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Original Research Article

Performance Evaluation of Active Bio-Based Molded Pulp Egg Trays Incorporated with Carica papaya Leaf Extract for Egg Shelf-Life Extension

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ABSTRACT

The rapid growth of global egg consumption requires sustainable packaging systems that preserve product quality while reducing the environmental impacts of petroleum-based and non-functional materials. This study develops a biodegradable molded pulp egg tray from recycled corrugated cardboard and functionalizes it with Carica papaya leaf extract as a natural bioactive agent for ambient egg storage. Positioned within a circular economy framework, the approach valorizes lignocellulosic waste into a higher-value packaging material with shelf-life–extending functionality. Two extract concentrations were incorporated into molded fiber trays and compared with a commercial tray over 21 days at room temperature. Egg quality was evaluated using albumen condition, yolk integrity, albumen index, yolk index, and flotation behavior as standardized freshness indicators. The extract-modified trays showed a slower decline in internal quality, with higher mean albumen index values (0.051 and 0.053) than the commercial tray (0.043) and improved yolk index retention (0.31 and 0.33 vs. 0.26). Visual observations confirmed better yolk structural integrity and delayed albumen thinning at extended storage time. These results indicate that incorporating papaya leaf extract into recycled molded fiber enhances preservation performance under non-refrigerated conditions. The study demonstrates a scalable strategy for transforming paper-based waste into functional, biodegradable food packaging that can reduce postharvest losses in regions lacking cold-chain infrastructure. The absence of physicochemical, microbiological, and migration analyses is recognized as a key limitation and priority for future work toward industrial implementation.

Keywords: *Active biodegradable packaging; circular economy; recycled corrugated cardboard; Carica papaya leaf extract; egg shelf life; bio-based functional materials; ambient food preservation.*

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INTRODUCTION

The intensification of global food distribution systems has amplified the demand for packaging materials that not only provide mechanical protection but also actively contribute to shelf-life extension while minimizing environmental burdens. Conventional egg packaging—typically manufactured from virgin or recycled molded fiber—functions primarily as a cushioning structure and does not address the biochemical and microbiological mechanisms responsible for quality deterioration during storage. At the same time, the continuous accumulation of corrugated cardboard waste represents a major circularity challenge, particularly in emerging economies where recycling efficiency remains low and downcycling dominates material recovery pathways (Bajpai, 2015; Geissdoerfer et al., 2017). The transformation of lignocellulosic waste into high-value, functionally active packaging therefore represents a strategic approach that simultaneously supports resource efficiency, reduces environmental impact, and mitigates postharvest food losses.

Eggs are highly nutritious but inherently perishable biological systems whose internal quality declines rapidly under ambient conditions. The deterioration process is governed by carbon dioxide diffusion through shell pores, moisture loss, albumen alkalization, depolymerization of the ovomucin–lysozyme complex, weakening of the vitelline membrane, and microbial penetration (Board & Tranter, 2017; Jones & Musgrove, 2013; Samli et al., 2005). These changes are quantitatively reflected in reductions in albumen index and yolk index, which are internationally recognized as reliable indicators of freshness and structural integrity (Haugh, 1937; Silversides & Villeneuve, 1994). In regions where cold-chain infrastructure is limited or economically inaccessible, the rapid decline in egg quality under room-temperature storage remains a critical technological and socioeconomic constraint. The development of energy-independent preservation strategies is therefore essential for improving food security, reducing distribution losses, and enhancing market accessibility for small-scale producers (Kemps et al., 2007).

Recent advances in sustainable materials science have positioned molded pulp as a promising biodegradable packaging platform due to its renewability, recyclability, low density, and relatively low energy consumption during processing. However, its role has largely remained passive, focusing on mechanical protection rather than functional performance. In parallel, the growing field of active packaging has demonstrated that the incorporation of natural bioactive compounds into polymeric and cellulose-based matrices can impart antimicrobial and antioxidant properties that delay food deterioration (Rhim et al., 2013; Yildirim et al., 2018). Plant-derived extracts rich in polyphenols, flavonoids, alkaloids, and proteolytic enzymes have been widely reported to inhibit microbial growth, scavenge free radicals, and stabilize biological macromolecules (Gyawali & Ibrahim, 2014). Among these, Carica papaya leaves represent an abundant but underutilized biomass resource containing papain, phenolic compounds, and other phytochemicals with demonstrated antibacterial, antifungal, and oxidative stability–enhancing activity (Aravind et al., 2013). The integration of such natural extracts into molded fiber structures offers a pathway toward fully bio-based, biodegradable, and functionally active packaging systems.

Despite the rapid growth of research on bioactive packaging, the functionalization of recycled molded pulp with phytochemical extracts for ambient egg preservation remains largely unexplored. Existing studies on molded fiber packaging have predominantly focused on improving mechanical strength, water resistance, or mineral reinforcement, while investigations into active functionality have been concentrated mainly on films and coatings rather than three-dimensional fiber structures (Hubbe et al., 2017; Khalil et al., 2011). Furthermore, most egg preservation technologies rely on refrigeration, edible coatings, mineral oil treatments, or modified atmosphere systems, which require additional processing steps, continuous energy input, or specialized infrastructure (Kemps et al., 2007; Waimaleongora-Ek et al., 2009). These limitations reduce their applicability in decentralized supply chains and low-resource environments.

Accordingly, this study develops and evaluates a bioactive molded pulp egg tray produced from recycled corrugated cardboard and functionalized with Carica papaya leaf extract as a natural preservation agent. The preservation performance of the developed trays is assessed through systematic monitoring of internal egg quality parameters over 21 days of ambient storage and compared with a commercial molded fiber tray. By integrating circular material valorization with active food packaging functionality, this work seeks to establish a sustainable, low-cost, and scalable strategy for reducing postharvest egg losses.

The novelty of this study lies in the development of a fully bio-based active packaging system derived from recycled lignocellulosic waste and functionalized with plant-based phytochemicals to extend egg shelf life under non-refrigerated conditions, thereby advancing the convergence of circular economy implementation, sustainable materials engineering, and decentralized food preservation technologies.

LITERATURE REVIEW

2.1 Circular Valorization of Lignocellulosic Waste for Sustainable Packaging

The transition from linear production models to circular material systems has accelerated research on the conversion of lignocellulosic residues into high-value packaging materials. Recycled corrugated cardboard, composed primarily of cellulose with residual hemicellulose and lignin, represents a renewable and biodegradable feedstock suitable for molded pulp processing (Bajpai, 2015). Molded fiber technology is widely recognized for its low energy consumption, recyclability, cushioning performance, and compatibility with high-throughput manufacturing, making it a viable substitute for expanded polystyrene and other petroleum-based protective materials (Didone et al., 2017). In the context of circular economy strategies, the valorization of recovered paper into functional packaging contributes to resource efficiency, landfill reduction, and carbon footprint mitigation (Geissdoerfer et al., 2017).

Despite these environmental advantages, conventional molded pulp products remain functionally passive and are designed primarily for mechanical protection. Their porous and hydrophilic fiber network, however, provides a high specific surface area and abundant hydroxyl groups that can serve as binding sites for functional additives. Recent developments in cellulose-based materials have emphasized the transformation of such passive structures into active systems capable of interacting with the packaged food and its surrounding microenvironment (Hubbe et al., 2017; Khalil et al., 2011). Functional upgrading not only extends the material life cycle of paper-based waste but also enhances its economic value by enabling performance-driven applications rather than commodity use.

2.2 Active Packaging Systems Based on Natural Bioactive Compounds

Active packaging has emerged as a major technological innovation for extending food shelf life by incorporating components that inhibit microbial growth, delay oxidative reactions, and regulate gas and moisture transfer. Unlike conventional barrier packaging, which provides only passive protection, active systems are designed to interact with the food surface or headspace through controlled release or localized activity (Yildirim et al., 2018). This functional approach has been widely recognized as a key strategy for reducing food losses and improving distribution efficiency.

Natural plant-derived extracts have gained significant attention as bioactive agents because of their biodegradability, low toxicity, and consumer acceptance. Polyphenols, flavonoids, tannins, alkaloids, and enzymatic proteins exhibit multiple antimicrobial and antioxidant mechanisms, including membrane disruption, metal ion chelation, free-radical scavenging, and enzyme inhibition (Gyawali & Ibrahim, 2014). These compounds can be immobilized within polymeric and lignocellulosic matrices, enabling gradual release and prolonged activity without direct contact with the food product (Rhim et al., 2013). Such systems align with the increasing demand for clean-label and environmentally benign preservation technologies.

2.3 Phytochemical Potential of Carica papaya Leaves for Bioactive Applications

Among plant-based bioresources, *Carica papaya* leaves represent an abundant yet underutilized source of functional phytochemicals. They contain proteolytic enzymes such as papain and chymopapain, as well as flavonoids, saponins, tannins, and alkaloids that exhibit antimicrobial, antioxidant, and anti-inflammatory properties (Aravind et al., 2013). These compounds have been shown to inhibit pathogenic and spoilage microorganisms and to stabilize biological macromolecules by reducing oxidative stress (Vuong et al., 2014).

While papaya leaf extracts have been extensively studied in pharmaceutical and nutraceutical applications, their integration into packaging materials remains limited. The utilization of this agricultural biomass in molded fiber matrices not only introduces bioactive functionality but also supports circular bioeconomy strategies by generating additional value from plant components that are typically discarded (Geissdoerfer et al., 2017). This dual valorization of industrial and agricultural residues represents an important step toward closed-loop material systems.

2.4 Mechanisms of Egg Quality Deterioration during Ambient Storage

Egg quality deterioration during storage is governed by a combination of physicochemical and microbiological processes. The diffusion of carbon dioxide through shell pores increases albumen pH, leading to the depolymerization of the ovomucin–lysozyme complex and progressive thinning of the thick albumen (Jones & Musgrove, 2013). Simultaneously, osmotic water transfer from albumen to yolk weakens the vitelline membrane and causes yolk

flattening, which is reflected in a reduction in yolk index (Samli et al., 2005). Microbial penetration through shell pores further accelerates internal degradation and poses food safety risks (Board & Tranter, 2017).

These changes are strongly temperature-dependent and occur rapidly under ambient conditions. The albumen index and yolk index are widely accepted as quantitative indicators of egg freshness because they reflect structural integrity and water redistribution within the egg (Haugh, 1937; Silversides & Villeneuve, 1994). Flotation behavior provides an additional indirect measure of air cell enlargement and internal quality decline. Technologies capable of slowing these processes without refrigeration are therefore essential for maintaining egg quality in decentralized distribution systems.

2.5 Conventional Egg Preservation Technologies and Their Limitations

Current egg preservation methods include refrigeration, mineral oil coating, edible films, and modified atmosphere storage. Refrigeration effectively slows physicochemical and microbial deterioration but requires continuous energy input and cold-chain infrastructure (Kemps et al., 2007). Mineral oil and edible coatings reduce gas exchange through the shell but involve additional processing steps and direct surface application (Waimaleongora-Ek et al., 2009). Modified atmosphere storage requires sealed systems and controlled environments, limiting its applicability in small-scale distribution networks.

Fiber-based egg trays, in contrast, are widely used and require no additional handling but have traditionally served only as cushioning materials. Their porous structure and moisture absorption capacity make them promising carriers for bioactive compounds. Functionalizing molded pulp trays with natural antimicrobial agents provides indirect preservation approach that simplifies application while maintaining compatibility with existing handling practices.

2.6 Integration of Bioactive Molded Fiber and Circular Food Preservation Systems

The convergence of recycled fiber technology, plant-derived bioactive compounds, and food preservation science represents a novel direction in sustainable packaging research. Embedding phytochemicals into molded pulp matrices enables the development of biodegradable active packaging capable of extending shelf life while simultaneously valorizing industrial and agricultural residues. This approach aligns with the principles of the circular economy, where material recirculation and product life extension are pursued simultaneously (Geissdoerfer et al., 2017).

Previous studies on molded pulp have primarily focused on mechanical reinforcement, water resistance, and mineral filler incorporation, with limited attention to active functionality (Didone et al., 2017). Moreover, most research on bioactive packaging has concentrated on films and coatings rather than three-dimensional fiber structures (Rhim et al., 2013). Systematic investigations that combine recycled fiber matrices, natural extract functionalization, and quantitative evaluation of egg freshness using standardized indices remain scarce. Therefore, the development and experimental assessment of papaya-leaf-extract–modified molded pulp egg trays provides a significant contribution to the advancement of circular bio-based active packaging and energy-independent food preservation technologies.

METHOD

3.1 Research Design

This study employed a controlled experimental design to develop and evaluate a bioactive molded pulp egg tray derived from recycled corrugated cardboard and functionalized with Carica papaya leaf extract. Two experimental formulations with different extract concentrations were compared with a commercially available molded fiber tray as the reference. Egg quality was monitored over 21 days under ambient storage to simulate decentralized distribution conditions where refrigeration is unavailable. Internal quality was assessed using albumen condition, albumen index, yolk condition, yolk index, and flotation behavior, which are internationally recognized indicators of egg freshness and structural integrity (Haugh, 1937; Samli et al., 2005; Silversides & Villeneuve, 1994). This comparative framework enabled direct evaluation of the preservation performance of the developed circular bio-based packaging relative to a conventional passive tray. The overall methodological workflow is presented in Figure 1.

3.2 Materials

Post-consumer corrugated cardboard was used as the lignocellulosic fiber source for molded pulp fabrication due to its high cellulose content and recyclability (Bajpai, 2015). Fresh papaya leaves (Carica papaya L.) were selected as the bioactive raw material based on their reported antimicrobial and antioxidant phytochemical composition (Aravind et al., 2013). A commercial wood adhesive served as a binder to enhance inter-fiber bonding and structural integrity of the molded trays, a common approach in molded fiber processing to improve mechanical stability (Didone et al., 2017).

Each tray was designed to accommodate 30 chicken eggs with nominal dimensions of 31 cm × 31 cm × 10 cm and an average thickness of approximately 0.5 cm. Fresh table eggs of uniform weight and initial quality were used as test samples to minimize biological variability.

Table 1. The formulation of the experimental trays

Material	Sample A	Sample B
Recycled corrugated cardboard pulp	500 g	500 g
Water	3000 ml	3000 ml
Papaya leaf extract	100 g	150 g
Wood adhesive	100 g	100 g

3.3 Preparation of Papaya Leaf Extract

Fresh papaya leaves were washed to remove surface contaminants and cut into small pieces to facilitate size reduction. The chopped leaves were then homogenized using a blender with the addition of a small amount of water to assist in extraction. The resulting slurry was filtered through a cloth to separate the liquid extract from the solid residue. The filtrate was collected and used immediately as the bioactive component in the molded pulp formulation. Two extract volumes, 100 mL and 150 mL, were prepared to investigate the effect of bioactive concentration on egg preservation performance.

3.4 Preparation of Recycled Fiber Pulp

Corrugated cardboard waste was shredded and soaked in water until complete fiber swelling and softening occurred. The hydrated material was mechanically disintegrated to produce a homogeneous pulp. Excess water was removed to obtain a workable consistency prior to blending with adhesive and papaya leaf extract. The preparation of recycled fiber pulp followed established molded fiber processing principles for producing uniform lignocellulosic slurries (Didone et al., 2017).

3.5 Fabrication of Molded Pulp Egg Trays

The bioactive pulp slurry was formed in a tray mold and manually pressed to obtain the desired geometry. Initial drying was conducted under solar exposure for 1–3 days to allow water removal and shape stabilization, followed by secondary drying for 1–2 days until a rigid structure was achieved. Solar drying was selected as a low-energy processing method consistent with circular and decentralized production systems. The resulting tray types are presented in Table 2.

Table 2. Egg tray samples.

Sample	Sample Variations	Description
Experimental Sample	Tray A	Molded pulp with 100 mL of papaya leaf extract
	Tray B	Molded pulp with 150 mL of papaya leaf extract
Reference Sample	-	A commercially available molded fiber tray

3.6 Storage Experiment

Each tray type was filled with fresh eggs and stored at ambient temperature for 21 days. Quality evaluation was conducted at day 0, day 7, day 14, and day 21. This storage duration reflects the commonly reported shelf-life limit of eggs under non-refrigerated conditions and allows observation of progressive quality deterioration (Jones & Musgrove, 2013).

3.7 Egg Quality Analysis

4.7.1 Albumen Condition

Albumen viscosity and the presence of blood spots were visually observed after breaking the egg onto a flat glass surface. Thick and cohesive albumen indicated higher freshness, whereas spreading and liquefaction reflected structural degradation (Samli et al., 2005).

4.7.2 Albumen Index

The albumen index was calculated as the ratio between albumen height and the average of albumen length and width, measured using a digital caliper. This parameter reflects the structural integrity of thick albumen and is widely used as a quantitative freshness indicator (Haugh, 1937).

$$Albumen\ Index = \frac{H}{\frac{1}{2}(L1 + L2)}$$

where
H = albumen height (mm)
L_1 = albumen length (mm)
L_2 = albumen width (mm)

4.7.3 Yolk Condition

Yolk shape and surface cleanliness were visually evaluated. A spherical and compact yolk indicates strong vitelline membrane integrity, whereas flattening reflects osmotic water migration and structural weakening (Silversides & Villeneuve, 1994).

4.7.4 Yolk Index

The yolk index was determined as the ratio between yolk height and yolk diameter. This index represents the resistance of the yolk membrane to deformation during storage (Samli et al., 2005). The yolk index was calculated using the following equation.

$$Yolk\ Index = \frac{H}{d}$$

where
h = yolk height (mm)
d = yolk diameter (mm)

4.7.5 Flotation Test

Whole eggs were immersed in water to observe buoyancy behavior. Sinking eggs were classified as fresh, while partial or complete flotation indicated air cell enlargement and internal quality decline (Jones & Musgrove, 2013).

3.8 Data Analysis

Albumen and yolk index values were calculated for each treatment and storage interval. The preservation performance of the bioactive trays was evaluated through comparative descriptive analysis relative to the commercial control. This approach is commonly applied in shelf-life studies to identify functional differences among packaging systems under controlled storage conditions (Kemps et al., 2007).

3.9 Methodological Limitations

The experimental design focused on functional performance under ambient storage and did not include microbiological enumeration, migration analysis, gas transmission measurement, or advanced structural characterization of the molded fiber matrix. These analyses are essential for mechanistic validation and industrial-scale implementation of active packaging systems (Rhim et al., 2013; Yildirim et al., 2018). In addition, statistical modeling of degradation kinetics was not performed and should be incorporated in future studies to enable predictive shelf-life estimation.

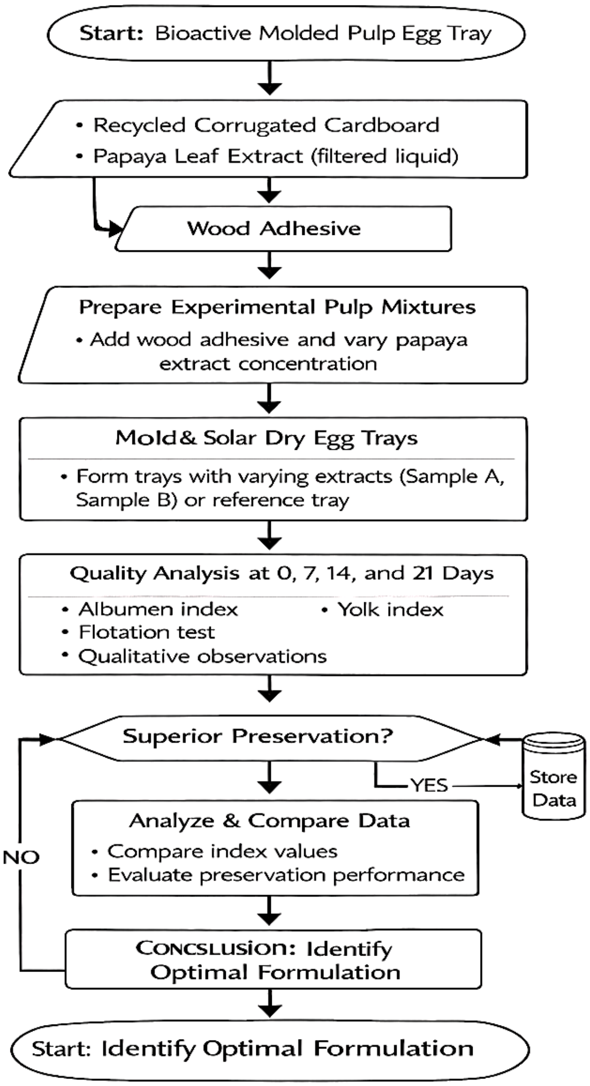


Figure 1. Research Flowchart diagram

RESULT

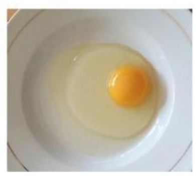
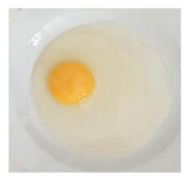
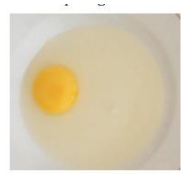
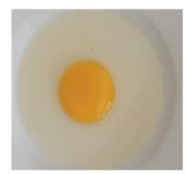
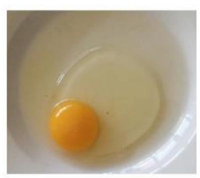
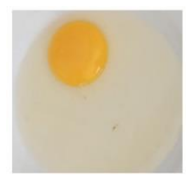
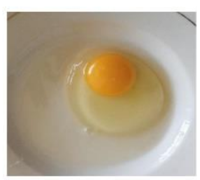
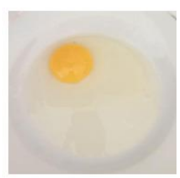
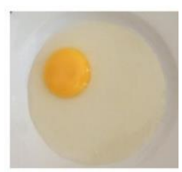
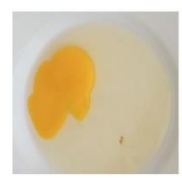
4.1 Physical Characteristics of the Developed Molded Pulp Egg Trays

The molded pulp trays produced from recycled corrugated cardboard and functionalized with *Carica papaya* leaf extract exhibited adequate structural integrity after solar drying and successfully accommodated 30 eggs per unit without visible deformation. The addition of the extract did not interfere with moldability, dimensional stability, or rigidity, indicating compatibility between the lignocellulosic fiber network and the bioactive component. This observation is consistent with previous studies demonstrating that cellulose-based matrices can act as effective carriers for functional additives due to their porous structure, high surface area, and abundant hydroxyl groups that facilitate physical entrapment and interfacial bonding (Hubbe et al., 2017; Khalil et al., 2011). The preservation of the open fiber network suggests that the trays retained the mass-transfer characteristics required for interaction with the egg microenvironment, a critical feature for active packaging performance (Yildirim et al., 2018).

4.2 Changes in Albumen Condition during Storage

At day 0 and day 7, albumen from all treatments remained thick, cohesive, and free from visible blood spots, confirming comparable initial freshness. By day 14, a reduction in viscosity was observed in all treatments; however, the liquefaction was visually less pronounced in eggs stored in the extract-functionalized trays. At day 21, albumen thinning and the appearance of blood spots were evident in all samples, but structural degradation was markedly more severe in the control. The progressive loss of albumen viscosity is associated with the depolymerization of the ovomucin–lysozyme complex caused by carbon dioxide diffusion and pH increase during storage (Jones & Musgrove, 2013; Samli et al., 2005). The slower degradation observed in the functionalized trays indicates a reduced rate of these physicochemical changes. The observation of albumen condition is visualized in Table 3.

Table 3. Albumen and yolk observation result.

Tray Type	Day 0	Day 7	Day 14	Day 21
Tray A – 100 mL extract				
Tray B – 150 mL extract				
Commercial tray (control)				

4.3 Albumen Index

The albumen index decreased progressively with storage time for all treatments, reflecting the expected deterioration of thick albumen structure. Nevertheless, the rate of decline differed among tray types. The average albumen index values over the 21-day storage period are presented in Table 3.

Table 4. Albumen index values.

Tray Type	Day 0	Day 7	Day 14	Day 21	Mean Albumen Index
Tray A – 100 mL extract	0.069	0.055	0.042	0.041	0.051
Tray B – 150 mL extract	0.068	0.056	0.043	0.043	0.053
Commercial tray (control)	0.066	0.051	0.028	0.027	0.043

Eggs stored in the extract-modified trays retained higher albumen index values throughout the storage period. After 14 days, the control exhibited a sharp reduction, reaching values approximately 35–36% lower than those of the functionalized trays. Relative to the control, the mean albumen index increased by 18.6% for Tray A and 23.3% for Tray B. Because albumen height is directly related to the integrity of the ovomucin network and the freshness of the egg (Haugh, 1937; Silversides & Villeneuve, 1994), the higher index values indicate a slower deterioration rate in the bioactive packaging system.

4.4 Changes in Yolk Condition

Visual evaluation revealed spherical and compact yolks in all treatments at the beginning of storage. By day 14, slight flattening occurred in all samples, but yolks stored in the extract-modified trays remained more cohesive. At day 21, yolks from the control treatment spread extensively on the plate, whereas those stored in the functionalized trays maintained a more defined geometry and showed no blood contamination. Yolk flattening is caused by osmotic water migration from albumen to yolk and weakening of the vitelline membrane during storage (Samli et al., 2005). The improved structural stability observed in the bioactive trays indicates delayed membrane degradation. The gradual changes in yolk condition are presented in Table 3.

4.5 Yolk Index

A gradual decrease in yolk index occurred with increasing storage time for all treatments. However, the magnitude of reduction differed significantly between the functionalized trays and the control.

Table 4. Yolk index values.

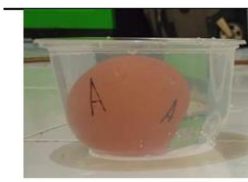
Tray Type	Day 0	Day 7	Day 14	Day 21	Mean Yolk Index
Tray A – 100 mL extract	0.43	0.36	0.29	0.18	0.31
Tray B – 150 mL extract	0.44	0.37	0.29	0.21	0.33
Commercial tray (control)	0.42	0.34	0.26	0.04	0.26

The control exhibited an approximately 80–81% reduction by day 21, indicating severe vitelline membrane weakening. In contrast, eggs stored in the extract-modified trays showed lower reductions of 58% (Tray A) and 52% (Tray B). Because the yolk index reflects resistance to deformation and internal water redistribution (Silversides & Villeneuve, 1994), the higher retained values confirm improved structural stability in the functionalized packaging system.

4.6 Flotation Behavior

The flotation test demonstrated a progressive decline in freshness for all treatments. All eggs sank at day 0 and day 7, indicating minimal air cell development. At day 14, partial flotation was observed primarily in the control, whereas eggs stored in the bioactive trays predominantly remained submerged. By day 21, flotation occurred more frequently in the control. Floating behavior is associated with moisture loss and air cell enlargement during storage (Jones & Musgrove, 2013). The delayed flotation in the functionalized trays indicates reduced mass transfer and slower internal deterioration. The visual observation of the eggs' floating behavior can be seen in Table 5.

Table 5. Eggs' floating behavior from Day 0 to Day 21

Duration	Tray A – 100 mL extract	Tray B – 150 mL extract	Commercial tray (control)
Day 0			
Day 7			
Day 14			
Day 21			

4.7 Comparative Preservation Performance

Both extract-modified trays showed superior performance compared with the commercial tray in maintaining internal egg quality under ambient conditions. The formulation containing 150 mL extract produced the highest mean albumen and yolk index values, demonstrating a concentration-dependent preservation effect. Increasing the extract volume from 100 mL to 150 mL resulted in a 3.9% higher mean albumen index and a 6.5% higher mean yolk index. The improved retention of albumen viscosity and yolk integrity indicates that the incorporation of papaya leaf extract delayed the physicochemical changes associated with egg aging, which are primarily driven by carbon dioxide diffusion, protein degradation, and osmotic water transfer (Jones & Musgrove, 2013; Samli et al., 2005).

DISCUSSION

The higher retention of albumen and yolk indices in the extract-modified trays indicates a slower progression of the physicochemical changes associated with egg aging under ambient storage. The decline in albumen height across treatments follows the established mechanism of carbon dioxide diffusion, albumen alkalization, and destabilization of the ovomucin–lysozyme network (Jones & Musgrove, 2013; Samli et al., 2005). The reduced rate of decline in the functionalized trays suggests that the bioactive fiber matrix influenced the storage microenvironment and delayed structural deterioration. Similarly, the higher yolk index at extended storage reflects improved vitelline membrane integrity and reduced osmotic water transfer, both of which are widely accepted indicators of freshness (Haugh, 1937; Silversides & Villeneuve, 1994).

The concentration-dependent response supports the functional role of phytochemical loading. Carica papaya leaves contain phenolics, flavonoids, alkaloids, and proteolytic enzymes with reported antimicrobial and antioxidant activity (Aravind et al., 2013; Gyawali & Ibrahim, 2014). Because microbial penetration through shell pores contributes to internal quality loss (Board & Tranter, 2017), the observed preservation effect is consistent with a reduced deterioration rate, although the mechanism cannot be confirmed without microbiological and release-kinetic analyses. From a materials perspective, the porous lignocellulosic network provides a suitable carrier for bioactive compounds, as widely reported for cellulose-based active packaging (Hubbe et al., 2017; Khalil et al., 2011). This indirect packaging-based approach avoids additional handling steps and is therefore compatible with decentralized distribution systems.

The divergence between treatments after approximately two weeks corresponds to the commonly reported ambient shelf-life threshold for eggs (Kemps et al., 2007; Stadelman, 1995), indicating practical relevance in cold-chain-limited regions. Within a circular economy framework, the integration of recovered paper and agricultural biomass links waste valorization with food-loss reduction (Bajpai, 2015; Geissdoerfer et al., 2017). Compared with refrigeration, coatings, and modified atmospheres, the developed tray operates without additional energy or processing steps (Kemps et al., 2007; Waimaleongora-Ek et al., 2009), which enhances scalability for small-scale supply chains.

The study is limited by the use of physical freshness indicators without microbiological enumeration, gas-transfer analysis, structural characterization, controlled release evaluation, or statistical degradation modeling. These analyses are required to verify the preservation mechanism and to meet the performance-validation framework for active packaging materials (Rhim et al., 2013; Yildirim et al., 2018). Nevertheless, the results demonstrate that recycled molded fiber can be functionally upgraded into a bio-based packaging system capable of extending the usable storage period of eggs under ambient conditions.

5.1 Scientific Implication

The findings show that waste-derived molded fiber can be engineered to influence food quality deterioration pathways, supporting the transition from passive to functional bio-based packaging (Bajpai, 2015; Geissdoerfer et al., 2017). The delayed reduction of albumen and yolk indices indicates that packaging design can indirectly affect the physicochemical processes governing egg aging (Jones & Musgrove, 2013; Samli et al., 2005). This expands the application of cellulose-based active materials from films and nanocomposites to three-dimensional molded structures (Hubbe et al., 2017; Khalil et al., 2011). The use of conventional freshness indices as packaging-performance metrics also strengthens the methodological integration between food science and materials engineering (Haugh, 1937;

Silversides & Villeneuve, 1994). Mechanistic validation through microbiological, structural, and kinetic analyses remains a priority for future work (Rhim et al., 2013; Yildirim et al., 2018)..

5.2 Practical and Industrial Implications

The process is compatible with existing molded-pulp manufacturing because the extract can be introduced at the slurry stage without altering forming or drying operations (Bajpai, 2015). By extending the functional storage period beyond the typical two-week ambient limit, the system can reduce spoilage in distribution networks where refrigeration is limited (Gustavsson et al., 2011; Kemps et al., 2007). The concentration-dependent response provides a practical formulation parameter for supply-chain-specific performance tuning (Yildirim et al., 2018). The integration of recycled fiber and agricultural biomass supports biodegradable, low-energy packaging while enabling product differentiation in the molded-fiber industry (Geissdoerfer et al., 2017; Hubbe et al., 2017). Industrial implementation will require extract standardization, migration testing, mechanical performance evaluation, and process-integration studies (Yildirim et al., 2018).

5.3 Limitations

The study did not quantify microbial load, oxidative stability, gas transfer, or release kinetics, which restricts mechanistic interpretation (Board & Tranter, 2017; Rhim et al., 2013). The absence of structural and mechanical characterization limits assessment of industrial handling performance (Hubbe et al., 2017; Khalil et al., 2011). Predictive shelf-life modeling and environmental and techno-economic assessments were also beyond the scope of this work but are necessary for industrial benchmarking (Geissdoerfer et al., 2017; Kemps et al., 2007). Performance validation under different temperature and humidity conditions is required for broader application (Samli et al., 2005).

5.4 Future Research Directions

Future studies should integrate microbiological enumeration, physicochemical monitoring, structural characterization, and release-kinetic modeling to establish the preservation mechanism and functional lifetime of the packaging system (Board & Tranter, 2017; Rhim et al., 2013; Yildirim et al., 2018). Statistical degradation modeling would enable predictive shelf-life estimation (Kemps et al., 2007). Life-cycle and techno-economic assessments are required to quantify sustainability and commercialization potential (Geissdoerfer et al., 2017). Evaluating other phytochemical sources, food products, and climatic conditions will determine the generalizability of the concept (Samli et al., 2005).

CONCLUSION

Recycled corrugated cardboard can be upgraded into a bio-based egg tray capable of delaying the decline of albumen and yolk indices during ambient storage. The higher index retention relative to a commercial tray indicates that packaging design can influence the physicochemical pathways of egg aging associated with carbon dioxide loss, albumen alkalization, and water migration (Jones & Musgrove, 2013; Samli et al., 2005). The concentration-dependent response highlights phytochemical loading as a key design parameter for fiber-based active packaging.

By combining waste paper and agricultural biomass in a single functional material, the study links material circularity with food-loss reduction (Bajpai, 2015; Geissdoerfer et al., 2017). The successful use of albumen and yolk indices as packaging-performance indicators provides a practical interdisciplinary evaluation framework (Haugh, 1937; Silversides & Villeneuve, 1994). The system should be regarded as a proof-of-concept because mechanistic validation, migration testing, structural characterization, statistical modeling, and environmental assessment are still required for industrial implementation (Rhim et al., 2013; Yildirim et al., 2018). Despite these limitations, the results demonstrate a scalable pathway toward biodegradable, energy-independent packaging for decentralized food distribution.

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