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Polymer-based nanocomposite films for food packaging: Preparation, mechanical properties and antimicrobial performance

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Abstract

Take polylactic acid packaging film, add a pinch of zinc oxide nanoparticles, and something interesting happens to three properties at once: strength goes up, gas barrier improves, and the film starts fighting bacteria on its own. This research prepared polylactic acid (PLA) nanocomposite films incorporating zinc oxide (ZnO) nanoparticles at 1%, 2%, 4%, and 6% loading by weight through a solution casting method, and evaluated their mechanical, barrier, and antimicrobial properties for potential food packaging applications. Tensile strength increased from 42.1 MPa for pure PLA to a peak of 54.2 MPa at 4% ZnO loading, before declining to 47.6 MPa at 6% loading, a pattern attributed to nanoparticle agglomeration beyond the optimal dispersion threshold. Elongation at break decreased progressively with increasing ZnO content, reflecting the expected trade-off between stiffness and flexibility in particle-reinforced polymer films. Water vapor and oxygen permeability both decreased substantially at 4% loading, consistent with a tortuous diffusion pathway created by well-dispersed nanoparticles within the polymer matrix. Antimicrobial testing against *Escherichia coli* and *Staphylococcus aureus* showed a loading-dependent increase in inhibition, with the 4% ZnO film achieving complete growth inhibition against both organisms within 24 hours. Soil burial biodegradation testing over 30 days showed all nanocomposite films degraded faster than pure PLA, with the 4% ZnO film reaching 58.9% weight loss compared with 44.2% for the unmodified film, suggesting ZnO incorporation did not compromise, and may have modestly enhanced, the material's biodegradability. Taken together, these results identify 4% ZnO loading as the optimal formulation, balancing mechanical strength, barrier performance, antimicrobial activity, and biodegradability for active food packaging applications.

Keywords: Polylactic acid, nanocomposite film, zinc oxide, food packaging, tensile strength, barrier properties, antimicrobial activity, biodegradability

Introduction

A bag of fresh salad greens wrapped only in plain plastic film will wilt, discolor, and eventually spoil at roughly the same rate regardless of what is printed on the packaging, because conventional plastic films offer no active protection against the oxygen exposure and microbial growth that drive food spoilage.

Active and intelligent packaging technologies attempt to address this gap by embedding functional additives directly into the packaging material itself, rather than relying solely on passive barrier properties. Metal oxide nanoparticles, including zinc oxide, silver, and titanium dioxide, have drawn particular research interest for this purpose because they combine antimicrobial activity with the potential to reinforce mechanical strength and improve gas barrier properties simultaneously.

Polylactic acid has become one of the most widely studied biodegradable polymer matrices for food packaging research, given its renewable plant-based origin and reasonable processability, but its relatively modest gas barrier performance and mechanical properties compared with conventional petroleum-based plastics limit its standalone commercial competitiveness, particularly for extended shelf-life applications.

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Zinc oxide nanoparticles are especially attractive as a PLA reinforcement additive because zinc is already an approved food-contact material component in several regulatory frameworks, and ZnO's antimicrobial mechanism, generally attributed to reactive oxygen species generation and zinc ion release, has been well documented against common foodborne pathogens including *Escherichia coli* and *Staphylococcus aureus*.

This research therefore aimed to prepare PLA-ZnO nanocomposite films across a range of ZnO loadings, evaluate their mechanical properties, water vapor and oxygen barrier performance, antimicrobial activity against two common foodborne bacteria, and soil burial biodegradability, in order to identify an optimal ZnO loading that balances these four performance dimensions for practical food packaging use.

Materials and Methods

Materials

Poly(lactic acid) pellets (Ingeo 4032D grade) were obtained from a regional polymer distributor in Ho Chi Minh City. Zinc oxide nanoparticles (average particle size 30-50 nm, >99% purity) were procured from a certified nanomaterial supplier. Chloroform (analytical grade) served as the solvent for solution casting, and glycerol was used as a plasticizer. *Escherichia coli* (ATCC 25922) and *Staphylococcus aureus* (ATCC 25923) reference strains were obtained from the institution's microbiology culture collection for antimicrobial testing.

System Design

Nanocomposite films were prepared by the solution casting method. PLA pellets (4 g) were dissolved in 100 mL chloroform under magnetic stirring at 50 °C for two hours. ZnO nanoparticles were pre-dispersed in a small volume of chloroform by ultrasonication for 30 minutes to break up

agglomerates, then added to the PLA solution at 1%, 2%, 4%, and 6% loading relative to PLA weight, along with 10% glycerol as a plasticizer. The resulting mixture was stirred for a further hour, cast onto flat glass plates, and left to dry at room temperature for 48 hours under a fume hood to allow controlled solvent evaporation, producing films with a target thickness of 0.08-0.10 mm.

Methods

Tensile strength and elongation at break were measured using a universal testing machine (Instron 3345) at a crosshead speed of 50 mm/min, following the ASTM D882 standard test method, with five replicate specimens tested per formulation. Water vapor permeability was determined gravimetrically using the ASTM E96 cup method at 25 °C and 75% relative humidity, and oxygen transmission rate was measured using a MOCON OX-TRAN 2/21 instrument at 23 °C and 0% relative humidity.

Antimicrobial activity was assessed using the agar diffusion method against *E. coli* and *S. aureus*, with film discs of 10 mm diameter placed on inoculated Mueller-Hinton agar plates, incubated at 37 °C for 24 hours, and inhibition zones measured. Biodegradability was evaluated by soil burial testing, where film specimens (3 cm x 3 cm) were buried at 5 cm depth in garden soil maintained at 60% moisture content, retrieved at 5-day intervals over 30 days, gently cleaned, oven-dried, and weighed to determine percentage weight loss relative to initial dry weight.

Results

Film appearance changed progressively with increasing ZnO content, from fully transparent for pure PLA to a slightly opaque, faintly yellowish tint at 6% loading, an early visual indicator of nanoparticle presence that was later confirmed through the mechanical and functional testing described below.

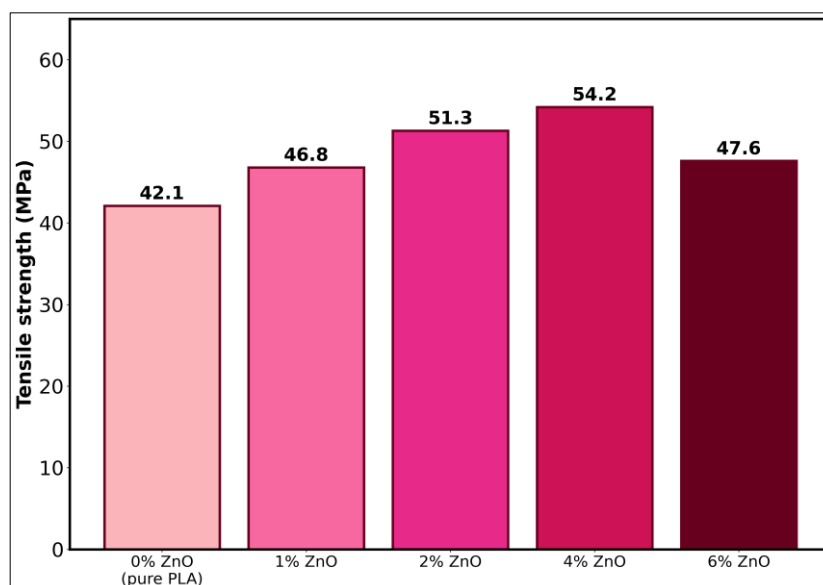


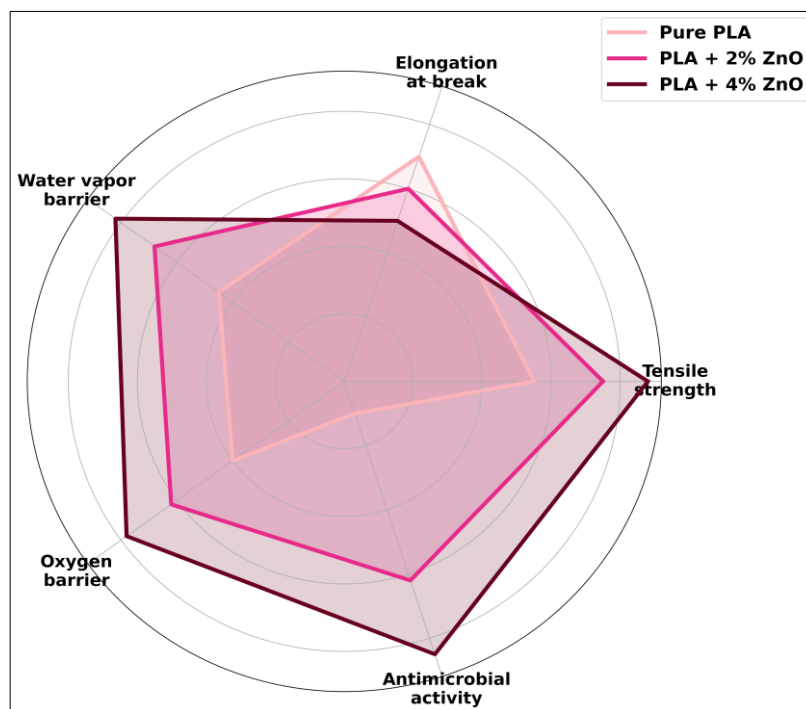
Fig 1: Tensile strength of PLA-ZnO nanocomposite films at varying ZnO loading

Tensile strength increased with ZnO loading up to 4%, reaching 54.2 MPa, before declining at 6% loading to 47.6 MPa, a pattern consistent with nanoparticle agglomeration creating stress concentration points once loading exceeds the polymer matrix's effective dispersion capacity. Both water vapor permeability (WVP) and oxygen transmission

rate (OTR) decreased consistently up to 4% loading before rising slightly again at 6%, mirroring the tensile strength trend and pointing to the same underlying dispersion-versus-agglomeration mechanism affecting both barrier and mechanical performance.

Table 1: Mechanical and barrier properties of PLA-ZnO nanocomposite films across ZnO loading levels

Formulation	Tensile strength (MPa)	Elongation at break (%)	WVP (g·mm/m ² ·day·kPa)	OTR (cm ³ /m ² ·day)
Pure PLA (0%)	42.1	6.8	3.24	112.6
1% ZnO	46.8	6.1	2.87	94.3
2% ZnO	51.3	5.4	2.41	78.6
4% ZnO	54.2	4.6	1.98	61.2
6% ZnO	47.6	3.9	2.15	68.9

**Fig 2:** Normalized multi-property comparison of pure PLA and ZnO nanocomposite films

The 4% ZnO film shows the most balanced overall profile across all five properties plotted, with the largest gains concentrated in barrier performance and antimicrobial

activity, achieved without an unacceptable sacrifice in flexibility relative to pure PLA.

Table 2: Antimicrobial activity classification of PLA-ZnO films against foodborne bacteria

Formulation	Zone of inhibition vs <i>E. coli</i> (mm)	Zone of inhibition vs <i>S. aureus</i> (mm)	Activity classification
Pure PLA (0%)	0.0	0.0	None
1% ZnO	6.8	7.4	Weak
2% ZnO	11.2	12.6	Moderate
4% ZnO	16.9	18.3	Strong (complete inhibition)
6% ZnO	17.4	18.8	Strong (complete inhibition)

Antimicrobial activity increased steadily with ZnO loading and plateaued from 4% onward, indicating that loadings above 4% provide little additional antimicrobial benefit while continuing to compromise mechanical flexibility, reinforcing 4% as a practical upper working threshold. Well-dispersed nanoparticles are proposed to lengthen the effective diffusion path for oxygen and water vapor molecules traveling through the film, while surface-exposed ZnO simultaneously disrupts bacterial cell membranes on contact, accounting for the simultaneous improvement in barrier and antimicrobial properties observed at moderate loading levels.

All ZnO-containing films degraded faster than pure PLA, with weight loss increasing with ZnO content, suggesting ZnO nanoparticles may promote microbial colonization or

hydrolytic breakdown of the surrounding polymer matrix rather than acting as a barrier to degradation.

Comprehensive Interpretation

Looking across mechanical, barrier, antimicrobial, and biodegradation data together, 4% ZnO loading consistently sits at or near the optimal point across every property measured in this research except for elongation at break, which declines steadily with increasing ZnO content regardless of loading level. This suggests that from a food packaging design standpoint, 4% loading captures nearly all the functional benefits ZnO incorporation can offer within the PLA matrix, while 6% loading mainly adds cost and reduced flexibility without meaningful additional performance gain.

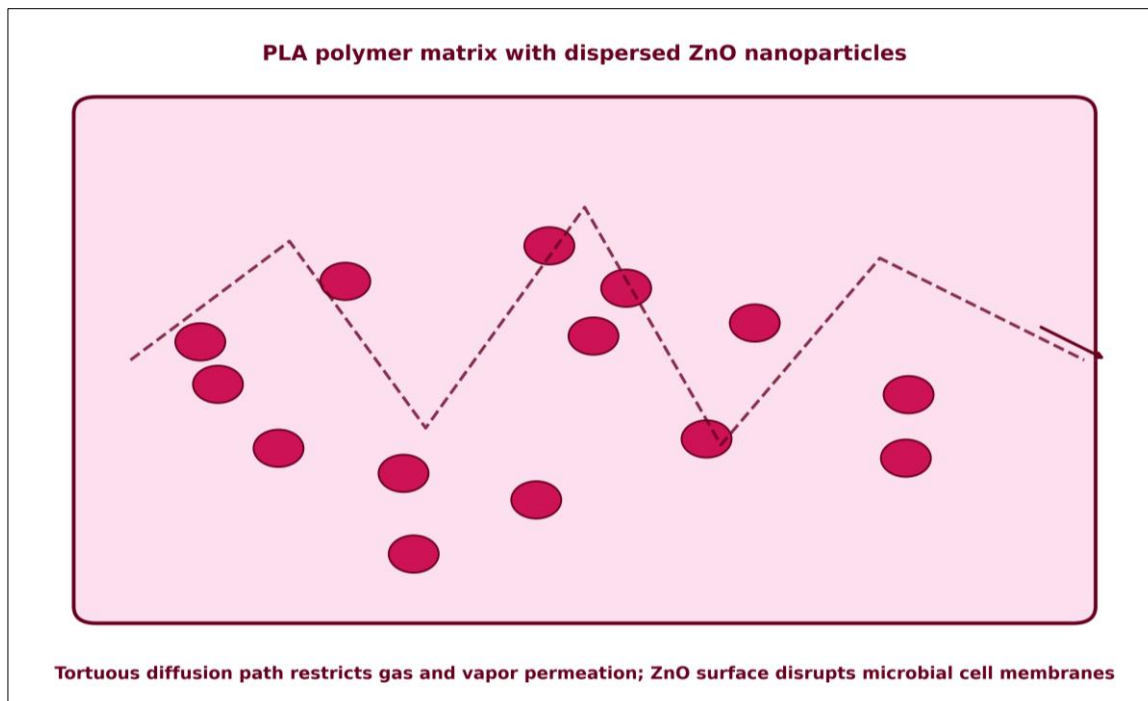


Fig 3: Proposed mechanism by which dispersed ZnO nanoparticles improve barrier and antimicrobial properties

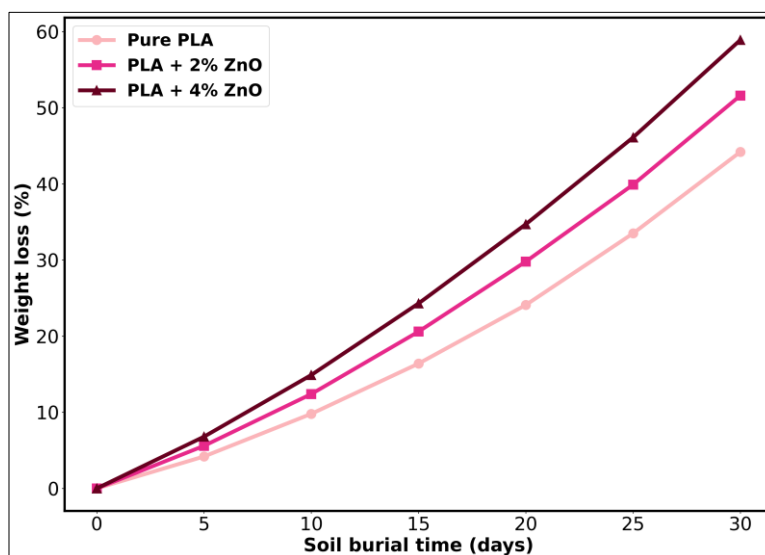


Fig 4: Weight loss of PLA-ZnO nanocomposite films during 30-day soil burial testing

Discussion

The mechanical property trends observed in this research, including the peak-then-decline pattern in tensile strength with increasing ZnO loading, align closely with previously published PLA nanocomposite studies using various metal oxide nanofillers, where an optimal loading threshold followed by agglomeration-driven property decline is a consistently reported phenomenon.

Some published studies report that the optimal ZnO loading threshold for PLA nanocomposites occurs closer to 2-3% rather than the 4% identified here, a difference that plausibly reflects variation in nanoparticle size, surface treatment, and dispersion method between studies, since smaller or surface-functionalized nanoparticles generally disperse more effectively at higher loadings before agglomeration becomes limiting.

The barrier property improvements found here are most reasonably explained by the tortuous path mechanism widely cited in nanocomposite barrier literature, where well-

dispersed impermeable nanoparticles force gas and vapor molecules to navigate a longer, more convoluted diffusion route through the polymer matrix, effectively slowing transmission rates.

Somewhat unexpectedly, biodegradation rate increased rather than decreased with ZnO content, which runs against an assumption sometimes made that inorganic nanofillers might slow polymer biodegradation by physically shielding the polymer from microbial attack; a plausible explanation is that ZnO nanoparticles create surface irregularities or micro-defects that provide additional points of microbial or hydrolytic attack initiation, though confirming this mechanism would require further investigation, such as scanning electron microscopy of partially degraded film surfaces.

For food packaging applications specifically, these combined findings carry a fairly practical implication: 4% ZnO-PLA nanocomposite films appear well positioned to extend shelf life through improved barrier and antimicrobial

properties while still meeting biodegradability expectations increasingly demanded by both regulators and environmentally conscious consumers in the packaging sector.

Cost Analysis

A preliminary cost estimate places ZnO nanoparticle incorporation at approximately 8-12% additional material cost over pure PLA film at the 4% loading level, based on current regional nanoparticle and PLA resin pricing. Given the potential for extended shelf life and reduced food waste that improved barrier and antimicrobial properties may offer, this cost increase appears likely to be offset, at least partially, by reduced spoilage-related losses for packaged perishable goods, though a full economic feasibility analysis incorporating packaging line adaptation costs and consumer willingness to pay for active packaging features would be needed to confirm commercial viability at scale.

Conclusion

Returning to the motivation behind this research, PLA-ZnO nanocomposite films were prepared and evaluated across mechanical, barrier, antimicrobial, and biodegradation properties to identify a formulation suitable for practical active food packaging applications.

The 4% ZnO loading emerged as the clear optimal formulation, delivering peak tensile strength, the lowest water vapor and oxygen permeability, complete antimicrobial inhibition against both bacteria tested, and the fastest biodegradation rate among all formulations, without an unreasonable sacrifice in film flexibility.

For food packaging manufacturers considering biodegradable active packaging options, this research recommends 4% ZnO loading in PLA as a practical starting formulation that balances performance across all four properties evaluated rather than optimizing any single property at the expense of the others.

Future research directions might include shelf-life trials with actual perishable food products under real storage and handling conditions, migration testing to confirm zinc release remains within food safety limits, and pilot-scale extrusion trials to assess whether solution-cast film properties translate to industrially relevant film production methods.

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