

Chitosan-Nanocellulose Composite Film from Shrimp Shell Waste and Sugarcane Bagasse for High-Performance Food Wrapping Applications

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ABSTRACT

Petroleum-based plastic food packaging creates a persistent waste burden, which motivates biodegradable alternatives made from waste biomass. This study aimed to develop chitosan–nanocellulose composite films from shrimp shell waste and sugarcane bagasse and to evaluate their suitability for food wrapping. Films were prepared by solvent casting at chitosan:nanocellulose ratios of 100:0 (F0), 90:10 (F1), 80:20 (F2), 70:30 (F3), and 60:40 (F4), and were assessed for mechanical properties, water vapor permeability (WVP), water solubility, antibacterial activity, soil burial biodegradation, and cherry tomato weight loss. One-way ANOVA showed significant formulation effects on tensile strength ($F(4, 20) = 74.00, p < .001, \eta^2 = .94$), which peaked at F3 (31.14 ± 1.97 MPa versus 14.33 ± 1.18 MPa for F0), and on WVP ($F(4, 20) = 183.43, p < .001, \eta^2 = .97$), which was lowest at F3. Elongation at break fell from 42.18% to 14.51% with increasing nanocellulose, and inhibition zones against *Escherichia coli* and *Staphylococcus aureus* decreased from F0 to F4, although F3 retained activity (12.75 and 11.20 mm). F3 also showed the highest 30-day soil burial weight loss (64.1%). In a 12-day cherry tomato trial, F3-wrapped fruit lost 8.99% of its weight, comparable to LDPE wrap (10.34%) and well below unwrapped fruit (36.21%). F3 was the most balanced of the tested formulations; characterization of the extracted materials and replicated storage data are needed to confirm these findings.

Keywords: Chitosan, Nanocellulose, Shrimp Shell Waste, Sugarcane Bagasse, Biodegradable Film, Food Packaging, Composite Film

INTRODUCTION

Conventional petroleum-based plastic food packaging extends shelf life and protects food during distribution. However, it is not biodegradable, and its waste accumulates in terrestrial and marine ecosystems. This concern has driven research on biodegradable, bio-based packaging made from renewable or waste biomass. Such materials address plastic pollution and add value to discarded agricultural and marine processing waste, in line with circular economy principles. Cellulose-based packaging with improved barrier and antibacterial properties has also been reported (Shi et al., 2022).

Chitosan is obtained by deacetylation of chitin extracted from crustacean shell waste (shrimp, crab). It is one of the most studied biopolymers for food packaging because of its film-forming capacity, biodegradability, biocompatibility, and antimicrobial activity against many foodborne bacteria. A recent evaluation confirmed that chitosan-based films extend the shelf life of several food categories (Barik et al., 2024). Studies on chitosan extraction from shrimp shell waste have established reproducible protocols that yield chitosan suitable for film formation (Öğretmen et al., 2022), and chitosan films from crab shell have been developed as multifunctional active packaging (Zaghib et al., 2024). Despite these advantages, chitosan films alone usually have limited mechanical strength and relatively high water vapor permeability. These weaknesses restrict their use in demanding food-wrapping applications and have motivated many reinforcement strategies.

Nanocellulose, cellulose refined to nanoscale dimensions by acid hydrolysis or mechanical fibrillation of cellulose-rich biomass, is widely investigated as a reinforcing filler for chitosan and other biopolymer films. Its high mechanical strength, high aspect ratio, and ability to form hydrogen-bonded networks with the chitosan matrix can improve both mechanical and barrier properties. Sugarcane bagasse, the fibrous residue left after juice extraction, is among the most abundant agro-industrial wastes in sugar-producing regions, including Indonesia, and is an underutilized nanocellulose source. Wu et al. (2025) extracted nanocellulose from bagasse and incorporated it into chitosan composite films, reporting improved mechanical and barrier properties relative to unreinforced chitosan. Related studies that combined chitosan from shrimp shells with cellulose nanofibers or microcrystalline cellulose from other residues, such as agave bagasse and durian rind, produced antibacterial and biodegradable films (de Oca-Vásquez et al., 2023; Haruna & Babel, 2026). More than 50% biodegradation within 30 days of soil burial has been reported for a dual-waste-valorization film (Haruna & Babel, 2026).

The closest earlier work on bagasse nanocellulose in chitosan films (Wu et al., 2025) concentrated on nanocellulose preparation and on the mechanical and barrier properties of the resulting films. Studies that pair shrimp shell chitosan with lignocellulosic fillers used agave bagasse or durian rind rather than sugarcane bagasse (de Oca-Vásquez et al., 2023; Haruna & Babel, 2026) (Table 1). The novelty of the present study therefore does not lie in using bagasse nanocellulose in chitosan films, which has been reported. It lies in the combination of three elements: (i) chitosan extracted from shrimp shell waste paired with nanocellulose from sugarcane bagasse, so that both components come from waste streams (dual-waste valorization); (ii) a systematic comparison of five nanocellulose loadings (0–40% of polymer mass) to locate the ratio that best balances competing



property requirements; and (iii) evaluation of mechanical, barrier, antibacterial, and biodegradation properties together with a direct storage trial against commercial low-density polyethylene (LDPE) wrap within one experimental framework. These elements are new only in combination, and this study should be read as an integrated evaluation rather than as the first report of bagasse nanocellulose–chitosan films.

Table 1. Comparison of the present study with closely related chitosan–cellulose film studies

Study	Cellulose/filler source	Chitosan source	Properties emphasized
Wu et al. (2025)	Sugarcane bagasse (nanocellulose, CNC)	Commercial chitosan (not shell-derived)	CNC/chitosan/glycerol optimization; SEM morphology; mechanical and barrier properties
de Oca-Vásquez et al. (2023)	Agave bagasse (cellulose nanofibers)	Shrimp shells	Antimicrobial activity of nanocomposite films (<i>E. coli</i>)
Haruna & Babel (2026)	Durian rind (microcrystalline cellulose)	Shrimp shells	Antibacterial, biodegradable packaging films
Zaghibib et al. (2024)	Algae (<i>Ulva</i> <i>lactuca</i>)	Crab shell	Antioxidant and antimicrobial properties of active films
This study	Sugarcane bagasse (nanocellulose)	Shrimp shells	Five ratios (0–40% nanocellulose): tensile, WVP, solubility, antibacterial, soil burial, and tomato storage vs. LDPE

Accordingly, this study aimed (1) to identify the chitosan:nanocellulose ratio that optimizes mechanical and barrier performance, (2) to characterize the antibacterial activity, water resistance, and biodegradability of the resulting films, and (3) to compare the weight-loss performance of the selected formulation with a commercial LDPE wrap and unwrapped fruit in a cherry tomato storage trial.

METHODS

Shrimp shell waste was collected from local seafood processing activity (Pameungpeuk, Garut, West Java, Indonesia), washed, dried at 60 °C for 24 h, and ground to 60 mesh; chitin was isolated by demineralization with 1.0 M HCl (1:10 g/mL solid-to-liquid ratio, 25 °C, 2 h), followed by deproteinization with 1.0 M NaOH (1:10 g/mL, 80 °C, 2 h), with each step followed by three washes with distilled water to a final pH of 7.0, and chitin was then deacetylated with 50% (w/v) NaOH at 100 °C for 4 h (1:20 g/mL), washed to pH 7.0, and dried at 60 °C for 24 h, giving yields of 32.4% for chitin and 21.7% for chitosan on a dry-weight basis, while sugarcane bagasse was collected as a residue from local sugarcane processing (Malang, East Java, Indonesia), washed, dried, and milled to 80 mesh, pretreated with 4% (w/v) NaOH at 80 °C for 2 h (1:20 g/mL) to remove lignin and hemicellulose, bleached with 5% (v/v) H₂O₂ at 70 °C for 2 h, and hydrolyzed with 60% (w/w) H₂SO₄

at 45 °C for 45 min (acid-to-cellulose ratio 10 mL/g), after which the reaction was stopped by dilution with cold water, the suspension was centrifuged at $10,000 \times g$ for 15 min in three cycles and dialyzed against distilled water (12–14 kDa membrane cut-off, 48 h) to pH 6.0–7.0, giving a yield of 38.5%; in this study, “nanocellulose” denotes the acid-hydrolyzed bagasse cellulose fraction, whose nanoscale dimensions were verified by TEM as reported in Section 3.1.

The chitosan was characterized by its degree of deacetylation (FTIR method, KBr pellet), viscosity-average molecular weight (Ubbelohde viscometry, 0.1 M acetic acid/0.2 M NaCl at 25 °C), ash content, moisture content, residual protein, and solubility in 1% (v/v) acetic acid, with chitin-to-chitosan conversion confirmed by FTIR (Shimadzu IRPrestige-21, $4000\text{--}400\text{ cm}^{-1}$, resolution 4 cm^{-1}), and the nanocellulose was characterized by TEM for particle dimensions and aspect ratio, XRD for the crystallinity index, FTIR for chemical changes after alkaline treatment and acid hydrolysis, and zeta potential for surface charge (Malvern Zetasizer Nano ZS, 25 °C, pH 7).

Composite films were prepared by solvent casting, in which chitosan was dissolved in 1% (v/v) aqueous acetic acid under magnetic stirring (400 rpm, 2 h, 25 °C) to give a 2% (w/v) solution, the nanocellulose suspension (1% w/v) was added at five chitosan:nanocellulose mass ratios of 100:0 (F0, pure chitosan control), 90:10 (F1), 80:20 (F2), 70:30 (F3), and 60:40 (F4), glycerol was added as plasticizer at 30% (w/w) of total polymer mass, and each formulation was homogenized (Ultra-Turrax, 12,000 rpm, 10 min), degassed under vacuum (15 min), cast (25 mL) onto a leveled polytetrafluoroethylene (PTFE) plate (casting area 100 cm^2), and dried at 40 °C and 50% RH for 24 h, after which films were conditioned at 25 °C and 50% RH for 48 h before testing, and residual acetic acid was neutralized with 1 M NaOH followed by extended drying for 24 h.

Tensile strength and elongation at break were measured with a universal testing machine (Instron 3369, load cell capacity 500 N) following ASTM D882, using dumbbell-shaped specimens ($100 \times 10\text{ mm}$; gauge length 50 mm) conditioned at 25 °C and 50% RH for 48 h and tested at a crosshead speed of 5 mm/min until fracture, with five specimens ($n = 5$) per formulation and thickness measured at five points on each specimen to calculate the cross-sectional area. Water vapor permeability (WVP) was determined gravimetrically by the cup method (ASTM E96/E96M), in which film specimens were sealed over test cups (exposed area 33.18 cm^2) containing anhydrous CaCl_2 and placed in a chamber at 25 °C and 75% RH, cups were weighed every 2 h for 24 h, and WVP was calculated from the slope of mass gain versus time, normalized for film thickness, exposed area, and the water vapor pressure difference; film thickness was measured with a digital micrometer (0.001 mm resolution) at five points per specimen, moisture content was determined by oven-drying specimens ($20 \times 20\text{ mm}$) at 105 °C to constant mass, and water solubility was determined by immersing pre-dried, pre-weighed specimens ($20 \times 20\text{ mm}$, initial dry mass $\approx 100\text{ mg}$) in 50 mL distilled water at 25 °C for 24 h, then drying the undissolved residue at 105 °C to constant mass, with all tests using five specimens ($n = 5$) per formulation.

Antibacterial activity was evaluated by an agar diffusion assay in which film specimens were placed in direct contact with the inoculated agar surface (film-disc contact diffusion), rather than in wells, against *Escherichia coli* (ATCC 25922) and *Staphylococcus aureus* (ATCC 25923), which are relevant to food spoilage and foodborne illness; bacterial suspensions were adjusted to 0.5



McFarland turbidity ($\approx 1.5 \times 10^8$ CFU/mL) and spread on Mueller-Hinton agar, sterilized film discs (diameter 6 mm, thickness 0.09 mm, mass 20 mg; sterilization by UV irradiation for 30 min per side) were placed on the surface, a positive control (tetracycline disc, 30 μ g) and a negative control (plasticizer/acetic acid-only film) were included, and pure nanocellulose film and a residual acetic acid/pH control were also tested, plates were incubated at 37 °C for 24 h, and the diameter of the clear zone was measured in millimeters (including the disc diameter), with each formulation tested in triplicate ($n = 3$) per organism with independent biological replicates. Biodegradability was assessed by a soil burial test in which pre-dried, pre-weighed film specimens (25 $\times$ 25 mm, initial mass $\approx$ 100 mg) were buried at 10 cm depth in garden soil from the Universitas Padjadjaran campus (pH 6.8, moisture 35%, 25 ± 2 °C), with $n = 3$ specimens per formulation and time point, retrieved at 5-day intervals over 30 days, gently cleaned of adhering soil, oven-dried at 60 °C to constant mass, and reweighed, and weight loss (%) was calculated as $(W_0 - W_t)/W_0 \times 100$, where W_0 is the initial dry mass and W_t is the dry mass at time t .

The formulation selected by the multi-criteria comparison in Section 3.6 (F3) was evaluated in a direct food preservation trial, using cherry tomatoes as a model perishable product because their spoilage under ambient storage is driven largely by weight loss; tomatoes (local market, breaker-to-pink ripeness stage, mean mass 12.5 ± 1.2 g) were divided into three groups of unwrapped (negative control), wrapped in commercial low-density polyethylene (LDPE) film (thickness 0.02 mm; benchmark control), and wrapped in the F3 film, each group comprising $n = 5$ independent packs/tomatoes, wrapped and sealed by heat sealing (LDPE) or manual wrapping with film overlap (F3), and all groups were stored under identical room conditions (25 ± 2 °C, $65 \pm 5\%$ RH) and weighed every 2 days for 12 days to determine cumulative percentage weight loss as an indicator of moisture retention.

Differences among the five formulations in tensile strength, elongation at break, WVP, thickness, moisture content, and water solubility ($n = 5$ per formulation) were tested by one-way ANOVA followed by Tukey's Honestly Significant Difference (HSD) test, effect size was expressed as $\eta^2 = F \times df_1 / (F \times df_1 + df_2)$, and 95% confidence intervals of means were calculated from the t distribution ($df = 4$); normality of residuals (Shapiro–Wilk test) and homogeneity of variances (Levene's test) were assessed, with Shapiro–Wilk $p > .05$ for all responses and Levene's test $p < .05$ for WVP and elongation at break, and because the sample variances were clearly unequal for some responses (for example, WVP), Welch's ANOVA with Games–Howell post-hoc comparisons was also computed as a sensitivity analysis, while inhibition zones, soil burial weight loss, and cherry tomato weight loss are reported as descriptive means only, with no inferential test applied to these three data sets, and analyses of the remaining properties were run in Python 3 with SciPy and statsmodels at $\alpha = 0.05$.

RESULTS

1. Characterization of Extracted Chitosan and Nanocellulose

Table 3 summarizes the physicochemical properties of the extracted chitosan and nanocellulose. The chitosan had a degree of deacetylation of 85.2%, a viscosity-average molecular

weight of 210 kDa, a moisture content of 8.4%, and low ash (1.2%) and residual protein (0.8%) contents, indicating adequate purity for film formation. These values are consistent with chitosan extracted from shrimp shell waste by similar alkaline deacetylation protocols, where the degree of deacetylation typically falls between 75% and 90% and the molecular weight between 150 and 350 kDa. The degree of deacetylation is particularly relevant here because it determines the density of protonatable amine groups, which govern both the solubility of chitosan in dilute acetic acid and its antibacterial activity. A value of 85.2% is high enough to ensure complete dissolution in 1% (v/v) acetic acid (confirmed by the solubility result) and to provide a substantial density of cationic amine groups at the film surface, which is consistent with the measurable inhibition zones observed for all formulations in Section 3.4.

The nanocellulose had a yield of 38.5%, a diameter of 15–30 nm, a length of 200–400 nm (aspect ratio ≈ 15), a crystallinity index of 68.5%, and a zeta potential of -32.4 mV. The diameter and length are within the range expected for cellulose nanocrystals obtained by sulfuric acid hydrolysis of bagasse, and the aspect ratio of approximately 15 is in the range where rod-like fillers are expected to reinforce a polymer matrix effectively. The crystallinity index of 68.5% is consistent with the partial removal of amorphous regions during acid hydrolysis and supports the interpretation that the reinforcing effect observed in Section 3.2 arises partly from the intrinsic stiffness of the crystalline domains. The zeta potential of -32.4 mV indicates a stable aqueous dispersion, which is important because aggregation of nanocellulose before casting would produce inhomogeneous films and could explain the decline in tensile strength and WVP performance observed at F4 (Sections 3.2 and 3.3). FTIR confirmed the conversion of chitin to chitosan (disappearance of the amide I band at 1655 cm^{-1} and reduction of the amide II band at 1550 cm^{-1}) and the removal of lignin and hemicellulose from bagasse (disappearance of bands at 1735 and 1510 cm^{-1}).

Table 3. Physicochemical characteristics of the extracted chitosan and nanocellulose

Material	Parameter	Method	Result
Chitosan	Extraction yield (%)	Gravimetric	21.7
Chitosan	Degree of deacetylation (%)	FTIR	85.2
Chitosan	Molecular weight (kDa)	Viscometry	210
Chitosan	Ash content (%)	Gravimetric	1.2
Chitosan	Moisture content (%)	Gravimetric	8.4
Chitosan	Residual protein (%)	Bradford	0.8
Chitosan	Solubility in dilute acetic acid	Visual	Soluble
Nanocellulose	Yield (%)	Gravimetric	38.5
Nanocellulose	Diameter / length (nm); aspect ratio	TEM	15–30 / 200–400; ≈ 15
Nanocellulose	Crystallinity index (%)	XRD	68.5
Nanocellulose	Zeta potential (mV)	Zetasizer	-32.4

2. Mechanical Properties

Figure 1 and Table 4 present the tensile strength and elongation at break of the five formulations. Tensile strength increased with nanocellulose incorporation from F0 (14.33 ± 1.18 MPa; 95% CI 12.87–15.80) to F3 (31.14 ± 1.97 MPa; 95% CI 28.69–33.59) and then declined at F4 (23.47 ± 1.84 MPa). One-way ANOVA showed a large formulation effect ($F(4, 20) = 74.00$, $p < .001$, $\eta^2 = .94$), and Tukey HSD showed that all pairwise differences were significant ($p < .05$) except F2 versus F4 ($p = .420$). The mean difference between F3 and F0 was 16.81 MPa (95% CI 14.35–19.27). Elongation at break decreased significantly and monotonically from 42.18% (F0) to 14.51% (F4) ($F(4, 20) = 140.28$, $p < .001$, $\eta^2 = .97$), consistent with the stiffening effect of a rigid filler in a flexible matrix.

Table 4. Mechanical properties by formulation (mean $\pm$ SD, $n = 5$)

Formulation	Chitosan:Nanocellulose	Tensile strength (MPa)	Elongation at break (%)
F0	100:0	14.33 ± 1.18	42.18 ± 4.10
F1	90:10	18.97 ± 0.91	36.26 ± 1.67
F2	80:20	25.32 ± 2.07	26.17 ± 1.33
F3	70:30	31.14 ± 1.97	19.99 ± 1.03
F4	60:40	23.47 ± 1.84	14.51 ± 0.84

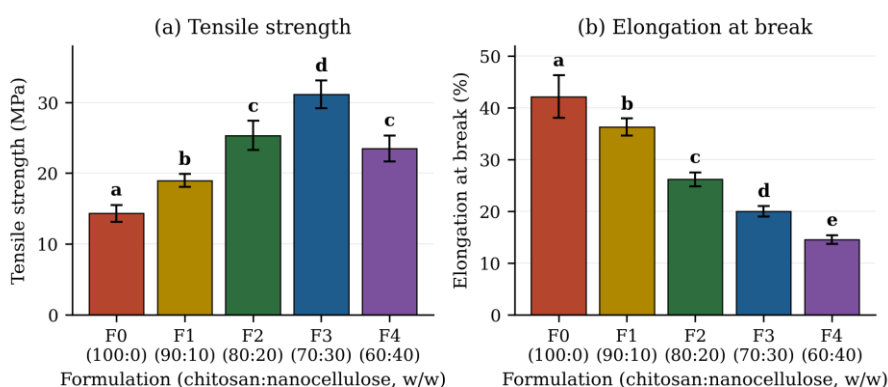


Figure 1. Tensile strength (a) and elongation at break (b) of chitosan–nanocellulose films at different chitosan:nanocellulose ratios (mean $\pm$ SD, $n = 5$; error bars = SD). Different letters indicate significant differences (Tukey HSD, $p < .05$)

3. Barrier and Physical Properties

Figure 2 and Table 5 present WVP, thickness, moisture content, and water solubility. WVP decreased with nanocellulose content from F0 (4.96×10^{-10} g/m·s·Pa; 95% CI 4.70–5.22) to a minimum at F3 (2.41×10^{-10} ; 95% CI 2.36–2.46) and increased slightly at F4 (2.74×10^{-10}) ($F(4, 20) = 183.43$, $p < .001$, $\eta^2 = .97$). All pairwise WVP differences were significant (Tukey HSD), including F3 versus F4. Water solubility decreased from 39.03% (F0) to 21.71% (F3) and was 24.36% at F4, and moisture content followed the same pattern (18.4% to 11.4%, then 12.7%). For these two parameters, however, F4 did not differ significantly from F3 (Tukey HSD $p = .148$ and $.095$, respectively), so the data indicate a plateau rather than a statistically supported rebound. Film thickness increased modestly

from 0.084 mm (F0) to 0.100 mm (F4), consistent with the added solid content; significant differences were found only in comparisons involving F4.

Table 5. Barrier and physical properties by formulation (mean $\pm$ SD, n = 5)

Formulation n	WVP ($\times 10^{-10}$ g/m $\cdot$ s $\cdot$ Pa)	Thickness (mm)	Moisture content (%)	Water solubility (%)
F0	4.96 $\pm$ 0.21	0.084 $\pm$ 0.004	18.4 $\pm$ 1.0	39.03 $\pm$ 1.25
F1	4.00 $\pm$ 0.27	0.087 $\pm$ 0.004	16.1 $\pm$ 0.8	32.39 $\pm$ 2.68
F2	3.12 $\pm$ 0.09	0.090 $\pm$ 0.005	13.9 $\pm$ 0.8	26.96 $\pm$ 1.07
F3	2.41 $\pm$ 0.04	0.092 $\pm$ 0.005	11.4 $\pm$ 0.8	21.71 $\pm$ 0.94
F4	2.74 $\pm$ 0.14	0.100 $\pm$ 0.006	12.7 $\pm$ 0.2	24.36 $\pm$ 2.02

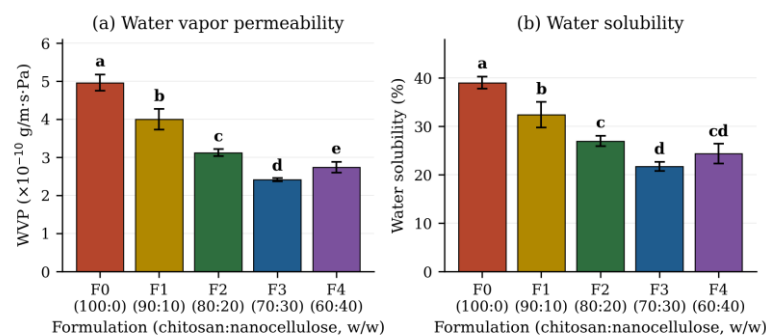


Figure 2. Water vapor permeability (a) and water solubility (b) of chitosan–nanocellulose films (mean $\pm$ SD, n = 5; error bars = SD). Different letters indicate significant differences (Tukey HSD, p < .05)

Table 6. One-way ANOVA and Welch's ANOVA for mechanical and physical properties (n = 5 per formulation; η^2 = effect size). Values for thickness, moisture content, and water solubility were computed from the reported means and SDs.

Parameter	ANOVA F(4, 20)	p	η^2	Welch F (df ₂)	Welch p
Tensile strength	74.00	< .001	.94	68.92 (9.7)	< .001
Elongation at break	140.28	< .001	.97	192.62 (9.7)	< .001
WVP	183.43	< .001	.97	213.79 (8.9)	< .001
Thickness	7.80	< .001	.61	5.80 (9.9)	.011
Moisture content	65.41	< .001	.93	52.46 (8.7)	< .001
Water solubility	80.31	< .001	.94	133.84 (9.8)	< .001

4. Antibacterial Activity

Figure 3 presents inhibition zones against *E. coli* and *S. aureus*. Inhibition zones decreased progressively with nanocellulose content for both organisms: from 16.61 mm (F0) to 9.42 mm (F4) for *E. coli*, and from 14.35 mm (F0) to 8.85 mm (F4) for *S. aureus*. All formulations produced a measurable zone, and F3 retained 12.75 mm (*E. coli*) and 11.20 mm (*S. aureus*), about 77–78% of the F0 values. No inferential test is reported for the inhibition zones, so the differences among formulations are descriptive. The decline is consistent with dilution of chitosan by nanocellulose. The zones, however, reflect the films as tested; because the control zone diameters described in Section 2.6 are not reported here, the contribution of chitosan itself cannot be separated from that of residual acetic acid and film pH.

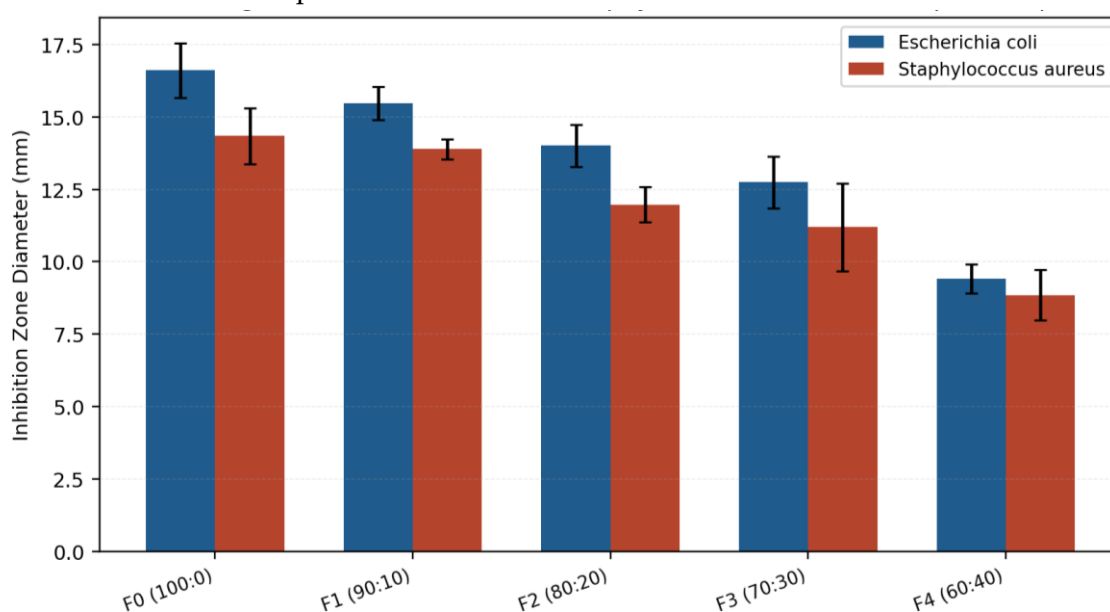


Figure 3. Inhibition zone diameters of chitosan–nanocellulose films against *Escherichia coli* and *Staphylococcus aureus* (mean $\pm$ SD, $n = 3$ per group)

5. Biodegradability

Figure 4 presents weight loss during 30 days of soil burial (mean of $n = 3$ specimens per formulation and time point; variability is not shown). All formulations lost weight progressively. After 30 days, weight loss was highest for F3 (64.1%), followed by F2 (55.1%), F4 (52.2%), F1 (46.3%), and F0 (40.2%). Weight loss increased with nanocellulose content up to F3 and decreased at F4, a pattern that parallels the mechanical and barrier results in Sections 3.2 and 3.3. This may reflect a balance between structural integrity and matrix porosity that allows microbial access, but film porosity and microbial activity were not measured, so this explanation is a hypothesis. No inferential test is reported for these data, so the ranking after 30 days is descriptive and the differences among formulations should not be read as statistically supported.

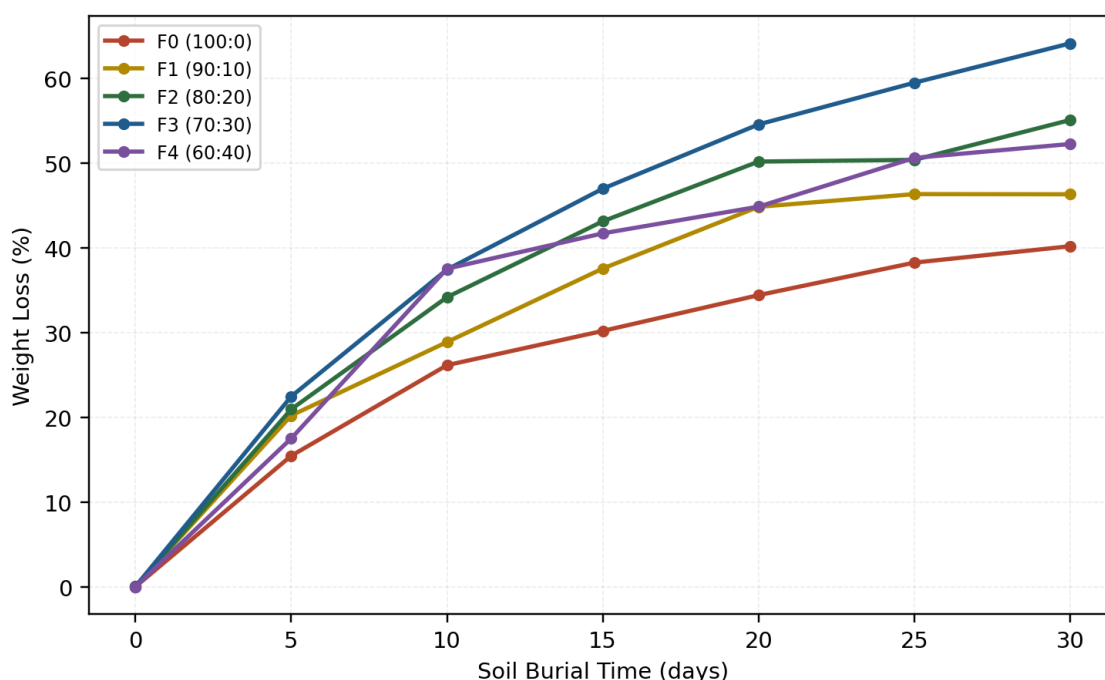


Figure 4. Soil burial weight loss of chitosan–nanocellulose films over 30 days (mean, $n = 3$; error bars not shown)

6. Selection of the Optimal Formulation

F3 was not the best formulation for every property, so the formulation for the storage trial was chosen by an explicit multi-criteria comparison. Five responses with complete data for all formulations (tensile strength, elongation at break, WVP, water solubility, and 30-day weight loss) were rescaled to 0–1 (1 = best value among the formulations, 0 = worst; WVP and solubility were inverted so that lower values score higher) and averaged with equal weights (Table 7). F3 had the highest composite score (0.84), followed by F2 (0.62) and F4 (0.55). F4 was inferior to F3 on every criterion and can be excluded outright. The ranking is sensitive to the weight given to elongation at break: F3 remains first unless this one criterion carries more than about 54% of the total weight, above which F1 would rank first (F0 and F2 overtake F3 only above about 55% and 59%). Antibacterial activity was not included in the score because it was evaluated separately (Section 3.4); F3 retained about 77–78% of the F0 zone diameter. F3 is therefore chosen as the best compromise among the tested formulations, on the premise that tensile strength, barrier performance, and biodegradation matter at least as much as extensibility. Applications that need high extensibility or maximum antibacterial activity would favor F2 or F1.

Table 7. Normalized property scores (0–1, higher is better) and equal-weight composite score

Formulation n	Tensile strength	Elongatio n at break	WVP	Water solubility	30-day weight loss	Composite score
F0	0.00	1.00	0.00	0.00	0.00	0.20
F1	0.28	0.79	0.38	0.38	0.26	0.42
F2	0.65	0.42	0.72	0.70	0.62	0.62
F3	1.00	0.20	1.00	1.00	1.00	0.84
F4	0.54	0.00	0.87	0.85	0.50	0.55

7. Food Preservation Performance

Formulation F3 (70:30) was tested in the storage trial on the basis of the composite ranking in Section 3.6. Figure 5 shows cumulative weight loss of cherry tomatoes over 12 days (mean of $n = 5$ tomatoes/packs per group; variability is not shown). Unwrapped tomatoes lost weight rapidly and almost linearly, reaching 36.21% at day 12. Both wraps greatly reduced weight loss: LDPE-wrapped tomatoes reached 10.34% and F3-wrapped tomatoes 8.99%. No inferential test was applied to these data. Without replicate-based variability and a statistical test, the 1.35-percentage-point difference between F3 and LDPE cannot be interpreted as superiority; the result is reported as comparable weight loss.

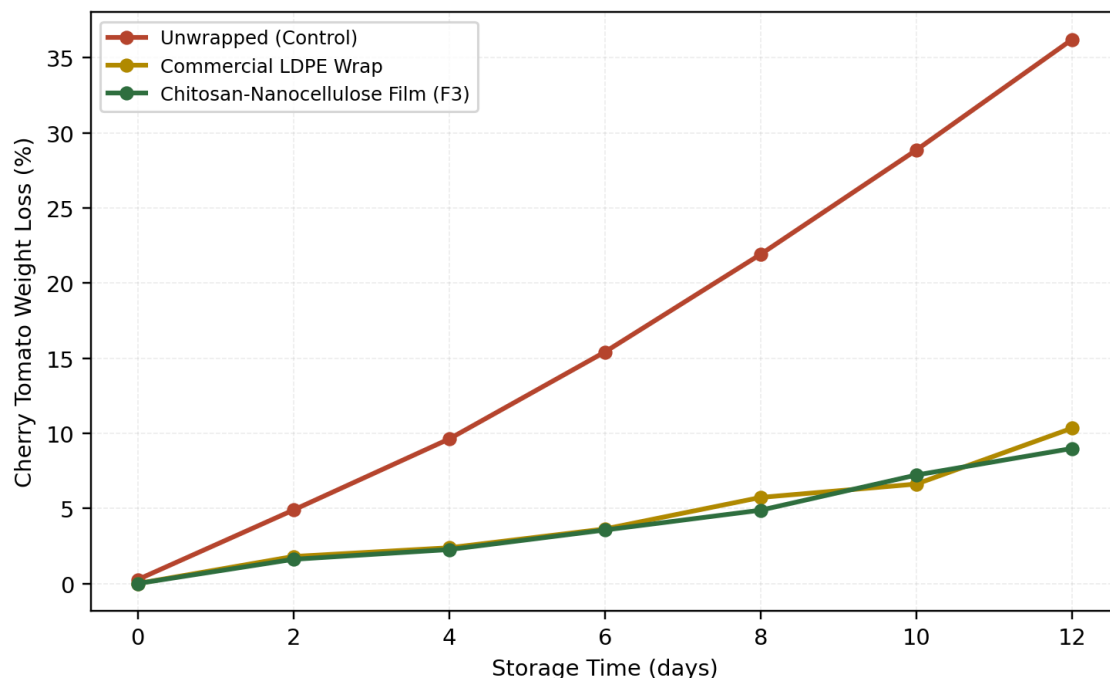


Figure 5. Weight loss of cherry tomatoes during 12 days of room-temperature storage under different wrapping conditions (mean, $n = 5$; error bars not shown)

DISCUSSION

Formulation F3 (70:30) gave the best values for tensile strength, WVP, and 30-day biodegradation, and the lowest mean water solubility (not significantly different from F4), but not for elongation at break or antibacterial activity. It is therefore best described as the most balanced of the tested formulations (Section 3.6), not as the best for every property. The response to nanocellulose loading was non-monotonic: properties improved up to an intermediate loading and declined at the highest loading (F4, 60:40). Similar behavior has been reported for chitosan–nanocellulose and chitosan–microcrystalline cellulose films, where the decline at high filler content is commonly attributed to particle aggregation, disruption of the continuous polymer network, and structural defects. No SEM or dispersion analysis was performed here, so this explanation remains a hypothesis. The tensile strength of F3 (31.14 MPa) is more than double that of the pure chitosan control. Finer cellulose particles may reinforce more efficiently, but a direct comparison with other chitosan–cellulose films (for example, Haruna & Babel, 2026) is limited because the films differ in formulation and testing conditions.

The decrease in WVP with nanocellulose content up to F3 is consistent with the barrier mechanism usually attributed to nanocellulose in biopolymer films, in which a high aspect ratio and hydrogen bonding with the chitosan matrix create a more tortuous path for water vapor (Wu et al., 2025). The dispersion of the nanocellulose within the films was not measured here, so this explanation is a hypothesis rather than an experimentally confirmed mechanism. The slight WVP increase at F4 parallels the drop in tensile strength at this formulation and may be associated with nanocellulose aggregation or reduced filler dispersion at higher loading, which could create discontinuities or micro-voids that offset the tortuosity effect. SEM or dispersion analysis would be needed to test this. For water solubility and moisture content, F4 did not differ significantly from F3, so the F4 “rebound” is statistically supported only for WVP and tensile strength.

The decline in antibacterial activity with increasing nanocellulose content was consistent across both organisms. It is expected if the activity depends on the protonated amine groups of chitosan, which interact electrostatically with negatively charged components of microbial cell membranes, because nanocellulose does not itself act as an antimicrobial and replaces chitosan mass, lowering the density of these groups at the film surface. This attribution remains tentative. The degree of deacetylation, which determines the density of protonatable amine groups, was 85.2% (Table 3), and residual acetic acid or film pH may also have contributed to the inhibition zones. F3 still produced clear zones against both organisms, retaining about 77–78% of the F0 diameter. The trade-off between mechanical/barrier performance and antibacterial activity is therefore real but does not remove antimicrobial activity at this ratio, which matters because food-contact packaging often has to balance partially competing requirements.

The tomato storage trial is the most application-oriented result. F3-wrapped tomatoes lost 8.99% of their weight over 12 days, compared with 10.34% for LDPE wrap and 36.21% for unwrapped fruit, so both wraps clearly reduced moisture loss. The 1.35-percentage-point difference between F3 and LDPE, however, was not tested statistically, and the replicate structure of this experiment is not shown ($n = 5$ per group, Section 2.8). The data therefore support the conclusion



that F3 performed comparably to LDPE under these conditions, not that it was superior. This is relevant to the common concern that biodegradable packaging trades function for sustainability, but it needs confirmation in replicated trials with additional quality indicators such as firmness, color, and microbial load.

These findings are relevant to Indonesia, a major producer of farmed shrimp, which generates large amounts of shell waste, and of sugarcane, which generates bagasse in sugar milling. Both are abundant, low-cost, and underused raw materials for sustainable packaging. Converting them into a single composite film offers a dual-waste valorization pathway consistent with circular economy principles. It could help address solid waste in the fisheries and sugar sectors and reduce demand for petroleum-based packaging.

This study has several limitations. First, the dispersion of the nanocellulose within the films and the film microstructure were not examined (for example, by SEM or AFM), so the mechanistic explanations above remain hypotheses. Second, the chitosan properties reported in Table 3 (such as the degree of deacetylation and molecular weight) were not varied, so their contribution to the mechanical and antibacterial results was not tested. Third, the antibacterial assay included controls for residual acetic acid and pH effects (Section 2.6), but the control results are not reported, so these effects cannot be separated from the activity of chitosan. Fourth, variability for the soil burial and storage experiments is not shown ($n = 3$ and $n = 5$, respectively; Sections 2.7 and 2.8), and these time-course data were not analyzed statistically. Fifth, the storage trial used a single product (cherry tomato), one storage condition (ambient room temperature), and weight loss as the only indicator. Finally, food-contact safety (migration, cytotoxicity, and regulatory compliance) was not assessed (see Tanpichai et al., 2022).

CONCLUSIONS

This study prepared chitosan–nanocellulose composite films from shrimp shell waste and sugarcane bagasse at five blending ratios. The 70:30 formulation (F3) gave the best balance of mechanical, barrier, and biodegradation performance among those tested. Compared with the pure chitosan control, F3 had more than double the tensile strength (31.14 MPa; $F(4, 20) = 74.00$, $p < .001$, $\eta^2 = .94$), significantly lower WVP ($F(4, 20) = 183.43$, $p < .001$, $\eta^2 = .97$), and the highest 30-day soil burial weight loss (64.1%). These gains came with lower elongation at break and smaller inhibition zones against *Escherichia coli* and *Staphylococcus aureus*, although F3 retained clear antibacterial activity. In the cherry tomato trial, F3-wrapped fruit lost 8.99% of its weight over 12 days, comparable to LDPE wrap (10.34%) and far less than unwrapped fruit (36.21%).

These results indicate that a film combining two abundant Indonesian waste streams can approach conventional plastic wrap in moisture retention while remaining biodegradable and antibacterial, which is a promising circular-economy pathway for food packaging. The conclusions are limited by the absence of film microstructure analysis (SEM/AFM), the limited replication reported for the storage and biodegradation tests, and the single food model. Future work should characterize the film structure, replicate the storage trial across more foods and conditions, and assess food-contact safety.

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