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Research Article

Economic and Environmental Performance of Cellulose Nanofibril-Coated Molded Pulp Trays for Fresh Fruit Packaging

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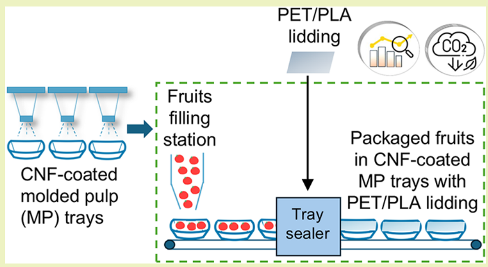
ABSTRACT: Cellulose nanofibrils (CNFs) offer a promising biodegradable packaging solution, yet their economic and environmental viability for large-scale fruit packaging applications remains under-explored. Based on lab-scale experimental data, this study presents a conceptualized industrial scale process for producing CNF-coated molded pulp (MP) trays with polyethylene terephthalate (PET) and polylactic acid (PLA) lidding for packaging of fresh fruits such as cherry tomatoes and berries. A comprehensive techno-economic analysis (TEA) and life cycle assessment (LCA) was conducted across five packaging scenarios to determine the minimum selling price (MSP) and global warming potential (GWP) for packaged cherry tomatoes, raspberries, and blueberries after 10 days at the retail shelf. To better capture the shelf-life benefits of CNF coatings, a novel supply chain model integrating on-site fruit packaging was proposed. Based on the economic analysis, the best-performing packaging configuration was uncoated MP trays with PET lidding for cherry tomatoes (\$5.73/kg), and coated MP trays with PET lidding for raspberries (\$41.40/kg) and blueberries (\$18.75/kg). A cradle-to-retail LCA, utilizing TRACI 2.2 methodology estimated their respective GWPs at 0.847, 1.65, and 1.92 kg CO_2e/kg, when CNF is produced via a mechanochemical process with low power consumption. Sensitivity analysis identified fruit wholesale cost and weight loss as the main economic drivers. Monte Carlo simulations quantified the uncertainty in the estimated MSP for each best-performing fruit packaging scenario at the retail shelf after 10 days, yielding 90% confidence interval values of \$3.94−7.49/kg for cherry tomatoes, \$27.44−57.88/kg for raspberries, and \$12.85−24.75/kg for blueberries.



KEYWORDS: *techno-economic analysis, life cycle assessment, cellulose nanofibril, molded pulp trays, fruit packaging*

INTRODUCTION

The preservation of food quality and safety relies heavily on packaging, yet current solutions present significant environmental challenges. While paper-based materials offer biodegradability and potential carbon sequestration in landfills, their barrier properties are limited. Conversely, traditional metal and glass packaging, although robust, incurs substantial energy costs during recycling and transport. Polymer-based packaging, particularly synthetic polymers such as polyethylene and polypropylene, is effective because of its low cost and versatile properties.[1] However, the nonbiodegradable nature of these petroleum-derived plastics contributes to increasing environmental pollution, including the creation and dissemination of microplastics within ecosystems, which poses a direct threat to biodiversity and human health.[2] This necessitates the development of sustainable, high-performance food packaging. Cellulose-based materials, due to their sustainability, versatility, and ongoing technological advancements, are positioned as promising alternatives for next-generation packaging solutions, with continued research focused on overcoming current limitations to allow additional applications.[3−6] Cellulose nanofibrils (CNFs) have gained global attention in food packaging applications because of their unique properties and the growing demand for sustainable materials. Derived from natural cellulose sources, CNFs exhibit exceptional mechanical strength, biodegradability, and versatility, making them ideal candidates for environmentally friendly packaging solutions. The high surface area-to-volume ratio of CNFs enables the formation of extremely thin, transparent, lightweight, and flexible films or coatings that provide effective barriers against water vapor, oxygen, and other gases.[7−9]

There has been growing interest from the scientific community in the use of cellulose-based nanomaterials for food packaging applications. Specifically, CNFs are employed as coatings to enhance the packaging properties of biopolymer-based films, thereby extending the shelf life of perishable food products.[10,11] One of the primary benefits of incorporating

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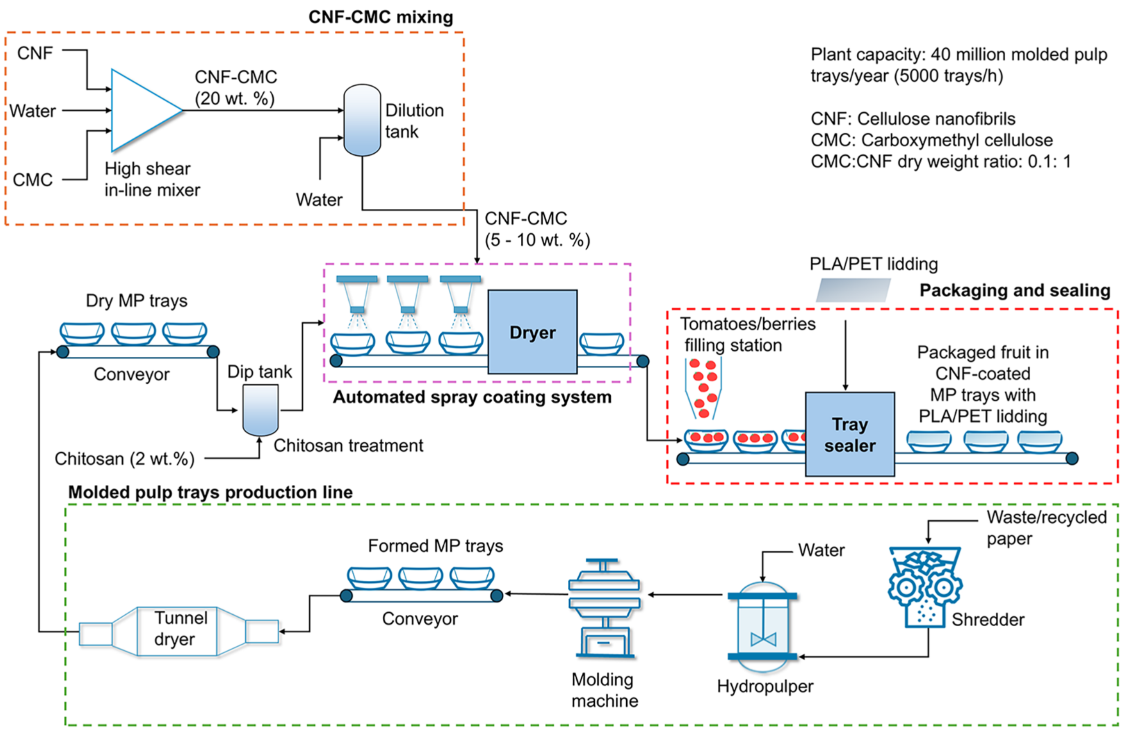

Figure 1. Process flow diagram to produce CNF coated MP trays with PET/PLA lidding for packaging fresh fruits such as cherry tomatoes, raspberries and blueberries.

CNFs into food packaging is their ability to enhance barrier properties. Researchers have previously demonstrated that incorporating CNFs into packaging materials results in notably decreased permeability. Adnan et al.[12] reported that the addition of 10% nanocellulose to conventional paper significantly reduced its air permeability, which slows the diffusion of gases that can lead to spoilage. Similarly, Braga et al.[13] highlighted that cellulose nanostructured films, when formed from pretreated fibers, strengthen the physical and barrier characteristics of packaging materials. These enhanced characteristics are essential for extending the shelf life of food products by decreasing oxygen transmission and moisture uptake.[14] Moreover, CNFs can also be utilized in various forms, such as coatings, fillers, and laminates, to further improve the functional properties of packaging.[14,15] CNF-based packaging systems can reduce water loss, delay browning and softening, decrease respiration rates, and preserve the appearance and total soluble solids of various fruits, thereby extending shelf life and maintaining fruit quality.[7,16−18]

The global CNF market size in 2025 was valued at $0.17 billion and is projected to reach $1.43 billion by 2035, demonstrating a robust compound annual growth rate (CAGR) of 23.8% over the period 2026−2035.[19] CNFs are typically obtained via mechanical fibrillation or chemical pretreatment followed by mechanical processing. This yields high aspect ratio nanofibers with widths of 4−20 nm and lengths of 500−2000 nm.[20,21] MP trays have gained much attention as eco-friendly alternatives to traditional petroleum-based packaging because of their biodegradability and recyclability.[22] However, they inherently possess porous structures that limit their moisture and grease barrier properties, which are crucial for preserving fruit and extending shelf life.[23] Recent studies have highlighted the efficacy of CNF as a coating material that can significantly improve the barrier properties of MP trays, which can extend the shelf life of fruits and vegetables. For example, Zhang and Youngblood[25] reported that a modified formulation of CNF and carboxymethyl cellulose (CMC) provided a robust grease-resistant coating for molded pulp containers, thus addressing the challenge posed by moisture and oxygen permeation often associated with uncoated pulp products. This CNF-based coating not only enhances the mechanical properties but also establishes perfluoroalkyl and polyfluoroalkyl substances (PFAS) free alternative that diminishes environmental concerns related to traditional coatings.[23]

Several studies have advanced the understanding of nanocellulose sustainability. Wong et al.[25] conducted an integrated LCA and TEA of nanocellulose synthesis via chlorine-free biomass pretreatments, while Lan et al.[26] developed a modeling framework for identifying environmentally greener and lower-cost pathways for nanomaterials production. Cho et al.[27] in their study reviewed green design approaches to cellulose-based materials, highlighting the intersection of sustainability and functionality. However, no prior study has conducted an integrated TEA-LCA evaluating CNF-coated MP trays for fresh fruit packaging across multiple fruit types and packaging scenarios, capturing the economic and environmental benefits of weight loss reduction through the functional unit. This study addresses that gap by building on the experimental work carried out by Zhang and Youngblood[24] and implements an industrial-scale process via integrated techno-economic analysis (TEA) and life-cycle assessment (LCA) to provide detailed economic and sustainability insights into the production of CNF coated MP trays with PET and PLA lidding for packaging fresh fruits including cherry tomatoes, raspberries and blueberries.

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EXPERIMENTAL SECTION

Process Modeling

The industrial-scale process was modeled based on experimental studies carried out by Zhang and Youngblood[24] and a detailed process model was developed in Microsoft Excel to produce CNF-coated MP trays using PET and PLA lidding for packaging fresh fruits such as cherry tomatoes, raspberries and blueberries. This process model was used for detailed material and energy balance assessments, enabling thorough TEA and LCA. The laboratory-scale experimental data was scaled up to industrial production by accounting for typical industry scaling factors and process equipment efficiencies. In addition, for quantification of the variability in scale-up assumptions, sensitivity and Monte Carlo simulation-based uncertainty analyses were conducted and this provided robust insights into the economic viability of the process. A simplified process flow diagram for the conceptualized process is shown in Figure 1. In the base case, the plant was designed to produce 5,000 MP trays per hour, corresponding to a fruit packaging capacity of 1,250 kg/h. The plant operates 7,884 h per year.

Process Description

The process begins with the MP tray production line, which consists of several key steps, such as pulping, wherein the waste/recycled paper are mixed with hot water in a hydropulper until a uniform pulp is formed. Next, the pulp is screened to remove contaminants such as plastics and sent to a storage tank. In the molding stage, specialized molds are submerged into the pulp suspension; vacuum suction draws the fibers onto the mold surface, shaping the pulp into trays with the desired thickness and strength while excess water is removed. This step is then followed by the drying step, where the produced MP trays are dried thoroughly.[28] The dried MP trays were then introduced into a dip tank where chitosan treatment was performed to improve the adhesion of the CNF coating onto the trays in the spray coating step. A CNF−CMC coating (5−10 wt %) was applied to the chitosan-treated MP trays via an automated spray coating system. An over spray of 10% is considered during the spray coating process. After drying, the spray-coated MP trays are sent to the packaging and sealing section. The fruits are first filled into the MP trays using a tray packaging machine and then sealed with PET/PLA lidding films via a tray sealer. The final product is packaged fruit inside MP trays with PLA/PET lidding and distributed to the retailers.

Proposed Supply Chain

In the United States, fresh fruits such as cherry tomatoes and berries are typically packed directly at farms into retail-ready plastic clamshells, which are then cooled and distributed to retailers.[29] This farm-based packing model minimizes fruit handling and is considered the industry standard. For our TEA and LCA, however, we adopt a centralized packing model in which cherry tomatoes and berries are purchased wholesale, packed onsite into CNF-coated MP trays, and subsequently distributed to retailers. This framework serves two purposes: first, it simplifies system boundaries and ensures transparent attribution of costs and benefits, including tray production and coating effects; second, it reflects a potential supply chain innovation in which centralized packing could reduce plastic use and extend fruit shelf life. In this study, shelf life is quantified as fruit weight loss (primarily from loss of water) after 10 days in MP trays, providing a measurable basis for linking packaging performance to economic and environmental outcomes. While this centralized model does not mirror current U.S. practices, it offers both a tractable analytical framework and a conceptual pathway for implementing the proposed packaging system. The centralized facility is an integrated operation that manufactures MP trays from waste/recycled paper at 5000 trays/h and packs fruit at 1250 kg/h (0.25 kg/tray). This integration is a deliberate design choice: the CNF spray coating step must occur after tray manufacturing and before fruit packing, requiring all three operations to be colocated. This would not be feasible at farm-level packing operations, which typically receive premanufactured trays from external suppliers. The centralized model therefore represents the enabling supply chain configuration for CNF coating technology adoption at commercial scale. While current U.S. fresh fruit packing is predominantly performed at the farm level, the centralized model represents a prospective scenario for technology adoption. As this is an nth plant TEA, all MSP results are inherently forward-looking and represent long-term cost targets under a mature, optimized facility configuration, which is standard practice in TEA methodology.

Based on the experimental work by Zhang and Youngblood,[24] five different fruit packaging configurations were considered and modeled in this study: (1) scenario 1: CNF-coated MP trays with PET lidding; (2) scenario 2: CNF-coated MP trays with PLA lidding (fully biobased coated alternative with improved moisture retention); (3) scenario 3: uncoated MP trays with PET lidding; scenario 4: uncoated MP trays with PLA lidding (fully biobased uncoated alternative); and scenario 5: uncoated MP trays with no lidding.

Techno-Economic Analysis

A detailed TEA was conducted to evaluate the economic viability of CNF-coated MP trays with PET/PLA lidding for packaging fresh fruits specifically cherry tomatoes, raspberries and blueberries. The TEA employed a discounted cash flow (DCF) analysis framework with 100% equity financing, which was based on established nth-plant assumptions, which reflect the performance and cost expectations of a mature, fully optimized industrial facility[30] (Table S1). The economic analysis involved rigorous estimation of total capital investment (TCI) and annual operating expenses (OPEX), derived from mass and energy balances. The equipment, operating labor and raw-material costs were updated to 2024 basis by using the Chemical Engineering Plant Cost Index (CEPCI), labor index and producer price index (PPI). For more details regarding the estimation of the total capital investment, annual operating cost and labor costs, refer to the Supporting Information (SI). The unit price of CNF was set at \$4.16/kg of dry CNF. This value is based on the MSP of \$3273/metric ton reported by Lan et al.,[26] who employed an nth-plant TEA framework, aligning with the methodological approach considered in this study and reflects mature, commercial-scale production economics rather than current low-volume market prices. The reported CNF price was adjusted from 2020 to 2024 cost basis by using the Producer Price Index (PPI). The unit prices for all material and energy inputs are listed in Table S12.

Minimum Selling Price, Sensitivity, and Uncertainty Analysis. For the assumed financial parameters (as shown in Table S1), the selling price of the product (packaged fruit in CNF-coated MP tray at the retail shelf after 10 days) is iterated until the net present value (NPV) of the plant is zero, thereby yielding the MSP. A univariate sensitivity analysis was carried out to evaluate the impact of individual economic and technical parameters on the MSP. Parameters for the sensitivity analysis were selected to represent the principal drivers of the MSP within the defined system boundary. In addition, a subsequent multivariate sensitivity analysis was performed based on the two biggest cost drivers identified from the univariate screening.

To assess the robustness of the estimated MSP, a Monte Carlo simulation−based uncertainty analysis (10,000 iterations) was performed. The economic parameters with considered probability distributions and corresponding minimum, maximum, and most likely values, are summarized in Table S16. The assumed lower and upper bounds for the parameters were consistent with those used in the sensitivity analysis. The analysis produced a probability distribution, from which the 90% confidence interval (defined as the fifth and 95th percentiles) was derived. This interval represents the expected range of minimum and maximum MSP values under realistic conditions.

Life-Cycle Assessment

Goal and Scope. The goal of this study was to conduct a cradle-to-retail LCA to quantify the environmental impacts of three fresh fruits (cherry tomatoes, raspberries and blueberries) packaged in CNF-coated MP trays at the retail shelf after 10 days in compliance with the ISO 14040 and 14044 standards.[31] The functional unit (FU) was defined as 1 kg of packaged fruit available at the retail shelf after 10 days. Accordingly, fruit input was fixed at 1250 kg/h, based on tray production capacity (5000 trays/h × 0.25 kg/tray), and remained constant across all five packaging scenarios. The scenarios differed only in the final mass of fruit available after 10 days, owing to differences in

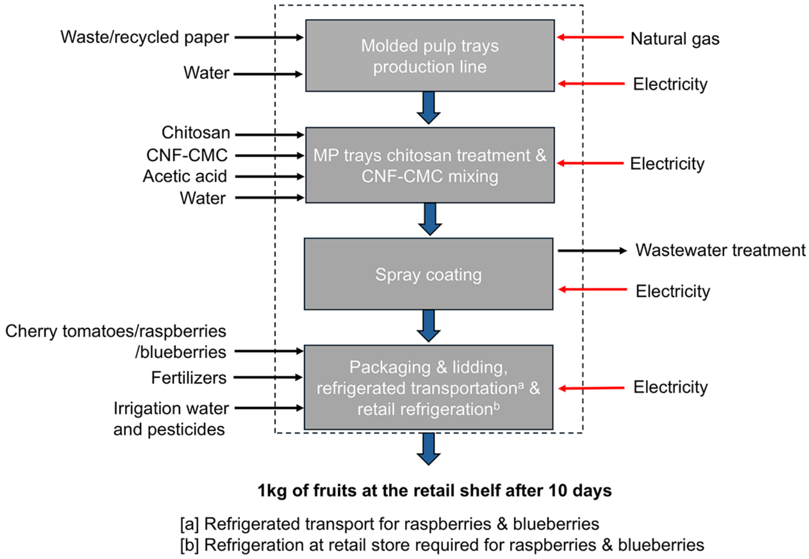

Figure 2. LCA Cradle-to-retail system boundary used in this study.

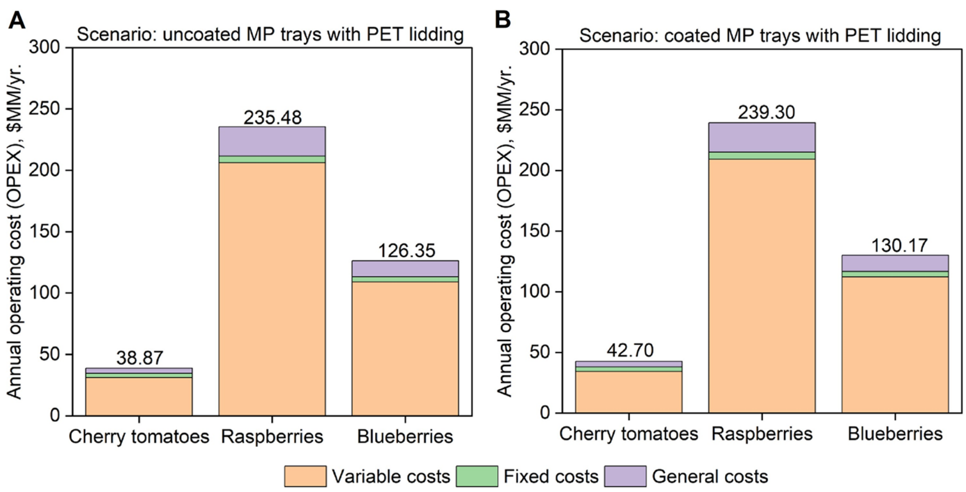

Figure 3. OPEX breakdown for fresh fruits packaged in (A) uncoated MP trays with PET lidding and (B) coated MP trays with PET lidding (at the retail shelf after 10 days).

weight loss (primarily due to loss of water from fruit). The life cycle inventory was therefore normalized to 1 kg of final product at retail. In scenarios with greater weight loss, such as in uncoated and unlidded trays, this normalization factor increased, assigning more input fruit and its associated upstream environmental burdens to each kilogram of delivered product. This FU is consistent with the explicit, decision-oriented approach validated by Frigerio et al.,[32] who showed that a shelf life-based FU is appropriate for comparing packaging systems that provide different levels of product protection.

The use and end-of-life phases of the packaged product were not included in this study. The end-of-life profile is largely similar across all five scenarios, as all use MP trays with either PET or PLA lidding; the only material difference is CNF coating that is expected to biodegrade along with the MP tray substrate. Furthermore, no reliable end-of-life data currently exists for CNF-coated MP trays under real-world waste management conditions; including speculative end-of-life scenarios would introduce additional uncertainty without improving comparative analysis. Future work should incorporate end-of-life modeling as data for these novel materials become available and claims regarding the sustainability benefits of CNF-coated MP trays should be interpreted within the context of the cradle-to-shelf boundary employed in this study.

Life Cycle Inventory. A cradle-to-retail LCA was performed using SimaPro 10.0.2 software, with background data sourced from DATASMART,[33] AGRIBALYSE v3.0,[34] and ecoinvent v3.11[35] databases. Foreground data to build the life cycle inventory (LCI), encompassing material inputs and energy utilization, were compiled from peer-reviewed publications and commercial reports (Tables S17–S23). In the absence of a U.S. specific LCI data set for berries, the AGRIBALYSE French raspberry and blueberry data set was adopted as a proxy for U.S. berry production and distribution. It should be noted that French and U.S. berry production differ in several respects, most notably the carbon intensity of the electricity grid, transportation distances, and agricultural practices. The use of a U.S. specific data set would therefore be expected to alter the absolute magnitude of the reported impact values. However, since the same berry LCI data set is applied uniformly across all five packaging scenarios, and since the FU is defined on an output basis (packaged fruit at retail after 10 days, accounting for weight loss), any such shift would propagate proportionally across all cases. Therefore, the comparative conclusions of this study are unaffected. The development of a U.S. specific berry production and distribution LCI data set is identified as a priority for future work.

As shown in Figure 2, the system boundary extends from raw material extraction through tray production, packaging operations,

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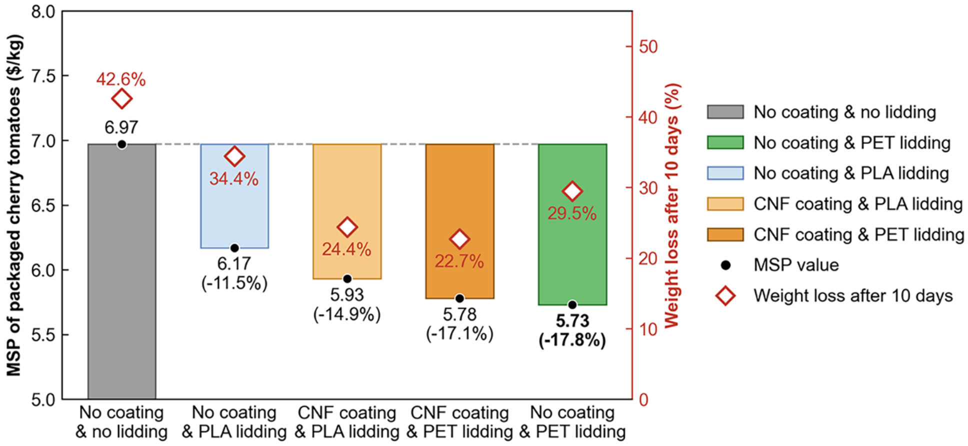

Figure 4. MSP comparison of different packaging configurations for cherry tomatoes at the retail shelf after 10 days.

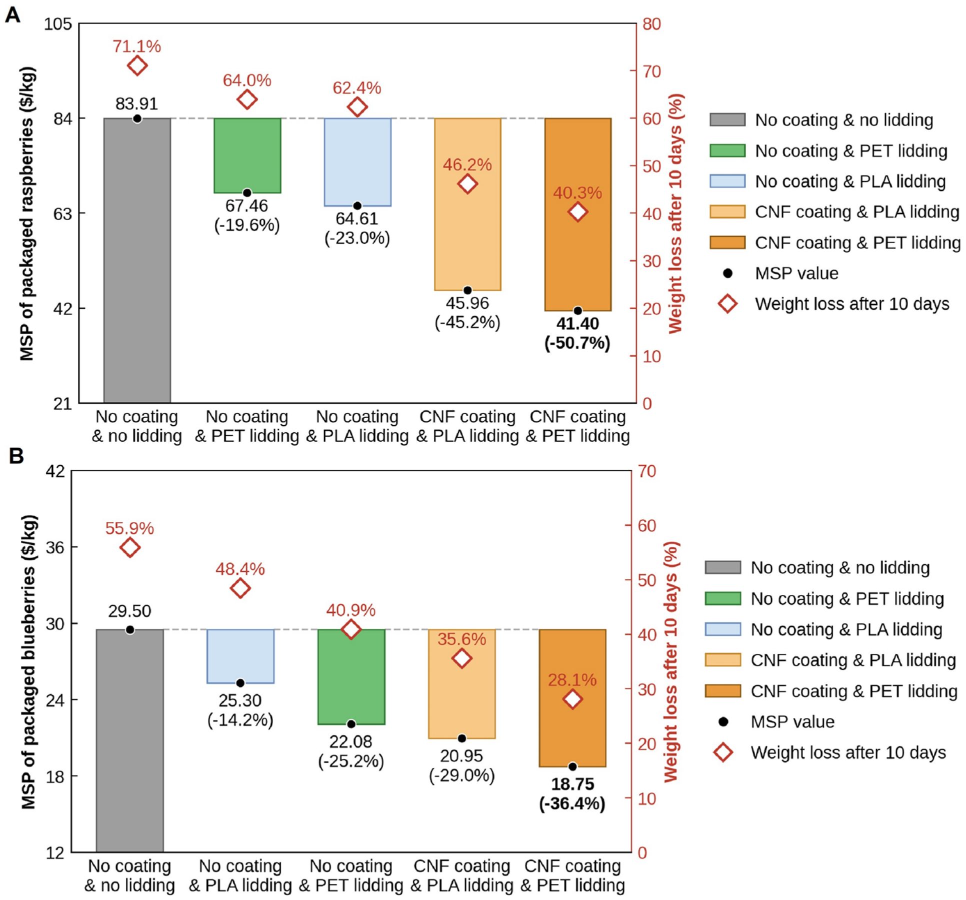

Figure 5. MSP comparison of different packaging configurations for (A) raspberries and (B) blueberries at the retail shelf after 10 days.

distribution, and storage to the retail shelf. As no coproducts were generated within the defined system, the study was modeled as a single-product system, and no allocation procedures were applied.

Impact Assessment. The cradle-to-retail life cycle environmental impacts were estimated using the TRACI 2.2 methodology[36] for the following 10 impact categories: ozone depletion (kg CFC-11 equiv), global warming (kg CO_2 eq), smog formation (kg O_3 eq), acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), marine eutrophication (kg N eq), carcinogenics (CTU_h), noncarcinogenics (CTU_h), respiratory effects (kg $PM_{2.5}$ eq) and ecotoxicity (CTU_e).

RESULTS AND DISCUSSION

Techno-Economic Analysis Results

The total fixed capital investment (FCI) for a 1250 kg/h fruit packaging plant was estimated at $4.81 million (MM) (CNF-coated with PLA/PET lidding), $2.00MM (uncoated with PET/PLA lidding), and $1.18MM (uncoated and without lidding). The percentage breakdown of the FCI remains uniform across all scenarios because the direct and indirect costs were calculated as fixed fractions of the delivered equipment cost (DEC) using standard factorial estimation.[37] Specifically, the direct costs account for 71% of the FCI and includes the

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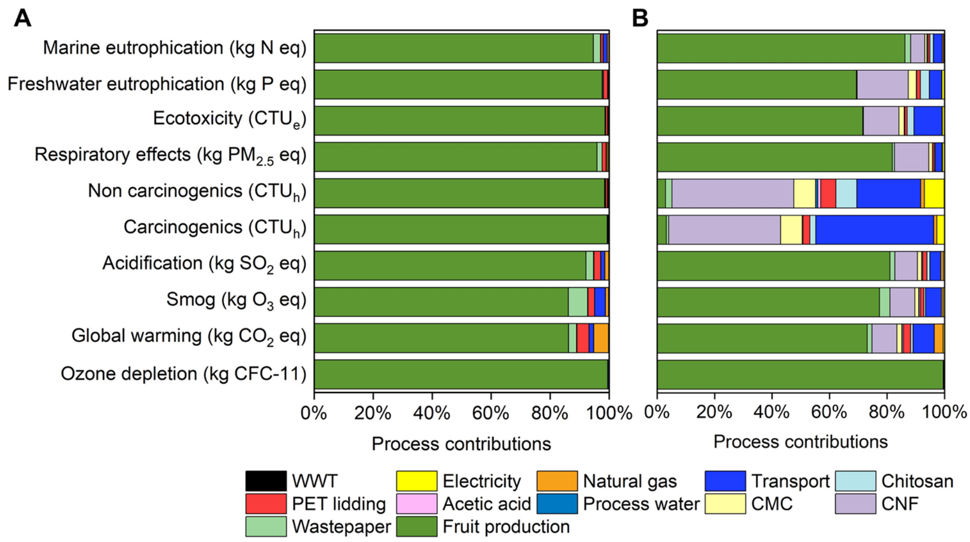

Figure 6. Contributions of process components to the overall environmental impact: (A) Cherry tomatoes packaged in uncoated molded pulp trays with PET lidding after 10 days at the retail shelf. (B) Raspberries packaged in CNF-coated molded pulp trays with PET lidding after 10 days at the retail shelf.

purchase and delivery of equipment, installation, instrumentation, piping and electrical systems, yard improvements, buildings and service facilities. The indirect costs contribute the remaining 29% of the FCI and cover costs related to engineering and supervision, construction, legal expenses, contractor's fee and contingency. A detailed breakdown of the equipment and capital costs for the scenarios considered in this study is provided in Tables S3–S6. The total investment costs, incorporating working capital and land costs, are estimated at $5.3MM (CNF-coated with lidding), $2.4MM (uncoated with lidding), and $1.5MM (uncoated without lidding).

The annual operating cost (OPEX), estimated as the sum of the variable, fixed and general operating costs for all the fruit packaging scenarios, is summarized in Tables S7-S11 and the assumptions for calculation of these costs is provided in the Supporting Information. The OPEX breakdown for the packaged fruits in coated and uncoated MP trays with PET lidding at the retail shelf after 10 days is shown in Figure 3 and it is evident that OPEX is primarily driven by the variable costs, particularly the wholesale purchase cost of fruits. For example, in case of cherry tomatoes packaged in uncoated and coated MP trays with PET lidding, 98 and 89% of the variable costs come from the wholesale purchase cost of the fruit, respectively. The OPEX structure was largely independent of scenario. The only cost components that varied between coated and uncoated configurations were the coating materials (CNF, CMC, chitosan, and acetic acid) and the associated process energy. Economic performance was therefore governed by the trade-off between this additional coating cost and the revenue gained from preserving saleable mass. The economic benefit from the application of the CNF-based coating to MP trays appears to be product dependent and greatest for fruits with higher susceptibility to weight loss and this is discussed more in the sections that follow.

Economic Viability of Cherry Tomatoes in Different Packaging Configurations

As seen from Figure 4, the MSP of cherry tomatoes packaged in uncoated MP trays with PET lidding after 10 days at the retail shelf was estimated to be $5.73/kg, 18% lower when compared to the uncoated and unlidded scenario ($6.97/kg). The application of the CNF-based coating to MP trays introduced a critical trade-off between the added material cost and the benefit of reduced weight loss of the fruit. For trays with PET lidding, the coating resulted in a slightly higher MSP of $5.78/kg. Although in this case, the coating reduced the weight loss of cherry tomatoes by 23% compared with that of uncoated trays with PET lidding, this improvement was still found to be insufficient to offset the material and associated energy cost of the coating. In contrast, the coated MP trays were more economically beneficial when paired with PLA lidding. In this fully biobased coated packaging system, the weight loss in cherry tomatoes was reduced by a more substantial 29% compared to the equivalent uncoated configuration. This was then sufficient to overcome the additional material and energy expense, making the coated-PLA system (MSP $5.93/kg) a more effective solution than its uncoated equivalent ($6.17/kg).

Economic Viability of Berries in Different Packaging Configurations

CNF-coated MP trays with PET and PLA lidding significantly reduced weight loss and improved the economic viability of packaged berries after 10 days at the retail shelf. As shown in Figure 5A and B, the estimated MSP for berries packaged in coated trays was substantially lower than the uncoated and unlidded scenarios. Specifically, the MSP for raspberries was estimated at $41.40/kg (PET) and $45.96/kg (PLA), representing a 51 and 45% reduction, respectively when compared to the uncoated and unlidded baseline ($83.91/kg). Similarly, the MSP for blueberries was reduced by 36 and 29%, dropping to $18.75/kg (PET) and $20.95/kg (PLA) when compared to the uncoated and unlidded baseline ($29.50/kg). Furthermore, these coated and lidded packaging configurations reduced weight loss in raspberries by 37% (PET) and 26% (PLA), and in blueberries by 31% (PET) and 26% (PLA) compared to their uncoated equivalents. This substantial improvement was sufficient not only to offset the material and energy costs of the coating, but also to make these packaging systems economically more viable than the alternative configurations considered.

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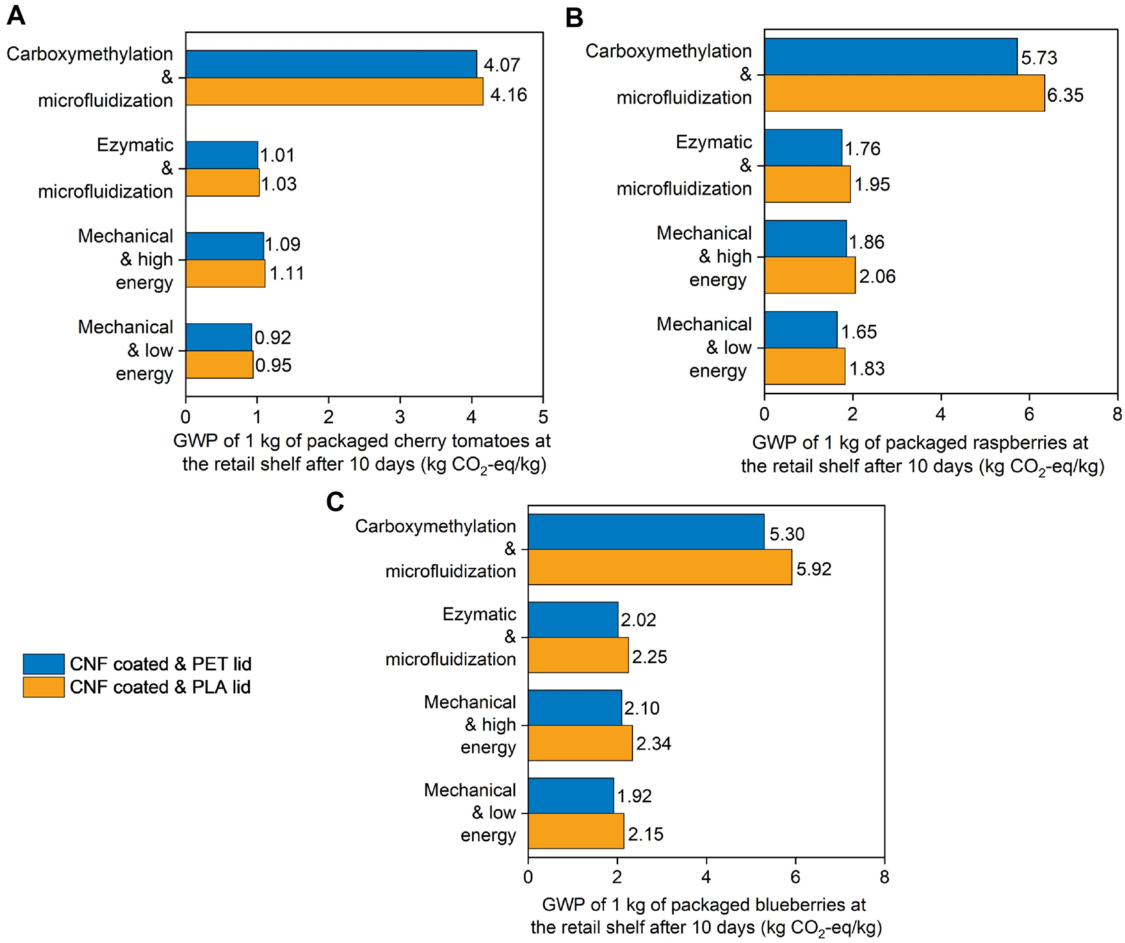

Figure 7. Impact of different CNF production scenarios on: (A) GWP of 1 kg of packaged cherry tomatoes at the retail shelf after 10 days. (B). GWP of 1 kg of packaged raspberries at the retail shelf after 10 days. (C) GWP of 1 kg of packaged blueberries at the retail shelf after 10 days.

Table 1. CNF Production Scenarios Considered in this Study (Adapted from Kane et al.[39])

Process	Key process steps	Reference
Carboxymethylation	Dispersion, washing and filtration, impregnation, carboxymethylation, washing and filtration, impregnation, washing and filtration and microfluidization.	Arvidsson et al.[43]
Enzymatic	Refining, mixing, incubation, mixing, washing, enzyme denaturation, washing, refining, microbicide addition and microfluidization.	Arvidsson et al.[43]
Mechanical - High energy	Powdering, wet cut milling, hot compressed water treatment and wet disk milling. The high energy scenario included electricity usage of 5.05 kWh/kg nanocellulose and heat usage of 6.84 MJ/kg nanocellulose.	Moon et al.[42]
Mechanical - Low energy	Powdering, wet cut milling, hot compressed water treatment and wet disk milling. The low energy scenario included electricity usage of 1.67 kWh/kg nanocellulose and heat usage of 2.93 MJ/kg nanocellulose.	Moon et al.[42]

Life Cycle Assessment Results

The FU adopted in this study captures the moisture-retention dimension of shelf life extension rather than shelf life in its entirety. Weight loss, which primarily reflects the loss of water from fruit, is a principal cause of postharvest deterioration in fresh fruit, directly initiating wilting, shriveling, loss of texture, and reduction of saleable weight.[38] Reducing water loss for the fruits packaged in MP trays with the CNF-based coating provides two reinforcing benefits. First, from an economic perspective, since fruit is sold by mass at retail, reduced water loss means more saleable product per unit of input fruit. Second, from an environmental perspective, the upstream burden of producing the fruit is allocated across more usable output. Each kg of packaged fruit at the retail shelf therefore carries a lower environmental footprint when water loss is minimized. These dual benefits are captured by our output-based functional unit, which naturally penalizes scenarios with higher moisture loss.

It is, however, acknowledged that other quality-determining factors, such as microbial spoilage and the development of off-flavors, are not reflected in the present FU. This scope reflects the boundary of the underlying experimental data (Zhang and Youngblood[24]), in which packages were purged with nitrogen and UV-sterilized prior to sealing, thereby suppressing microbial activity and isolating fruit water loss as the dominant differentiator between scenarios. The present results should therefore be interpreted as a water loss-based comparison under controlled, microbially suppressed conditions. Future work should incorporate experimentally measured microbial growth, firmness, and sensory quality into a more comprehensive, multiattribute FU.

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The full LCA results, evaluated via the TRACI 2.2 methodology, are presented in Tables S24–S29 for the best performing fruit packaging scenarios. As shown in Figure 6, most of the environmental impacts are driven by a few key inputs. In the uncoated & PET lidded scenario (Figure 6A), fruit production emerges as the most dominant contributor, accounting for 86.3 to 99.5% of the total impacts across the evaluated categories. Other contributors include wastepaper (0.03–6.6%), natural gas (0.01–5%), PET lidding (0.2–4.9%), transportation (0.01–3.7%), electricity (0.01–0.5%) and process water (0.02–0.3%). In the CNF-coated and PET lidded scenario (Figure 6B), the main contributors to the total impacts across the evaluated categories were fruit production (3–99.6%) and the CNF coating (0.1–42.4%). Other contributors include transportation (0.2–41.1%), CMC (0.03–7.6%), chitosan (0.05–7.3%), electricity (0.002–6.9%), PET lidding (0.01–5.3%), wastepaper (0.002–3.6%), natural gas (0–3%) and process water (0.03–0.8%). The wastewater treatment (WWT) contributions were negligible.

As shown in Figure 7, the CNF production method was found to have a notable effect on the GWP of the process. The main CNF production scenarios considered in this study with the key process steps are summarized below in Table 1. LCI data for the CNF production scenarios (Tables S17–S20) were taken from literature[39−43] and integrated into the inventory of the CNF-coated MP tray fruit packaging system to assess the effect of CNF production route on overall GWP. GWP values for these scenarios were recalculated in this study using TRACI 2.2 characterization factors.

When MP trays are coated with CNFs produced via a mechanochemical process that combines wet disk milling and mild hot-compressed water (HCW) treatment with low power consumption,[40−42] the GWPs of cherry tomatoes, raspberries and blueberries packaged in CNF-molded pulp trays with PET and PLA lidding are reduced by 78, 71, and 64%, respectively, compared with those of the CNF production scenario involving carboxymethylation pretreatments and microfluidization (Figure 7).

The estimated GWP of the different packaging configurations for cherry tomatoes, raspberries and blueberries, with mechanical pretreatment and low power consumption scenario used for CNF production, are shown in Table 2. The results highlight the strong influence of weight loss of fruit at the retail shelf on the GWP of berries compared to cherry tomatoes. In the case of cherry tomatoes, the estimated GWP for the uncoated scenarios was 8 and 4% lower than that for the coating scenarios with PET and PLA lidding, respectively. The modest reduction in fruit weight loss after 10 days at the retail shelf, when packaged in coated MP trays was insufficient to overcome the associated burdens from the CNF production process. However, in case of berries, the reduction in fruit weight loss in coated MP trays with PET lidding was quite substantial, thereby helping to compensate for the resulting GWP from CNF production. As a result, the GWP values for packaged raspberries and blueberries at the retail shelf after 10 days were 32 and 10% lower, respectively, than those of the equivalent uncoated packaging configurations. The LCA results for the different CNF production scenarios considered in this study, including the remaining environmental impact categories, are summarized in Table S30.

Table 2. Estimated GWP of Packaged Fruits for All Packaging Configurations (At the Retail Shelf After 10 Days and for CNF Production via Mechanical Treatment and Low Energy)

Type of packaging	Wt. loss tomatoes after 10 days[24] (%)	GWP of packaged fruit (kg CO_2eq/kg)
	Cherry tomatoes	
CNF coating & PLA lidding	24.4	0.945
CNF coating & PET lidding	22.7	0.923
Uncoated & PLA lidding	34.4	0.911
Uncoated & PET lidding	29.5	0.847
Uncoated & no lidding	42.6	0.998
	Raspberries	
CNF coating & PLA lidding	46.2	1.83
CNF coating & PET lidding	40.3	1.65
Uncoated & PLA lidding	62.4	2.31
Uncoated & PET lidding	64	2.41
Uncoated & no lidding	71.1	2.91
	Blueberries	
CNF coating & PLA lidding	35.6	2.15
CNF coating & PET lidding	28.1	1.92
Uncoated & PLA lidding	48.4	2.45
Uncoated & PET lidding	40.9	2.14
Uncoated & no lidding	55.9	2.81

Combined Analysis of All Packaging Configurations Based on MSP and GWP

To improve decision making, all packaging configurations were compared jointly using estimated MSP and GWP on a per-functional-unit basis (1 kg of packaged fruit at the retail shelf after 10 days). For each fruit, the best-performing configuration was defined as the scenario exhibiting both the lowest MSP and the lowest GWP. Based on this comparison (Table 3), the best-performing configuration was identified to be fruit-dependent: the uncoated tray with PET lidding performed best for cherry tomatoes, whereas in case of berries, the CNF-coated MP trays with PET lidding was the best performing scenario. Fully biobased configurations were also identified separately. Among the fully biobased configuration, the CNF-coated tray with PLA lidding provided improved moisture retention relative to the uncoated and PLA lidding scenario and was found to be the most competitive biobased option for berries.

Sensitivity and Uncertainty Analysis Results

Sensitivity analysis was performed to evaluate the influence of key economic and technical parameters on the estimated MSP of the packaged fruit at the retail shelf after 10 days. The analysis was performed for the best performing scenarios for each fruit, as shown in Figure 8.

Across the 3 fruits, the main MSP drivers were identified as wholesale purchase cost of the fruit and the 10-day fruit weight-loss percentage. Wholesale fruit cost represents an independent market-driven economic input, whereas the 10-day fruit weight-

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Table 3. Combined Analysis of all Packaging Configurations Based on WL,[a] MSP,[b] and GWP[c]

Case	Cherry tomatoes	Raspberries	Blueberries	Decision support
Uncoated and no lidding	*WL*: 42.6 *MSP*: 6.97 *GWP*: 0.998	*WL*: 71.1 *MSP*: 83.91 *GWP*: 2.91	*WL*: 55.9 *MSP*: 29.50 *GWP*: 2.81	Dominated on MSP and GWP basis.
Uncoated and PET lidding	*WL*: 29.5 *MSP*: **5.73*** *GWP*: **0.847***	*WL*: 64.0 *MSP*: 67.46 *GWP*: 2.41	*WL*: 40.9 *MSP*: 22.08 *GWP*: 2.14	Best overall for cherry tomatoes.
Uncoated and PLA lidding	*WL*: 34.4 *MSP*: 6.17 *GWP*: 0.911	*WL*: 62.4 *MSP*: 64.61 *GWP*: 2.31	*WL*: 48.4 *MSP*: 25.30 *GWP*: 2.45	Fully biobased uncoated alternative; dominated on MSP and GWP basis.
CNF coating and PET lidding	*WL*: 22.7 *MSP*: 5.78 *GWP*: 0.923	*WL*: 40.3 *MSP*: **41.40*** *GWP*: **1.65***	*WL*: 28.1 *MSP*: **18.75*** *GWP*: **1.92***	Best overall for raspberries and blueberries.
CNF coating and PLA lidding[e]	*WL*: 24.4 *MSP*: 5.93 *GWP*: 0.945	*WL*: 46.2 *MSP*: 45.96 *GWP*: 1.83	*WL*: 35.6 *MSP*: 20.95 *GWP*: 2.15	Fully biobased coated alternative with improved moisture retention; near-competitive for berries.

[a]Fruit weight loss (%) after 10 days.[24] [b]Minimum selling price ($/kg). [c]Global warming potential (kg CO_2-eq/kg). All values are reported per functional unit (1 kg of packaged fruit at the retail shelf after 10 days). *Best-performing overall configuration for the indicated fruit, defined as the scenario exhibiting both the lowest MSP and the lowest GWP.

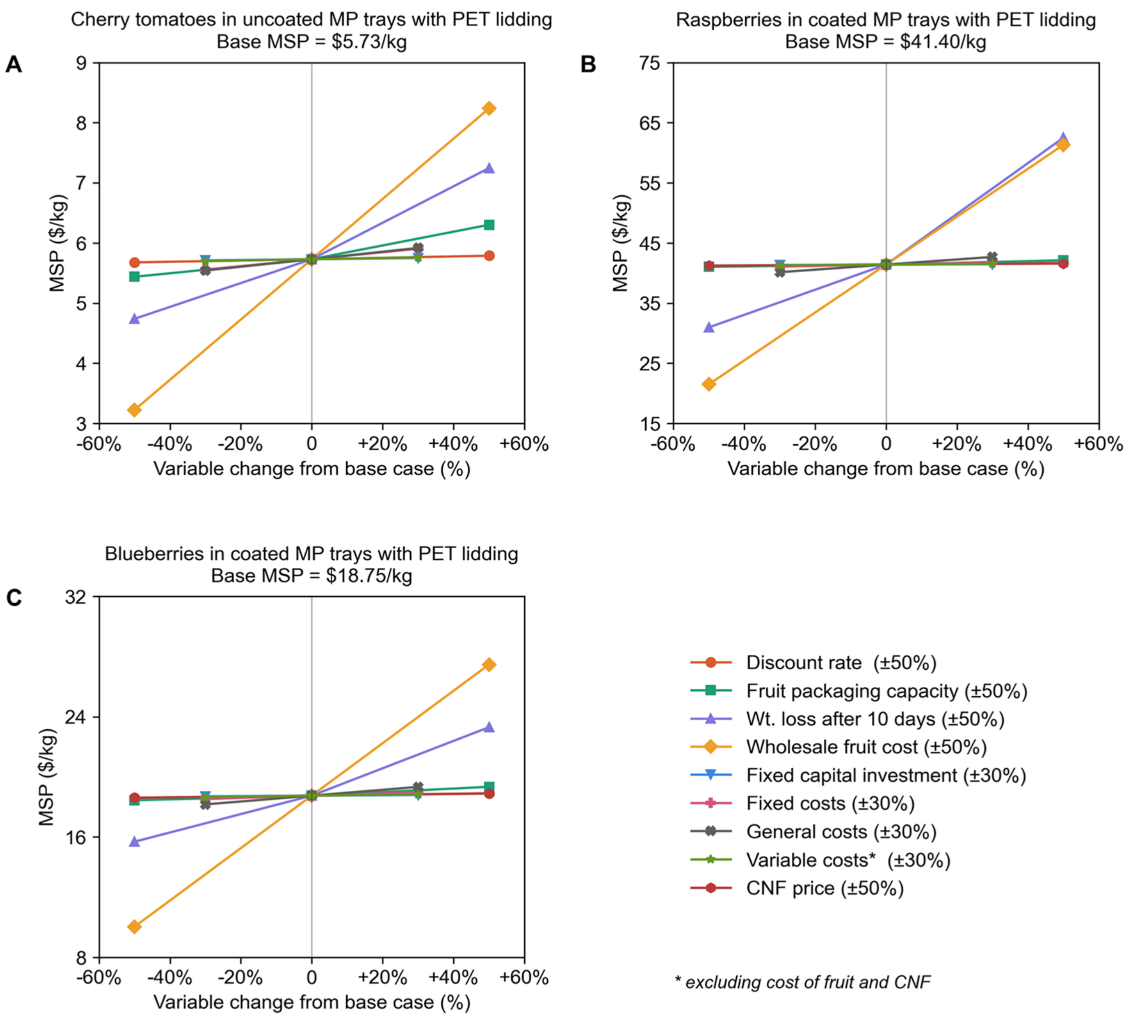

Figure 8. MSP sensitivity analysis for the best-performing fruit packaging configurations at the retail shelf after 10 days. All data shown in Figure 8 are available in the Supporting Information: Table S13 for (A), Table S14 for (B) and Table S15 for (C).

loss percentage is a scenario-specific packaging-performance outcome derived from experimental data.[24] For each fruit and packaging scenario, the 10-day fruit weight-loss percentage was varied by ±50% around its corresponding baseline value in the

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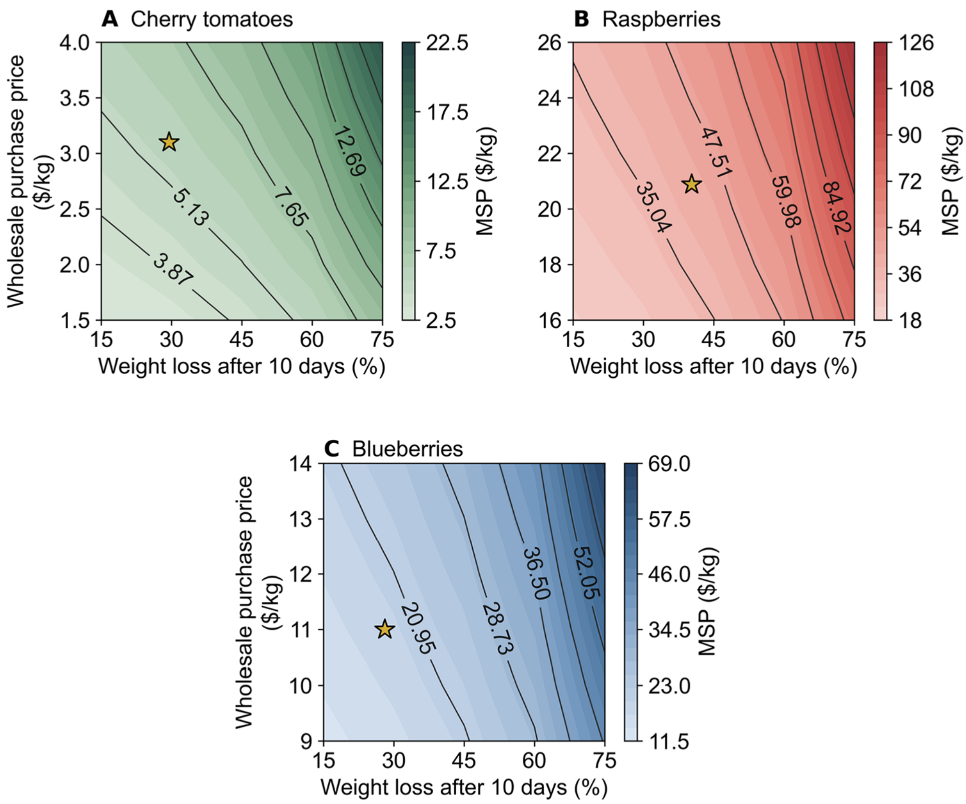

Figure 9. Multivariate sensitivity analysis for the combined impact of wholesale fruit cost and weight loss of fruit after 10 days at the retail shelf on (A) MSP of cherry tomatoes packaged in uncoated MP trays with PET lidding. The base case MSP calculated as \$5.73/kg and highlighted with a star. (B) MSP of raspberries packaged in coated MP trays with PET lidding. The base case MSP calculated as \$41.40/kg and highlighted with a star. (C) MSP of blueberries packaged in coated MP trays with PET lidding. The base case MSP calculated as \$18.75/kg and highlighted with a star.

univariate sensitivity analysis while all other parameters were held constant. Therefore, its inclusion in the univariate sensitivity analysis was intended to evaluate the responsiveness of MSP to this performance-derived model parameter, rather than to treat fruit weight loss as an independently adjustable coating design variable. Changes in plant capacity, defined by fruit packaging capacity, had only a modest effect on the MSP of cherry tomatoes, and an even smaller effect on the MSP of the best-performing packaging configurations for raspberries and blueberries. The reason is that the best-performing scenario for cherry tomatoes did not require coating. In comparison, for raspberries and blueberries, the best-performing scenarios involved applying a CNF-based coating to MP trays, and the additional material and energy costs reduced the relative impact of plant capacity on MSP.

Since wholesale fruit cost and the 10-day fruit weight-loss percentage had the largest influence on MSP, these two parameters were selected for subsequent multivariate analysis (Figure 9). Exploring their combined influence provides critical insight into how simultaneous changes in principal cost drivers affect the MSP, revealing economic dynamics beyond what can be inferred from separate univariate results alone. For instance, a combined 20% increase in the wholesale purchase cost of fruit and weight loss of fruit at the retail shelf after 10 days increased the MSP of cherry tomatoes, raspberries and blueberries by 28.2, 37.9, and 28.7%, respectively, when compared with the baseline MSPs for the best performing fruit packaging configurations. This further suggests that the economic viability of the process is largely determined by the prevailing market conditions, which in turn dictate the purchase price of the fruits, while the MSP of the packaged fruits at the retail shelf can be reduced through improved moisture retention provided by the CNF coating.

Based on the MSP uncertainty analysis carried out for the best performing fruit packaging scenarios, the 90% confidence intervals (CI) of the MSP were as follows: (a) \$3.94/kg to \$7.49/kg in the case of cherry tomatoes packaged in uncoated MP trays with PET lidding (Figure 10A); (b) \$27.44/kg to \$57.88/kg in the case of raspberries packaged in coated MP trays with PET lidding (Figure 10B); and (c) \$12.85/kg to \$24.75/kg in the case of blueberries packaged in coated MP trays with PET lidding (Figure 10C). Cherry tomatoes exhibited low economic uncertainty (median MSP \$5.63/kg; SD: 1.07). Whereas raspberries (median MSP: \$40.92/kg; SD: 9.29) and blueberries (median MSP \$18.57/kg; SD: 3.57) showed much broader MSP ranges, indicating substantially higher economic risk. The wider confidence interval observed for berries reflects the greater variability in weight loss between coated and uncoated scenarios for this fruit type. This indicates that the economic viability of CNF coating for berries is more sensitive to coating performance than for cherry tomatoes, where weight loss differentials are more consistent. For producers, this suggests that quality control of the coating application process is particularly critical for high-value, high-moisture-loss fruits such as berries. The uncertainty could be narrowed by obtaining more precise weight-loss data from pilot-scale coating trials, reducing uncertainty in raspberry wholesale pricing through market analysis, and optimizing the CNF coating process to achieve more consistent moisture barrier performance.

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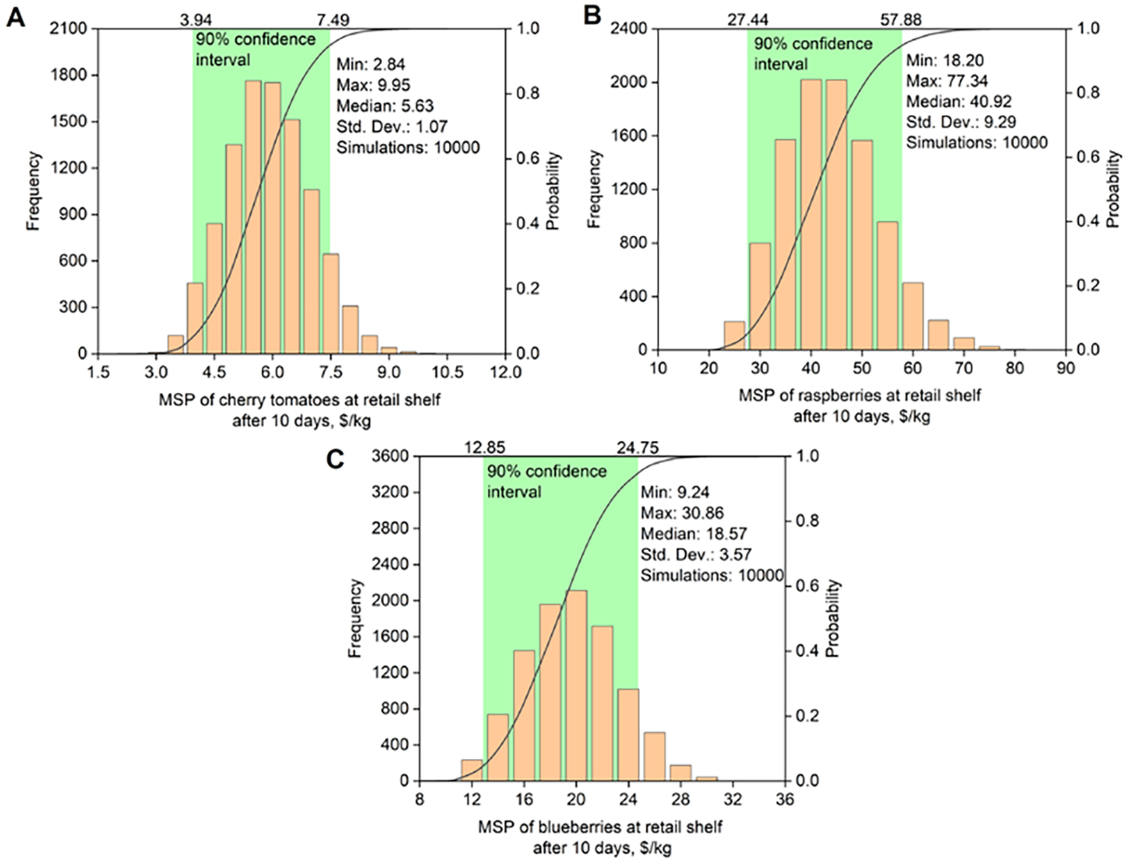

Figure 10. MSP uncertainty analysis results for the best-performing scenarios: (A) MSP of cherry tomatoes packaged in uncoated MP trays with PET lidding at the retail shelf after 10 days. (B) MSP of packaged raspberries in coated MP trays with PET lidding at the retail shelf after 10 days. (C) MSP of packaged blueberries in coated MP trays with PET lidding at the retail shelf after 10 days.

CONCLUSIONS

Utilizing lab-scale experimental data, this study conceptualized a plant scale process to produce CNF-coated MP trays with PET/PLA lidding for fresh fruit packaging. Based on n^{th} plant assumptions, which reflect the performance of a mature and fully optimized industrial facility, TEA was carried out to quantify the economic viability of five different packaging scenarios. A new supply chain involving the packaging of fresh fruits on site to capture the beneficial impact of the CNF coating in terms of reduced weight loss of the fruit at the retail shelf was proposed. The best performing packaging scenarios for each fruit were identified and ranked based on MSPs and GWPs. The MSPs of packaged cherry tomatoes, raspberries and blueberries at the retail shelf after 10 days were estimated at $5.73, $41.40, and $18.75/kg, respectively. The MSP results are based on n^{th} plant assumptions, representing a mature, fully optimized facility. While pioneer-plant costs for emerging technologies can be 2 to 5 times higher than n^{th} plant estimates, the CNF coating process employs standard, commercially available equipment (spray coating systems, conveyor lines, drying systems) already manufactured at scale for other industrial applications. The novelty lies in the application to MP trays, not in the equipment itself, which significantly reduces the gap between n^{th} plant and pioneer-plant costs. Nonetheless, early adopters may face moderately higher costs due to process optimization and integration learning curves, and readers should interpret the MSP results as long-term achievable targets rather than near-term costs.

The cradle-to-retail LCA results based on the TRACI 2.2 methodology estimated the GWP of the packaged cherry tomatoes, raspberries and blueberries after 10 days at the retail shelf as 0.847 (uncoated MP tray with PET lidding), 1.65 (coated MP tray with PET lidding) and 1.92 kg CO_2e/kg (coated tray with PET lidding), respectively. In addition, different CNF production scenarios were modeled to evaluate the changes in GWP. The sensitivity analysis revealed high MSP sensitivity to changes in the wholesale purchase cost of the fruit and weight loss of the fruit after 10 days at the retail shelf. For the best performing scenarios, uncertainty analysis via Monte Carlo simulations quantified the variability in the estimated MSP of the packaged fresh fruits at the retail shelf after 10 days, yielding a 90% confidence interval of $3.94−7.49/kg for cherry tomatoes, $27.44−57.88/kg for raspberries and $12.85−24.75/kg for blueberries. In conclusion, this study demonstrates the economic and environmental performance of CNF-coated MP trays with PET/PLA lidding for fresh fruit packaging and highlights the potential scalability of these packaging systems to industrial levels. Together, these findings position CNF-based packaging as a promising pathway toward sustainable, commercially feasible alternatives to conventional fruit packaging systems.

ASSOCIATED CONTENT

Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the paper and its Supporting

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Information file. Any additional data will be made available upon request.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.6c02159.

Information regarding the assumptions used in the economic analysis, equipment purchase cost, capital investment, and annual operating cost breakdown; sensitivity and uncertainty analysis parameter data; life-cycle inventory (LCI) data; and detailed life cycle assessment results (PDF)

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Notes

The authors declare no competing financial interest.

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