CHAPTER V

CONCLUSIONS

5.1 Conclusion

This research presented a conceptual design for comprehensive protection of fragile and sensitive agricultural products, particularly fresh fruits, against mechanical damage during transportation and delivery processes. Guava, selected as an exemplary of sensitive agricultural produce, was subjected to foam net drop testing using finite element method (FEM) analysis. The methodology integrated computer-aided design modeling through SolidWorks with analytical simulations performed via ANSYS software for drop test evaluation. Results demonstrated the successful application of finite element analysis in modeling fruit behavior under impact conditions and effectively evaluated critical design parameters (specifically size and number of filaments) in cushion net foam packaging systems. The analysis revealed significant correlations between these design variables and stress distribution patterns within the guava specimens, providing quantitative insight into protective packaging optimization for sensitive agricultural products.

The drop test conducted from a height of 200 mm was used to evaluate the effectiveness of different filament diameters (2.5, 3.5, and 4.5 mm) in reducing the maximum equivalent stress exerted on guava during impact. The unprotected sample exhibited the highest stress at 0.0821 MPa. When a 2.5 mm filament was used, the stress decreased to 0.0728 MPa, with a reduction of approximately 11.32%. Increasing the filament thickness to 3.5 mm further reduced the stress to 0.0696 MPa (15.22% reduction), and the 4.5 mm filament achieved the greatest reduction to 0.0670 MPa, representing an 18.39% decrease.

Impact of filament size, number, and density on cushioning performance

This study demonstrated that filament dimeter, filament number, and foam density significantly affect the impact protection performance of the NRLF cushion net for guava. Thicker filaments, particularly the 4.5 mm variant, exhibited superior energy absorption capabilities, effectively reducing the maximum equivalent stress experienced by the fruit during impact. Therefore, increasing filament dimeter was recommended to enhance cushioning performance during handling and transportation.

Regarding filament number and density, a consistent trend was observed where reducing either parameter led to an increase in maximum stress values across all tested densities (420, 397, and 345 kg/m³). For instance, at 420 kg/m³, the maximum stress increased from 0.0566 MPa (25 filaments) to 0.0635 MPa (15 filaments), reflecting an approximate 12.19% rise. Similar increases were found for 397 kg/m³ (10.73%) and 345 kg/m³ (9.93%). Comparing across densities at a fixed filament number, reducing the foam density from 420 kg/m³ to 345 kg/m³ at 25 filaments resulted in a 4.95% increase in maximum stress. These findings confirm an inverse relationship between material density and cushioning efficiency.

Overall, these results illustrate a clear engineering trade-off between weight reduction and protective performance. While decreasing foam density and filament quantity contributes to lighter, more material-efficient designs, it also compromises impact resistance, leading to higher stress transmission to the fruit. Furthermore, peak stress was consistently observed approximately 0.013 seconds after impact, underscoring the importance of early-stage energy absorption in cushioning system design.

Maintaining adequate filament thickness, sufficient filament numbers, and appropriate material density are thus essential strategies for achieving an optimal balance between lightweight packaging and reliable protection, supporting the development of sustainable, bio-based packaging solutions.

5.2 Suggestions

The findings of this study provide a foundation for continued research in protective packaging for fragile agricultural products. The following recommendations are proposed for future investigations:

1. Multi-layered Cushion Designs: Explore the effectiveness of composite foam net structures incorporating varied filament thicknesses and density gradients to optimize energy absorption while maintaining lightweight properties.
2. Material Innovation: Investigate alternative bio-based and biodegradable materials with comparable or enhanced mechanical performance relative to natural rubber latex foam (NRLF) to improve environmental sustainability and address resource constraints.
3. Dynamic Real-world Testing: Complement simulation data with experimental validation through physical drop testing under authentic transportation conditions to verify the reliability, durability, and performance of the proposed protective designs.
4. Fruit Variety Application: Extend the established methodology to diverse sensitive horticultural products (e.g., mangoes, tomatoes, berries) to develop customized cushioning solutions based on specific morphological characteristics and mechanical properties.
5. Experimental Validation: While computational modeling provides valuable insights, physical prototype testing through standardized drop tests would validate simulation results and facilitate practical implementation in commercial settings.
6. Extended Impact Scenarios: Future investigations should incorporate diverse impact conditions, including variable drop heights (300-1000 mm), multiple impact angles (0-90°), and sequential impact events to more accurately represent real-world transportation environments.

7. Alternative Geometric Configurations: Systematic evaluation of varied cushion net architectures—such as hexagonal arrangements and cross-linked filament patterns—could potentially enhance energy dispersion characteristics and structural adaptability.
8. Hybrid Material Systems: Integration of natural rubber latex foam with complementary eco-friendly materials (e.g., starch-based composites, PLA derivatives) warrants investigation to develop multi-functional cushioning systems offering optimized mechanical performance with enhanced biodegradability.
9. Post-harvest Quality Assessment: Comprehensive analysis of cushioning material effects on fruit quality parameters during extended storage periods should examine critical factors including respiratory gas exchange, moisture retention, and tissue damage metrics.
10. Economic Feasibility Analysis: Rigorous cost-benefit assessment comparing conventional packaging solutions with NRLF-based systems is essential to determine commercial viability and adoption potential across agricultural supply chains.

These strategic research directions build upon current findings and support the development of sustainable, scalable protective packaging innovations for global agricultural distribution networks.