Dhall, 2013).

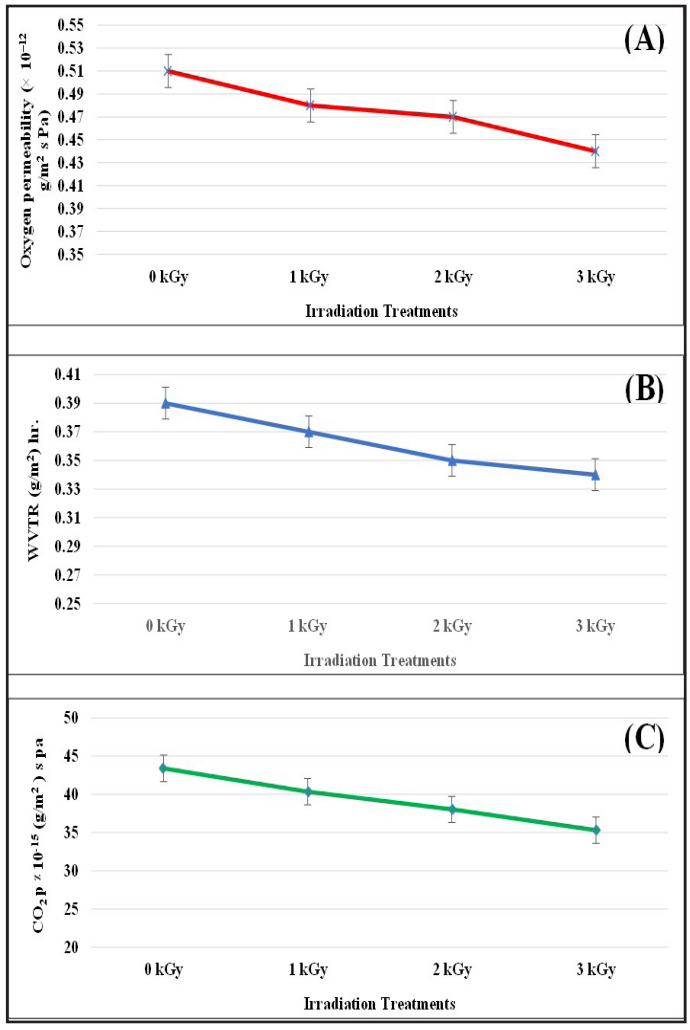

Figure (6): Characterization of CMC/Glyc film properties, (A) Oxygen Permeability, (B) Water Vapor Rate Transmission (WVTR), (C) CO_2 Permeability

In general, CO_2 passes through films more easily than O_2, as shown in **Figure (6, A and C)**. While O_2 is technically smaller (3.1Å) than CO_2 (3.4Å), the chemical "compatibility" or solubility of CO_2 within the film material is much higher. This higher solubility allows CO_2 to permeate faster, even though its larger size slightly slows down

its physical movement (diffusion) through the polymer chains (Robertson *et al*., 2013). Permeability of both CO_2 and O_2 in unirradiated CMC/Glyc was 43.42 and 0.51 cm^3/m^2·day, respectively. The CMC/Glyc film should regulate gas exchange effectively, ensuring that CO_2 levels do not reach inhibitory concentrations or trigger anaerobic respiration within the fruit's internal environment. As well as, did not deplete the O_2 (Chakravartula *et al*., 2019). Irradiation treatment (low doses) reduces the gas permeability (O_2 and CO_2) and the reduction increased with irradiation dose level increased, because the new cross-links create a denser "mesh" that molecules can't easily pass through (Beghetto *et al*., 2026) and (Mahmud *et al*., 2026). However, at 3 kGy of irradiation, CO_2 and O_2 were 35.32 and 0.44 cm^3/m^2·day, respectively. The process of gas permeation through polymer matrices is multifaceted, involving a complex interplay of variables. These factors are categorized into gas-specific attributes—including molecular size, polarity, and chemical inertness—and material-specific characteristics, such as the degree of crystallinity, the extent of cross-linking, and the inherent stiffness of the polymer chains (Chakravartula *et al*., 2019). The results indicate that CMC/Glyc films subjected to irradiation treatment maintain favorable gas permeability. This performance facilitates the development of an optimal modified atmosphere, which extends product shelf life while successfully avoiding the risk of anaerobic conditions.

Conclusions

The findings confirm that CMC/Glycerol films treated with an irradiation dose of 3 kGy represent a high-potential, eco-friendly candidate for the food packaging industry. These films offer a rare combination of high transparency, improved mechanical durability, and tuned gas barrier properties, making them effective for extending the shelf life of both fresh produce and moisture-sensitive food products.

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