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Smart Juice Clarification System Using Bio-Polymer Membrane

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Abstract
Juice clarification is essential for producing high-quality, safe, and visually appealing fruit juices, yet conventional methods such as chemical treatment, thermal processing, and synthetic membranes often result in nutrient loss, high energy consumption, and environmental concerns. This research presents a Smart Juice Clarification System using a biodegradable biopolymer membrane fabricated from polylactic acid (PLA) with chloroform as the solvent and Chitrak mool powder as a natural functional additive. Chitrak mool is incorporated due to its bioactive compounds, which enhance filtration performance and provide antimicrobial properties. Membrane films are prepared with four different Chitrak mool concentrations—5%, 10%, 15%, and 20%—and characterized using Differential Gel Analysis (DGA), Fourier Transform Infrared Spectroscopy (FTIR), and X-ray Tomography (XRT) to evaluate structural integrity, chemical composition, and porosity. The 20% formulation demonstrates the highest turbidity removal efficiency and fouling resistance. The system integrates smart sensors to continuously monitor key parameters such as turbidity, pressure, flow rate, and membrane fouling, enabling real-time optimization and automated cleaning cycles. Data from the sensors is processed through a microcontroller-based control system, which adjusts operational parameters to maintain optimal filtration performance. Experimental results indicate that the proposed system can efficiently clarify fruit juices with minimal nutrient loss while remaining energy-efficient and environmentally friendly. This approach demonstrates a scalable, intelligent, and sustainable solution for modern juice processing, combining biodegradable materials with smart monitoring for enhanced product quality and operational efficiency. The system has potential for adoption in industrial and small-scale food processing applications.

Keywords: *Biopolymer membrane; Juice clarification; Membrane filtration; Membrane fouling detection; Smart monitoring*

1. Introduction
The global demand for fresh, nutritious, and minimally processed fruit juices continues to rise, driven by increasing consumer awareness of health and wellness. Juice clarification is a critical process in the beverage industry, aimed at removing suspended particles and other turbidity-causing components to produce visually appealing and stable products. Traditional clarification methods such as chemical fining, enzymatic treatment, and thermal processing have been widely used; however, these techniques often result in nutrient degradation, flavor loss, high energy consumption, and the generation of

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chemical waste. Membrane-based filtration has emerged as a promising alternative to conventional clarification methods due to its ability to operate at ambient temperatures, preserve bioactive compounds, and reduce chemical usage. Microfiltration and ultrafiltration processes using polymeric membranes can effectively remove turbidity while maintaining the nutritional and sensory qualities of fruit juices. However, membrane fouling remains the primary technical challenge limiting the widespread adoption of membrane technology in the juice processing industry. Recent advances in biopolymer materials have opened new possibilities for developing environmentally friendly and biodegradable membranes. Biopolymers such as polylactic acid (PLA), chitosan, cellulose derivatives, and alginate offer advantages including biocompatibility, biodegradability, and reduced environmental impact compared to conventional synthetic polymers. This research addresses the critical need for intelligent monitoring in membrane-based juice clarification by presenting a Smart Juice Clarification System that integrates a biopolymer membrane with real-time fouling detection and automated process control.

2. Materials And Methods

2.1. Biopolymer Membrane Fabrication

The biopolymer membranes were fabricated using the solvent casting method with polylactic acid (PLA) as the base polymer and Chitrak mool (Plumbago zeylanica) powder as the bioactive additive. Chloroform was selected as the solvent due to its excellent dissolution properties for PLA. Four different membrane formulations were prepared with varying Chitrak mool concentrations: 5%, 10%, 15%, and 20% (w/w relative to PLA weight). PLA pellets were dissolved in chloroform at 10% (w/v) under continuous magnetic stirring at room temperature for 4 hours. Chitrak mool powder was added in the desired proportions and stirred for 2 hours. The solution was degassed under vacuum, cast onto clean glass plates, and allowed to evaporate slowly at room temperature for 48 hours. The membrane films were peeled and stored in a desiccator until characterization. Figure 1 Fabricated Membrane[1].


Figure 1 Fabricated Membrane

2.2. Membrane Characterization

Differential Gel Analysis (DGA):
DGA was performed to assess thermal properties and crystallinity. Samples (5-10 mg) were heated from 30°C to 200°C at 10°C/min under nitrogen atmosphere to determine glass transition temperature, melting temperature, and crystallinity[2].

Fourier Transform Infrared Spectroscopy (FTIR):
FTIR spectra were recorded in 4000-400 cm^{-1} range using ATR accessory. Spectra were analyzed to identify functional groups and confirm Chitrak mool incorporation into the PLA matrix[3].

X-ray Tomography (XRT):
XRT analysis examined internal structure, porosity, and Chitrak mool particle distribution. Three-dimensional reconstruction quantified pore size distribution, void fraction, and structural uniformity[4].

2.3.System Design and Components

The Smart Juice Clarification System integrates membrane filtration with real-time monitoring and automated control. The system consists of five primary subsystems: membrane filtration unit, fluid handling system, vacuum generation unit, visual monitoring system, and control interface[5].

Membrane Filtration Unit:

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The core unit consists of a hermetically sealed, airtight container with transparent viewing windows. The food-grade stainless steel membrane holder provides uniform feed distribution while preventing edge leakage. Multiple gaskets and O-ring seals ensure leak-proof operation during pressure-driven and vacuum-assisted filtration modes[6].

FIGURE 2 Membrane Filtration Unit

Fluid Handling System:

A dual peristaltic pump configuration provides precise control. Pump A delivers raw juice at programmable flow rates (10-500 mL/min). Pump B creates vacuum on the permeate side by extracting air, generating pressure differentials up to 0.5 bar. Both pumps use stepper motors controlled via micro stepper driver for smooth operation[7].

Control System Hardware:

The system uses Raspberry Pi 4 Model B (4GB RAM) interfacing with peripheral devices through GPIO pins. A micro stepper driver board (TB6600) provides precise motor control with 1/256 step resolution. The camera module is a Raspberry Pi Camera Module V3 with wide angle[8].

2.4. Computer Vision-Based Fouling Detection

A camera-based monitoring system assesses membrane condition in real-time through image processing. The system captures frames at 2-second intervals with controlled LED illumination for consistent image quality[9].

The fouling detection algorithm operates through:

- Image acquisition at 2-second intervals,
- Preprocessing with grayscale conversion and Gaussian filtering,
- Segmentation using adaptive thresholding,
- Feature extraction quantifying fouling coverage and surface roughness,
- Fouling percentage calculation, and
- Classification into three states: Good (0-30% fouling), Moderate (30-60%), and Severe (>60%).

When fouling exceeds threshold values, the system generates automated visual and audible alerts through the GUI, enabling timely intervention before significant flux decline occurs[10].

2.5. Graphical User Interface

A comprehensive GUI was developed using Python with Tkinter framework. The interface runs on the Raspberry Pi and displays on a 7-inch touchscreen. Features include: control panel with individual buttons for Pump A, Pump B, camera, and air supply; membrane selection dropdown; real-time video display with overlay indicators; numerical fouling metrics with color-coded status; and results display for historical data. The interface provides clear visual feedback through color-coded indicators (green for good, yellow for moderate, red for severe fouling). All parameters are logged to SQLite database for historical analysis.

2.6.Experimental Procedure

Fresh fruits were washed, peeled, and mechanically extracted. Raw juice was stored at 4°C prior to filtration with no pretreatment. The membrane was installed in the filtration unit and the system was primed with deionized water. Feed pump was set to 200 mL/min constant flow rate. Vacuum pump created approximately 0.3 bar transmembrane pressure. Camera monitoring recorded membrane condition throughout experiments. Experiments ran for 2-hour periods or until >50% flux decline. Permeate volume was measured at 15-minute intervals. Feed and permeate samples were analyzed for turbidity (turbidimeter), color (colorimeter), total soluble solids (refractometer), and pH (pH meter).

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Clarification efficiency was calculated as percentage turbidity reduction.

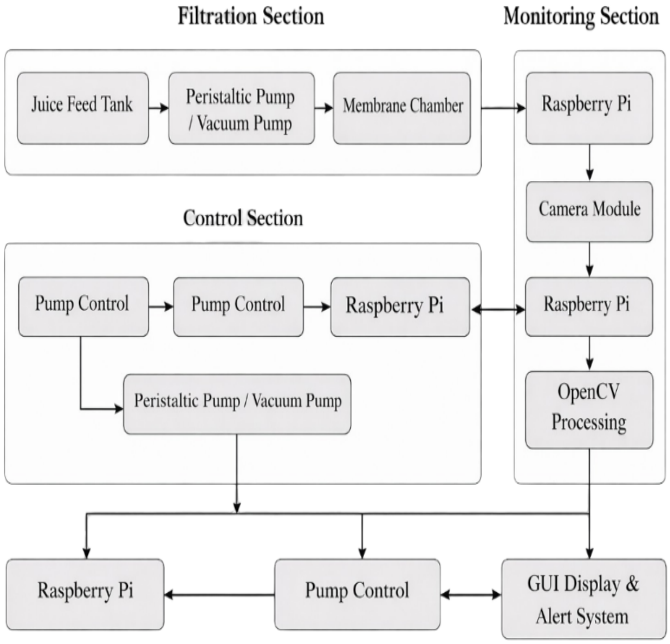

Figure 2 System Architecture of Smart Juice Clarification System using Biopolymer membrane

3. Results And Discussion

3.1. Membrane Characterization Results

DGA analysis showed that pure PLA membrane had a glass transition temperature (Tg) of approximately 58°C, while Chitrak mool-containing membranes exhibited slightly lower Tg values (55-57°C) due to plasticizing effects. The degree of crystallinity decreased with increasing Chitrak mool content, enhancing permeability. FTIR spectra confirmed successful Chitrak mool incorporation. Pure PLA showed characteristic peaks at 1750 cm^{-1} (C=O stretching), 2995 cm^{-1} (C-H stretching), and 1180 cm^{-1} (C-O stretching). Chitrak mool membranes displayed additional peaks at 3300-3500 cm^{-1} (hydroxyl groups) and 1600-1650 cm^{-1} (aromatic compounds), with intensity proportional to Chitrak mool concentration. XRT analysis revealed enhanced porosity with increasing Chitrak mool concentration. The 20% formulation demonstrated the highest pore density and most uniform pore size distribution, with average pore diameters of 0.1-0.5 micrometers, ideal for juice clarification.Shown as Table 1 Membrane Condition Classification.

Table 1 Membrane Condition Classification

S. No.	Fouling Percentage	Condition
1	0 – 40%	Good
2	41 – 80 %	Moderate
3	81 – 100%	Clogged

3.2. System Performance

The Smart Juice Clarification System demonstrated effective performance in clarifying fruit juices. Initial flux rates varied by membrane formulation, with the 20% Chitrak mool membrane showing the highest initial flux of approximately 45 L/m²·h under vacuum-assisted operation. Pressure-driven filtration without vacuum resulted in approximately 30% lower flux rates. Turbidity reduction efficiency exceeded 90% for all formulations, with the 20% Chitrak mool membrane achieving 95% removal. Clarified juice maintained excellent color characteristics with minimal browning, and total soluble solids showed less than 3% variation, indicating good retention of dissolved sugars and flavor compounds. Pure PLA membranes experienced rapid flux decline of approximately 60% within the first hour due to severe surface fouling. Chitrak mool-containing membranes exhibited improved fouling resistance, with the 20% formulation maintaining 75% of initial flux after 2 hours. This enhanced performance is attributed to antimicrobial and antioxidant properties of Chitrak mool.

3.3. Fouling Detection Performance

The computer vision-based fouling detection system successfully monitored membrane condition in real-time. The algorithm accurately quantified fouling progression, with calculated percentages showing strong correlation ($R^2 > 0.92$) with independently measured flux decline data. This validates visual monitoring as an effective indicator of membrane performance. The early warning capability was particularly valuable. Visual fouling detection indicated membrane condition changes an average of 12-15 minutes before significant flux decline (>20%) was observed in flow measurements. This advance notice provides operators sufficient time to adjust parameters, initiate cleaning cycles, or switch membranes, minimizing process disruption.

The automated alert system functioned reliably, generating appropriate warnings when fouling thresholds were exceeded. False positive rates were minimal (<5%), occurring primarily during transient disturbances. False negative rates were effectively zero. Color-coded status indicators provided clear, intuitive feedback.

3.4.Comparison with Conventional Methods

Compared to conventional juice clarification methods, the Smart Juice Clarification System demonstrated significant advantages. Energy consumption was reduced by approximately 60% compared to thermal processing methods, as the system operates at ambient temperature. Processing time for batch clarification was reduced by 40% compared to traditional settling and fining methods.
Product quality improvements were evident in multiple parameters. Vitamin C retention was 85-90% in membrane-clarified juice compared to 60-70% in thermally processed juice. Color values were closer to fresh juice characteristics, and sensory evaluation panels consistently rated membrane-clarified juice higher for flavor and overall acceptability.The environmental benefits of biopolymer membranes are substantial. Unlike synthetic polymer membranes that persist for decades, PLA-based membranes are biodegradable under composting conditions. The use of Chitrak mool further enhances sustainability. Cost analysis indicates that while initial investment is higher, reduced operating costs, extended membrane life, and improved product quality provide favorable return on investment over 3-5 years.

3.5.System Integration and Automation

The integration of multiple subsystems into a cohesive automated platform represents significant advancement toward Industry 4.0 implementation in food processing. The Raspberry Pi-based control system successfully coordinated pump operation, camera monitoring, data logging, and user interface functions without performance bottlenecks. Response times for operator inputs were instantaneous (<100 ms), and the system maintained stable operation for extended periods (>8 hours continuous) without failures. The modular architecture facilitates future expansion. Additional sensors such as pressure transducers, flow meters, and pH probes can be easily integrated. The Python-based control software is well-documented for modification. Cloud connectivity can be added for remote monitoring and centralized management of multiple processing units. The user interface design proved effective in reducing operator training requirements. New operators achieved proficiency within 2-3 hours of training, compared to typical training periods of 1-2 days for conventional membrane systems. Visual feedback enabled quick issue diagnosis and corrective actions. Data logging supported process optimization through detailed historical records.

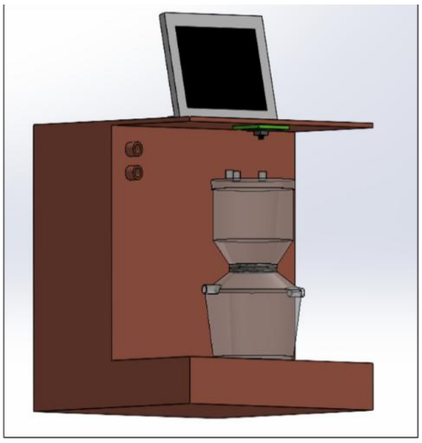

Figure 3 Prototype Design of Smart Juice Clarification System using Biopolymer

Conclusion

This research successfully developed and validated a Smart Juice Clarification System that integrates biodegradable biopolymer membranes with intelligent monitoring and automated control. Biopolymer membranes fabricated from PLA with Chitrak mool powder demonstrated excellent juice clarification performance, with the 20% formulation achieving 95% turbidity removal and superior fouling resistance. Comprehensive characterization using DGA, FTIR, and XRT confirmed successful incorporation of Chitrak mool and revealed enhanced porosity for filtration applications. The integrated smart monitoring system successfully detected membrane fouling 12-15 minutes before significant flux decline, enabling proactive maintenance and minimizing process disruption. Computer vision-based fouling detection demonstrated high accuracy ($R^2 > 0.92$ correlation with flux data) with minimal false positives and zero false negatives. The dual peristaltic pump configuration with vacuum assistance increased flux by approximately 30% compared to pressure-driven filtration alone. The GUI-based control interface reduced operator training time by 60-70% compared to conventional membrane systems. Compared to thermal processing, the system achieved 60% energy reduction while improving vitamin C retention by 20-25%. The proposed system addresses critical challenges in sustainable juice processing by combining environmentally friendly materials with intelligent automation. This work represents a significant step toward Industry 4.0 implementation in food processing, demonstrating how smart sensors, computer vision, and automated control can enhance traditional unit operations. Future development will focus on incorporating machine learning algorithms for enhanced fouling prediction, expanding the system to handle wider juice varieties, conducting industrial-scale validation studies, and developing automated cleaning-in-place protocols triggered by fouling detection.

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