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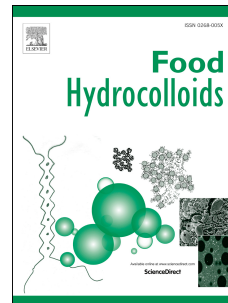
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Accepted Manuscript

Comprehensive characterization of active chitosan-gelatin blend films enriched with different essential oils

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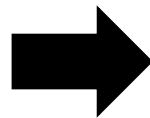


Chitosan

+



Gelatin

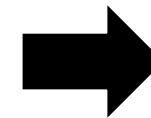


Chitosan-Gelatin Blend
FFS

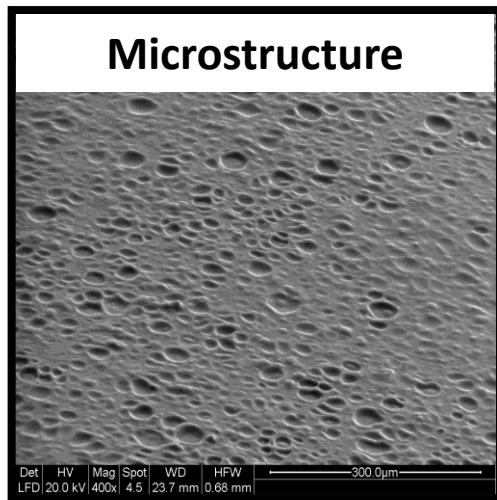
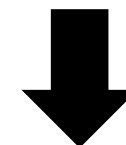
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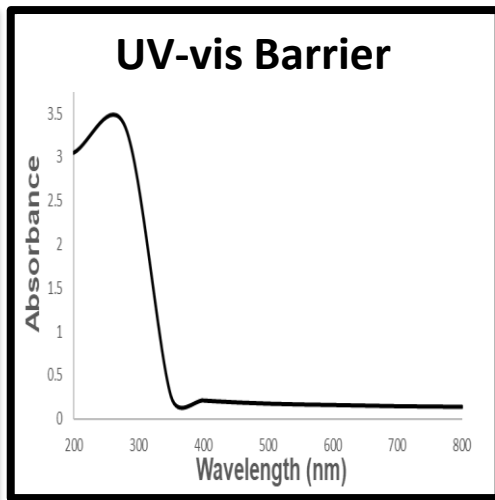
Essential oil (EO)



Chitosan-Gelatin-EO
FFS



Microstructure

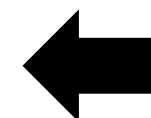


UV-vis Barrier

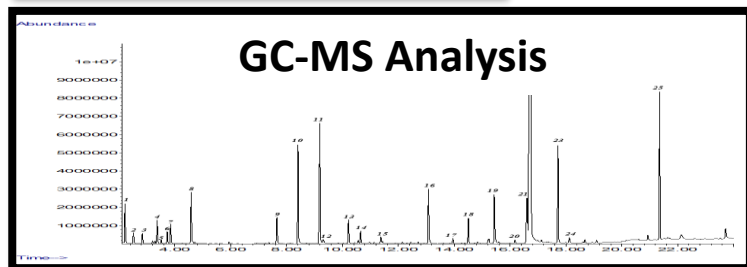


Antibacterial Activity

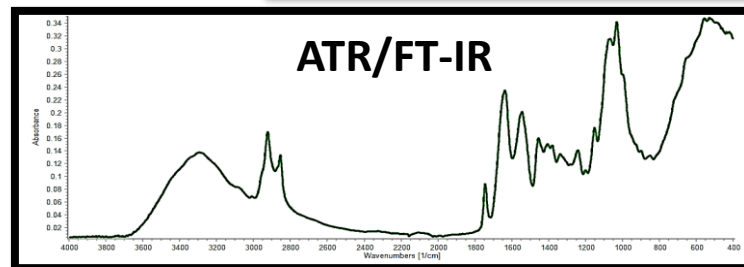
Food
Packaging
Applications



Chitosan-Gelatin-EO Film



GC-MS Analysis



ATR/FT-IR

1 **Comprehensive characterization of active chitosan-gelatin blend films enriched with**
2 **different essential oils**

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12 **Abstract**

13 Natural extracts and plant essential oils (EOs) have long been recognized as valid
14 alternatives to synthetic food additives owing to their proved wide-spectrum antimicrobial
15 capacity. The main aim of this study was to characterize the physical, mechanical, water
16 barrier, microstructural and antimicrobial properties of chitosan-gelatin blend films enriched
17 with cinnamon, citronella, pink clove, nutmeg and thyme EOs. The film microstructure
18 determined by scanning electron microscopy, showed that all active films had heterogeneous
19 surface: in particular, films including cinnamon, nutmeg and thyme EOs showed remarkable
20 pores on the surface. The possible interaction of chitosan-gelatin blend film with incorporated
21 EOs was investigated using Fourier-transform infrared (FT-IR) spectroscopy. Presence of
22 new bands and changes in the FT-IR spectra confirmed intermolecular interactions between
23 the chitosan-gelatin matrix and the EOs. The antimicrobial activity of films was determined
24 using the disk diffusion assay. Active films inhibited the growth of four major food bacterial
25 pathogens including *Campylobacter jejuni*, *Escherichia coli*, *Listeria monocytogenes* and
26 *Salmonella typhimurium* and, among the tested EOs, thyme was the most effective ($p < 0.05$).
27 The active films can be considered as effective barriers against UV light. The incorporation of
28 EOs to the chitosan-gelatin film increased thickness, moisture content, water vapor

29 permeability, b^* and ΔE^* values ($p < 0.05$) while it decreased L^* value, light transparency and
30 opacity ($p < 0.05$). Overall, the characterization of functional properties revealed that chitosan-
31 gelatin films incorporated with EOs could be used as environmentally friendly active food
32 packaging with antimicrobial properties and potential to extend the shelf-life of food products.

33 **Keywords:** Bio-Based Active Packaging; Chitosan-Gelatin Blend; Essential Oil; Scanning
34 Electron Microscopy (SEM); Fourier-Transform Infrared Spectroscopy (FT-IR)

35 1. Introduction

36 Environmental concerns as well as consumer demand for natural, minimally processed,
37 preservative-free and high-quality food, have raised the attention of food packaging
38 industries on the development of bio-based films enriched with natural compounds. Bio-
39 based films have been considered as attractive alternatives to plastic packaging due to their
40 excellent biodegradability, moreover, they can be blended with active compounds such as
41 antimicrobial agents to protect food against microbial deterioration and to extend the shelf life
42 of food products (De Leo et al., 2018; Shen & Kamdem, 2015).

43 Among biopolymers, chitosan (CS) and gelatin (GL) have shown outstanding film forming
44 property, non-toxicity, biocompatibility, biodegradability, stability and commercial availability.
45 The CS is a linear polysaccharide, commercially obtainable from deacetylation of chitin. This
46 polycationic biopolymer is soluble in solutions with pH below 6.5 due to the protonation of the
47 amino group (Bonilla, Poloni, Lourenço, & Sobral, 2018). The positively charged amino group
48 of CS interacts with negatively charged microbial cell membranes leading to the leakage of
49 proteinaceous and other intracellular constituents of the microorganisms (Bonilla & Sobral,
50 2016). Owing to the intrinsic antimicrobial property, chitosan has attracted considerable
51 commercial interest from food packaging companies as a natural alternative to synthetic
52 plastics.

53 GL is a natural water-soluble protein, obtainable from the partial hydrolysis of collagen. It has
54 a unique amino acid sequence with high contents of proline, glycine and hydroxyproline,
55 which help in the formation of a flexible film with excellent barrier properties to gases, volatile
56 compounds, oils and UV light (Wu, Sun, Guo, Ge, & Zhang, 2017; Figueroa-Lopez, Andrade-

57 Mahecha, & Torres-Vargas, 2018). Previous studies showed that CS and GL have good
58 barrier to gases such as CO₂ and O₂. However, their use is currently limited due to weak
59 mechanical and water barrier properties. Since CS and GL are hydrophilic biopolymers with
60 good affinity and compatibility, blending CS and GL (CS-GL) to form a composite film may
61 improve mechanical and water barrier response compared to single component films. This is
62 due to the ability to associate through electrostatic interaction between the negatively
63 charged carboxyl group of GL and the positively charged amino group of CS at appropriate
64 pH conditions, and strong hydrogen bond formation (Bonilla et al., 2018; Haghghi et al.,
65 2019). Therefore, blending could combine the advantages of these two biopolymers as well
66 as minimize their disadvantages (Hosseini, Rezaei, Zandi, & Ghavi, 2013; Wang, Qian, &
67 Ding, 2018).

68 Natural extracts and plant EOs are secondary metabolites of plants that are complex
69 mixtures of low molecular weight compounds. EOs have long been recognized as valid
70 alternatives to synthetic food additive owing to their proved wide-spectrum antimicrobial
71 capacity. Antimicrobial activity of EOs is due to the presence of mono- and sesquiterpenes,
72 mono- and sesquiterpene hydrocarbons and phenolic compounds. These components
73 interact with polysaccharides, fatty acids and phospholipids of bacterial membranes and
74 cause cell death due to the loss of ions and cellular contents (Burt, 2004).

75 Combination of CS and GL bio-based films with EOs to create bio-based active films is one
76 of the promising strategies that is employed by the food industries to reduce the use of
77 chemical additives (Jamróz, Juszczak, & Kucharek, 2018). The incorporation of EOs into the
78 films instead of applying them directly on foods is an alternative to extend the shelf life of the
79 food and to achieve the desired goal with lower oil concentrations, thus limiting strong aroma
80 and possible changes in the organoleptic properties of the food (Salgado, López-Caballero,
81 Gómez-Guillén, Mauri, & Montero, 2013). In many cases, the active compounds are released
82 slowly onto the food surface from the active films, which act as an active compound reservoir
83 for an extended period. Furthermore, owing to their hydrophobic nature, EOs could improve
84 the water barrier properties of hydrophilic biopolymers such as CS and GL. In this study,

85 cinnamon (*Cinnamomum zeylanicum*), citronella (*Cymbopogon nardus*), pink clove (*Eugenia*
86 *caryophyllata*), nutmeg (*Myristica fragrans*) and thyme (*Thymus vulgaris*) were selected for
87 incorporation into CS-GL blend films due to their sensory acceptability and compatibility with
88 food and for their proved antimicrobial properties (Figuroa-Lopez et al., 2018; Ojagh,
89 Rezaei, Razavi, & Hosseini, 2010; Peng & Li, 2014; Shen & Kamdem, 2015; Wu, Sun, Guo,
90 Ge, & Zhang, 2017). Due to the natural origin of EOs, the majority of them have been
91 considered as GRAS by the US Food and Drug Administration (FDA, 2013). Upon addition of
92 EOs into the films, it is also important to evaluate their effects on microstructure, optical
93 properties, mechanical strength, water vapor permeability, moisture content and solubility of
94 the resulting film. However, literature concerning the effects of these EOs on the functional
95 properties of CS-GL blend film is not available. Therefore, the purpose of the present work
96 was to characterize CS-GL films enriched with different EOs including cinnamon, citronella,
97 pink clove, nutmeg and thyme to evaluate some physical, optical, mechanical, water barrier
98 and microstructural properties for potential applications as active food packaging. Moreover,
99 their antimicrobial activity against four common food bacterial pathogens including
100 *Campylobacter jejuni*, *Escherichia coli*, *Listeria monocytogenes* and *Salmonella typhimurium*,
101 was investigated.

102 **2. Material and methods**

103 **2.1 Materials and reagents**

104 Chitosan (CS) with a molecular weight of 100-300 kDa was obtained from Acros Organics™
105 (China). Gelatin (GL) with bloom 128°-192° was purchased from AppliChem GmbH
106 (Darmstadt, Germany). Glycerol ($\geq 99.5\%$) was purchased from Merck (Darmstadt,
107 Germany). Acetic acid ($\geq 99.5\%$) was obtained from Brenntag S.p.A (Milan, Italy). Five types
108 of commercial EOs including cinnamon, citronella, pink clove, nutmeg and thyme were
109 purchased from Solime S.r.l (Cavriago, Reggio Emilia, Italy). Tween 80 was purchased from
110 Sigma-Aldrich (Italy). Brain heart infusion agar (BHIA) was purchased from Biolife (Milan,
111 Italy).

112 **2.2. Preparation of film-forming solutions and films**

113 Preparation of films was adapted from Bonilla & Sobral (2016) with slight modifications. In
114 this study, five different types of films based on a CS-GL blend enriched with EOs
115 (cinnamon, citronella, pink clove, nutmeg and thyme) were analyzed. A film without EO was
116 used as a control. All film forming solutions (FFS) with and without EOs were prepared
117 separately. CS FFS (2%, w/v) was prepared by dissolving CS in an acetic acid solution (1%,
118 v/v) under continuous stirring at 55°C for 30 min. GL FFS (2 %, w/v) was prepared by
119 dissolving GL in distilled water, first being allowed to swell at 7°C for 15 min and then stirred
120 at 55 °C for 30 min. Glycerol (25% w/w of CS or GL) was then added as a plasticizer into
121 both FFS, followed by additional stirring for 30 min. CS-GL blend solution was prepared by
122 mixing CS and GL FFS at 1:1 ratio. Moreover, different types of EOs (1%, v/v) together with
123 Tween 80 (0.2%, v/v EO) were added to FFS, followed by stirring at 55 °C for additional 30
124 min. All FFS were degasified with a vacuum pump (70 kPa) for 15 min to remove bubbles
125 from the FFS. Films were obtained by casting 20 mL of the FFS into Petri dishes (14.4 cm in
126 diameter) and drying at 25±2 °C overnight in the chemical hood at ambient relative humidity
127 (RH) of 45%.

128 **2.3. Gas Chromatography-Mass Spectrometer (GC-MS) analysis of essential oils** 129 **volatile profiles**

130 The volatile profiling of the EOs used for incorporation in CS-GL films was carried out by
131 GC-MS analyses using an Agilent (Palo Alto, CA, USA) 6890N GC equipped with a 30 m
132 length, 0.25 mm i.d., 0.25 µm film thickness, fused silica capillary column (Stabilwax®-DA,
133 Restek) coupled with an Agilent 5973 Network mass selective detector. EOs were suitably
134 diluted with acetone and 1 µL was injected into the GC injector port set at 250 °C at 10:1 split
135 ratio. The oven temperature program was as follows: initial temperature 60 °C, then ramp to
136 200°C at 8°C/min and hold for 1 min, finally ramp to 240 °C at 20 °C/min and hold for 3.5
137 min. Helium was used as the carrier gas at a flow rate of 1.0 mL/min. Mass spectrometer
138 parameters were as follows: ion source, 230°C; electron energy, 70 eV; multiplier voltage,
139 1447 V; GC/MS transfer line, 250 °C; and a scan range of 33–650 mass units. Identification
140 of compounds was carried out by comparison with spectra libraries.

141 **2.4. Scanning electron microscopy**

142 Scanning electron microscopy (SEM) of the surface and cross-section of the films were
143 obtained with the use of a scanning electron microscope (FEI, Quanta 200, Oregon, USA).
144 Film samples were fixed on a stainless-steel support with a double side conductive adhesive.
145 The analysis was conducted in low vacuum (0.6 Torr) at an acceleration voltage of 20 kV.

146 **2.5. Attenuated Total Reflection (ATR) / Fourier-Transform Infrared (FT-IR)** 147 **Spectroscopy**

148 The infrared spectra of different films were obtained using an ATR/FT-IR spectrometer (type
149 Alpha, Bruker Optik GmbH, Ettlingen, Germany). Spectra were collected from two different
150 locations from the top and bottom of the same samples in the 4000-400 cm^{-1} wavenumber
151 range by accumulating 64 scans with a spectral resolution of 4 cm^{-1} .

152 **2.6. Thickness and mechanical properties**

153 Film thickness was measured with a digital micrometer (SAMA Tools measuring Instruments
154 & NTD equipment, Viareggio, Italia) at five different random positions (one at the center and
155 four at the edges). The means of these five separate measurements were recorded.

156 The tensile stress (TS), elongation at break (EAB) and elastic modulus (EM) were
157 determined using a dynamometer (Z1.0, ZwickRoell, Italy) according to ASTM standard
158 method D882 (ASTM, 2001a). The films with known thickness were cut into rectangular
159 strips (9 x 1.5 cm^2). Initial grip separation and cross-head speed were set at 70 mm and 10
160 mm/s, respectively. Measurements were repeated 10 times. The software TestXpert® II
161 (V3.31) (ZwickRoell, Ulm, Germany) was used to record the TS curves. TS was calculated by
162 dividing the maximum load to break the film by the cross-sectional area (thickness) of the film
163 and expressed in MPa. EAB was calculated by dividing film elongation at rupture by the initial
164 grip separation expressed in percentage (%). EM was calculated from the initial slope of the
165 stress-strain curve and expressed in MPa. TS and EAB were evaluated for ten samples from
166 each type of film.

167 **2.7. UV barrier, light transmittance, opacity value and color**

168 The barrier properties of films against UV and visible light were determined at the UV (200,
169 280 and 350 nm) and visible (400, 500, 600, 700 and 800 nm) wavelengths onto square film
170 samples ($2 \times 2 \text{ cm}^2$) using a Jasco V – 550 UV/Vis spectrophotometer (Jasco Corporation,
171 Tokyo, Japan) as described by Bellelli, Licciardello, Pulvirenti & Fava (2018). The opacity of
172 the films was calculated by Eq. (1):

$$173 \text{ Opacity value} = \frac{-\log T_{600}}{x} \quad (1)$$

174 where T_{600} is the fractional transmittance at 600 nm and x is the film thickness (mm). The
175 greater opacity value represents the lower transparency of the film. For each film, four
176 readings were taken at different points and average values were determined.

177 The color of films was measured with a CR-400 Minolta colorimeter (Minolta Camera, Co.,
178 Ltd., Osaka, Japan) at room temperature, with D65 illuminant and 10° observer angle. The
179 instrument was calibrated with a white standard ($L^* = 99.36$, $a^* = -0.12$, $b^* = -0.07$) before
180 measurements. Results were expressed as L^* (luminosity), a^* (red/green) and b^*
181 (yellow/blue) parameters. The total color difference (ΔE^*) was calculated using the following
182 Eq. (2):

$$183 \Delta E^* = \sqrt{[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]} \quad (2)$$

184 where ΔL^* , Δa^* and Δb^* are the differences between the corresponding color parameter of the
185 samples and that of a standard white plate used as the film background. For each film, five
186 readings were taken at different points and the average values were determined from the top
187 and bottom sides.

188 **2.8. Moisture content and water solubility**

189 Moisture content (MC) of the films was determined by measuring weight loss upon drying to
190 constant weight in an oven at $105 \pm 2^\circ \text{C}$ according to the following Eq. (3):

$$191 \text{ MC (\%)} = \frac{M_w - M_d}{M_w} \times 100 \quad (3)$$

192 Where, M_w and M_d are the initial weight and dry weight of the film, respectively.

193 The initial dry matter content of each film was determined by drying to constant weight in an
194 oven at $105 \pm 2^\circ \text{C}$ (W_i) and then each film was immersed in 50 mL distilled water at 25°C .

195 After 24 h, the film samples ($2 \times 2 \text{ cm}^2$) were dripped and dried to constant weight at 105 ± 2
196 $^\circ\text{C}$ (W_f) to determine the weight of dry matter which was not solubilized in water. The
197 measurement of water solubility (WS) was determined according to the following Eq. (4):

$$198 \text{ WS (\%)}: \frac{W_i - W_f}{W_i} \times 100 \quad (4)$$

199 where, W_i and W_f are initial and final weight of the film, respectively.

200 **2.9. Water vapor transmission rate and water vapor permeability**

201 Water vapor transmission rate (WVTR) of the films was determined gravimetrically in
202 triplicate according to the ASTM E96 method (ASTM, 2001b) with some modifications. Films
203 were sealed on top of glass test cups with an internal diameter of 10 mm and a depth of 55
204 mm filled with 2 g anhydrous CaCl_2 (0% RH). The cups were placed in desiccators containing
205 BaCl_2 (75% RH), which were maintained in incubators at $45 \text{ }^\circ\text{C}$. WVTR was determined
206 using the weight gain of the cups and was recorded and plotted as a function of time. Cups
207 were weighted daily for 7 days to guarantee the steady state permeation. The slope of the
208 mass gain versus time was obtained by linear regression ($r^2 \geq 0.99$). WVTR (g /day m^2) and
209 WVP (g mm/kPa day m^2) were calculated according to the following Eqs. (5) and (6):

$$210 \text{ WVTR} = \frac{\Delta W}{\Delta t \times A} \quad (5)$$

$$211 \text{ WVP} = \frac{\text{WVTR} \times L}{\Delta P} \quad (6)$$

212 where $\Delta W/\Delta t$ is the weight gain as a function of time (g/day), A is the area of the exposed
213 film surface (m^2), L is the mean film thickness (mm) and ΔP is the difference of vapor
214 pressure across the film (kPa).

215 **2.10. In vitro antimicrobial activity**

216 Antibacterial activity test on films was assessed against four typical food bacterial pathogens
217 including *Listeria monocytogenes* (UNIMORE 19115), *Escherichia coli* (UNIMORE 40522),
218 *Salmonella typhimurium* (UNIMORE 14028) and *Campylobacter jejuni* (UNIMORE 33250)
219 using the disk diffusion assay according to (Haghighi et al., 2019). Films (sterilized with UV
220 light) were cut into a disc shape of 22 mm diameter and placed on the surface of BHIA agar
221 plates, which had been previously streaked with 0.1 mL of inocula containing 10^6 CFU/mL of

222 tested bacteria. The plates were then incubated at 30 °C for 24 h (*C. jejuni* plates were
223 incubated at 37 °C). The diameter of the inhibition zones was measured with a caliper and
224 recorded in millimeters (mm). All tests were performed in triplicates.

225 **2.11. Statistical analysis**

226 The statistical analysis of the data was performed through analysis of variance (ANOVA)
227 using SPSS statistical program (SPSS 20 for Windows, SPSS INC., IBM, New York). The
228 differences between means were evaluated by Tukey's multiple range test ($p < 0.05$). The
229 data were expressed as the mean \pm SD (standard deviation).

230 **3. Results and discussion**

231 **3.1. Composition of the essential oils**

232 The volatile profiles of the tested EOs are shown in Tab. 1, which reports the major
233 compounds with their relative abundance (%). Typical chromatograms for each EO are
234 available in the supplementary material (Appendix A). As it can be inferred, eugenol alone
235 accounted for more than 51% of the total peak area of cinnamon EO, while 14 other
236 components contributed from 1 to 6.7% to the total peak area, with β -caryophyllene and
237 benzyl benzoate prevailing, followed by acetyleugenol and linalool, among the most
238 represented. Some differences between our results and other studies were observed, as
239 reported by Wang et al. (2018), cinnamaldehyde was the most representative components of
240 cinnamon EO. The other main constituents were eugenol (19.188%), linalool (4.563%), and
241 beta-caryophyllene (4.551%). In fact, the chemical compositions of the EOs may be varied
242 depending on geographical and climate conditions, herbal species, age, ecotypes,
243 geographical origins and method of drying and isolation of the EOs (Khezrian & Shahbazi,
244 2018).

245 The volatile profile of citronella was characterized by citronellal, geraniol and β -citronellol,
246 accounting for about 56%, δ -cadinene, citronellyl acetate, elemol and limonene which,
247 together, made another 22.5%, while other 7 compounds added at least 1% each to the total
248 peak area. Similar finding is reported by Chen et al. (2014) who noted that citronella EO was
249 rich in citronellal (26.23%), geraniol (19.75%) and citronellol (12.96%).

250 Pink clove EO was the simplest among the studied substances, since it was mainly
251 composed of eugenol (96.5% of total peak area), with minor contributions of carvacrol, β -
252 caryophyllene and vanillin.

253 Nutmeg EO was composed by about 22.7% sabinene, 14.9 and 10.3% α - and β -pinene,
254 respectively, and many other terpenic compounds, 7 representing 3-7% and 7 more ranging
255 from 1 to 3% of total peak area. Our results on chemical profiling of the nutmeg EO was in
256 accordance with Morsy (2016).

257 Thyme EO was characterized by p-cymene, thymol and carvacrol, which, together,
258 represented almost 80% of the total chromatographic area. Linalool, α -pinene and borneol
259 contributed for another 13%, while β -myrcene, limonene, β -caryophyllene, camphene and
260 1,8-cineol accounted for about 1% each. Jouki, Yazdia, Mortazavia, Koocheki, & Khazaei
261 (2014) also reported that thymol (46.42%), p-cymene (22.31%) and carvacrol (12.42%) were
262 the most representative components of thyme EO.

263 **3.2. Microstructure**

264 The surface and cross-section images of CS-GL film (control) and CS-GL film enriched with
265 different EOs (active films) are presented in Fig. 1 and Fig. 2, respectively. The
266 microstructure or internal morphological structures of the film depend on the interactions
267 between film components which directly affect the final physical, optical, mechanical and
268 barrier properties. The surface of control films was smooth and homogenous and did not
269 show pores or cracks (Fig. 1a) indicating the formation of an ordered matrix. Active films
270 showed heterogenous surface that resulted from oil droplets after drying. Both CS and GL
271 have a hydrophilic nature. The incorporation of EO in the FFS is usually carried out by
272 emulsification of the aqueous solution containing the polymer; when the film is dried, droplets
273 of lipid remain embedded into the polymer matrix (Siracusa et al., 2018), as observed in the
274 surface of films incorporated with citronella, pink clove and thyme EOs (Fig. 1b, d, and f).
275 Furthermore, cinnamon and nutmeg films showed remarkable pores on the surface (Fig. 1b
276 and e). The presence of pores might be attributed to the high volatility of these EOs during
277 the drying process (Yao, Ding, Shao, Peng, & Huang, 2017).

278 A compact and continuous structure without phase separation can be observed in the cross-
279 section of the control film (Fig. 2a) indicating high compatibility among CS and GL to form a
280 blend. The cross-section of active films showed discontinuities and heterogenous structure
281 indicating the occurrence of oil droplets. Moreover, irregular structures with the presence of
282 air bubbles in active films were observed (Fig. 2b, c, d, e, and f). Bonilla et al. (2018) also
283 reported that CS-GL blend film containing eugenol and ginger EOs had uncompact texture
284 with sponge-like structure due to the uneven dispersion of EOs with hydrophobic nature from
285 the aqueous phase during the film drying process.

286 **3.3. Attenuated Total Reflection (ATR) / Fourier-Transform Infrared (FT-IR)** 287 **Spectroscopy**

288 ATR/FT-IR spectroscopy was performed to characterize the structural and spectroscopic
289 changes due to the incorporation of the EOs into the CS-GL film matrix by measuring the
290 absorbance in the wavenumber range of 4000-400 cm^{-1} at a resolution of 4 cm^{-1} . The FT-IR
291 spectra of control and active films are shown in Fig. 3. The control film spectrum showed the
292 characteristic band at 1636 cm^{-1} (amide-I) due to the $\nu(\text{C}=\text{O})$ stretching vibration. A strong
293 peak at 1636 cm^{-1} may be taken as evidence of the presence of a significant amount of β -
294 sheet secondary structures of GL in CS-GL film (Haghighi et al., 2019). The peak at 1545 cm^{-1}
295 (amide-II) corresponds to a combination band of the $\nu(\text{C}-\text{N})$ stretching and $\delta(\text{N}-\text{H})$ bending
296 vibrations and the weak band at about 1245 cm^{-1} (amide III) has been assigned to another
297 coupled vibration of the $-\text{CONH}-$ functionality (Bonilla & Sobral, 2016). The broad absorption
298 band between about 3600 and 3200 cm^{-1} corresponds to $\nu(\text{O}-\text{H})$ and $\nu(\text{N}-\text{H})$ stretching
299 vibrations of hydrogen-bonded O-H and N-H functionalities. The band doublet at 2927/2874
300 cm^{-1} can be assigned to antisymmetric and symmetric $\nu_{\text{as}}(\text{CH}_3/\text{CH}_2)/\nu_{\text{s}}(\text{CH}_3/\text{CH}_2)$ stretching
301 vibrations of CH_3 and CH_2 functionalities. The peaks at 849, 898, 995, 1030, 1150 cm^{-1} can
302 be assigned to saccharide structures of the CS biopolymer in the CS-GL blend film network
303 (Shen & Kamdem, 2015).

304 The ATR/FT-IR spectra of the active films showed partly characteristic additional bands of
305 the incorporated EOs. It has to be mentioned, however, that due to the low amounts of

306 admixed EOs, only the most intense absorptions of specific functionalities are observable in
307 the spectra. In Fig. 3 the spectra have been arranged (from top to bottom) in the order of
308 increasing $\nu(\text{C}=\text{O})$ bands in the wavenumber range $1720\text{-}1740\text{ cm}^{-1}$ that can be assigned to
309 ester, aldehyde or ketone functionalities of the EO admixtures. Thus, pink clove and thyme
310 do not show these bands. However, while the spectrum of thyme is - with the exception of
311 weak additional bands in the $2800\text{-}3000\text{ cm}^{-1}$ range due to aliphatic functionalities - very
312 similar to the control spectrum, the spectrum of pink clove shows a very characteristic
313 additional peak at 1515 cm^{-1} that belongs to the aromatic ring vibration of the main
314 constituent (eugenol) of pink clove. The CS-GL-Citronella film showed a small new peak at
315 1733 cm^{-1} and slight changes in the $\nu(\text{CH})$ absorption range originating from ester and
316 aldehyde functionalities and aliphatic structures, respectively, of the citronella admixture. The
317 ATR/FT-IR spectra of CS-GL-Cinnamon film showed new peaks in the aliphatic $\nu(\text{CH})$
318 absorption range, at 1743 cm^{-1} , and a significant shoulder at 1515 cm^{-1} , due to aliphatic
319 functionalities, ester and the aromatic structure of linalool, and eugenol components,
320 respectively. The largest changes in the $\nu(\text{CH})$ and $\nu(\text{C}=\text{O})$ absorption ranges are reflected in
321 the CS-GL-Nutmeg film. These changes can be traced back to a major component of
322 nutmeg, trimyristin, a saturated fat which is the triglyceride of myristic acid.
323 Several of the admixed EOs contain alcoholic OH functionalities but their signatures are too
324 weak and buried in the high-wavenumber wing of the intense, broad $\nu(\text{NH})$ band of the CS-
325 GL film. Nevertheless, it can be assumed that the admixed C=O and OH functionalities of the
326 EOs contribute to intermolecular interactions with the hydroxyl and amino groups of the CS-
327 GL film network.

328 **3.4. Thickness**

329 The thickness values for control and active films are reported in Tab. 2. Thickness ranged
330 from $21.66\text{ }\mu\text{m}$ to $33.41\text{ }\mu\text{m}$: the control film had the lowest value ($p < 0.05$), while
331 incorporation of EOs into the CS-GL film increased the thickness ($p < 0.05$). Bearing in mind
332 that all films were prepared by casting the same amount of FFS on Petri dishes with the
333 same surface, the difference in thickness might be explained by the different composition of

334 FFS. Indeed, the addition of low molecular weight EOs into the FFS resulted in disrupting
335 and restructuring of intermolecular interactions between CS and GL, increasing free volumes
336 and the mobility of macromolecules, as it was confirmed by SEM images. Moreover, different
337 chemical compounds present in EOs (Tab. 1) may enhance the spatial distance within the
338 film matrix which lead to thicker films (Khezrian & Shahbazi, 2018). A similar effect of EO on
339 film thickness was reported by Ojagh et al. (2010). In contrast, Siracusa et al. (2018) found
340 that addition of citral EO to pectin and sodium alginate films significantly reduced thickness.
341 This might be due to an increase in homogeneity and to the creation of a well-organized and
342 dense network upon addition of citral EO, but also to the extended drying time required.

343 **3.5. Mechanical properties**

344 The tensile strength (TS), percent elongation at break (EAB%) and elastic modulus (EM) are
345 the most common mechanical parameters for food packaging applications (Acevedo-Fani,
346 Salvia-Trujillo, Rojas-Graü, & Martín-Belloso, 2015). A bio-based film must be resistant to the
347 normal stress that occurs in the application, shipping and handling to maintain the integrity
348 and properties of foods. The mechanical properties of control and active films are presented
349 in Tab. 2. The TS is the measurement of film strength: the films incorporated with cinnamon
350 and pink clove EOs showed lower TS than the control film ($p < 0.05$), whereas, films
351 incorporated with citronella, nutmeg and thyme were as resistant as the control film. Several
352 studies reported that the addition of EO reduced TS by decreasing cohesion forces within the
353 polymers in the film matrix (Acevedo-Fani, Salvia-Trujillo, Rojas-Graü, & Martín-Belloso,
354 2015). It seems likely that strong polymer-polymer interactions between CS and GL
355 molecules are partially replaced by the weaker polymer-oil interactions in the film matrix.
356 Also, EO as a hydrophobic compound causes heterogenous film network and discontinuous
357 microstructure by rearrangement of biopolymers, leading to a decline in the mechanical
358 resistance as it has been confirmed by SEM images (Atarés & Chiralt, 2016; Kim, Beak, &
359 Song, 2018). In contrast, a different result was reported by Ojagh et al. (2010), who found
360 that the addition of EO to CS films significantly increased the TS value. Authors concluded
361 that the strong interaction between CS and EO determined a cross-linking effect leading to

362 an increase in TS. The TS of packaging film must be more than 3.5 MPa, according to
363 conventional standards (Hosseini, Rezaei, Zandi, & Farahmandghavi, 2015). In this study,
364 the TS value of control and active CS-GL films ranged from 29.54 to 47.72 MPa which is a
365 high value for its application as packaging material.

366 The EAB is related to the film flexibility and stretchability. The EAB values ranged from
367 2.18% to 2.90% indicating that all films were quite brittle. No significant difference was
368 observed in the EAB of control and active films ($p>0.05$). Souza et al. (2017) also found that
369 the incorporation of different EOs and hydroalcoholic extracts into CS film did not induce
370 significant differences in EAB values.

371 The EM stands for the resistance of the film to elastic deformation and this parameter
372 indicates the rigidity or stiffness of the film. A low EM value corresponds to a flexible film
373 while a larger EM value indicates a more rigid material. The cinnamon-added films showed
374 the lowest EM value (1340 MPa) meaning that the CS-GL film lost its stiffness and became
375 more flexible with the addition of cinnamon EO ($p<0.05$). However, films containing citronella,
376 pink clove, nutmeg and thyme EOs showed EM values similar to the control film. Overall, it
377 seems that cinnamon EO acts as plasticizer, since it determines a lower TS and a higher
378 EAB (softer and more extensible film). Nutmeg and thyme seem to act as crosslinkers,
379 slightly increasing TS. However, the effects on mechanical properties, are hardly noticeable
380 and may depend on the low relative amounts of EO in the FFSs.

381 **3.6. UV barrier, light transmittance and opacity value**

382 UV barrier, light transmittance and opacity value of control and active films are presented in
383 Tab. 3. Active films behave as effective UV barriers, since transmittance value was below
384 10% at 280 nm for these films. The UV barrier property of bio-based films is an important
385 parameter for food packaging applications since it can retard lipid oxidation and preserve the
386 organoleptic properties of the packaged food, thereby prolonging its shelf-life (Ramos,
387 Valdés, Beltrán, & Garrigós, 2016).

388 Active films showed lower transmittance in the visible range (350-800 nm) than the control
389 film indicating that the incorporation of EOs into the film matrix reduced the transparency of

390 the film. The light barrier property is an important factor for food preservation to avoid photo-
391 oxidation of organic compounds and degradation of vitamins and other pigments (Figueroa-
392 Lopez et al., 2018). The control and CS-GL-Thyme films can be considered as transparent
393 (opacity value: 2.62 and 5.23 respectively) while films containing cinnamon, citronella, pink
394 clove and nutmeg EOs were less transparent. Overall, the transparency of the films
395 decreased with the addition of EOs due to the light scattering of oil droplets (with a different
396 refractive index) in the CS-GL film network which interferes with the transmission of light.
397 Similar results were reported by Bonilla, Poloni, Lourenco & Sobral (2018) and Kim et al.
398 (2018).

399 **3.7. Color**

400 The color values (L^* , a^* and b^*) and total color difference (ΔE^*) of control and active films are
401 shown in Tab. 4. The L^* value, indicating lightness, decreased upon addition of EOs. This
402 value varied between 98.32 and 95.33, which means that all the films were almost clear. A
403 similar result was reported by (Bonilla & Sobral, 2016).

404 The a^* value, expressing the green-red color component, was negative for all films except for
405 those added with cinnamon and pink clove, which showed a slightly positive a^* value (+1.92
406 and +1.33, respectively) due to the presence of red colored substances in the cinnamon and
407 pink clove EOs.

408 The b^* value measures the blue-yellow color component. This value significantly increased
409 upon addition of EOs ($p < 0.05$), as to indicate the gain of a slight yellow color. The CS-GL
410 films incorporated with cinnamon and pink clove showed the highest b^* value (7.97 and 6.90,
411 respectively) which, in agreement with the a^* value, demonstrate the presence of colored
412 compounds into the extracts.

413 The total color difference (ΔE^*) measures the overall color change of a test sample compared
414 with a reference color. The ΔE^* value varied from 2.50 in the control film to 8.74 in CS-GL-
415 Cinnamon film. The addition of EOs to the CS-GL film generally increased the ΔE^* value
416 ($p < 0.05$). The CS-GL films incorporated with cinnamon and pink clove showed the highest
417 ΔE^* values ($p < 0.05$) mainly due to the lower brightness (L^*) and to the increase observed in

418 the colorimetric coordinate a^* and b^* . Some relation can be found also between the higher
419 ΔE^* and the lowest light transmission values observed in the wavelength range 350-500 nm,
420 which suggest that the compounds present in cinnamon and pink clove EOs absorb in this
421 range, which corresponds to the yellow-red color measured by the a^* and b^* coordinates.
422 Nevertheless, the color of the developed films can change the overall appearance of the food
423 inside the packaging and affecting customer acceptance (Atarés & Chiralt, 2016).

424 **3.8. Moisture content, water solubility and water vapor permeability**

425 The moisture content (MC), water solubility (WS) and water vapor permeability (WVP) of
426 control and active films are presented in Tab. 5. The control film showed the lowest MC value
427 (15.80%), while the addition of EOs increased the MC value ($p < 0.05$). The MC is a
428 parameter related to the total free volume occupied by water molecules in the network of the
429 films. The loose microstructure of active films caused the film matrix to have a relatively high
430 free volume and consequently increased the MC as confirmed by SEM images. Similarly,
431 Abdollahi, Rezaei, & Farzi (2012) reported that the addition of rosemary EO to the CS film
432 increased the MC. Authors concluded that the increase in the MC value might be related to
433 the breakup of the film network, which caused an increasing amount of water molecules
434 between polymer chains. In contrast, Nisar et al. (2018) reported that addition of clove EO to
435 pectin film reduced the MC value due to the hydrophobic properties of the EOs and
436 interaction of oil components with hydroxyl groups of pectin film. This could limit the
437 interaction of hydroxyl groups with water molecules, leading to a reduction of MC.

438 The WS reflects the water resistance and the biodegradability of films (Zhang, Ma, Critzer,
439 Davidson, & Zhong, 2015). Moreover, the WS can determine the release of antimicrobial
440 substances from the films when placed in contact with the food surface (Abdollahi et al.,
441 2012). Water resistance or insolubility is usually essential for potential application of the bio-
442 based films for food packaging applications especially in humid environments (Nisar et al.,
443 2018). The WS of control film was determined as 23.61 %. Addition of nutmeg EOs to the
444 CS-GL film reduced the WS ($p < 0.05$) due to the high hydrophobic nature of nutmeg, while,
445 films incorporated with cinnamon, citronella, pink clove and thyme EOs showed an increase

446 in WS ($p < 0.05$). This might be due to the difference in hygroscopic properties of these EOs
447 by which they attract water molecules and the ability to establish polymer-oil interactions
448 which weaken the CS-GL interactions (Gómez-Estaca, López de Lacey, López-Caballero,
449 Gómez-Guillén, & Montero, 2010; Nisar et al., 2018).

450 The shelf life of some food products is directly related to the transfer of water between the
451 product and the external environment in which they are introduced. Generally, packaging
452 material should reduce this transfer of water to preserve foods from moisture (de Moraes
453 Crizel et al., 2018; Hosseini, Rezaei, Zandi, & Farahmandghavi, 2016; Kim et al., 2018).
454 Therefore, effective control of moisture transfer is a desirable property for the food packaging
455 industry. The CS-GL films containing cinnamon, citronella, pink clove and thyme had higher
456 WVP values compared to the control film ($p < 0.05$). The irregular structures with the presence
457 of air bubbles and oil droplets in these films might lead to a weakening of intermolecular
458 interactions between polymer molecules, resulting in an open structure and increased water
459 vapor transfer across the films and consequently an increase of the WVP value. A similar
460 result was reported by Atarés, Bonilla, & Chiralt (2010) that addition of ginger EO to soy
461 protein isolate increased the WVP. These authors concluded that addition of ginger EO might
462 cause disruption in film network and affect the microstructure properties which is a
463 determining factor in WVP value. In this study, despite the statistical differences, the WVP
464 varied between 0.8 and 1.2 (g mm/kPa day m^2). In practical terms, this means that all films
465 were highly permeable to water vapor.

466 **3.9. *In vitro* antimicrobial activity**

467 Antimicrobial activity of films was evaluated by the disk diffusion assay. The details of
468 antimicrobial activity of control and active films against *C. jejuni*, *E. coli*, *L. monocytogenes*
469 and *S. typhimurium* are shown in Tab. 6. The control film did not show an inhibitory effect
470 against any of the tested microorganisms. The absence of inhibitory character could be
471 explained by the limitation of CS diffusion in agar medium or incapability of GL to inhibit
472 bacterial growth as it has been reported by other authors (Leceta, Guerrero, Ibarburu,
473 Dueñas, & De La Caba, 2013), so that only microorganisms in direct contact with the active

474 sites of CS in the CS-GL film network are inhibited (Haghighi et al., 2019; Yuan, Chen, & Li,
475 2016). Incorporating EOs into the films revealed an antimicrobial effect. In general, due to the
476 hydrophobic nature of EOs, they can interact with polysaccharides, fatty acids and
477 phospholipids of bacteria cell membranes and make them more permeable, so that leakage
478 of ions and cell contents leads to bacterial cell death (Burt, 2004; Salvia-Trujillo, Rojas-Graü,
479 Soliva-Fortuny & Martín-Belloso, 2015). In this study, all active films inhibited the growth of
480 the tested microorganisms. Thyme EO was the most effective ($p < 0.05$). Thyme EO showed
481 inhibition activity which was, for all pathogens excluding *L. monocytogenes*, at least double
482 compared to the other EOs. This might be due to the higher WS of CS-GL-Thyme films
483 compared to the other films (Tab. 5). Moreover, thymol and carvacrol are two main phenolic
484 compounds (monoterpenoids) representing 44.2% of the total chromatographic area in
485 thyme EO (Tab. 1). The high antimicrobial activity of phenolic compounds such as thymol
486 and carvacrol has been attributed to structural and functional damages to the bacterial
487 cytoplasmic membrane and to the inhibition of intracellular metabolic pathways (Cao, Yang,
488 & Song, 2018). It should be noted that thyme EO exerted the highest inhibition against *C.*
489 *jejuni*, *E. coli* and *S. typhimurium*, while its antimicrobial effectiveness against *L.*
490 *monocytogenes* was lower and comparable with other EOs. In general, the tested EOs were
491 more effective against *C. jejuni* compared to the other considered microorganisms, showing
492 inhibition haloes from 1.5 to 5-fold wider. The only exception to this observation was
493 represented by nutmeg EO, which showed higher inhibition (comparable with the other EOs)
494 of *E. coli* and *L. monocytogenes* but which, however, yielded the lowest effectiveness, hardly
495 noticeable against *C. jejuni* and *S. typhimurium*.

496 **4. Conclusions**

497 In this study, bio-based CS-GL blend active films enriched with cinnamon, citronella, pink
498 clove, nutmeg and thyme EOs (1%, v/v) were developed and their physical, optical,
499 mechanical, water barrier and microstructural properties were evaluated for active food
500 packaging applications. The FT-IR spectra confirmed intermolecular interactions between
501 functional groups of the EOs with the hydroxyl and amino groups of the CS-GL film network.

502 The results showed that the incorporation of different EOs could notably improve the UV
503 barrier properties of CS-GL film, however, light transparency was reduced. The developed
504 films, with special regards for those including thyme EO, possessed noticeable antimicrobial
505 activity against common food pathogens. The moisture content and water vapor permeability
506 of CS-GL film increased by EOs incorporation due to the microstructure change and
507 presence of pores on the surface as confirmed by SEM. The results suggest that the CS-GL
508 films enriched with different EOs could be used as environmentally friendly, active food
509 packaging with antimicrobial properties and potential to extend the shelf life of food products.

510 **Declarations of interest**

511 None.

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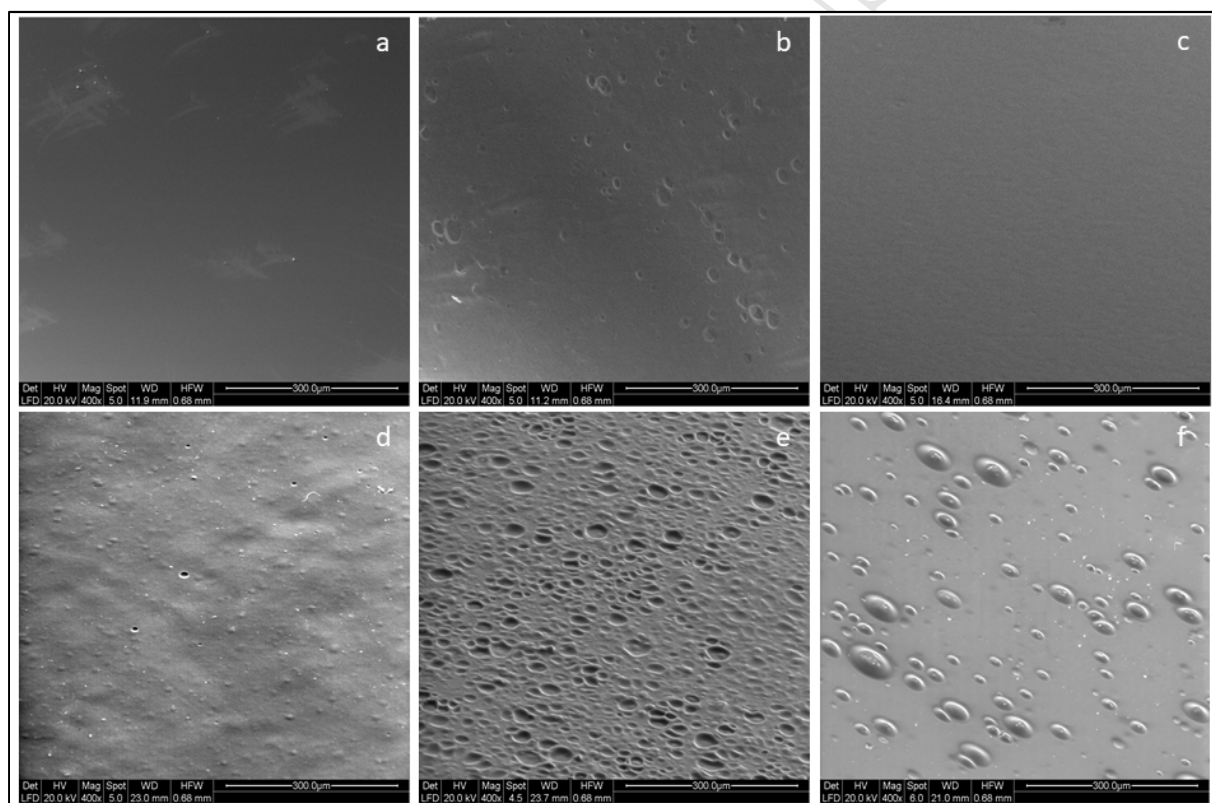
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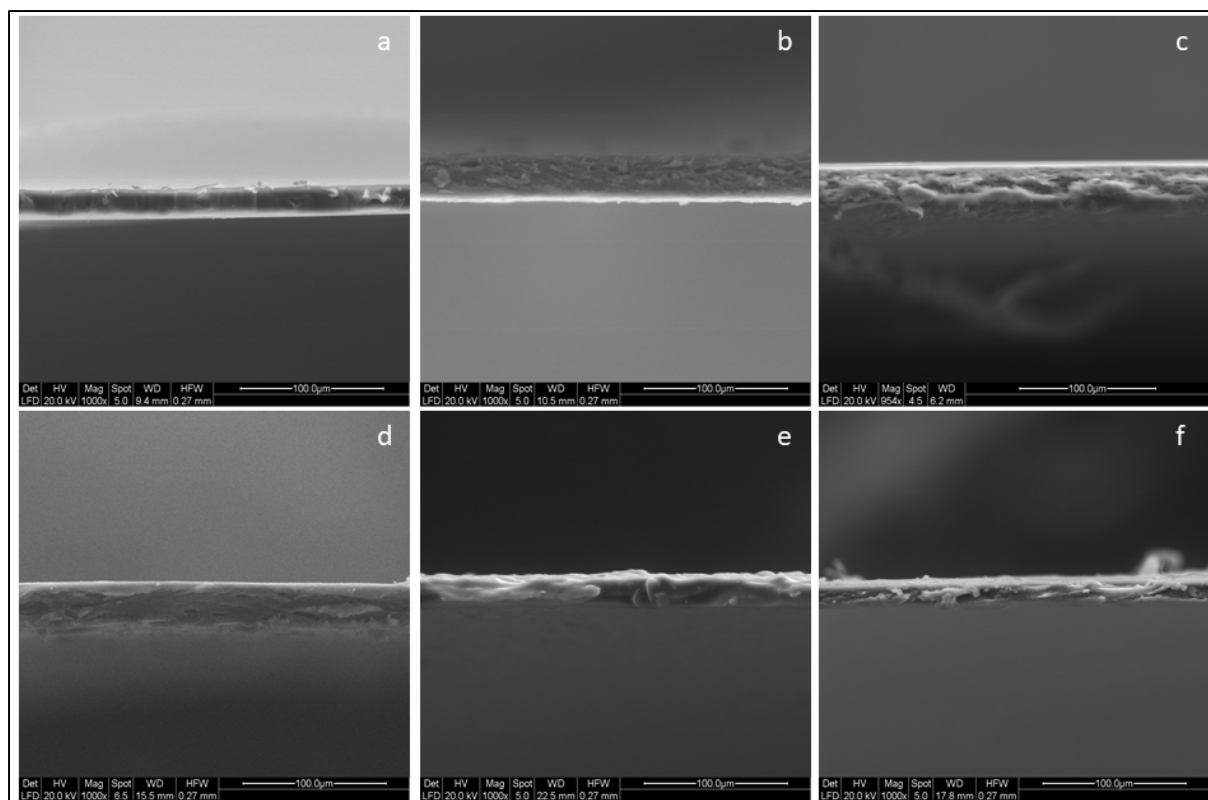


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681 **Fig. 1.** Scanning electron microscopy (SEM) images of the surface of films. a: Chitosan-Gelatin blend

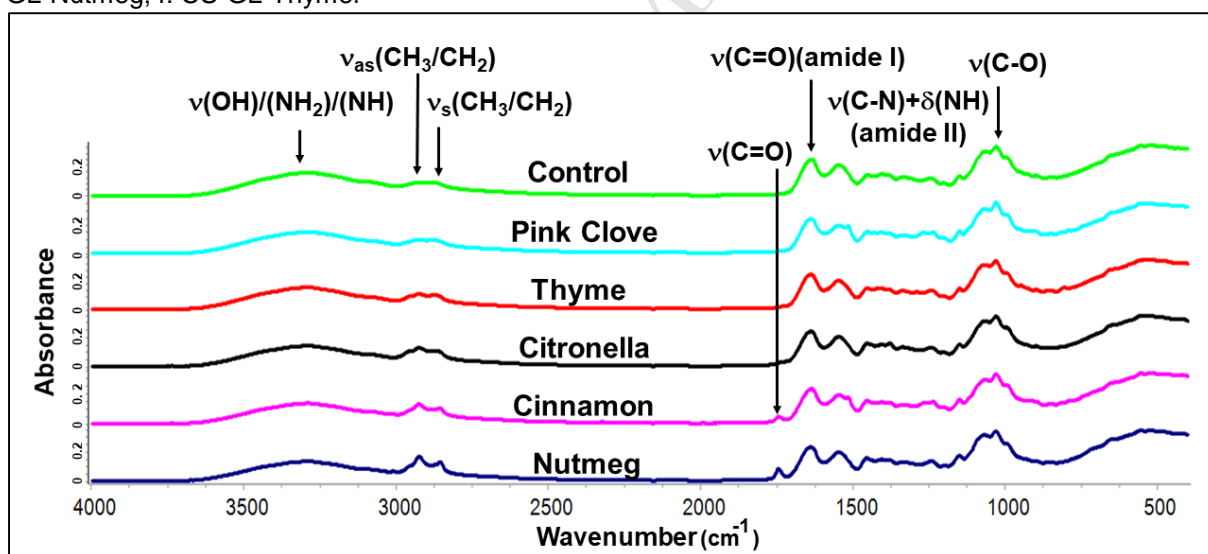
682 (CS-GL) as a control; b: CS-GL-Cinnamon; c: CS-GL-Citronella; d: CS-GL-Pink Clove; e: CS-GL-

683 Nutmeg; f: CS-GL-Thyme.



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Fig. 2. Scanning electron microscopy (SEM) images on the cross-section of films. a: Chitosan-Gelatin blend (CS-GL) as a control; b: CS-GL-Cinnamon; c: CS-GL-Citronella; d: CS-GL-Pink Clove; e: CS-GL-Nutmeg; f: CS-GL-Thyme.



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Fig. 3. ATR-FT-IR spectra of films based on a: Chitosan-Gelatin blend (CS-GL) as a control and those enriched with EOs (1%, v/v).

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710 **Table 1.** Relative volatile composition (main components) of the tested EOs.

NO.	RT* (min)	Compounds name	Cinnamon	Citronella	Pink clove	Nutmeg	Thyme
1	2.23	α-pinene	1.8	-	-	14.9	4.2
2	2.45	α -fenchene	-	-	-	-	0.2
3	2.52	camphene	0.6	-	-	0.3	1.2
4	2.85	β-pinene	0.5	-	-	10.3	0.4
5	2.97	sabinene	-	-	-	22.7	-
6	3.21	δ -3-carene	-	-	-	1.3	-
7	3.30	β -myrcene	-	-	-	2.4	1.3
8	3.37	α -phellandrene	1.1	-	-	1.1	-
9	3.52	α -terpinene	0.2	-	-	3.6	-
10	3.74	limonene	0.6	4.4	-	4.5	1.3
11	3.85	β -phellandrene	1.0	-	-	3.4	-
12	3.85	1,8-cineol	-	-	-	-	0.8
13	4.26	γ -terpinene	-	-	-	5.6	-
14	4.59	p-cymene	2.6	-	-	3.0	34.9
15	4.72	α -terpinolene	-	-	-	2.1	-
16	7.12	α -cubebene	1.5	-	-	0.2	-
17	7.25	trans thujan-4-ol	-	-	-	0.7	-
18	7.55	citronellal	-	23.9	-	-	-
19	7.65	α -copaene	-	-	-	0.9	-
20	8.13	camphor	-	-	-	-	0.5
21	8.39	linalool	4.6	1.1	-	0.3	6.6
22	8.51	β -terpineol	-	-	-	0.6	-
23	8.71	1-terpineol	-	-	-	0.3	-
24	8.87	isopulegol	-	3.1	-	-	-
25	8.93	α -fenchyl acetate	-	-	-	0.3	-
26	9.06	β -elemene	-	3.3	-	-	-
27	9.17	β -caryophyllene	6.7	0.1	0.8	1.0	1.2
28	9.31	4-terpineol	0.4	-	-	7.2	-

29	10.07	citronellyl acetate	-	5.4	-	-	-
30	10.16	isoborneol	-	-	-	-	0.4
31	10.21	α -humulene	1.3	0.3	-	-	-
32	10.43	α -amorphene	-	0.4	-	-	-
33	10.59	camphene	-	-	-	0.3	-
34	10.64	α -terpineol	0.6	-	-	0.7	-
35	10.65	borneol	-	-	-	-	2.3
36	10.77	β -cubebene	-	2.5	-	-	-
27	10.96	α -muurolene	-	1.1	-	-	-
38	11.21	citral	-	0.5	-	-	-
39	11.37	δ -cadinene	0.3	8.0	-	0.7	-
40	11.54	β-citronellol	-	13.0	-	-	-
41	11.99	nerol	-	0.2	-	-	-
42	12.66	geraniol	-	19.2	-	-	-
43	13.07	safrole	2.9	-	-	1.8	-
44	13.96	allylbenzene	0.2	-	-	-	-
45	14.51	caryophyllene oxide	1.3	-	0.3	-	0.4
46	14.83	methyleugenol	-	-	-	0.7	-
47	15.21	α -amorphene	-	0.8	-	-	-
48	15.43	cinnamaldehyde	2.7	-	-	-	-
49	15.59	elemol	-	4.6	-	-	-
50	16.18	spathulenol	0.2	-	-	-	-
51	16.61	cinnamyl acetate	3.4	-	-	-	-
52	16.69	eugenol	51.2	2.5	96.5	0.3	-
53	16.78	thymol	-	-	-	-	30.2
54	16.83	muurolol	-	0.6	-	-	-
55	17.12	carvacrol	-	-	1.1	-	14.0
56	17.28	α -eudesmol	-	0.4	-	-	-
57	17.35	elemicin	-	-	-	2.9	-
58	17.37	α -cadinol	-	1.4	-	-	-
59	17.71	acethyleugenol	4.7	-	-	-	-
60	17.80	myristicin	-	-	-	4.8	-
61	18.12	cinnamyl alcohol	0.4	-	-	-	-
62	18.68	chavicol	-	-	0.5	-	-
63	20.93	vanillin	-	-	0.8	-	-
64	21.36	benzyl benzoate	6.7	-	-	-	-

711 * Retention time

712 The dominant compounds are indicated in bold.

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714 **Table 2**

715 Thickness, tensile strength (TS), elongation at break (EAB) and elastic modulus (EM) of the films
716 based on chitosan-gelatin blend (CS-GL) as a control and those enriched with EOs (1%, v/v).

Film sample	Thickness (μm)	TS (MPa)	EAB (%)	EM (MPa)
CS-GL-Control	21.87 \pm 1.18 ^a	41.49 \pm 4.09 ^{bc}	2.56 \pm 0.09 ^{ab}	2231 \pm 226.13 ^{bc}
CS-GL-Cinnamon	32.84 \pm 1.91 ^c	29.54 \pm 2.84 ^a	2.88 \pm 0.04 ^b	1340 \pm 056.00 ^a
CS-GL-Citronella	30.40 \pm 1.59 ^c	36.41 \pm 3.15 ^{ab}	2.18 \pm 0.25 ^a	2017 \pm 200.89 ^b
CS-GL-Pink clove	32.28 \pm 2.16 ^c	32.44 \pm 2.96 ^a	2.47 \pm 0.28 ^{ab}	2201 \pm 074.36 ^b
CS-GL-Nutmeg	27.40 \pm 2.27 ^b	47.72 \pm 1.47 ^c	2.52 \pm 0.21 ^{ab}	2374 \pm 205.16 ^{bc}
CS-GL-Thyme	26.67 \pm 1.30 ^b	45.18 \pm 3.78 ^c	2.56 \pm 0.18 ^{ab}	2661 \pm 239.86 ^c

717 Values are given as mean \pm SD (n = 3).

718 Different letters in the same column indicate significant differences (p<0.05).

719

720 **Table 3**

721 UV and visible light transmittance (T%) and opacity value (600 nm) of the films based on chitosan-
722 gelatin blend (CS-GL) as a control and those enriched with EOs (1%, v/v).

Film sample	Light Transmission (%) at different wavelength (nm)								Opacity value
	200	280	350	400	500	600	700	800	
CS-GL-Control	0.16	38.21	67.12	78.81	85.64	87.62	88.52	88.78	02.62 ± 0.07 ^a
CS-GL-Cinnamon	0.02	0.01	11.36	21.50	25.89	28.42	30.39	31.57	16.67 ± 1.20 ^d
CS-GL-Citronella	0.03	3.05	16.70	22.15	27.84	31.38	34.89	37.64	15.27 ± 2.05 ^{bc}
CS-GL-Pink clove	0.02	0.01	07.93	26.84	35.24	41.22	44.48	46.60	12.02 ± 0.90 ^b
CS-GL-Nutmeg	0.05	7.53	28.83	37.06	45.04	49.54	53.64	56.29	11.14 ± 0.93 ^b
CS-GL-Thyme	0.09	0.05	57.68	64.45	69.66	72.77	75.07	76.55	05.23 ± 0.47 ^a

723 Values are given as mean ± SD (n = 3).

724 Different letters in the same column indicate significant differences (p<0.05).

725

726 **Table 4**

727 Color parameters (L*, a* and b*) and total color difference (ΔE^*) of the films based on chitosan-gelatin
728 blend (CS-GL) as a control and those enriched with EOs (1%, v/v).

Film sample	Color parameters			
	L*	a*	b*	ΔE^*
CS-GL-Control	98.32 ± 0.34 ^c	-0.52 ± 0.09 ^a	2.16 ± 0.02 ^a	2.50 ± 0.16 ^a
CS-GL-Cinnamon	96.44 ± 1.35 ^{ab}	+1.33 ± 0.28 ^b	7.97 ± 0.76 ^c	8.74 ± 0.39 ^c
CS-GL-Citronella	97.61 ± 0.24 ^{bc}	-0.86 ± 0.06 ^a	4.53 ± 0.25 ^b	4.95 ± 0.32 ^b
CS-GL-Pink clove	95.33 ± 0.38 ^a	+1.92 ± 0.86 ^b	6.90 ± 0.35 ^c	8.31 ± 0.56 ^c
CS-GL-Nutmeg	97.55 ± 0.17 ^{bc}	-0.83 ± 0.11 ^a	4.74 ± 0.50 ^b	5.17 ± 0.56 ^b
CS-GL-Thyme	97.84 ± 0.13 ^{bc}	-0.59 ± 0.09 ^a	4.30 ± 0.19 ^b	4.63 ± 0.22 ^b

729 Values are given as mean ± SD (n = 3).

730 Different letters in the same column indicate significant differences (p<0.05).

731

732 **Table 5**

733 Moisture content (MC), water solubility (WS), water vapor transmission rate (WVTR) and water vapor
734 permeability (WVP) of the films based on chitosan-gelatin blend (CS-GL) as a control and those
735 enriched with EOs (1%, v/v).

Film sample	MC (%)	WS (%)	WVP 75:0% RH (g mm/kP day m ²)
CS-GL-Control	15.80 ± 0.33 ^a	23.61 ± 0.58 ^b	0.8172 ± 0.0027 ^a
CS-GL-Cinnamon	18.71 ± 0.80 ^b	30.24 ± 0.75 ^d	1.1344 ± 0.1298 ^{bc}
CS-GL-Citronella	19.15 ± 0.44 ^b	26.53 ± 0.53 ^c	1.1396 ± 0.2069 ^{bc}
CS-GL-Pink clove	23.78 ± 1.81 ^c	29.51 ± 1.40 ^d	1.2460 ± 0.4576 ^c
CS-GL-Nutmeg	17.71 ± 1.39 ^{ab}	20.36 ± 1.09 ^a	0.8853 ± 0.1237 ^{ab}
CS-GL-Thyme	18.78 ± 0.97 ^b	31.67 ± 1.71 ^d	1.2851 ± 0.3761 ^c

736 Values are given as mean ± SD (n = 3).

737 Different letters in the same column indicate significant differences (p<0.05).

738

739 **Table 6**

740 Inhibition zone diameters of the film disks (22 mm diameter) based chitosan-gelatin blend (CS-GL-
741 Control) as a control and those enriched with EOs (1%, v/v).

Film sample	<i>C. jejuni</i>	<i>E. coli</i>	<i>L. monocytogenes</i>	<i>S. typhimurium</i>
CS-GL-Control	N. D.	N. D.	N. D.	N. D.
CS-GL-Cinnamon	5.33 ± 0.94 ^{bb}	2.66 ± 0.47 ^{aA}	1.98 ± 0.49 ^{aA}	1.00 ± 0.14 ^{aA}
CS-GL-Citronella	4.33 ± 1.88 ^{abA}	2.83 ± 0.70 ^{aA}	2.32 ± 0.49 ^{aA}	2.83 ± 0.70 ^{aA}
CS-GL-Pink clove	5.33 ± 0.94 ^{bb}	3.50 ± 0.24 ^{aAB}	2.42 ± 0.35 ^{aA}	3.00 ± 0.14 ^{aA}
CS-GL-Nutmeg	0.44 ± 0.15 ^{aA}	2.75 ± 0.35 ^{aC}	2.33 ± 0.47 ^{abC}	0.99 ± 0.46 ^{aAB}
CS-GL-Thyme	11.33 ± 0.94 ^{cc}	5.66 ± 0.47 ^{bb}	3.00 ± 0.14 ^{aA}	6.17 ± 0.70 ^{bb}

742 Values are given as mean ± SD (n = 3). N.D means as not detected.

743 Different lowercase letters in the same column indicate significant differences (p<0.05).

744 Different capital letters in the same row indicate significant differences (p<0.05).

Highlights:

- Production of films based on chitosan-gelatin enriched with essential oils
- Determination of the physical, mechanical and barrier properties
- Demonstration of the interaction between chitosan-gelatin and essential oils
- Improving UV barrier of chitosan-gelatin film by addition of essential oils
- Effectiveness of active films against common food bacterial pathogens

Keywords: Bio-Based Active Packaging; Chitosan-Gelatin Blend; Essential Oil; Scanning Electron Microscopy (SEM); Fourier-Transform Infrared Spectroscopy (FT-IR)

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