Industrial Crops & Products 211 (2024) 118213

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

# Economic and environmental analysis of producing soy protein-cellulose-based bionanocomposite fruit coating

Naveenkumar Rajendran [a,b,*], Troy Runge [a], Richard D. Bergman [b], Prakash Nepal [b], Neethu T. Pottackal [c], Muhammad M. Rahman [c]

[a] Biological Systems Engineering, University of Wisconsin, Madison, WI 53706, USA
[b] Forest Products Laboratory, USDA Forest Service, Madison, WI 53726, USA
[c] Department of Materials Science and NanoEngineering, Rice University, Houston, TX 77030, USA

ARTICLE INFO

*Keywords:*
Fruit coating
Cellulose nanocrystal
Soy protein isolate
Techno-economic analysis
Life cycle assessment

ABSTRACT

Food waste especially for perishable fruit is highly problematic for a global society that continues to grow in population. Coating fruit is one such approach to minimize waste. To assess economic and environmental risks and opportunities of a novel fruit-coating solution before industrial deployment is pursued, an industrial-scale process model was developed based on an optimized experimental process to produce soy protein isolate-cellulose nanocrystal bionanocomposite coating for perishable fruits (avocado for this study). Techno-economic analysis and life cycle assessment were carried out to understand the financial viability and the environmental performance of the soy protein isolate-cellulose nanocrystal fruit coating solution production process at the commercial scale. The estimated minimum selling price of soy protein isolate-cellulose nanocrystal fruit coating solution was $0.59/kg, which is competitive with existing fruit coating solutions (e.g., solvent-based wax). The minimum cost of applying a coating to avocado fruit was approximately $0.01/fruit. A sensitivity analysis indicated that the estimated economic outcomes were still favorable, even when raw material costs, tax rate, and project's lifetime were varied by ±50%, with soy protein isolate costs having the largest impact on the estimated measures of profitability. The cradle-to-gate life cycle assessment results indicated that an industrial-scale soy protein isolate-cellulose nanocrystal fruit coating solution production process estimates a carbon footprint of 0.33 kg $CO_2$ eq/kg of solution produced which is higher than the water-based wax solution and lower than the solvent-based wax solution.

## 1. Introduction

Fruits are edible products with a limited shelf life. Commercial fruit production goes through various supply chain stages such as harvesting, sorting, cleaning, grading, packaging, and transport, which means there are days to weeks between harvest to when they are consumed. External factors such as physical damage during handling and transport, microbial contamination (fungi and bacteria), and environmental factors (temperature, humidity, moisture) further reduce fruit's quality and shelf life. Because of these factors, a substantial amount of fruits are wasted each year, resulting in large economic losses as well as threats to human and animal health (el Khetabi et al., 2022). According to FAO (2011), around 40–50% of the fruits and vegetables produced worldwide are wasted annually before being consumed. Improved postharvest handling, packing, transportation, and storage are needed to reduce physical damage to fruits and their contamination, which will not only further result in improved fruits shelf life, supply chain, and profitability but also reduced food waste generation and the associated environmental impacts (Bhattacharjee et al., 2021).

Various methods are currently used to improve the shelf lives of perishable fruits (Han et al., 2018). However, these methods are either too costly, time-consuming, and harmful to human health if consumed, or they alter the appearance and flavor of the fruit. Fruit coatings and packaging films, which act as a protective barrier to reduce microbial contamination and spoilage from environmental factors (Zhang et al., 2022a,2022b), are two commonly practised commercial methods used to extend fruit shelf life. Petroleum and polyethylene-based waxes and chemical fungicides have been used as a fruit coating material for many decades to reduce fruit decay and increase shelf life. However, increased utilization of petroleum waxes and fungicides negatively affects the

* Corresponding author at: Biological Systems Engineering, University of Wisconsin, Madison, WI 53706, USA.
*E-mail address:* nrajendiran@wisc.edu (N. Rajendran).

https://doi.org/10.1016/j.indcrop.2024.118213
Received 15 November 2023; Received in revised form 29 January 2024; Accepted 4 February 2024
Available online 21 February 2024

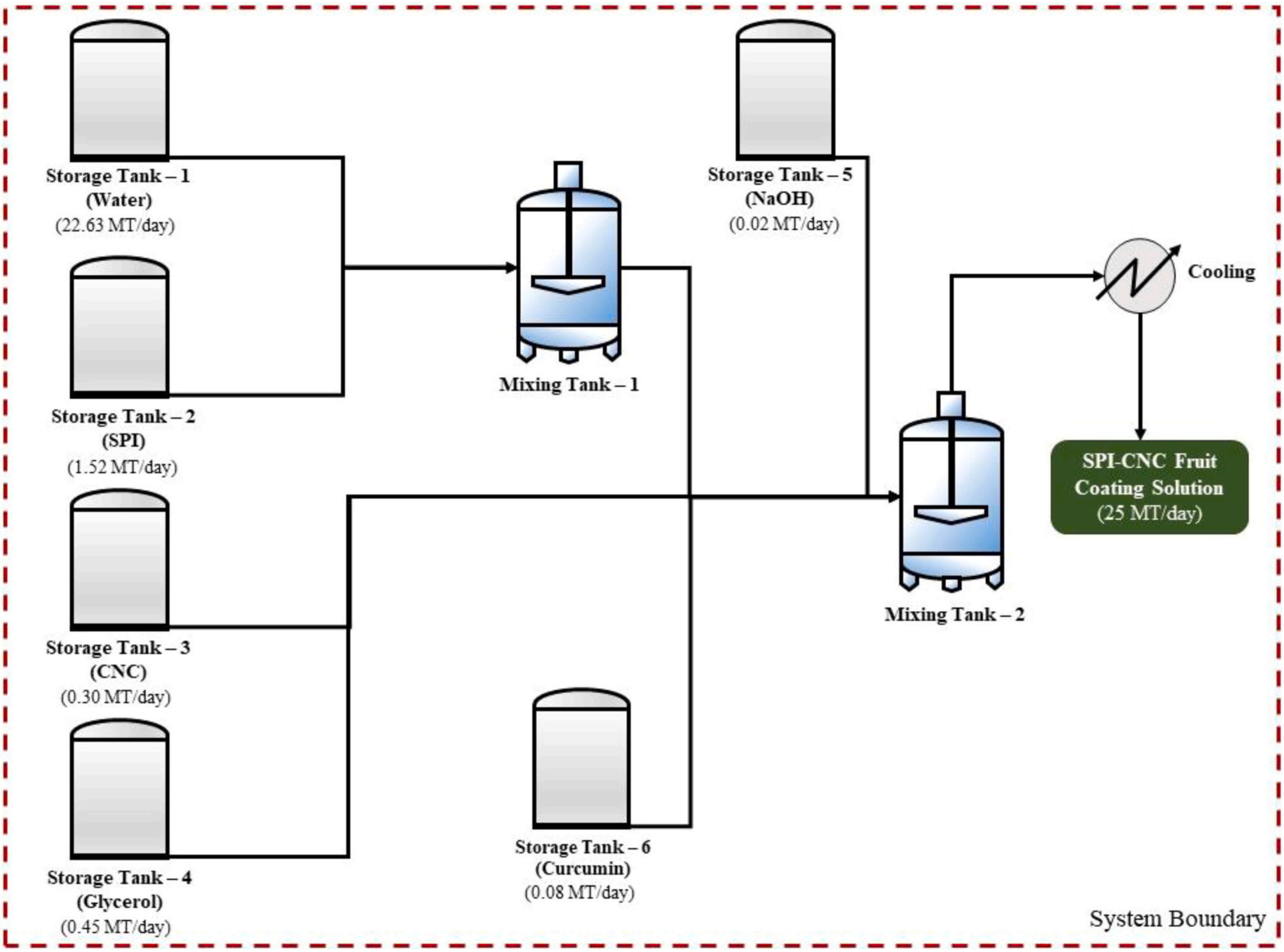



**Fig. 1.** Process flow of soy protein isolate-cellulose nanocrystal fruit coating solution preparation.

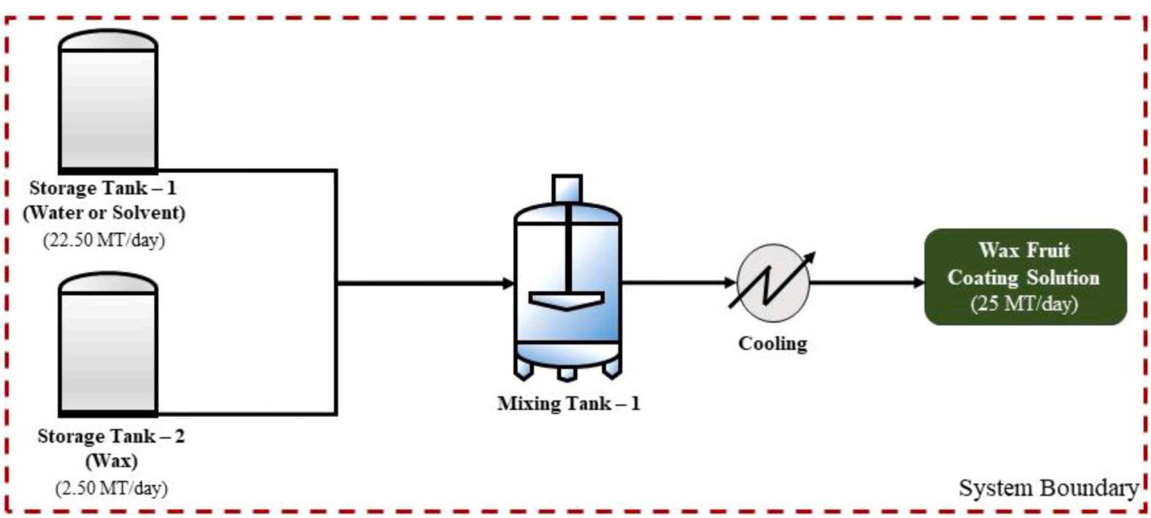



**Fig. 2.** Process flow of wax-based fruit coating solution preparation.

environment and human health (el Khetabi et al., 2022).

Food-grade materials are often used to coat edible fruit, making it safe for consumption. Commonly used ingredients of edible fruit coatings include protein, polysaccharides, and lipids usually added with plasticizers to increase the physicochemical properties (Khorram et al., 2017). Edible films and coatings had a worldwide market value of USD 2.70 billion in 2021, and it is anticipated that this market would grow at a CAGR of 7.7% from 2022 to 2028 (Grand View Research, 2020). Various protein isolates are used to prepare protein-based fruit coatings, and these include soy protein (Zhang et al., 2022a,2022b), whey protein

**Table 1**
Life-cycle inventory database unit processes used to build emissions inventory of fruit coating solution production process.

| Inputs | LCI unit processes (Long Trail Sustainability., 2021) |
|---|---|
| Cellulose nanocrystal | (Rajendran et al., 2023) |
| Glycerol | DATASMART (US EI 2.2): Glycerine, from soybean oil, at esterification plant/US US-EI U |
| NaOH | DATASMART (US EI 2.2): Sodium hydroxide, production mix, at plant/kg NREL/RNA U |
| SPI | Agro-footprint 5 – Mass Allocation: Soybean protein-isolate, at processing/US Mass |
| Paraffin | DATASMART (US EI 2.2): Paraffin, at plant/US- US-EI U |
| Water | DATASMART (US EI 2.2): Water, deionised, at plant/US* US-EI U |
| Ethyl alcohol | DATASMART (US EI 2.2): Ethanol, denatured, corn stover, biochemical/kg/RNA |
| Steam | DATASMART (US EI 2.2): Steam, for chemical processes, at plant/US US-EI U |
| Electricity | DATASMART (US EI 2.2): Electricity, medium voltage, at grid, 2019/US US-EI |

(Muley and Singhal, 2020), fish protein (da Costa de Quadros et al., 2020), quinoa protein (Robledo et al., 2018), sesame protein (Sharma et al., 2018) and pea protein (Narin et al., 2020). Among these, soy protein isolate (SPI) is considered an excellent coating material because of its favorable coating and film-forming properties, preventing gas and solvent from entering the food (Galus, 2018). Although SPI is a sustainable source of a low-cost and eco-friendly edible coating (Li et al., 2019). Adding various active substances to SPI helps produce a high-quality coating with enhanced properties. For instance, Li et al. reported that the SPI added with cinnamaldehyde and zinc oxide showed high antifungal activity and maintained the fruit quality when coated on a banana (Li et al., 2019). Similarly, an edible coating made of SPI-chitosan composite increased the shelf life of apricots at 2 °C, reduced weight loss and maintained their firmness (Zhang et al., 2018). Likewise, edible coatings prepared using SPI with hydroxypropyl methylcellulose were shown to maintain the freshness of grapes and cherry tomatoes better than uncoated fruits (Zhang et al., 2022a,2022b). In another study, coatings prepared with SPI and honey applied on fresh-cut pineapple showed greater retention of phenolic compounds, maintained quality, and increased shelf life by 16 days when stored at 4 °C (Yousuf and Srivastava, 2019).

Recent studies have focused on using cellulose nanomaterials (CNM) as the additive substance in food packaging because of their favorable mechanical, physical, chemical, and thermal properties (Balasubramaniam et al., 2020; Hai et al., 2020; Niu et al., 2018). CNMs are produced from lignocellulosic biomass (wood and cotton), algae, microbial processes (bacteria and fungi) and sea animals (tunicate), which have two major types based on their physical sizes such as cellulose nanocrystal (CNC) and cellulose nanofiber (CNF) (Jung et al., 2020).

Three factors are usually taken into consideration in any effective strategy to prolong the postharvest life of perishable products: maturity and senescence, dehydration, and rate of microbial development. A few additional factors including safety, membrane-forming ability, biocompatibility, and biodegradability should be taken into account. The utilization of agro-protein and cellulose nanomaterials in fruit coating applications hasn't been explored yet. Jung et al. (2020) developed an edible coating with egg-derived poly (albumen) protein and CNC. The coating effectively reduced microbial growth, respiration, and dehydration of fruits while being edible and washable (Jung et al., 2020). Unfortunately, there are currently relatively few combinations of coatings available, and the literature has often fallen short of expectations when applied on a large scale. Although a few patents related to fruit and vegetable coatings involving cellulose nanomaterials have been recorded, they are different from our work's aims, materials combination, and methods (Rahman et al., 2022; Zhao et al., 2021).

Therefore, this study aims to fill the current research gap by describing the development of a large-scale commercial process of a novel SPI-CNC fruit coating solution production and associated economic and environmental implications, which were achieved through an integration of information provided through process modeling, techno-economic analysis (TEA), and life cycle assessment (LCA). The specific objective of this study was to investigate the financial viability and environmental impacts of the process of coating solution preparation and fruit coating at the commercial scale.

## 2. Experimental section

This study identifies the economic and environmental implications of SPI-CNC fruit coating solution preparation. These included performing a TEA and LCA to comprehend the economic and environmental performance of the developed process. In this study, the optimized materials mass balance and experimental process data were collected by Muhammad M. Rahman and Neethu T. Pottackal from Rice University, USA.

### 2.1. Experimental methods

The bionanocomposite fruit coating solution was synthesized as follows- first, SPI powder was mixed with deionized water 1:15 (w/v) for 15 min. After the mixing process, glycerol (30 wt% of SPI) and cellulose nanocrystals (10, 20, and 30 wt% of SPI) were added to the solution. The solution mixture was stirred for 30 min. NaOH solution was used to adjust the mixture pH to 10.5. The curcumin powder (5 wt% of egg white powder) with deionized water was incorporated and stirred for 30 min at 80 °C. The mixture was then cooled to room temperature. After cooling, the bionanocomposite solution was ready to coating onto fruits. In this study, avocados were soaked completely into the solution and the fruit was dried on a rack at room temperature (Rahman et al., 2022).

### 2.2. Techno-economic analysis

A detailed process model was developed using SuperPro Designer Software V.12 (Intelligen, Inc., 2020) based on the optimized results from the experimental work. The process model to produce SPI-CNC fruit coating solution at the commercial scale is shown in Fig. 1. The preparation of the wax solution is shown in Fig. 2. In this flow, the materials and composition were modified. The production process plant capacity was 25 MT/day. The annual operating time was 7920 h. The plant's lifetime was 20 years. The interest rate assumed for the discounted cash flow analysis was 10%. The income tax rate was 21% (IRS, 2017). The process was divided into two sections solution preparation and coating process. In the solution preparation process, the equipment's cost was calculated using the SuperPro V.12 built-in cost model. The fruit coating machine data were collected from commercial company websites. The coating machine capacity was approximately 5000 fruits per hour. The raw materials costs were collected from available e-commerce websites, local vendors, and literature. The unit costs of SPI, dry CNC, glycerol, NaOH, curcumin, wax (general) and ethanol were assumed \$3.50/kg, \$4.69/kg, \$1.50 /kg, \$0.55/kg, \$ 505/kg, \$5/kg and \$0.75/kg respectively (Rajendran et al., 2023; www.alibaba.com, 2022, 2023; www.chemanalyst.com., 2023; www.made-in-china.com., 2023; www.selinawamucii.com., 2023).

The economic analysis considered two major input costs: capital investment and operating costs. The total capital investment represented all fixed costs associated with a process and included i) direct fixed capital costs, which further included the cost of equipment purchase, installation, buildings etc. (total plant direct cost); cost of engineering and construction (total plant indirect costs); and other costs such as the contractor's fee and contingencies, ii) working capital costs, which are funds needed to operate the business such as investment in raw materials and consumables, etc., iii) startup and validation costs, which are

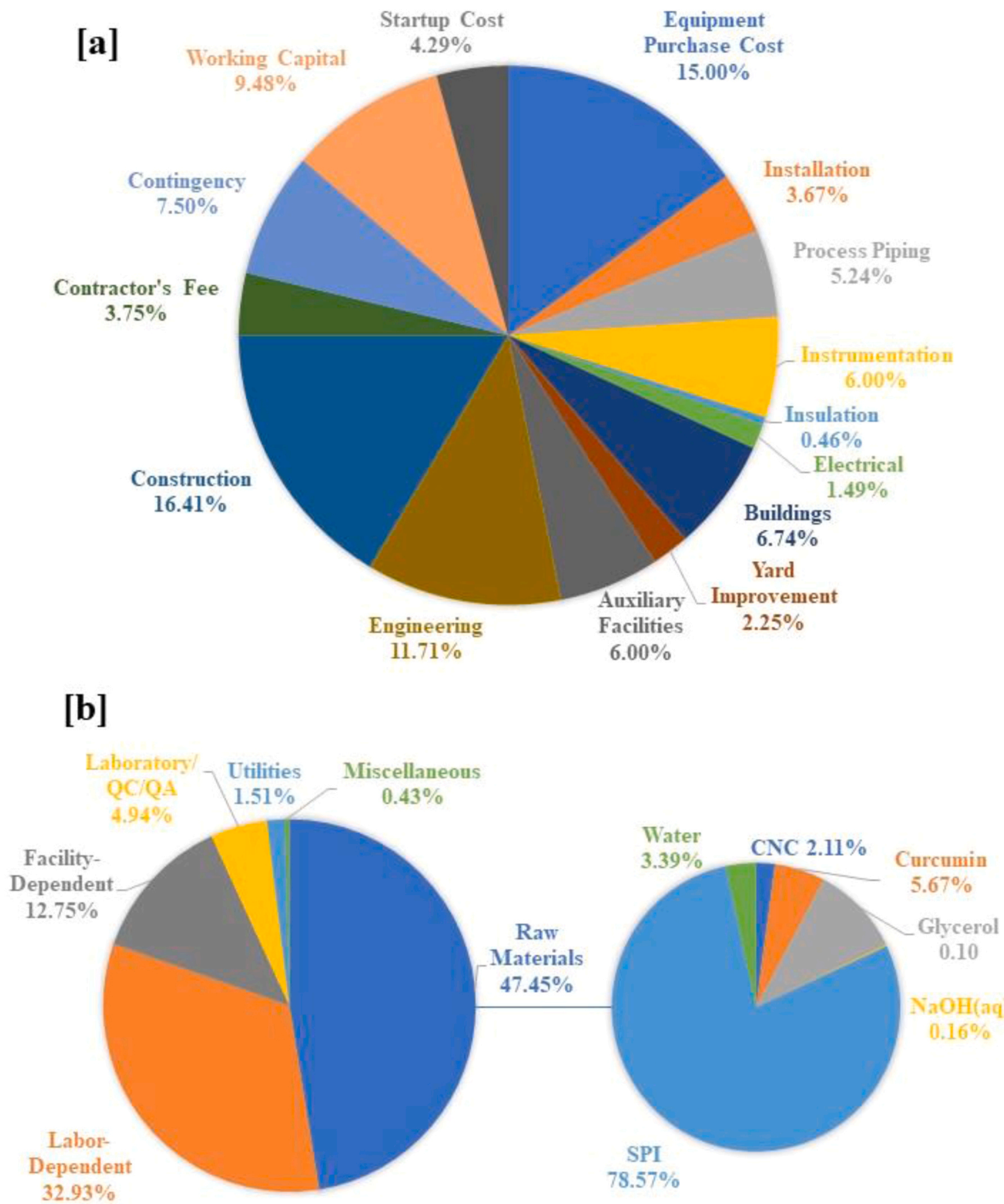



**Fig. 3.** (a) Capital investment and (b) operating costs of the soy protein isolate-cellulose nanocrystal fruit coating solution production process, scaled up at the industrial level.

associated with one-time pre-opening expenses needed to prepare a new plant for operation, and iv) up-front research and development costs, which are related to the cost of research and development needed before a product is manufactured. The factors for most of the fixed costs were calculated based on equipment costs. The operating cost of the project included the annual costs of raw materials, consumables, labor, utilities, and power (Naveenkumar and Baskar, 2020).

The assumptions and data for the economic analysis allowed us to calculate unit production cost and minimum selling price (MSP). The MSP represents the price needed to make NPV equal to zero, and it allows us to compare the economic feasibility of the SPI-CNC fruit coating solution production technology with the conventional wax-based fruit coating production technology in the existing markets.

### 2.3. Life cycle assessment

The life cycle environmental impacts of the fruit coating solution production processes were assessed using a cradle-to-gate (LCA method based on the ISO 14040 and 14044 standards (ISO, 2006a, 2006b). The material and energy flow data from the process model were used to develop the life-cycle inventory (LCI) for the SPI-CNC-based fruit coating solution process. The SimaPro 9.1 LCA modelling software (PRé Consultants., 2021) was used to estimate the associated life-cycle impact categories following TRACI 2.1 methodology (Bare, 2011). The

**Table 2**
Estimated key outcomes of economic evaluation of soy protein isolate-cellulose nanocrystal fruit coating solution production process compared to commercial alternatives.

| Economic Variables | Unit | SPI-CNC | Wax (Water-Based) | Wax (Solvent-Based) |
|---|---|---|---|---|
| Total capital investment | million $ | 3.68 | 1.61 | 2.11 |
| Operating cost | million $ | 4.70 | 5.17 | 10.67 |
| Cost basis annual rate | MT/yr | 8250 | 8250 | 8250 |
| Net unit production cost | $/kg | 0.57 | 0.63 | 1.29 |
| Minimum selling price | $/kg | 0.59 | 0.64 | 1.31 |

**Table 3**
The minimum and maximum values assumed for the sensitivity analysis of raw material costs for the soy protein isolate-cellulose nanocrystal fruit coating solution at commercial scale.

| Raw materials | Minimum value ($/kg) | Base value ($/kg) | Maximum value ($/kg) |
|---|---|---|---|
| Soy protein isolate | 1.75 | 3.50 | 5.25 |
| Cellulose nanocrystal | 4.37 | 8.73 | 13.10 |
| Curcumin | 2.53 | 5.05 | 7.58 |
| Glycerol | 0.75 | 1.50 | 2.25 |
| NaOH | 0.28 | 0.55 | 0.83 |

Cumulative Energy Demand (CED) method was used to determine the primary energy consumption. The scope of this LCA study was to quantify the environmental impacts of SPI-CNC-based fruit coating solution from raw material extraction to production ready to leave the gate and compared it with other wax-based fruit coating solutions. The functional unit was 1.0 kg of the fruit coating solution assuming equal mass was applied per fruit and lasted the same time. The LCA was carried out considering only the SPI-CNC-based fruit coating solutions as final products. The LCI database is shown in Table 1.

## 3. Results and discussion

### 3.1. Experimental results

In this study, we evaluated the effectiveness of the coating in preserving freshness in avocados. We selected avocado as it is one of the most perishable and expensive fruits. The avocados exhibited a noticeable difference on the peel and interior after applying coating. The exterior of the coated avocados maintained a light green color while the uncoated samples shrank in size and darkened in coloring. The cross-section of the avocado showed that the uncoated samples had a brown layer near the peel indicating over-ripening while the coated samples had yellow-green flesh throughout confirming its freshness. After seven days, coated avocadoes showed a significant difference in appearance, firmness, and weight retainment compared to the uncoated avocadoes. The coating maintained more than 90% firmness after 7 days and resulted in a 25% reduction in weight loss after 10 days when compared to the control batch.

### 3.2. Process model

The preparation of the coating solution initially involves the transfer of 1.52 MT/day of SPI and 22.63 MT/day of water to the solid mixer from the storage facility. The water and solid protein are stored in a flat bottom tank and in a silo, respectively. The water transfer uses the centrifugal pump, and the protein transfer uses a pneumatic conveyor. After the transfer of water and solid protein, a mixing process is carried out for 30 min at room temperature, resulting in 24.15 MT/day of SPI-water mixture. The next process involves mixing the SPI-water mixture with 0.30 MT/day of 10% CNC and 0.45 MT/day of glycerol and transferring it to the solid mixture, where 0.02 MT/day of sodium hydroxide and 0.08 MT/day of curcumin are mixed further. This mixing process is carried out for 30 min at 80 °C. The final hot mixture is cooled to 25 °C and packed in a plastic container with a capacity of 1000 kg. The process produces 25 MT/day and 8250 MT/yr of SPI-CNC fruit coating solution.

### 3.3. Economic analysis

Fig. 3 and Table 2 summarize the project's costs and outcomes of economic analysis for the base scenario. The capital investment of the 25 MT/day SPI-CNC-fruit coating production plant was estimated at 3.68 million dollars, which included the direct fixed capital (86.23%), working capital (13.96%), and startup and validation costs (4.40%). The costs related to construction (16.41%), equipment purchases (15.00%) and engineering (11.71%) occupied the largest shares of total capital investment (Fig. 3a). The annual operating cost was estimated at $4.70 million (Fig. 3b). The cost of raw materials shared almost half of the total operating costs (47.45%), followed by the costs of labor (32.93%), facility (12.75%), laboratory/QA/QC (4.94%), utilities (1.51%), and miscellaneous (0.43%). The cost of SPI was the largest cost within the raw material cost category (78.57%).

Unit production cost is the key to deciding the selling price of products. The estimated unit production cost of the solution was $0.57/kg. The analysis also estimated MSP to identify the minimum price at which the investment project is still financially feasible. The estimated base case MSP of the SPI-CNC fruit coating solution, which was estimated as the minimum price at which NPV was zero, was $0.59/kg. We find that the cost of preparing SPI-CNC solution was much lower or competitive compared to most of the common alternatives in the existing markets (Table 2). For example, the costs of common raw solid waxes range from $1/kg to $10/kg (www.alibaba.com, 2022). Commercial wax solutions are mainly water and food-grade solvent-based. In this study, the wax solution was prepared using water and food-grade ethyl alcohol, and the calculated water-based and solvent-based wax solution price is $0.64/kg and $1.31/kg respectively, which is higher than the estimated MSP of the SPI-CNC solution. In solvent-based wax solutions, solvent price is a major economic factor. In this study, the economic analysis of wax solution preparation was not discussed in detail, but the values were shown in Table 2. The analysis also calculated the minimum cost of applying the coating of SPI-CNC solution on avocado, which was estimated at about $0.01/fruit, the cost was calculated based on the fruit coating plant and SPI-CNC fruit coating solution minimum selling price, given the amount of solution needed per fruit, 40 ml. The coating process was not included in the sensitivity analysis.

A sensitivity analysis was conducted to understand how changes in key techno-economic factors would affect the MSP of the SPI-CNC fruit coating solution production project. The variation of ±50% in raw materials price varies (Table 3) the MSP between $0.52–0.66/kg, and the SPI shows the major impact on the MSP (Fig. 4). Monte Carlo simulation (Program (or Project) Evaluation and Review Technique (PERT) distribution with 10,000 iterations) was used to investigate the MSP of SPI-CNC fruit coating solution.

### 3.4. Environmental impact analysis

Table 4 summarizes materials and energy inputs added per kg of

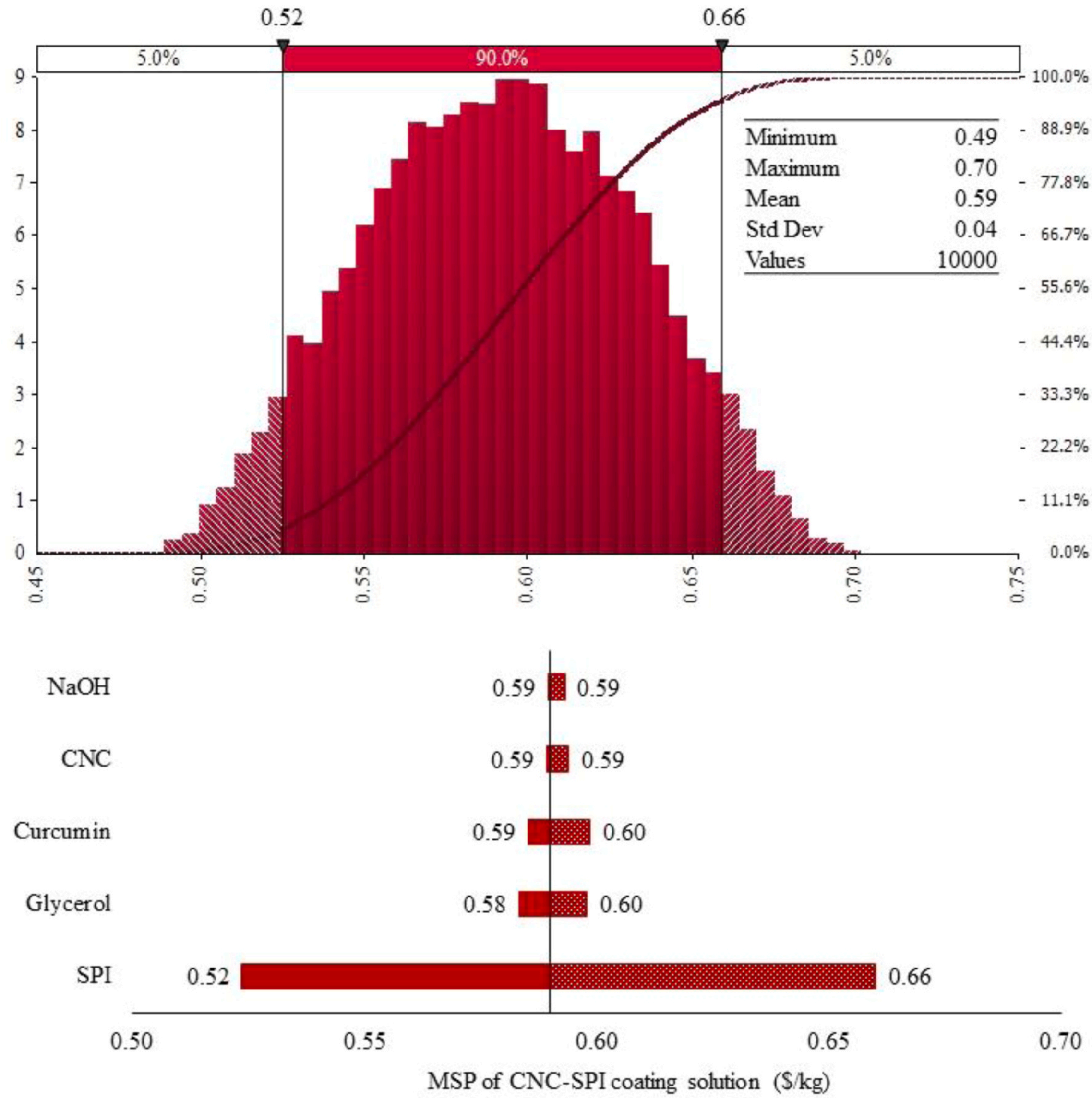



**Fig. 4.** Uncertainty analysis of minimum selling price of soy protein isolate-cellulose nanocrystal fruit coating solution.

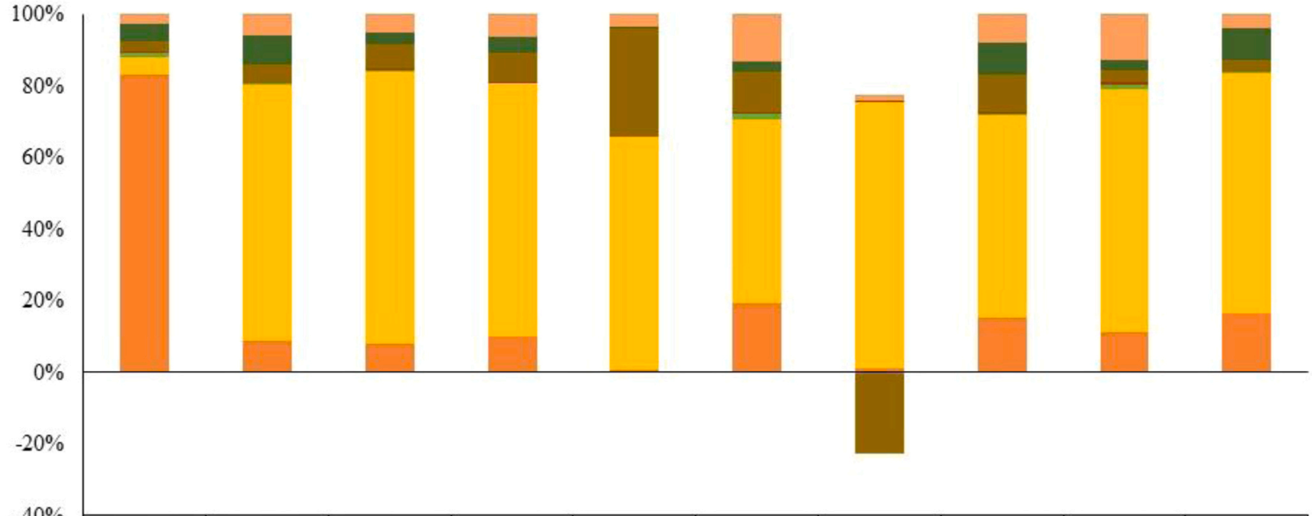
**Table 4**
Materials and energy added in the industrial scale soy protein isolate-cellulose nanocrystal fruit coating solution production process.

| | **Per kg of SPI-CNC coating solution** | **Paraffin Wax** (Water-Based) | **Paraffin Wax** (Solvent-Based) |
|---|---|---|---|
| **Material** | | | |
| Cellulose nanocrystal (kg) | 0.00243 | - | - |
| Curcumin (kg) | 0.00303 | - | - |
| Glycerol (kg) | 0.01820 | - | - |
| NaOH(aq) (kg) | 0.00079 | - | - |
| Soy protein isolate (kg) | 0.06067 | - | - |
| Paraffin (kg) | - | 0.10000 | 0.10000 |
| Water (kg) | 0.91488 | 0.90000 | - |
| Ethyl alcohol (kg) | - | - | 0.90000 |
| **Energy** | | | |
| Steam (kg) | 0.09654 | 0.00014 | 0.00014 |
| Electricity (kW-h) | 0.03241 | 0.03000 | 0.30000 |

Note: The estimates are based on the scaled-up process model, which was guided by the optimized experimental process.

coating solution in the process of producing fruit coating solution at the industrial scale. Water constitutes the largest input (0.91 kg) going into the production of 1 kg of SPI-CNC fruit coating solution, followed by SPI (0.06 kg). Similarly, the process consumed 0.03 kW-h of electricity and 0.097 kg of steam power in producing 1 kg of the coating solution. The coating process was not included in the LCA analysis.

Fig. 5 summarizes the contribution of each input to the estimated impacts under each environmental impact category. Production of one kg of SPI-CNC fruit coating solution showed a cradle-to-gate carbon footprint (global warming impact (GWI)) of 0.33 kg $CO_2$ eq. For most impact categories, SPI-CNC had lower environmental impacts. Evaluation of the contribution of each input on individual impact categories revealed that SPI had the largest contributions in most of the impact categories. In the composition, 6.07% of SPI was used which comprised 69.98% of GWI. In ozone depletion, CNC shows the major contribution. In addition, we reiterate that our results are based on cradle-gate stages, therefore it did not cover the transportation of fruit coating solution to final destinations in environmental impact analyses. These transportation impacts would tend to be the same for all these types of solutions. In a comparative analysis, the water-based paraffin solution shows a lower GWI than SPI-CNC solution because the GWI of SPI production is higher than paraffin production. The SPI production process




| | Ozone depletion (kg CFC-11 eq) | Global warming (kg $CO_2$ eq) | Smog (kg $O_3$ eq) | Acidification (kg $SO_2$ eq) | Eutrophication (kg N eq) | Carcinogenics (CTUh) | Non carcinogenics (CTUh) | Respiratory effects (kg PM2.5 eq) | Ecotoxicity (CTUe) | Fossil fuel depletion (MJ surplus) |
|---|---|---|---|---|---|---|---|---|---|---|
| Electricity | 7.87E-10 | 1.93E-02 | 6.84E-04 | 7.58E-05 | 3.88E-05 | 7.00E-10 | 2.53E-09 | 4.77E-06 | 5.67E-02 | 2.50E-02 |
| Steam | 1.37E-09 | 2.53E-02 | 4.62E-04 | 5.87E-05 | 5.29E-06 | 1.54E-10 | 4.98E-10 | 5.58E-06 | 1.27E-02 | 5.61E-02 |
| Glycerol | 8.28E-10 | 1.62E-02 | 9.21E-04 | 9.81E-05 | 3.40E-04 | 6.10E-10 | -4.04E-08 | 6.20E-06 | 1.50E-02 | 2.10E-02 |
| NaOH | 1.19E-10 | 1.02E-03 | 3.91E-05 | 3.74E-06 | 1.72E-06 | 3.50E-11 | 3.33E-10 | 2.23E-07 | 3.49E-03 | 1.30E-03 |
| Water | 3.56E-10 | 9.90E-04 | 4.69E-05 | 4.05E-06 | 2.14E-06 | 7.55E-11 | 3.53E-10 | 3.25E-07 | 5.35E-03 | 1.30E-03 |
| SPI | 1.31E-09 | 2.28E-01 | 1.03E-02 | 8.74E-04 | 7.30E-04 | 2.75E-09 | 1.33E-07 | 3.45E-05 | 3.01E-01 | 4.28E-01 |
| CNC | 2.37E-08 | 2.77E-02 | 1.08E-03 | 1.22E-04 | 9.04E-06 | 1.04E-09 | 2.13E-09 | 9.26E-06 | 4.93E-02 | 1.05E-01 |

**Fig. 5.** Contribution of each unit process of soy protein isolate-cellulose nanocrystal fruit coating solution on the estimated individual environmental impact category.

required a large volume of steam which increases the overall environmental impact of SPI. The GWI of solvent-based paraffin solution was higher than the SPI-CNC solution. The cumulative energy demand of SPI-CNC fruit coating solution is 4.97 MJ, and SPI only accounted for 69.62%. The SPI production utilized a large amount of non-renewable, fossil which increased overall SPI-CNC solution cumulative energy demand. The cumulative energy of water and solvent-based paraffin wax solution is 6.17 MJ and 71.7 MJ respectively. In water-based solution, paraffin wax only accounted for 93.84%. In solvent-based solution, corn-based ethanol accounted for 91.49% and paraffin wax accounted for 8.08%. In overall conclusion, SPI-CNC fruit coating solution shows lower cumulative energy demand than both water and solvent-based paraffin wax solution. The use of crude protein helps reduce the environmental impact and cumulative energy demand of protein-based fruit coating solution.

## 4. Conclusions

The analysis indicated that the SPI-CNC fruit coating solution production process would be highly profitable and result in lower environmental impacts given our process design and choice of parameter values, which were based on the combination of data and assumptions guided by our experiments and publicly available literature. The MSP of SPI-CNC fruit coating solution was $0.59/kg which was lower than both water and solvent-based solution. Unlike the other environmental impacts, GWI impact of 1 kg of SPI-CNC solution was 0.33 kg $CO_2$ eq which is lower than a solvent-based wax solution but higher than a water-based wax solution. The presented results should not be taken as a true indication of potential performance but should be considered as likely performance given our current knowledge of the scaled-up production process of SPI-CNC fruit coating solution. The utilization of crude protein and the development of the CNC production process help to reduce the overall environmental impact further.

## CRediT authorship contribution statement

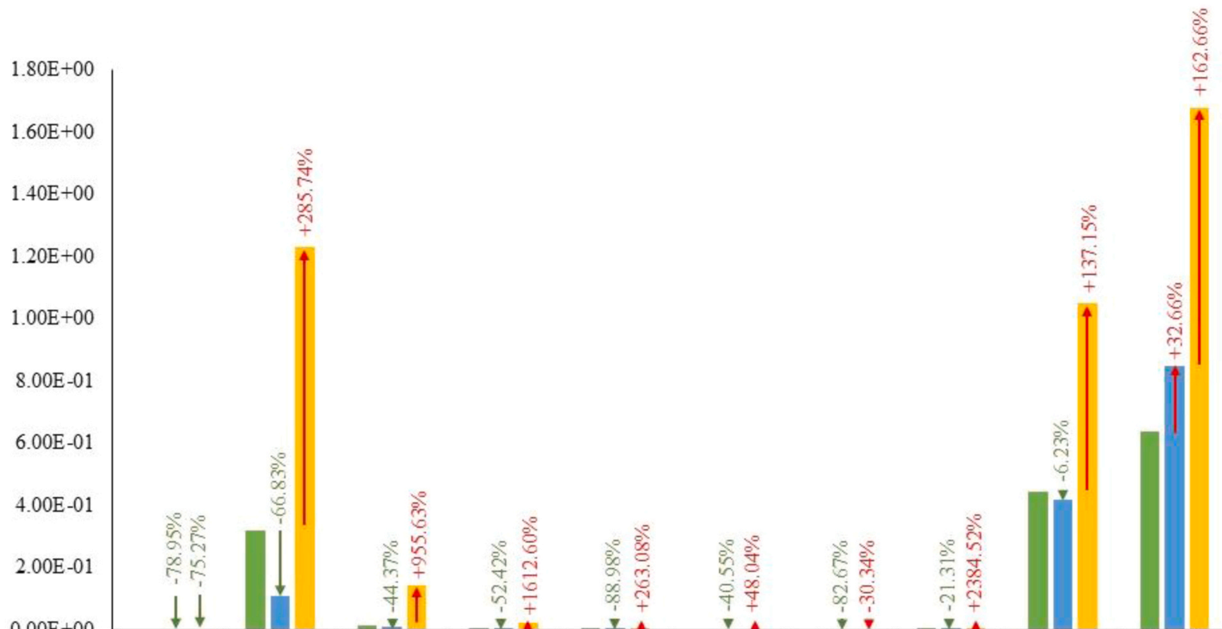
**Rajendran Naveenkumar:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Runge Troy:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **Bergman Richard D.:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **Nepal Prakash:** Writing – review & editing, Visualization, Validation. **Pottackal Neethu T.:** Writing – original draft, Resources. **Rahman Muhammad M.:** Writing – review & editing, Resources.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.




| | Ozone depletion | Global warming | Smog | Acidification | Eutrophication | Carcinogenics | Non carcinogenics | Respiratory effects | Ecotoxicity | Fossil fuel depletion |
|---|---|---|---|---|---|---|---|---|---|---|
| SPI-CNC Fruit Coating | 2.85E-08 | 3.18E-01 | 1.35E-02 | 1.24E-03 | 1.13E-03 | 5.36E-09 | 9.82E-08 | 6.09E-05 | 4.43E-01 | 6.38E-01 |
| Paraffin (Water) | 6.00E-09 | 1.06E-01 | 7.53E-03 | 5.89E-04 | 1.24E-04 | 3.19E-09 | 1.70E-08 | 4.79E-05 | 4.16E-01 | 8.46E-01 |
| Paraffin (Solvent) | 7.05E-09 | 1.23E+00 | 1.43E-01 | 2.12E-02 | 4.09E-03 | 7.94E-09 | 6.84E-08 | 1.51E-03 | 1.05E+00 | 1.68E+00 |

SPI-CNC Fruit Coating ■ Paraffin (Water) ■ Paraffin (Solvent)

**Fig. 6.** Comparison of soy protein isolate-cellulose nanocrystal, paraffin with water, and paraffin with solvent fruit coating solution life-cycle environmental impacts.

## Acknowledgements

This project was made possible by financial and technical assistance provided by the U.S. Endowment for Forestry and Communities, Inc., under project 21–00288. The findings and conclusions in this report are those of the author(s) and should not be construed to represent any official USDA or U.S. Government determination or policy. This research was supported in part by the U.S. Department of Agriculture, Forest Service. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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