

Bioactive okra mucilage films with *Aloysia citrodora* extract: a natural approach to fish preservation under refrigeration

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ABSTRACT

Background and Objectives: This study investigated the extraction of okra mucilage and its application in developing bioactive films enriched with *Aloysia citrodora* extract for food packaging. The effects of microwave-assisted extraction and UV treatment on film properties and preservation performance were evaluated.

Materials and Methods: Okra mucilage was extracted using conventional solvent and microwave-assisted methods. The phenolic profile of *A. citrodora* extract was analyzed by HPLC-DAD. Films containing up to 2% extract were prepared and subjected to UV treatment. Mechanical properties, thickness, water vapor permeability (WVP), antioxidant capacity (TPC and DPPH), antimicrobial activity, and preservation efficacy were assessed in refrigerated fish fillets.

Results: Microwave extraction slightly improved mucilage yield (8.7 vs. 8.3 g/100 g). Luteolin-7-O-diglucuronide and verbascoside were the dominant phenolics. UV-treated films with 2% extract showed higher tensile strength (45.71 MPa) and lower WVP (4.36 g mm/m² day kPa) compared to the controls. Antioxidant activity and antimicrobial inhibition against foodborne pathogens were significantly enhanced. Treated films delayed *Pseudomonas aeruginosa* growth in fish fillets.

Conclusion: Combining microwave extraction and UV treatment improved film functionality, highlighting their potential as natural active packaging materials.

Keywords: Food preservation; Antimicrobial agents; Antioxidants; Polysaccharides; Plant extracts

INTRODUCTION

In recent years, growing consumer awareness of food safety, environmental sustainability, and health has driven demand for natural preservatives and eco-friendly packaging materials. Perishable foods such as fish are highly susceptible to microbial spoilage, lipid oxidation, and sensory deterioration during refrigerated storage (1). Conventional synthetic preservatives and plastic packaging materials, while effective, pose health and environmental concerns due to chemical migration and non-biodegradability (2).

As a result, attention has shifted toward developing biodegradable active packaging systems that integrate natural antimicrobial and antioxidant agents into edible films or coatings (3). Among various natural polymers, okra (*Abelmoschus esculentus*) mucilage has shown considerable potential as a biodegradable film-forming agent. Okra mucilage is mainly composed of rhamnogalacturonan polysaccharides with a galacturonic acid-rhamnose backbone and branched sugar side chains. This structure gives high viscosity, strong water-holding and emulsifying properties, allowing the formation of flexible films

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with good barrier performance. Compared with biopolymers such as chitosan, okra mucilage provides better flexibility and moisture retention, making it well suited for incorporating bioactive compounds into edible films (4, 5). It exhibits excellent viscosity, water-holding capacity, and emulsifying properties, largely attributed to its complex polysaccharide composition (6, 7). Okra mucilage films can form uniform, flexible matrices that act as barriers against oxygen and moisture, making them suitable carriers for active compounds. However, to further enhance their functional properties, incorporation of plant-derived bioactive extracts has become a popular strategy. One promising botanical additive is lemon verbena (*Aloysia citrodora*), an aromatic plant known for its strong antimicrobial and antioxidant properties due to a high content of essential oils and phenolic compounds such as citral, limonene, and geraniol (8). These compounds have demonstrated efficacy in inhibiting a wide range of foodborne pathogens and in retarding oxidative degradation in protein- and fat-rich foods. The efficacy of these bioactives, however, significantly depends on the extraction method used (9, 10). For instance, microwave-assisted extraction offers advantages over conventional solvent methods by enabling rapid cell rupture, reduced solvent usage, and improved retention of thermolabile compounds (11, 12). This study compared microwave-assisted and conventional solvent extraction methods to recover bioactive compounds from *A. citrodora*, evaluating phenolic content, antioxidant and antimicrobial activity, and incorporation into okra mucilage films. UV treatment was also applied to improve film structure and bioactive performance by promoting cross-linking and enhancing the stability and release of active compounds (13). Moreover, UV exposure may induce the formation of reactive quinones and radicals from phenolic precursors, which exert stronger inhibitory effects on microbial cell walls (14). Although bioactive films have advanced, few studies have examined the combined effects of okra mucilage, lemon verbena extract (*A. citrodora*), and UV/microwave treatments on preserving high-value fish such as beluga sturgeon. Due to its high moisture and fat content, beluga sturgeon is highly perishable and serves as an ideal model to evaluate natural preservation strategies. The novelty of this study lies in the synergistic use of ultrasound-modified okra mucilage and *A. citrodora* extract, which enhances antimicrobial and antioxidant activity, thereby im-

proving the shelf life and quality of beluga sturgeon fillets. This distinguishes our work from previous studies. Accordingly, the study developed okra mucilage-based edible films incorporated with lemon verbena extract obtained via microwave and solvent extraction, followed by UV treatment. The films were evaluated for antibacterial activity, and preservation effectiveness during refrigerated storage, offering insights into multifunctional, biodegradable packaging for extending the shelf life and safety of fresh fish products.

MATERIALS AND METHODS

Materials and reagents. Okra, lemon verbena, and fresh beluga sturgeon were sourced locally and processed immediately for films and experiments.

Extraction of *Aloysia citrodora* (lemon verbena) extracts and ultrasound treatment of films. Solvent extraction of *A. citrodora* leaves was conducted according to the method reported by (15). Extraction of *A. citrodora* leaves was performed according to the method described in (16). Ultrasound treatment was applied to okra mucilage films using a 13 mm probe at 150 W/cm² for 10 minutes at room temperature to enhance bioactive compound dispersion and film properties (17). Film codes include: NN (control), NS1 and NS2 (okra films with 1% and 2% extract via solvent extraction), NM1 and NM2 (okra films with 1% and 2% extract via microwave extraction).

Identification of major compounds in *Aloysia citrodora* extract by HPLC-DAD and MS/MS. Major compounds in *A. citrodora* extract were identified using HPLC-DAD coupled with MS/MS (18), based on retention times, UV, and mass spectra.

Film formation. Okra mucilage films with 1-2% lemon verbena extract were cast, dried for 24 h, and UV-treated for 1 h to improve their properties (19).

Determination of physical properties of the films. Film thickness was measured at five points per sample using a micrometer (Mitutoyo, Japan) with 0.001 mm precision, and the average was reported (20).

Determination of mechanical properties of the films. Film tensile strength and elongation were mea-

sured using a texture analyzer (ASTM D882) after 48 h conditioning at 25°C and 50 ± 5% RH (21).

Determination of structural properties of the films. ATR–FTIR was used to study interactions in films containing lemon verbena extract (22).

Determination of functional properties of the films. The total phenolic content of the films was measured using the Folin–Ciocalteu method, and their antioxidant activity was assessed using the DPPH assay, following the procedure described by (10).

Microbiological assay. Antimicrobial activity of the films was tested against *Staphylococcus aureus*, *Bacillus cereus*, and *Escherichia coli* using the agar disk diffusion method (23).

Evaluation of the effect of films on the quality of *Huso huso* filets during storage. For selective enumeration of *P. aeruginosa* (ATCC 27853), 100 µL of each dilution was plated on cetrimide agar and incubated at 25°C for 48 hours, after which colonies were counted (24).

Sensory evaluation. Sensory evaluation of raw coated fish filets was conducted by a trained panel of 23 members (25–35 years) following Pesavento et al. (33). Appearance, odor, texture, and overall acceptability were rated on a 5-point hedonic scale (5 = best, 1 = worst). Samples with mean scores below 3.5 were considered unacceptable (25).

Statistical analysis. Experiments were conducted in triplicate, and results are reported as mean ± SD. Statistical analysis was performed using Minitab 16, with one-way ANOVA and Tukey's post-hoc test at $p < 0.05$. Graphs were created using Microsoft Excel 2013.

RESULTS

Yield of okra mucilage extraction and identification of major compounds in *Aloysia citrodora* extract. The yield of okra mucilage was determined for both conventional solvent extraction and microwave-assisted extraction. Using the solvent extraction method, dried okra pods yielded 8.3 ± 0.2 g per 100 g of dried pods. In comparison, microwave-assisted extraction produced 8.7 ± 0.3 g per 100 g of dried

Pods. The microwave-assisted method resulted in a slightly higher yield than the conventional solvent extraction method. The retention times, peak areas, and relative contents of the compounds identified in *Aloysia citrodora* extract are presented in Table 1. Chromatographic analysis revealed four major compounds: Luteolin-7-O-diglucuronide, verbascoside, chrysoeriol-7-O-diglucuronide, and isoverbacoside. These compounds represented the predominant phenolic constituents detected in the extract. The identified compounds exhibited distinct retention times and peak areas, indicating differences in their relative abundance. Luteolin-7-O-diglucuronide and verbascoside showed the highest relative proportions among the detected compounds.

The mechanical properties of okra mucilage-based films, including tensile strength (TS) and elongation at break (E), are presented in Fig. 1. Both parameters were affected by UV treatment and the incorporation of *Aloysia citrodora* extract. The tensile strength of the films increased following UV treatment. The untreated control film (NN) exhibited the lowest TS value (34.19 ± 4.19 MPa), whereas the highest TS (45.71 ± 3.62 MPa) was observed in the film containing 2% microwave-extracted *Aloysia citrodora* extract subjected to UV irradiation (UM2). Films containing the extract without UV exposure showed moderate TS values compared to the control. Differences between extraction methods of the plant extract did not result in statistically significant variations in TS. The untreated control film (NN) showed the highest E value (12.11%), indicating greater flexibility. Films containing *Aloysia citrodora* extract without UV treatment (NS1, NS2, NM1, NM2) exhibited slightly lower E values, ranging from 11.91% to 11.83%. In contrast, all UV-treated films (UN, US1, US2, UM1, UM2) showed reduced elongation at break, with values between 9.86% and 9.46%. The lowest E value (9.46%) was recorded for the UM2 formulation. These results indicate that UV irradiation reduced film flexibility while increasing tensile strength.

The thickness of okra mucilage-based films is presented in Table 2. UV treatment and extraction methods did not significantly affect film thickness ($p < 0.05$). In contrast, the incorporation of *Aloysia citrodora* extract increased film thickness, with the highest value observed at 2% extract concentration (0.71 ± 0.04 mm). The increase in thickness corresponded with the addition of extract and the associated rise in dry matter content within the film matrix.

Table 1. Retention times, peak areas, and relative contents of major phenolic compounds in *Aloysia citrodora* extract

Phenolic Compound	Retention Time (min)	Peak Area (A ²)	Relative Content (%)
Luteolin-7-O-diglucuronide	11.12	78.201	57.28
Verbascoside	7.58	13.192	21.27
Chrysoeriol-7-O-Diglucuronide	5.24	32.158	42.22
Isoverbascoside	8.83	26.131	18.59
Total	—	—	96.79

Retention times correspond to HPLC-DAD analysis. Peak areas were calculated from diode array detector chromatograms, and relative contents (%) represent the proportion of each compound within the total phenolic fraction.

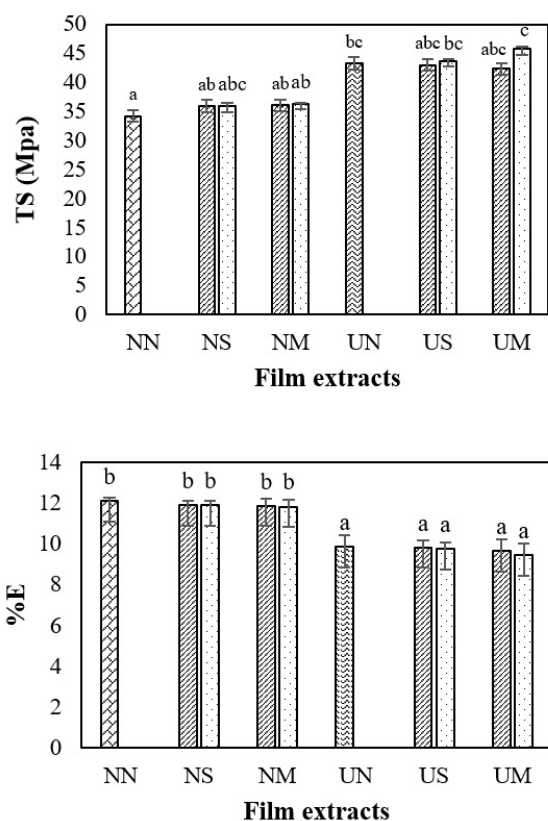


Fig. 1. Effect of UV treatment and incorporation of *Aloysia citrodora* extract on the mechanical properties of okra mucilage-based films. Data are presented as mean \pm standard deviation ($n = 3$). Different letters denote statistically significant differences ($p < 0.05$). Abbreviations: NN, untreated film; NS, film with solvent-extracted *Aloysia citrodora* extract (1% or 2%); NM, film with microwave-extracted *Aloysia citrodora* (1% or 2%); UN, UV-treated film without extract; US, UV-treated film with solvent extract 1% or 2%; UM, UV-treated film with microwave extract (1% or 2%).

Table 2. Thickness and WVP of okra mucilage-based films.

Sample	Thickness	WVP (g mm/ m ² day kPa)
NN	0.53 \pm 0.01 ^{ab}	6.89 \pm 0.52 ^e
NS1	0.55 \pm 0.02 ^{abc}	6.47 \pm 0.19 ^{de}
NS2	0.59 \pm 0.02 ^{bcd}	6.73 \pm 0.86 ^e
NM1	0.57 \pm 0.01 ^{abc}	6.63 \pm 0.61 ^{de}
NM2	0.61 \pm 0.00 ^{cd}	6.42 \pm 0.40 ^{bcd}
UN	0.52 \pm 0.01 ^a	5.21 \pm 0.43 ^{ab}
US1	0.61 \pm 0.00 ^{cd}	5.38 \pm 0.55 ^{abc}
US2	0.71 \pm 0.04 ^e	4.36 \pm 0.21 ^a
UM1	0.60 \pm 0.01 ^{cd}	5.37 \pm 0.60 ^{abc}
UM2	0.65 \pm 0.02 ^d	4.89 \pm 0.29 ^a

Data are means \pm SD ($n = 3$). Values with different letters are significantly different ($p < 0.05$). ^{a-e} significance difference in the columns ($p < 0.05$).

This consistency reflected the uniform concentration of okra mucilage across all formulations. In contrast, water vapor permeability (WVP) varied significantly between treatments. The highest WVP was measured in the control film (NN), whereas the lowest WVP was observed in the film containing 2% *Aloysia citrodora* extract and subjected to UV irradiation (US2), indicating a significant reduction in permeability ($p < 0.05$). The extraction method did not produce statistically significant differences in WVP, but both the extract concentration and UV treatment contributed to lower permeability values. The FTIR spectra of okra mucilage-based films, including the control (without *Aloysia citrodora* extract), the film containing the extract, and the UV-treated film containing the extract, are shown in Fig. 2. The control film exhibited characteristic polysaccharide absorption bands, with a broad

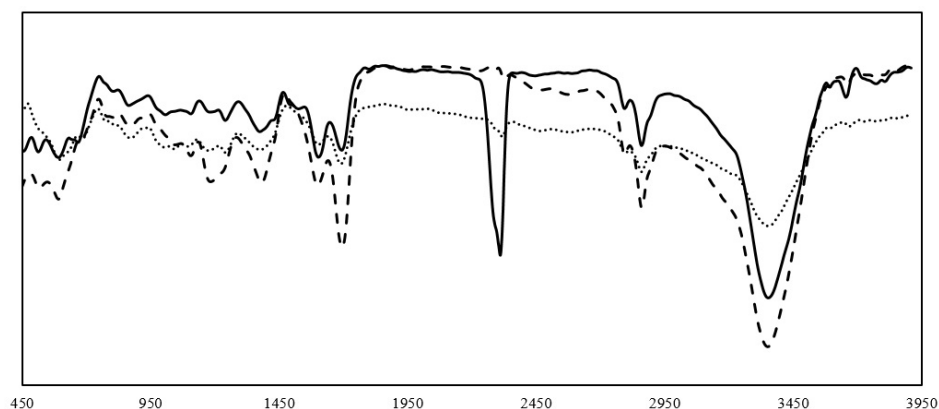


Fig. 2. FTIR spectra of okra mucilage-based edible films: control film without *Aloysia citrodora* extract (solid line), film containing *A. citrodora* extract (dotted line), and UV-treated film containing *A. citrodora* extract (dashed line).

O–H stretching around 3400 cm^{-1} and C–H stretching near 2900 cm^{-1} . Incorporation of *Aloysia citrodora* extract caused a slight decrease in the intensity of the O–H stretching band, indicating potential hydrogen bonding interactions between the extract's phenolic compounds and the film matrix. UV treatment further accentuated these changes, suggesting enhanced molecular interactions or structural rearrangements. Variations were also observed in the fingerprint region ($600\text{--}1500\text{ cm}^{-1}$), reflecting modifications in the polysaccharide network and the presence of polyphenolic compounds from the extract.

The antioxidant properties of okra mucilage-based films containing *Aloysia citrodora* extract were evaluated. Films with 2% extract (NS2) exhibited the highest total phenolic content (TPC) at $18.96 \pm 0.72\text{ mg GAE/g}$ and the greatest DPPH radical scavenging activity at $20.62 \pm 1.03\%$ (Fig. 3). In contrast, films without extract (NN and UN) showed the lowest TPC and antioxidant activity. Antioxidant performance was primarily influenced by extract concentration rather than UV treatment. Films containing 2% extract demonstrated nearly double the DPPH scavenging activity compared to films with 1% extract, indicating a dose-dependent effect. No significant differences were observed between microwave-assisted and solvent extraction methods. The results confirm that the phenolic compounds in *Aloysia citrodora* extract contributed to the films' antioxidant activity.

The antimicrobial activity of okra mucilage-based films containing *Aloysia citrodora* extract was evaluated against *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus cereus* using the disk diffusion method (Table 3). Films containing 2% extract (NS2, NM2,

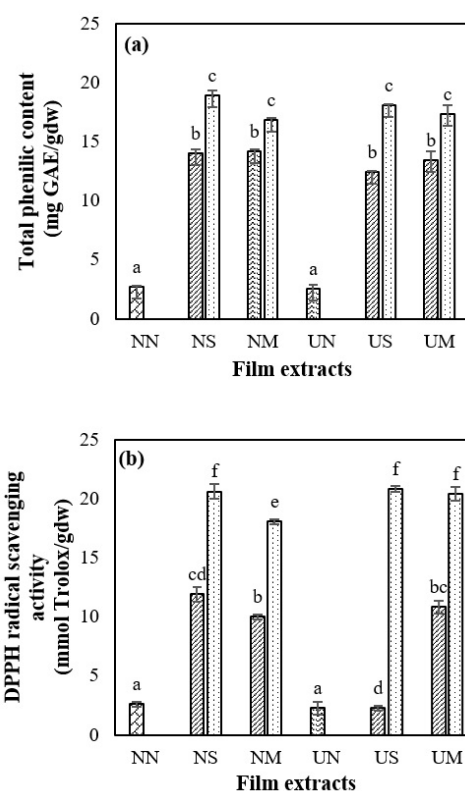


Fig. 3. Antioxidant properties of bioactive films containing *Aloysia citrodora* extract, showing TPC (a) and DPPH radical scavenging activity (b). Data are presented as mean values \pm standard deviation ($n = 3$). Different letters represent statistically significant differences ($p < 0.05$). Abbreviations: NN, untreated film; NS, film with solvent-extracted *Aloysia citrodora* extract (1% or 2%); NM, film with microwave-extracted *Aloysia citrodora* (1% or 2%); UN, UV-treated film without extract; US, UV-treated film with solvent extract (1% or 2%); UM, UV-treated film with microwave extract (1% or 2%).

Table 3. Antimicrobial activity of edible films containing *Aloysia citrodora* extract against *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus cereus* measured by disk diffusion method.

Treatment	<i>Escherichia coli</i>	<i>Staphylococcus aureus</i>	<i>Bacillus cereus</i>
NN	-	-	-
NS1	7.43 ± 0.21 ^a	8.23 ± 0.48 ^b	7.45 ± 0.25 ^a
NS2	9.20 ± 0.29 ^c	10.08 ± 0.17 ^d	10.78 ± 0.33 ^c
NM1	7.29 ± 0.06 ^a	8.70 ± 0.37 ^{bc}	7.64 ± 0.43 ^a
NM2	8.85 ± 0.50 ^{bc}	9.31 ± 0.38 ^c	8.94 ± 0.30 ^c
UN	-	-	-
US1	7.51 ± 0.50 ^a	7.68 ± 0.12 ^a	7.18 ± 0.04 ^a
US2	9.15 ± 0.18 ^c	10.22 ± 0.48 ^d	10.36 ± 0.10 ^d
UM1	7.72 ± 0.40 ^{ab}	8.19 ± 0.02 ^b	8.23 ± 0.20 ^b
UM2	9.01 ± 0.04 ^c	10.45 ± 0.29 ^d	10.14 ± 0.26 ^d

Data are means ± SD (n = 3). Values with different letters are significantly different (p < 0.05). ^{a-c} significance difference in the columns (p < 0.05).

US2, UM2) exhibited significantly larger inhibition zones compared to films with 1% extract and control films (NN and UN), which showed no antimicrobial activity. For *Bacillus cereus*, the highest inhibition zone was observed in NS2 (10.78 ± 0.33 mm), followed by US2 (10.36 ± 0.10 mm) and UM2 (10.14 ± 0.26 mm). *Staphylococcus aureus* was strongly inhibited by US2 (10.22 ± 0.48 mm) and UM2 (10.45 ± 0.29 mm), while *E. coli* showed smaller but statistically significant inhibition in NS2 (9.20 ± 0.29 mm) and US2 (9.15 ± 0.18 mm). The extraction method and extract concentration influenced antimicrobial performance, with 2% extract and microwave-assisted extraction yielding the highest activity. UV treatment also contributed to increased antimicrobial effects in treated films. The population of *Pseudomonas aeruginosa* in refrigerated fish fillets increased significantly (p < 0.05) over storage time in all samples. Untreated controls (NN and UN) exceeded the spoilage threshold of 7 log CFU/g by day 8. Films containing *Aloysia citrodora* extract inhibited the growth of *P. aeruginosa* in a concentration-dependent manner. The 2% extract treatments, particularly ultrasound-assisted films (UM2), showed the strongest antimicrobial effect, maintaining bacterial counts below the spoilage threshold longer than 1% extract films. The enhanced inhibition in UM2 was associated with improved extract dispersion, reduced micro-porosity, and increased film homogeneity, which promoted sustained release of bioactive compounds and stronger barrier properties. While 1% extract films delayed bacterial growth, they were insufficient to prevent counts from exceed-

ing spoilage levels by day 12. These results indicate that higher extract concentrations and combined film treatments are more effective in controlling *P. aeruginosa* proliferation during refrigerated storage.

DISCUSSION

The results demonstrated that microwave-assisted extraction enhanced the recovery of okra mucilage compared with the conventional solvent extraction method. This improvement suggests that the application of microwave energy facilitated more efficient disruption of plant cell structures, leading to improved mass transfer and release of polysaccharides. Similar observations have been reported for microwave-assisted extraction of plant biopolymers, where rapid internal heating improves extraction efficiency and reduces processing time (26). From a practical perspective, the higher yield obtained through microwave-assisted extraction indicates its potential as a more efficient and scalable technique for mucilage production. The identification of four major phenolic compounds in *Aloysia citrodora* extract highlights the chemical richness and functional potential of this plant material. The predominance of luteolin-7-O-diglucuronide and verbascoside suggests that these compounds may substantially influence the extract's bioactivity. Phenolic compounds with similar structures are widely recognized for their antioxidant properties and their ability to interact with biopolymer matrices through hydrogen bonding and other

intermolecular interactions (18). Such interactions may improve the structural cohesion and functional performance of edible films. The enhancement in tensile strength following UV treatment indicates the formation of a denser and more interconnected polymer network within the okra mucilage matrix. UV irradiation likely promoted cross-linking reactions between polysaccharide chains and phenolic compounds present in *Aloysia citrodora* extract, leading to improved intermolecular bonding and structural reinforcement (22). Such network strengthening is essential for improving film durability, load-bearing capacity, and resistance to mechanical stress during handling and storage. The simultaneous reduction in elongation at break reflects decreased polymer chain mobility as cross-link density increases. This inverse relationship between tensile strength and flexibility is commonly observed in cross-linked biopolymer systems, where enhanced rigidity limits extensibility (27). Therefore, UV treatment effectively shifted the films toward a stronger but less flexible structure. In contrast, the incorporation of *Aloysia citrodora* extract at 1-2% without UV exposure produced minimal changes in elongation, suggesting that the phenolic compounds were well dispersed within the matrix and did not significantly disrupt the native polymer arrangement (4). This indicates good compatibility between the extract and okra mucilage, allowing the films to maintain mechanical integrity while potentially benefiting from the extract's bioactive properties. 1-2% extract concentrations had little effect on film flexibility, as the low bioactive levels preserved the polymer network while still offering antioxidant and antimicrobial benefits. The increase in film thickness with the addition of *Aloysia citrodora* extract highlights the influence of solute content on the structural properties of okra mucilage-based films. Higher extract concentrations contributed additional solids to the film matrix, resulting in thicker films (28). This effect is important because film thickness directly influences barrier performance, mechanical strength, and the controlled release of bioactive compounds. Thicker films can better protect against moisture and oxygen transfer, increasing their suitability for food packaging. Consistent solubility ensures predictable behavior in applications requiring controlled dissolution or biodegradability. The observed reduction in water vapor permeability (WVP) in films containing the extract and treated with UV highlights the ability to enhance barrier

properties through structural modification. UV treatment likely promoted cross-linking and densification of the polymer matrix, while the extract added solids and facilitated interactions within the network, further improving the film's protective function (29). Lower WVP improves the film's effectiveness as a moisture barrier, which is critical for food packaging and preservation, as it can help reduce water loss, slow microbial growth, and maintain product quality. These findings demonstrate that combining bioactive extracts with UV treatment offers a practical strategy to modulate the barrier performance of okra mucilage-based films while retaining desirable solubility characteristics (13). The FTIR analysis demonstrates that incorporating *Aloysia citrodora* extract and applying UV treatment significantly alter the structure of okra mucilage-based films. Changes in O–H stretching and the fingerprint region suggest that phenolic compounds interact with the polysaccharide matrix, likely through hydrogen bonding, forming a more compact and cohesive polymer network. According to the tortuous path theory, this denser and more uniform matrix increases the diffusion path for water molecules, enhancing water vapor resistance. UV treatment further amplifies these effects, indicating additional cross-linking or structural rearrangements. These findings show that combining bioactive extracts with UV processing can effectively fine-tune the films' functional properties, including rigidity, tensile strength, and barrier performance (30). The results demonstrate that the antioxidant capacity of okra mucilage-based films can be effectively enhanced through the incorporation of *Aloysia citrodora* extract. The dose-dependent increase in TPC and DPPH scavenging activity indicates that higher extract concentrations provide more phenolic compounds, which act as active agents for neutralizing free radicals. This enhancement is significant for the development of functional edible films, as increased antioxidant activity can help protect food products from oxidative degradation and extend shelf life (31). UV treatment alone did not enhance the films' antioxidant activity, indicating that the phenolic-rich *Aloysia citrodora* extract is the main contributor to their bioactivity. This emphasizes the critical role of extract concentration in designing films with targeted antioxidant properties. Antibacterial tests showed that incorporating the extract effectively inhibited foodborne pathogens, particularly *Staphylococcus aureus* and *Bacillus cereus*. The in-

crease in inhibition zones with higher extract concentrations highlights the importance of dosage, as greater amounts of phenolics and terpenoids provide sufficient bioactive compounds to achieve strong antimicrobial effects (23). Microwave-assisted extraction improved antimicrobial activity, likely by preserving heat-sensitive bioactive compounds and enabling their more efficient release into the film matrix. This highlights that optimized extraction methods can enhance the effectiveness of plant-based films without increasing extract concentration. UV treatment further enhanced microbial inhibition, possibly by promoting cross-linking and photochemical activation of phenolic compounds, which improves their stability and uniform dispersion within the film (13). Uniform microwave heating promotes effective disruption of plant cell walls, facilitating the release of intracellular constituents, while shorter extraction times and lower solvent exposure limit thermal and oxidative degradation. The higher susceptibility of Gram-positive bacteria compared to Gram-negative *E. coli* emphasizes that the films' effectiveness can vary with bacterial structure (32). The results demonstrate that *Aloysia citrodora* extract effectively suppresses the growth of *P. aeruginosa*, a key psychrotrophic spoilage organism in chilled fish. The concentration-dependent antimicrobial effect highlights the importance of optimizing extract levels to achieve meaningful preservation. Ultrasound-assisted films (UM2) provided additional benefits by improving extract dispersion and reducing film micro-porosity, which enhanced the sustained release of bioactive compounds and reinforced the barrier against microbial contamination (33). The antimicrobial effect of *A. citrodora*, due to compounds like citral, limonene, and geranial, disrupts bacteria and inhibits growth. The 2% extract, especially in ultrasound-assisted films (UM2), shows stronger activity from better dispersion, reduced porosity, and enhanced release of bioactives, improving barrier properties and delaying spoilage. The sensory evaluation highlights the practical significance of *Aloysia citrodora*-enriched okra films in preserving the quality and consumer acceptability of perishable fish products. By maintaining higher scores for odor, color, texture, and overall acceptability, the films effectively delayed spoilage while preserving the original flavor profile, which is critical for high-value seafood like beluga sturgeon (25). Microwave-assisted extraction combined with UV treatment provided

additional benefits, likely by enhancing the stability and dispersion of bioactive compounds within the film matrix. These findings indicate that functional edible coatings can extend shelf life and maintain sensory appeal without introducing off-flavors, demonstrating their potential for industrial application in seafood preservation (34).

CONCLUSION

This study demonstrated that microwave-assisted extraction effectively improved the recovery of okra mucilage and preserved bioactive phenolic compounds from *Aloysia citrodora*. Incorporating the extract and applying UV treatment significantly enhanced the functional properties of okra mucilage-based films. UV irradiation strengthened the film structure, while the phenolic-rich extract improved antioxidant and antimicrobial activities. Additionally, the combination of extract and UV treatment enhanced the films' barrier properties against water vapor. Overall, the synergistic use of microwave extraction, UV treatment, and *A. citrodora* extract produced mechanically robust, biologically active, and environmentally friendly edible films, highlighting their potential as sustainable multifunctional packaging for improving food quality and shelf life. Future work may include testing the film's biodegradability in soil and evaluating its performance on other fatty fish species to further assess environmental sustainability and broader applicability. In conclusion, plant-extract-based edible films present a sustainable, natural, and effective strategy for extending the shelf life of perishable seafood.

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