Supporting Information

Systematic Investigation of Metal–Phenolic Network-Capped Starch Nanoparticles as Sustainable Coatings for Postharvest Fruit Preservation

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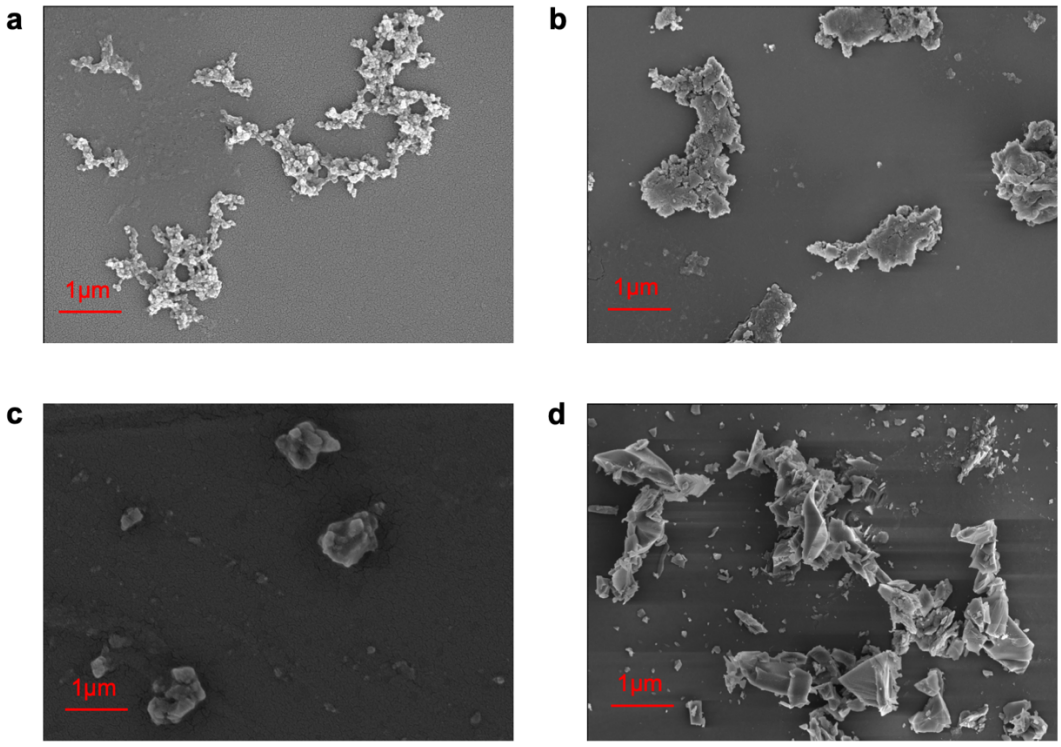

Figure S1. Scanning electron microscopy (SEM) images of 4 MPNs: (a) Fe-TA-MPN, (b) Fe-EGCG-MPN, (c) Zn-TA-MPN, (d) Zn-EGCG-MPN.

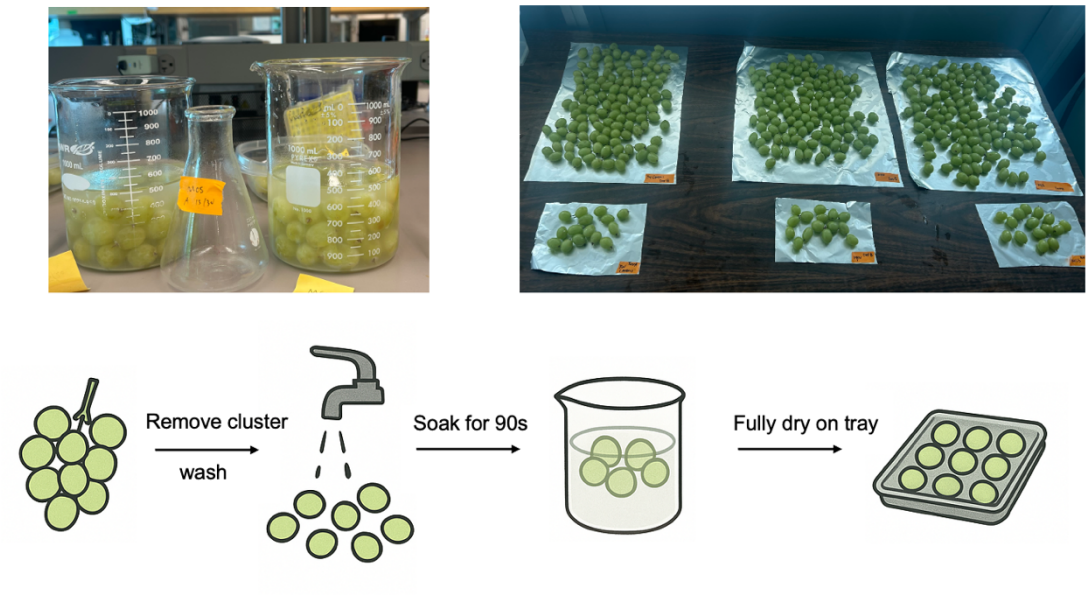

Figure S2. Pre-processing and dipping–coating procedure for grape samples. Representative images and schematic workflow illustrate the preparation of grape berries prior to treatment. Individual berries were first detached from the clusters, rinsed with tap water to remove surface impurities, and then immersed in coating solutions for 90 s. Following immersion, the grapes were transferred to trays and air-dried completely before storage or subsequent analysis. This procedure ensured uniform coating deposition and minimized variability across samples.

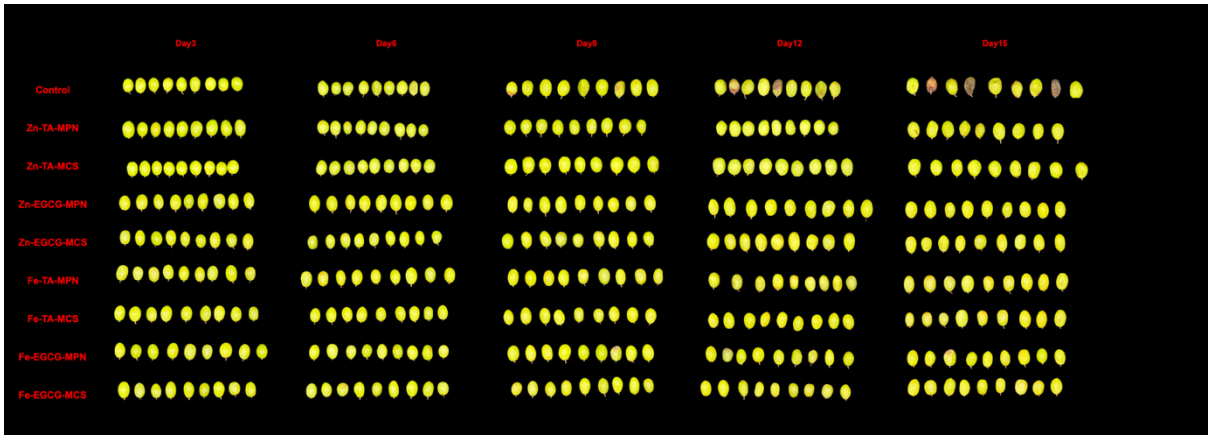

Figure S3. Visual appearance of grapes over 15 days of storage (all replicates, n=9)

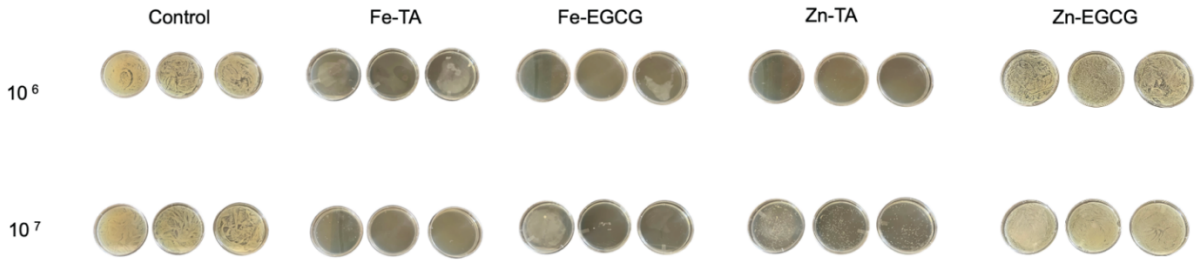

Figure S4. Antibacterial properties of MCS composite coating solutions against *Staphylococcus epidermidis*. Representative agar plates (n = 3) show visibly reduced bacterial colonies in the presence of MCS formulations compared with the untreated control, demonstrating their inhibitory effect on microbial growth.

Table S1. Weight loss of grapes subjected to different treatments during 15 days of storage.

Data are expressed as mean ± standard deviation (n = 5).

Day	3	6	9	12	15
Tap water	9.03 ± 0.91^{c}	16.49 ± 1.38^{b}	23.16 ± 0.58^{b}	32.96 ± 0.72^{c}	34.88 ± 6.26^{b}
Zn-TA-MPN	7.06 ± 0.75^{b}	12.28 ± 1.56^{a}	16.51 ± 1.89^{a}	24.00 ± 2.65^{b}	26.09 ± 3.58^{a}
Zn-TA-MCS	7.04 ± 0.56^{b}	12.36 ± 0.89^{a}	16.54 ± 1.22^{a}	23.75 ± 1.44^{b}	25.43 ± 1.36^{a}
Zn-EGCG-MPN	4.81 ± 0.41^{a}	10.71 ± 0.91^{a}	15.04 ± 1.43^{a}	18.66 ± 1.47^{a}	21.61 ± 1.61^{a}
Zn-EGCG-MCS	5.20 ± 0.16^{a}	11.53 ± 0.37^{a}	15.93 ± 0.53^{a}	19.82 ± 0.59^{a}	22.89 ± 0.72^{a}
Fe-TA-MPN	4.70 ± 0.13^{a}	10.52 ± 3.14^{a}	14.51 ± 3.83^{a}	18.26 ± 3.31^{a}	21.13 ± 3.42^{a}
Fe-TA-MCS	4.46 ± 0.55^{a}	9.98 ± 0.96^{a}	13.37 ± 0.60^{a}	17.35 ± 1.49^{a}	20.15 ± 1.65^{a}
Fe-EGCG-MPN	5.12 ± 0.35^{a}	11.34 ± 0.65^{a}	15.58 ± 1.22^{a}	19.82 ± 1.16^{a}	23.04 ± 1.45^{a}
Fe-EGCG-MCS	5.00 ± 0.65^{a}	10.91 ± 1.39^{a}	15.74 ± 1.16^{a}	19.79 ± 1.48^{a}	23.79 ± 2.27^{a}

Table S2. Firmness of grapes subjected to different treatments during 15 days of storage.

Data are expressed as mean ± standard deviation (n = 5).

Storage day (d)	3	6	9	12	15
Tap water control	914.37 ± 306.33^{a}	464.51 ± 397.37^{a}	452.89 ± 388.13^{a}	105.98 ± 164.27^{a}	10.67 ± 1.41^{a}
Zn-TA-MPN	967.75 ± 414.05^{a}	727.94 ± 178.54^{b}	699.98 ± 374.43^{b}	351.87 ± 296.28^{b}	49.24 ± 66.41^{b}
Zn-TA-MCS	1020.09 ± 450.73^{a}	688.89 ± 437.76^{b}	779.49 ± 631.16^{c}	428.18 ± 253.90^{b}	82.62 ± 67.75^{b}
Zn-EGCG-MPN	1995.14 ± 315.77^{b}	904.66 ± 734.56^{c}	435.94 ± 255.95^{b}	260.53 ± 72.50^{b}	61.51 ± 90.98^{b}
Zn-EGCG-MCS	2569.03 ± 783.47^{b}	1061.27 ± 456.48^{d}	448.30 ± 346.53^{b}	254.60 ± 89.16^{b}	103.37 ± 122.25^{b}
Fe-TA-MPN	2503.43 ± 487.41^{c}	889.33 ± 83.09^{c}	698.01 ± 303.02^{b}	279.56 ± 102.20^{b}	72.14 ± 110.25^{b}
Fe-TA-MCS	2656.27 ± 287.18^{c}	924.86 ± 869.94^{d}	808.69 ± 261.27^{c}	355.71 ± 98.10^{b}	138.56 ± 223.55^{c}
Fe-EGCG-MPN	1952.74 ± 193.39^{c}	852.64 ± 579.35^{b}	632.85 ± 389.58^{b}	204.98 ± 166.62^{b}	74.51 ± 112.99^{b}
Fe-EGCG-MCS	2763.10 ± 440.61^{c}	868.37 ± 157.95^{c}	602.63 ± 359.56^{b}	238.30 ± 207.29^{b}	120.01 ± 191.42^{b}

Table S3. Color parameters of grapes subjected to different treatments during 15 days of storage.

The CIELAB color space was used to evaluate changes in fruit appearance over time. The **L*** value represents lightness (0 = black, 100 = white), where higher values indicate brighter fruit surfaces. The **a*** value denotes the red–green axis, with positive values corresponding to redness and negative values to greenness. The **b*** value reflects the yellow–blue axis, where higher positive values indicate greater yellowness. Data are expressed as mean ± standard deviation (n = 5).

Color value	Treatment	3	6	9	12	15
L*	Control	41.74±1.41^{a}	39.25±0.73^{a}	40.42±0.51^{a}	36.27±1.64^{a}	32.61±0.89^{a}
	Zn-TA-MPN	42.53±0.85^{a}	42.16±0.28^{b}	42.37±0.91^{b}	40.86±0.33^{c}	39.72±0.28^{c}
	Zn-TA-MCS	43.17±1.13^{b}	43.13±1.28^{c}	42.80±0.69^{c}	41.75±0.41^{c}	41.27±0.50^{d}
	Zn-EGCG-MPN	42.19±0.82^{a}	41.80±1.76^{b}	41.32±0.53^{a}	40.49±0.15^{c}	39.17±0.69^{c}
	Zn-EGCG-MCS	42.11 ± 0.72^{a}	41.23 ± 0.91^{b}	42.05 ± 0.70^{b}	40.86±1.03^{c}	40.02±0.13^{d}
	Fe-TA-MPN	42.26 ± 0.59^{a}	40.88 ± 0.62^{b}	40.11 ± 2.51^{b}	37.80 ± 2.67^{b}	37.25±0.96^{b}
	Fe-TA-MCS	42.54 ± 1.26^{a}	43.16 ± 2.01^{b}	41.05 ± 0.50^{b}	39.39 ± 0.54^{b}	38.05±3.23^{c}
	Fe-EGCG-MPN	43.54±1.40^{b}	43.51±0.84^{c}	41.63±0.31^{b}	40.05±0.73^{b}	37.09+2.16^{b}
	Fe-EGCG-MCS	42.71±0.62^{a}	41.26±0.93^{b}	41.05±0.50^{a}	39.18±2.51^{b}	39.76±1.41^{c}
a*	Control	-1.94±0.55^{a}	-2.07±0.17^{a}	-3.15±0.26^{a}	-2.71±1.26^{a}	-3.99±1.51^{a}
	Zn-TA-MPN	-1.58±0.29^{a}	-1.29±0.64^{b}	-2.06±0.92^{b}	-2.25±0.18^{a}	-2.93±1.22^{b}
	Zn-TA-MCS	-1.73±0.31^{a}	-1.69±0.74^{a}	-2.30±0.79^{b}	-2.32±0.64^{a}	-2.57±0.26^{c}
	Zn-EGCG-MPN	-1.68±0.40^{a}	-1.74±0.52^{a}	-2.66±1.04^{b}	-2.51±0.42^{a}	-2.77±0.83^{c}
	Zn-EGCG-MCS	-1.44±0.62^{a}	-1.83±0.22^{a}	-1.96±0.37^{a}	-2.04±0.59^{a}	-2.27±0.16^{c}
	Fe-TA-MPN	-1.39±0.51^{b}	-1.32±0.45^{a}	-1.81±0.06^{b}	-1.95±1.02^{a}	-2.10±0.96^{b}
	Fe-TA-MCS	-1.88±0.60^{b}	-1.94±0.37^{b}	-2.16±0.38^{b}	-2.41±1.30^{a}	-2.77±1.16^{a}

	Fe-EGCG-MPN	-1.57±0.27[a]	-1.69±0.77[a]	-1.81±0.30[a]	-2.17±0.62	-2.69±1.08[a]
	Fe-EGCG-MCS	-1.82±1.10[b]	-2.14±0.51[a]	-1.93±1.26[a]	-2.71±0.46	-3.06±0.25[a]
b*	Control	7.93±0.17[a]	9.27±0.20[a]	11.31±0.94[a]	13.05±1.12[a]	14.97±1.45[a]
	Zn-TA-MPN	7.26±0.39[a]	8.92±1.71[a]	9.21±0.36[b]	9.95±0.79[a]	10.71±1.25[c]
	Zn-TA-MCS	7.30±0.52[a]	7.99±0.95[a]	9.10±0.83[b]	10.28±0.96[b]	10.47±1.04[c]
	Zn-EGCG-MPN	7.71±0.29[a]	9.17±0.66[a]	10.08±1.31[b]	10.46±0.73[a]	10.80±1.20[b]
	Zn-EGCG-MCS	7.33±0.18[a]	8.47±0.50[a]	9.79±1.70[b]	9.62±1.84[b]	9.78±0.99[c]
	Fe-TA-MPN	6.14±0.77[a]	7.05±0.28[a]	8.41±0.19[b]	10.03±0.68[a]	11.70±1.15[c]
	Fe-TA-MCS	6.02±1.24[a]	6.87±0.92[a]	7.93±0.20[b]	9.25±0.14[a]	10.62±0.79[c]
	Fe-EGCG-MPN	6.51±0.27[a]	8.03±1.07[a]	9.30±1.43[b]	9.18±0.26[b]	11.08±0.36[c]
	Fe-EGCG-MCS	6.28±0.49[a]	7.45±0.30[a]	8.20±1.24[c]	9.77±0.18[b]	10.89±1.31[d]

Table S4. Total phenolic content of grapes subjected to different treatments during 15 days of storage.

Data are expressed as mean ± standard deviation (n = 5).

Day	3	6	9	12	15
Tap water	138.90 ± 9.19[b]	132.57 ± 23.15[b]	114.10 ± 11.77[a]	75.14 ± 21.18[b]	54.33 ± 13.38[b]
Zn-TA-MPN	172.19 ± 18.37[a]	164.33 ± 4.99[b]	136.67 ± 11.47[a]	99.14 ± 11.88[a]	77.43 ± 8.16[a]
Zn-TA-MCS	234.00 ± 81.63[a]	170.81 ± 10.81[b]	151.48 ± 9.16[a]	117.19 ± 9.32[a]	109.38 ± 13.53[a]
Zn-EGCG-MPN	186.76 ± 22.65[a]	156.90 ± 16.42[b]	140.48 ± 9.28[a]	103.10 ± 8.00[a]	85.24 ± 6.78[a]
Zn-EGCG-MCS	256.48 ± 31.72[a]	159.71 ± 7.11[b]	144.10 ± 12.47[a]	115.95 ± 6.20[a]	99.57 ± 7.53[a]
Fe-TA-MPN	211.19 ± 10.08[a]	173.52 ± 8.24[a]	127.67 ± 6.00[a]	106.76 ± 11.37[a]	89.81 ± 14.11[a]
Fe-TA-MCS	241.62 ± 8.94[a]	193.62 ± 6.12[a]	130.52 ± 9.37[a]	109.67 ± 4.62[a]	105.05 ± 17.08[a]
Fe-EGCG-MPN	206.86 ± 15.14[a]	178.52 ± 13.50[a]	109.52 ± 19.36[b]	99.00 ± 10.11[a]	79.38 ± 3.99[a]
Fe-EGCG-MCS	246.10 ± 26.21[a]	212.05 ± 22.51[a]	145.67 ± 21.99[a]	115.67 ± 7.47[a]	102.76 ± 10.94[a]

Table S5. Total soluble solid of grapes subjected to different treatments during 15 days of storage.

Data are expressed as mean ± standard deviation (n = 5).

Day	3	6	9	12	15
Tap water control	16.50 ± 0.50[b]	16.50 ± 1.32[a]	15.67 ± 1.04[b]	11.50 ± 1.32[b]	10.33 ± 0.58[b]
Zn-TA-MPN	17.17 ± 0.29[a]	17.33 ± 0.76[a]	16.33 ± 0.29[a]	13.33 ± 0.58[a]	12.83 ± 1.04[a]
Zn-TA-MCS	17.67 ± 0.29[a]	18.00 ± 0.50[a]	16.50 ± 0.50[a]	14.17 ± 0.76[a]	13.17 ± 0.29[a]
Zn-EGCG-MPN	17.33 ± 0.58[a]	18.00 ± 0.87[a]	16.33 ± 0.58[a]	13.83 ± 1.04[a]	12.50 ± 1.32[a]
Zn-EGCG-MCS	18.33 ± 0.76[a]	18.67 ± 0.29[a]	17.67 ± 0.29[a]	14.83 ± 0.29[a]	13.33 ± 0.76[a]
Fe-TA-MPN	17.50 ± 1.00[a]	17.67 ± 0.76[a]	15.83 ± 0.58[b]	13.67 ± 0.29[a]	12.33 ± 0.76[a]
Fe-TA-MCS	18.33 ± 0.29[a]	17.67 ± 1.04[a]	16.83 ± 0.29[a]	14.67 ± 1.04[a]	12.67 ± 0.58[a]
Fe-EGCG-MPN	17.33 ± 0.76[a]	17.83 ± 0.58[a]	15.33 ± 0.58[b]	13.50 ± 0.87[a]	12.83 ± 1.15[a]
Fe-EGCG-MCS	18.17 ± 0.29[a]	18.17 ± 0.29[a]	16.33 ± 1.04[a]	14.50 ± 0.50[a]	12.83 ± 1.04[a]

Table S6. pH of grapes subjected to different treatments during 15 days of storage.

Data are expressed as mean ± standard deviation (n = 5).

Day	3	6	9	12	15
Tap water	3.13 ± 0.04[a]	3.22 ± 0.02[b]	3.24 ± 0.02[a]	3.14 ± 0.03[a]	3.22 ± 0.02[a]
Zn-TA-MPN	3.16 ± 0.02[a]	3.30 ± 0.05[a]	3.27 ± 0.02[a]	3.19 ± 0.02[a]	3.18 ± 0.03[a]
Zn-TA-MCS	3.14 ± 0.05[a]	3.29 ± 0.02[a]	3.26 ± 0.02[a]	3.16 ± 0.02[a]	3.15 ± 0.03[a]
Zn-EGCG-MPN	3.17 ± 0.04[a]	3.24 ± 0.02[a]	3.27 ± 0.01[a]	3.24 ± 0.07[a]	3.25 ± 0.06[a]
Zn-EGCG-MCS	3.19 ± 0.03[a]	3.23 ± 0.02[a]	3.28 ± 0.02[a]	3.24 ± 0.04[a]	3.21 ± 0.08[a]
Fe-TA-MPN	3.19 ± 0.03[a]	3.23 ± 0.03[a]	3.21 ± 0.03[a]	3.23 ± 0.07[a]	3.19 ± 0.02[a]
Fe-TA-MCS	3.15 ± 0.01[a]	3.20 ± 0.03[b]	3.24 ± 0.06[a]	3.22 ± 0.04[a]	3.19 ± 0.03[a]
Fe-EGCG-MPN	3.19 ± 0.05[a]	3.25 ± 0.02[a]	3.22 ± 0.06[a]	3.22 ± 0.05[a]	3.19 ± 0.02[a]
Fe-EGCG-MCS	3.20 ± 0.02[a]	3.24 ± 0.03[a]	3.22 ± 0.03[a]	3.23 ± 0.05[a]	3.18 ± 0.02[a]

Table S7. Total acidity of grapes subjected to different treatments during 15 days of storage.

Data are expressed as mean ± standard deviation (n = 5).

Day	3	6	9	12	15
Tap water control	9.17 ± 0.25[a]	8.90 ± 0.17[a]	8.43 ± 0.15[a]	7.93 ± 0.35[a]	7.67 ± 0.15[a]
Zn-TA-MPN	9.70 ± 0.35[a]	9.30 ± 0.70[a]	8.90 ± 0.30[a]	8.23 ± 1.07[a]	8.17 ± 0.31[a]
Zn-TA-MCS	9.63 ± 0.31[a]	9.47 ± 0.25[a]	8.80 ± 0.36[a]	8.50 ± 0.20[a]	8.37 ± 0.50[a]
Zn-EGCG-MPN	9.30 ± 0.10[a]	9.17 ± 0.12[a]	8.53 ± 0.15[a]	8.33 ± 0.25[a]	8.13 ± 0.40[a]
Zn-EGCG-MCS	9.53 ± 0.06[a]	9.33 ± 0.31[a]	8.80 ± 0.10[a]	8.47 ± 0.15[a]	8.13 ± 0.15[a]
Fe-TA-MPN	9.33 ± 0.35[a]	8.90 ± 0.10[a]	8.60 ± 0.26[a]	8.17 ± 0.25[a]	8.03 ± 0.21[a]
Fe-TA-MCS	9.47 ± 0.21[a]	9.13 ± 0.12[a]	8.63 ± 0.12[a]	8.23 ± 0.21[a]	7.93 ± 0.06[a]
Fe-EGCG-MPN	9.27 ± 0.21[a]	8.93 ± 0.21[a]	8.67 ± 0.32[a]	8.27 ± 0.21[a]	8.10 ± 0.17[a]
Fe-EGCG-MCS	9.57 ± 0.21[a]	9.10 ± 0.10[a]	8.80 ± 0.10[a]	8.47 ± 0.12[a]	8.17 ± 0.15[a]

Table S8. Colony enumeration of *S. epidermidis* after mixing with different treatments and incubated overnight at 37 °C.

Concentration (CFU/mL)		Control	Fe-EGCG-MCS	Fe-TA-MCS	Zn-EGCG-MCS	Zn-TA-MCS
10^6	plate 1	TNTC	0	0	278	13
	plate 2	TNTC	0	0	295	5
	plate 3	TNTC	0	0	TNTC	7
10^7	plate 1	TNTC	9	1	TNTC	65
	plate 2	TNTC	0	6	TNTC	129
	plate 3	TNTC	3	0	TNTC	206