

Physico-chemical, antimicrobial and antioxidant properties of gelatin-chitosan based films loaded with nanoemulsions encapsulating active compounds

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Table 1. Encapsulation efficiencies of cinnamaldehyde, α -tocopherol and garlic oil and mean droplet sizes, polydispersity indices (PDI), ζ -potential and pH values of the O/W nanoemulsions containing these encapsulated active compounds, as a function of storage time (all systems stored at $4\pm 1^\circ\text{C}$).

Samples*	Time (Days)	Encapsulation efficiency			Droplet size (nm)	PDI	ζ -potential (mV)	pH
		Cinnamaldehyde (%)	α -tocopherol(%)	GO(%)				
Control (N_1)	0	----	---	----	$157.0 \pm 4.1^{\text{aA}}$	$0.19 \pm 0.02^{\text{bA}}$	$-17.3 \pm 0.6^{\text{aA}}$	$6.1 \pm 0.0^{\text{abA}}$
	30	----	---	----	$158.2 \pm 2.9^{\text{aA}}$	$0.20 \pm 0.02^{\text{bA}}$	$-16.0 \pm 1.4^{\text{bA}}$	$6.0 \pm 0.0^{\text{bcA}}$
	60	----	---	----	$161.2 \pm 5.9^{\text{aA}}$	$0.23 \pm 0.02^{\text{aA}}$	$-17.2 \pm 0.9^{\text{abA}}$	$6.1 \pm 0.0^{\text{aA}}$
	90	----	---	----	$156.9 \pm 4.7^{\text{aA}}$	$0.21 \pm 0.02^{\text{bA}}$	$-18.1 \pm 1.0^{\text{aA}}$	$6.0 \pm 0.0^{\text{cA}}$
α -t/Cin (N_2)	0	$100 \pm 0.0^{\text{aA}}$	$57.1 \pm 1.1^{\text{aA}}$	----	$123.1 \pm 1.5^{\text{aB}}$	$0.16 \pm 0.01^{\text{aB}}$	$-14.2 \pm 0.5^{\text{aC}}$	$5.3 \pm 0.0^{\text{aD}}$
	30	----	---	----	$121.5 \pm 0.6^{\text{aC}}$	$0.16 \pm 0.04^{\text{aB}}$	$-12.3 \pm 0.3^{\text{bC}}$	$5.1 \pm 0.0^{\text{bC}}$
	60	----	---	----	$121.9 \pm 2.7^{\text{aC}}$	$0.15 \pm 0.01^{\text{aB}}$	$-13.7 \pm 0.9^{\text{aC}}$	$4.7 \pm 0.1^{\text{cC}}$
	90	$99.7 \pm 0.3^{\text{aA}}$	$46.6 \pm 0.4^{\text{bB}}$	----	$122.4 \pm 2.5^{\text{aC}}$	$0.15 \pm 0.01^{\text{aBC}}$	$-13.7 \pm 1.0^{\text{aC}}$	$4.6 \pm 0.0^{\text{dB}}$
α -t/GO (N_3)	0	----	$52.4 \pm 0.4^{\text{aA}}$	$92.2 \pm 1.9^{\text{aA}}$	$111.0 \pm 2.0^{\text{aC}}$	$0.16 \pm 0.0^{\text{aB}}$	$-15.9 \pm 0.7^{\text{abB}}$	$6.0 \pm 0.0^{\text{aB}}$
	30	----	---	---	$112.5 \pm 2.4^{\text{aD}}$	$0.14 \pm 0.02^{\text{aB}}$	$-15.5 \pm 0.6^{\text{abA}}$	$5.4 \pm 0.0^{\text{bB}}$
	60	----	---	---	$111.2 \pm 1.9^{\text{aD}}$	$0.14 \pm 0.01^{\text{aB}}$	$-16.0 \pm 0.8^{\text{aB}}$	$4.9 \pm 0.0^{\text{cB}}$
	90	----	$47.8 \pm 0.2^{\text{bA}}$	$88.5 \pm 2.7^{\text{aA}}$	$111.5 \pm 1.9^{\text{aD}}$	$0.14 \pm 0.01^{\text{aC}}$	$-15.0 \pm 0.9^{\text{bB}}$	$4.3 \pm 0.0^{\text{dD}}$
α -t/Cin and GO (N_4)	0	$93.9 \pm 2.6^{\text{aA}}$	$56.7 \pm 3.1^{\text{aA}}$	$70.9 \pm 2.0^{\text{aB}}$	$124.8 \pm 1.4^{\text{bB}}$	$0.15 \pm 0.01^{\text{bB}}$	$-14.4 \pm 0.7^{\text{aC}}$	$5.5 \pm 0.0^{\text{aC}}$
	30	---	---	---	$126.4 \pm 2.2^{\text{bB}}$	$0.16 \pm 0.02^{\text{bB}}$	$-13.7 \pm 0.4^{\text{bB}}$	$4.9 \pm 0.0^{\text{bD}}$
	60	---	---	---	$130.0 \pm 1.1^{\text{aB}}$	$0.20 \pm 0.01^{\text{aC}}$	$-13.8 \pm 0.5^{\text{abC}}$	$4.7 \pm 0.0^{\text{cC}}$
	90	$89.6 \pm 0.6^{\text{aB}}$	$45.2 \pm 0.3^{\text{bC}}$	$61.6 \pm 0.1^{\text{bB}}$	$126.6 \pm 3.0^{\text{bB}}$	$0.16 \pm 0.02^{\text{bB}}$	$-14.5 \pm 0.6^{\text{aBC}}$	$4.5 \pm 0.0^{\text{dC}}$

Mean values \pm standard deviation (n = 3). Different lower case letters in the same column indicate significant differences ($p < 0.05$) for the same sample over different days and different capital letters indicate significant differences ($p < 0.05$) among different samples measured at the same time interval (day).

Cin: cinnamaldehyde; α -t: α -tocopherol; GO: garlic oil.

* N_1 : Control nanoemulsion (no encapsulated species); N_2 : α -tocopherol/cinnamaldehyde; N_3 : α -tocopherol/garlic oil; N_4 : α -tocopherol/cinnamaldehyde and garlic oil-loaded nanoemulsion.

Table 2. Physical/Mechanical properties of gelatin-chitosan films loaded with O/W nanoemulsions containing encapsulated active compounds.

Sample *	Thickness (mm)	Moisture content (%)	Solubility in water (%)	Swelling (g/g)	TS (MPa)	EB (%)	EM (MPa)
<i>Films N₀</i>	0.082 ± 0.001 ^a	18.2 ± 0.8 ^a	50.8 ± 0.7 ^a	26.9 ± 2.8 ^b	19.0 ± 2.1 ^a	89.1 ± 6.4 ^d	101.4 ± 4.5 ^a
<i>Films N₁</i>	0.081 ± 0.002 ^a	17.8 ± 1.8 ^a	47.5 ± 0.6 ^b	30.6 ± 0.6 ^a	10.0 ± 1.1 ^{bc}	123.3 ± 1.3 ^a	29.0 ± 3.6 ^c
<i>Films N₂</i>	0.081 ± 0.002 ^a	18.2 ± 1.8 ^a	44.0 ± 2.1 ^c	27.4 ± 2.5 ^{ab}	11.4 ± 1.0 ^b	108.7 ± 2.2 ^c	37.3 ± 2.5 ^b
<i>Films N₃</i>	0.081 ± 0.002 ^a	17.3 ± 2.1 ^a	43.1 ± 2.3 ^c	30.3 ± 1.5 ^a	8.9 ± 0.9 ^c	111.7 ± 4.8 ^{bc}	30.1 ± 4.9 ^c
<i>Films N₄</i>	0.082 ± 0.001 ^a	18.1 ± 2.0 ^a	48.9 ± 0.9 ^{ab}	25.3 ± 0.8 ^b	9.8 ± 3.7 ^{bc}	113.2 ± 2.1 ^b	39.2 ± 3.6 ^b

Mean values ± standard deviation (n = 3). Different letters in the same column indicate significant differences (p<0.05).

* *N₀*- Control 1: film without nanoemulsion; *N₁*- Control 2: film with control nanoemulsion (no encapsulated species); *N₂*: α -tocopherol/cinnamaldehyde; *N₃*: α -tocopherol/garlic oil; *N₄*: α -tocopherol/cinnamaldehyde and garlic oil-loaded nanoemulsion.

TS: Tensile strength; EB: Elongation at break; EM: Elastic modulus.

Table 3. Light transmittance (%) and transparency of gelatin-chitosan films loaded with O/W nanoemulsions containing encapsulated active compounds.

Sample*	Light transmittance (%)						Transparency value
	Wavelength (nm)						
	250	280	350	450	600	800	
<i>Films N₀</i>	22.2 ± 0.3 ^a	23.9 ± 0.6 ^a	80.0 ± 0.4 ^a	90.9 ± 0.2 ^a	94.7 ± 0.2 ^a	97.6 ± 0.2 ^a	0.29 ± 0.01 ^c
<i>Films N₁</i>	5.0 ± 0.7 ^b	9.6 ± 0.3 ^b	66.3 ± 0.7 ^{bc}	77.6 ± 0.5 ^d	83.7 ± 0.4 ^d	88.8 ± 0.4 ^e	0.96 ± 0.02 ^a
<i>Films N₂</i>	0.0 ± 0.0 ^c	0.1 ± 0.0 ^d	63.7 ± 1.4 ^d	85.7 ± 0.6 ^b	91.4 ± 0.4 ^b	95.4 ± 0.4 ^b	0.48 ± 0.02 ^d
<i>Films N₃</i>	0.1 ± 0.0 ^c	0.7 ± 0.0 ^c	67.5 ± 1.7 ^b	83.8 ± 1.7 ^c	87.7 ± 1.4 ^c	91.2 ± 1.4 ^d	0.71 ± 0.09 ^b
<i>Films N₄</i>	0.0 ± 0.0 ^c	0.1 ± 0.0 ^d	65.0 ± 1.0 ^{cd}	84.5 ± 0.6 ^{bc}	88.9 ± 0.5 ^c	92.5 ± 0.6 ^c	0.63 ± 0.03 ^c

Mean values ± standard deviation (n = 3). Different letters in the same column indicate significant differences (p<0.05).

* *N₀*- Control 1: film without nanoemulsion; *N₁*- Control 2: film with control nanoemulsion (no encapsulated species); *N₂*: α-tocopherol/cinnamaldehyde; *N₃*: α-tocopherol/garlic oil; *N₄*: α-tocopherol/cinnamaldehyde and garlic oil-loaded nanoemulsion.

Table 4. Thermal properties and roughness characteristics of gelatin-chitosan films loaded with O/W nanoemulsions containing encapsulated active compounds.

Sample*	1 st Scan			2 nd Scan	Roughness	
	T _g (°C)	ΔH _g (J/g)	T _m (°C)	T _g (°C)	R _a (nm)	R _q (nm)
Films N ₀	45.6 ± 0.6 ^a	12.1 ± 0.8 ^b	54.9 ± 0.8 ^a	8.6 ± 2.2 ^{ab}	7.5	11.1
Films N ₁	46.2 ± 0.8 ^a	9.3 ± 0.9 ^a	53.5 ± 0.2 ^a	12.1 ± 1.1 ^a	44.1	58.6
Films N ₂	45.5 ± 0.4 ^a	9.0 ± 0.2 ^a	54.4 ± 0.2 ^a	8.2 ± 2.7 ^{ab}	31.4	40.5
Films N ₃	46.6 ± 2.3 ^a	9.6 ± 0.8 ^a	56.6 ± 5.2 ^a	10.4 ± 3.1 ^{ab}	39.5	53.9
Films N ₄	45.6 ± 0.4 ^a	9.3 ± 0.5 ^a	54.6 ± 0.2 ^a	6.7 ± 1.4 ^b	32.3	42.6

Mean values ± standard deviation (n = 3). Different letters in the same column indicate significant differences (p<0.05).

* N₀- Control 1: film without nanoemulsion; N₁- Control 2: film with control nanoemulsion (no encapsulated species); N₂: α-tocopherol/cinnamaldehyde; N₃: α-tocopherol/garlic oil; N₄: α-tocopherol/cinnamaldehyde and garlic oil-loaded nanoemulsion.

T_g: Glass transition temperature; T_m: Melting temperature; ΔH_g: Melting enthalpy; R_a: average roughness; R_q: root-mean-square roughness.

Table 5. Inhibition halos against *P. aeruginosa* and *L. monocytogenes* and Trolox Equivalent Antioxidant Capacity (TEAC) of gelatin-chitosan films loaded with O/W nanoemulsions containing encapsulated active compounds.

Sample*	Zone of inhibition (mm ²)		TEAC ($\mu\text{mol TE/g dried film}$)		
	<i>P. aeruginosa</i>	<i>L. monocytogenes</i>	DPPH* method	ABTS*+ method	FRAP assay
<i>Films N₀</i>	0.0 \pm 0.0 ^c	0.0 \pm 0.0 ^a	0.0 \pm 0.0 ^c	0.0 \pm 0.0 ^d	6.9 \pm 0.4 ^e
<i>Films N₁</i>	0.0 \pm 0.0 ^c	0.0 \pm 0.0 ^a	0.0 \pm 0.0 ^c	1.3 \pm 0.0 ^c	39.8 \pm 0.2 ^d
<i>Films N₂</i>	138.2 \pm 2.4 ^a	0.0 \pm 0.0 ^a	0.2 \pm 0.0 ^a	2.6 \pm 0.1 ^a	49.9 \pm 1.2 ^c
<i>Films N₃</i>	138.2 \pm 0.0 ^a	0.0 \pm 0.0 ^a	0.1 \pm 0.0 ^b	2.5 \pm 0.0 ^a	81.5 \pm 2.2 ^a
<i>Films N₄</i>	65.4 \pm 1.4 ^b	0.0 \pm 0.0 ^a	0.1 \pm 0.0 ^b	2.3 \pm 0.1 ^b	68.3 \pm 2.9 ^b

Mean values \pm standard deviation (n = 3). Different letters in the same column indicate significant differences (p<0.05).

* *N₀*- Control 1: film without nanoemulsion; *N₁*- Control 2: film with control nanoemulsion (no encapsulated species); *N₂*: α -tocopherol/cinnamaldehyde; *N₃*: α -tocopherol/garlic oil; *N₄*: α -tocopherol/cinnamaldehyde and garlic oil-loaded nanoemulsion.