ABSTRACT

The fruits and vegetables supply chain (FVSC) is critical for food and nutrition security, farmer livelihoods, and climate mitigation, yet it is characterized by high post-harvest losses, institutional inefficiencies, and carbon-intensive operations. Existing studies largely address these challenges in isolation, with limited empirical validation of farmer-centric barriers and inadequate integration of environmental and economic decision-making. The present study develops a comprehensive, system-level analytical framework to evaluate sustainability barriers, carbon emission dynamics, and optimization pathways in the FVSC, with empirical applications to litchi and cauliflower supply chains in eastern India. Primary data collected from 616 farmers were analysed to identify sustainability constraints at the farm level. Exploratory factor analysis statistically consolidated nineteen observable barriers into seven latent constructs- Post-Harvest Quality Index (PQI), Cooperative Empowerment Index (CEI), Transport Infrastructure Index (TII), Government Policy Index (GPI), Socio-economic Index (SEI), Insurance Reach Index (IRI), and Credit Accessibility Index (CAI). Second-order Confirmatory Factor Analyses, validated sustainability as a hierarchical latent construct with strong model fit and reliability. CART analysis further revealed post-harvest loss indicators as dominant behavioural drivers influencing overall sustainability outcomes. To capture systemic interdependencies, a trapezoidal fuzzy DEMATEL-GGA-AHP framework was developed. The results identified government policy and credit accessibility as key driving criteria, while post-harvest quality emerged as the most critical effect-receiving dimension, demonstrating that upstream institutional and financial constraints manifest as downstream losses. Environmental impacts were quantified using a Circular Tiered Hybrid Life Cycle Assessment (CrTH-LCA). Household waste was identified as the dominant carbon hotspot in the litchi supply chain (40.44%), whereas fertilizer-intensive cultivation accounted for 79.84% of emissions in cauliflower supply chain. Circular waste valorisation reduced emissions by up to 27.9 times and demonstrated strong economic feasibility. Production forecasting using deep learning models (LSTM and GRU) outperformed traditional approaches and enabled forward-looking carbon projections. A multi-objective MILP-based cost-carbon optimization framework was used to identify optimal trade-offs between economic performance and emission reduction. The study establishes that FVSC sustainability failures are systemic rather than isolated and provides a robust, farmer-centric decision-support framework for low-carbon, resilient horticultural supply chains.

Keywords: Fruits and Vegetables Supply Chain, Farmer-Centric Sustainability Barriers, Trapezoidal Fuzzy, DEMATEL-GGA-AHP, Circular Tiered Hybrid Life Cycle Assessment, Carbon Emission, Deep Learning, Forecasting, Optimization