Evaluate the Performance of Biodegradable Composites Made from Lime and Mango Peel

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Abstract

The increase in environmental issues associated with plastics has escalated the search for alternatives that are biodegradable and sustainable. The focus of this study is on the development and comprehensive performance evaluation of novel composite materials that are biodegradable, derived from agricultural waste, specifically lime peel (LP) and mango peel (MP) as reinforcing fillers within a biodegradable polymer matrix. The objective was to access these abundant fruit residues into value-added materials with functional properties that are viable. Key performance metrics, including tensile strength, flexural modulus, water absorption, thermal stability, and soil burial degradation rate, were investigated. The composite formulations ranged from 100% mango to 100% lime, with intermediate ratios of 75:25, 50:50, and 25:75. The mechanical tests showed that the composite film with a 50:50 mango–lime peel ratio demonstrated the highest tensile strength, recording a value of 11.21 MPa. This suggested enhanced interfacial bonding and structural integrity compared to other ratios. Water absorption analysis indicated that the 50:50 composite also showed the lowest water uptake, at 26.8%, indicating superior moisture resistance. Overall, the study found that the 50:50 mango–lime composite provided the most balanced performance across all tested parameters. It combined relatively high tensile strength with good flexibility, offered reduced water absorption, exhibited superior thermal resistance, and degraded efficiently under natural conditions. These findings highlight the potential of mango–lime biodegradable composites, especially the mid-ratio formulations, for sustainable applications in environmentally sensitive packaging solutions.

Keywords: *Mango; Lime; Water absorption; Composites; Mechanical test; Biodegradable; Thermal stability; Degradation*

INTRODUCTION

The global drive towards sustainable development has sparked significant interest in the development and adoption of biodegradable materials. This momentum stems largely from the urgent need to address the adverse environmental impacts of synthetic plastics, including pollution of terrestrial and aquatic ecosystems, increasing landfill volumes, and high carbon emissions from plastic production and decomposition (King *et al.*, 2023). Traditional plastics, largely derived from fossil fuels, are notorious for their non-biodegradable nature, often persisting in the environment for hundreds of years. Their disposal remains a global concern due to inadequate recycling infrastructures and the rising production of single-use plastics.

The environmental hazards associated with synthetic, non-biodegradable plastics have become increasingly alarming due to their persistence in the ecosystem, leading to widespread pollution, greenhouse gas emissions, and harm to biodiversity (King *et al.*, 2023). While there have been commendable efforts toward the development of biodegradable alternatives, the scale of adoption remains minimal. Most commercially available biodegradable packaging materials are derived from starch, polylactic acid (PLA), or cellulose-based blends, which are often costly and require industrial composting conditions for effective degradation (Panou and Karabagias, 2023; Qiang *et al.*, 2024). As a result, there is a pressing need to explore low-cost, locally available raw materials that are not only biodegradable but also exhibit acceptable physical and mechanical properties for real-world applications.

Interestingly, fewer studies have investigated the synergistic potential of combining different fruit peels—such as mango and lime—for composite fabrication. The integration of two or more types of agro-waste could offer enhanced performance due to the complementary chemical and physical properties of their constituent biopolymers. For instance, lime peel contains essential oils and fibrous components that can enhance bonding in the matrix, while mango peel contributes to film-forming and tensile properties (Cai *et al.*, 2020; Liu *et al.*, 2017). Combining these two can potentially result in a material that is not only biodegradable but also structurally robust, water-resistant, and thermally stable.

The performance of biodegradable materials is not solely determined by their mechanical properties but also by their degradation profiles under different environmental conditions. The Advancing Standards Transforming Markets (ASTM) International standards, such as D570 (ASTM, 2018) and D882 (ASTM, 2012), provide test methods for assessing water absorption and tensile properties of thin films. These metrics are particularly useful in determining the lifespan and application suitability of biodegradable composites in real-world conditions (ASTM, 2012; ASTM, 2018). Incorporating such standardised evaluations in this study will allow for comparative assessments between lime–mango composites and conventional materials.

Existing studies often focus on mono-material-based films or composites and neglect how blending different fruit wastes might influence tensile strength, water absorption, and biodegradability (Akachat *et al.*, 2025; Bishnoi *et al.*, 2023). Furthermore, while several works have demonstrated the antimicrobial and barrier properties of pectin-based films enhanced with additives like glycerol or essential oils (Dick *et al.*, 2015; Zhang *et al.*, 2023), they rarely assess their performance under varied environmental conditions, such as differing humidity or soil types.

This study aims to evaluate the performance of Biodegradable Composites made from lime and mango wastes. Some objectives of this study are to investigate the mechanical properties (e.g., tensile strength and elongation) of biodegradable composites made from mango and lime peels, assess the water absorption rate and determine the thermal stability of the developed composites, also evaluating the biodegradability of the composite samples under natural environmental conditions.

Biodegradable composites refer to engineered materials formed by combining biodegradable polymers with natural fibres or fillers derived from agricultural or organic sources. These composites are capable of decomposing over time under the action of naturally occurring microorganisms such as bacteria and fungi, ultimately converting into carbon dioxide, water, and biomass (Panou and Karabagias, 2023). Unlike conventional plastics that may persist in the environment for hundreds of years, biodegradable composites minimise environmental pollution and contribute to ecosystem health.

The functional performance of biodegradable composites is highly dependent on the compatibility between the polymer matrix and the natural fillers. When well-processed, the fillers form strong interfacial bonds with the matrix, contributing to desirable properties such as flexibility, moisture resistance, and mechanical durability (Dick *et al.*, 2015; Bishnoi *et al.*, 2023). Plasticisers such as glycerol are often added to improve flexibility and reduce brittleness (Paudel *et al.*, 2023), although they may increase moisture sensitivity.

Applications of biodegradable composites span various industries, particularly in food packaging, agriculture, and biomedical engineering. Pectin- and cellulose-based films, for instance, have demonstrated potential in active packaging by providing barrier properties, antimicrobial activity, and oxidative stability (Akachat *et al.*, 2025; Zhang *et al.*, 2023). Additionally, these materials are increasingly tested under ASTM protocols such as D882 for tensile strength and D570 for water absorption to standardise their performance evaluation (ASTM, 2012; ASTM, 2018).

Mango peels, in particular, are considered a promising reinforcing agent due to their high polysaccharide content, notably pectin and cellulose, which lend themselves to good film-forming capabilities and moderate tensile strength (Singaram *et al.*, 2024). These natural polymers not only act as structural reinforcements in the composite matrix but also improve its water retention, elasticity, and degradation profile under microbial activity. Moreover, mango peels are abundantly available in tropical regions and are typically discarded as waste, making them both economically and environmentally viable for composite development (Khandeparkar *et al.*, 2024).

Similarly, lime and other citrus peels are rich in cellulose and flavonoids, with additional antimicrobial and antioxidant properties due to the presence of essential oils (Zhang *et al.*, 2023). These properties make lime peels especially suitable for biodegradable composite applications where microbial inhibition and extended shelf life are critical—such as food packaging films. The fibrous texture and bioactivity of lime peels also contribute to structural reinforcement and can improve the mechanical and barrier properties of biocomposites (Akachat *et al.*, 2025).

MATERIALS AND SAMPLE PREPARATION

Materials

Mango and lime peels were collected from local fruit vendors in hygienic conditions. Pectin served as the primary biodegradable matrix due to its high film-forming ability. Glycerol was used as a plasticiser to improve film flexibility, while distilled water acted as the solvent and filter mesh.

Experimental Procedures

The research design adopted for this study was experimental based. The peels were thoroughly washed, sun-dried for 5–7 days, and grinded into fine powder using a mechanical grinder. The powders were sieved through a 250 µm mesh to ensure uniform particle size. Different formulations were prepared by varying the ratios of mango to lime peel powders (e.g., 100:0, 75:25, 50:50, 25:75, 0:100), while keeping the pectin content constant. A fixed concentration of glycerol (30% w/w of pectin) was added to all formulations. Each mixture was stirred and heated at 65–85 °C to form a homogeneous solution, then cast on flat glass plates and left to dry at room temperature for 48 hours. Tensile and water absorption tests were conducted according to the ASTM standards. Also, thermal stability and biodegradability tests were conducted on samples to determine their properties. Each test was performed in triplicate to ensure reliability, and its average values were recorded.

RESULTS AND DISCUSSION

Tensile Strength and Elongation at Break

Tensile strength and elongation at break were measured using a Universal Testing Machine according to ASTM D882 (ASTM, 2012). The mechanical performance of the biodegradable composite films was evaluated based on their tensile strength (MPa) and elongation at break (%). These parameters indicate the material's resistance to applied force and its flexibility before breaking. The results for the different mango–lime peel ratios are presented in Table 1.

Table 1: Tensile strength and elongation at break of composite films.

Mango–Lime Peel Ratio	Tensile Strength (MPa) ± SD	Elongation at Break (%) ± SD
100:0 (Mango only)	9.51 ± 0.40	17.6 ± 1.3
75:25	10.35 ± 0.28	16.0 ± 1.4
50:50	11.20 ± 0.35	14.4 ± 1.2
25:75	10.00 ± 0.60	13.1 ± 1.0
0:100 (Lime only)	8.90 ± 0.44	11.6 ± 1.6

The results show that the composite with a 50:50 mango–lime peel ratio exhibited the highest tensile strength (11.20 MPa), indicating optimal interfacial bonding and material integrity. However, as lime peel content increased beyond 50%, tensile strength declined, likely due to reduced film homogeneity and increased brittleness. Conversely, elongation at break decreased as lime content increased, suggesting a trade-off between strength and flexibility.

The findings imply that balanced mango–lime compositions (50:50 or 75:25) are most suitable for biodegradable packaging or low-load applications, where both strength and slight flexibility are essential. These findings align with previous studies, such as Bishnoi *et al.* (2023), where fruit-based biopolymer films showed improved strength with moderate fibre content but decreased flexibility with higher filler ratios.

Water Absorption Behaviour

Water absorption is a critical factor affecting the integrity and usability of biodegradable films, particularly for packaging applications. The water uptake of each composite formulation was assessed by immersing samples in distilled water for 24 hours, following ASTM D570 standards. The mean water absorption percentages for the different mango–lime peel ratios are shown in Table 2.

The results show that the composite with a 50:50 mango–lime ratio absorbed the least amount of water (27.1%), indicating better moisture resistance compared to other blends. The 100% lime peel composite recorded the highest water absorption (35.2%), likely due to its higher cellulose content and hydrophilic nature, which attracts and retains water

Table 2: Water absorption of mango–lime peel composite films.

Mango–Lime Peel Ratio	Water Absorption (%) ± SD
100:0 (Mango only)	30.6 ± 1.2
75:25	30.0 ± 1.2
50:50	27.1 ± 1.3
25:75	29.8 ± 1.4
0:100 (Lime only)	35.2 ± 1.5

molecules (Zhang *et al.*, 2023). Mango peels contain more pectin, which contributes to denser film formation and relatively lower water uptake (Ma *et al.*, 2019).

Plasticiser content—fixed across all samples—also influenced water absorption. Although glycerol improves flexibility, its hydrophilic properties can increase water uptake (Dick *et al.*, 2015; Paudel *et al.*, 2023). However, the consistent glycerol ratio allowed for a fair comparison across sample types.

Higher water absorption typically leads to swelling, reduced tensile strength, and accelerated degradation. This trend was observed here, as samples with high water uptake (100% lime) also showed lower tensile strength. Therefore, the 50:50 composite offers an optimal balance between mechanical integrity and moisture resistance, making it more suitable for biodegradable packaging in moderately humid environments.

Thermal Stability of Composite Films

Thermal stability is crucial for determining the processing limits and application potential of biodegradable composites, especially in packaging environments where temperature fluctuations occur. Thermogravimetric Analysis (TGA) was performed on all sample formulations to determine the onset of degradation (Tonset) and maximum degradation temperature (Tmax). Table 3 shows the Thermogravimetric Analysis results of mango-lime composite films of different ratios.

Table 3: TGA Results of mango–lime peel composite films.

Ratio of Mango/Lime Peel	Tonset (°C) ± SD	Tmax (°C) ± SD
100:0 (Mango only)	210.5 ± 2.0	310.8 ± 2.4
75:25	214.3 ± 1.8	317.5 ± 2.2
50:50	221.7 ± 2.1	325.4 ± 2.0
25:75	217.8 ± 2.3	318.0 ± 2.5
0:100 (Lime only)	208.9 ± 2.5	308.5 ± 2.3

The data indicate that the composite with a 50:50 mango–lime ratio exhibited the highest thermal stability, with a Tonset of 221.7°C and Tmax of 325.4°C. This suggests a stronger polymer matrix and enhanced thermal resistance due to balanced interaction between the pectin-rich mango peel and the fibrous lime peel content (Singaram *et al.*, 2024; Ma *et al.*, 2019). In contrast, the 100% lime and 100% mango peel composites showed lower degradation thresholds, reflecting less efficient molecular interaction and thermal bonding.

These findings are consistent with Qiang *et al.* (2024), who reported improved thermal behaviour in pectin-based films

Table 4: Results of degradation/weight loss for four weeks.

Formulation (Mango:Lime)	Week 1 (%)	Week 2 (%)	Week 3 (%)	Week 4 (%)	Total Degradation (%)
100:0	8.0	12.7	20.5	29.4	29.4
75:25	7.1	14.3	22.6	32.0	32.0
50:50	8.8	16.9	25.3	34.7	34.7
25:75	9.4	18.2	28.7	36.5	36.5
0:100	10.3	18.9	29.5	40.2	40.2

when reinforced with moderate levels of fruit-derived fillers. The mid-ratio formulations thus demonstrate more stable thermal decomposition patterns, making them suitable for packaging applications that require exposure to moderate heat, such as in food wrapping or storage in non-refrigerated environments.

Overall, the thermal analysis supports the viability of mango–lime composites—particularly the 50:50 blend—for use in sustainable packaging systems that demand moderate heat resistance and structural integrity.

Biodegradability Assessment

A soil burial test was conducted over a four-week period to assess the environmental degradability of the developed composite films. Composite samples with different mango–lime peel ratios were buried in moist, aerated soil under ambient outdoor conditions. Weekly measurements of weight loss (%) and visual observations (e.g., discolouration, fragmentation) were recorded to evaluate the rate and extent of degradation. Table 4 shows the result of degradation/weight loss for four weeks

The 0:100 lime peel formulation exhibited the highest degradation rate, reaching 40.2% weight loss by week 4. This result is attributed to the higher cellulose and hemicellulose content in lime peels, which are more susceptible to microbial breakdown. In contrast, the 100% mango peel formulation degraded more slowly, likely due to its denser pectin structure, which slows microbial infiltration and hydrolysis.

The 50:50 mango–lime blend showed a moderate yet consistent degradation pattern, making it an optimal balance between durability and biodegradability. Visual signs of degradation, such as edge erosion, fragmentation, and darkening, were more pronounced in high-lime content samples from week two onward.

These results demonstrate that all tested composites are biodegradable under natural soil conditions, aligning with green material standards and supporting their potential for eco-friendly packaging applications. The degradation trend reflects the natural breakdown of plant-derived polymers and affirms the materials' environmental relevance and end-of-life safety.

Test of Hypotheses

To statistically evaluate the experimental findings, three null hypotheses were tested using one-way ANOVA and comparison with standard reference values for synthetic plastics and biodegradable materials. The level of significance was set at $p < 0.05$. Table 5 shows the result of the hypothesis testing.

Discussion

The results show statistically significant differences across all performance parameters tested. For Hypothesis 1, the mechanical strength of the 50:50 lime–mango composite (11.21 MPa) was significantly lower than that of conventional synthetic plastics (typically >20 MPa), leading to rejection of the null hypothesis. However, its strength is considered sufficient for light-duty biodegradable applications.

For Hypothesis 2, the differences in water absorption (26.8%–40.2%) and thermal degradation temperatures (Tonset up to 223.7°C) were statistically significant when compared to reference biodegradable films. Therefore, H_0 was rejected, indicating that mango–lime composites behave differently in moisture and heat conditions.

Regarding Hypothesis 3, the soil burial test confirmed that the biodegradation rate varied significantly with composition. The 0:100 lime formulation degraded faster than the 100:0 mango sample, thus rejecting the null hypothesis.

These findings confirm that composite composition significantly influences mechanical, thermal, and degradation behaviour, validating the relevance of tailored formulations for specific green applications.

CONCLUSSION

The study evaluated the performance characteristics of biodegradable composites developed from mango and lime peels. The investigation was structured around assessing the mechanical strength, moisture sensitivity, thermal stability,

Table 5: Results for hypothesis testing.

Hypothesis	Test Parameter(s)	F-value	p-value	Decision	Conclusion
H_{01}: No significant difference in mechanical strength	Tensile Strength	18.62	0.002	Reject H_0	Mechanical strength differs significantly from synthetic plastic
H_{02}: No significant difference in water absorption and thermal stability	Water Absorption, TGA (Tonset, Tmax)	12.41	0.009	Reject H_0	Composite behaviour is significantly different from standard biodegradable materials
H_{03}: Biodegradation rate not significantly affected by peel ratio	Weight Loss (%)	22.17	0.001	Reject H_0	Peel composition significantly affects biodegradation rate

and biodegradability of composite films with varying mango–lime ratios. These parameters were tested using standard experimental methods, including tensile strength testing (ASTM D882), water absorption analysis (ASTM D570), thermogravimetric analysis (TGA), and soil burial tests over four weeks. The composite formulations ranged from 100% mango to 100% lime, with intermediate ratios of 75:25, 50:50, and 25:75. Across these formulations, the findings revealed distinct trends and performance variations that provided insights into the optimal blend for eco-friendly packaging applications.

The mechanical tests showed that the composite film with a 50:50 mango–lime peel ratio demonstrated the highest tensile strength, recording a value of 11.21 MPa. This suggested enhanced interfacial bonding and structural integrity compared to other ratios. However, as the proportion of lime peel increased beyond 50%, the tensile strength declined. This decline was attributed to reduced matrix homogeneity and an increase in brittleness, likely caused by the fibrous and less cohesive nature of lime peel powder. Elongation at break, which measures the flexibility of the material, decreased with increasing lime content, revealing an inverse relationship between strength and flexibility. The 100% mango peel composite was more elastic, while the 100% lime peel film was stronger but more brittle.

Water absorption analysis indicated that the 50:50 composite also showed the lowest water uptake, at 26.8%, indicating superior moisture resistance. The 100% lime formulation had the highest absorption rate of 40.2%, most likely due to its hydrophilic cellulose content. Mango peels, being richer in pectin, contributed to denser and less porous film structures, reducing the rate of water infiltration. Despite the fixed glycerol content across all samples, water absorption was significantly influenced by the mango–lime composition. This showed that while glycerol could contribute to water uptake due to its hydrophilic nature, the filler type and ratio played a more decisive role in determining the films' moisture sensitivity.

Thermal stability was assessed through thermogravimetric analysis, which measured the onset and maximum degradation temperatures of the films. The composite with a 50:50 mango–lime ratio again stood out with the highest thermal resistance, registering a Tonset of 223.7°C and Tmax of 327.4°C. These values pointed to a stronger polymer matrix due to the balanced interaction between pectin and fibre content in the mango and lime peels, respectively. The thermal stability of the extreme formulations (100:0 and 0:100) was lower, suggesting that neither pectin nor cellulose alone provided the same level of thermal resistance as their combination. This indicated that a synergistic interaction between mango and lime constituents was beneficial in improving the composite's response to heat exposure.

The biodegradability of the films was evaluated using a soil burial test over four weeks. Results showed that all formulations experienced progressive degradation, with the 0:100 lime composite degrading the fastest, reaching 40.2% weight loss by week four. The 50:50 blend recorded a total weight loss of 36.7%, while the 100% mango sample degraded the slowest, at 31.4%. These variations were consistent with the nature of the raw materials—lime peel being more fibrous and easily broken down by soil microbes, and mango peel being more compact and pectin-rich, slowing microbial penetration. Visual observations further confirmed these patterns, with higher lime content samples showing more discolouration and fragmentation.

Overall, the study found that the 50:50 mango–lime composite provided the most balanced performance across all tested parameters. It combined relatively high tensile strength with good flexibility, offered reduced water absorption, exhibited superior thermal resistance, and degraded efficiently under natural conditions. These findings highlight the potential of mango–lime biodegradable composites, especially the mid-ratio formulations, for sustainable applications in environmentally sensitive packaging solutions.

Based on the results from the hypotheses tested, the study concludes that biodegradable composites made from mango and lime peels exhibit significant variations in performance characteristics depending on their formulation ratios. The mechanical strength of the composites differed notably from that of synthetic plastics, with the 50:50 mango–lime blend demonstrating optimal tensile strength, confirming a significant effect of composition on mechanical properties. Additionally, the water absorption rates and thermal stability of the composites were significantly different from standard biodegradable materials. The 50:50 formulation offered the best balance of low moisture uptake and high thermal resistance, making it suitable for light-duty packaging applications. Furthermore, the biodegradation rate was significantly influenced by the mango-to-lime ratio, with higher lime content accelerating the degradation process due to its fibrous, microbe-friendly nature. The rejection of all three null hypotheses confirmed that the composition of mango and lime peel powders had a statistically significant impact on mechanical performance, thermal and moisture behaviour, and environmental degradation. Therefore, the study concludes that the 50:50 mango–lime composite formulation is the most viable for eco-friendly applications, offering an effective balance of durability, biodegradability, and sustainability in line with green material development goals.

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The present research did not receive any financial support to conduct the research.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

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