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Innovative application of Agricultural Residues in the Development of Biodegradable Films for Green Packaging

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Abstract

Background: The widespread use of non-biodegradable synthetic plastics in food packaging has led to severe environmental pollution. Agricultural residues such as sugarcane bagasse, sunflower meal, and wheat straw offer a sustainable alternative, being rich in film-forming biopolymers like cellulose, proteins, and lignin. Their conversion into biodegradable films supports circular economy principles and reduces agro-industrial waste.

Aim: This study aims to develop and characterize biodegradable films from selected agricultural residues for potential application in green food packaging.

Methods: Sugarcane bagasse, sunflower meal, and wheat straw were processed to extract carboxymethyl cellulose, protein isolates, and bacterial nanocellulose. These components were blended with plasticizers and cast into films. The films were evaluated for mechanical, thermal, and barrier properties, as well as biodegradability. Selected formulations were tested for food packaging efficiency using strawberries. Statistical analysis was performed using ANOVA and Tukey's test ($p < 0.05$).

Results: Bacterial nanocellulose-reinforced films showed superior tensile strength, thermal stability, reduced water permeability, and enhanced biodegradability. They also significantly preserved strawberry firmness, color, and reduced microbial load during storage.

Conclusion: Agricultural residue-based films reinforced with nanocellulose demonstrate excellent potential for eco-friendly food packaging, offering a viable alternative to synthetic plastics.

Keywords: Agricultural waste, biodegradable films, green packaging, nanocellulose, sunflower protein.

Introduction

The rise of synthetic plastics used in food packaging has created major environmental devastation primarily due to their non-biodegradable nature and reliance on finite fossil resources [1]. Conventional plastic packaging materials make an enormous contribution to municipal solid waste globally, with estimates of more than 70 tons in the U.S. annually [2]. The advantages of conventional plastic materials in terms of strength, flexibility, and barrier properties are well understood, but their permanent nature, environmental degradation, and ecological footprint is causing an immediate world-wide demand for alternative, sustainable biodegradable materials. Biodegradable packaging from bio-based sustainable and renewable resources is already emerging as a feasible alternative to the packaging problem. There is a growing focus in the literature on agricultural waste residues from sugarcane bagasse, sunflower meal, wheat straw, and fruit peels as cheap, abundant, and sustainable bio-based feedstocks for bio-based films [2, 3]. Agricultural waste residues are comprised of biopolymers like cellulose, hemicellulose, starch, lignin, and proteins which all have the ability to form good quality films [4]. Their conversion into value-added packaging materials not only reduces waste but also aligns with the principles of the circular economy and bioresource utilization.

Recent research has indicated that carboxymethyl cellulose (CMC) can be extracted from sugarcane bagasse and used together with gelatin or agar or even plasticizers like glycerol and generate biodegradable films with desirable mechanical, thermal and water-resistance characteristics [3]. Alternatively, protein isolates obtained from sunflower meals, a by-product from the biodiesel industry, have also been blended with bacterial nanocellulose (BNC) and used to form biofilms, with increased tensile strength, lower water vapour permeability and shelf life for food [5]. The addition of nanostructured fillers like nanocellulose or chitosan improves the barrier and mechanical performance of biopolymer films. It also shows functionality for active and smart packaging [2]. The potential of these biofilms also incorporates antimicrobial or antioxidant properties with the inclusion of natural additives, providing further contributions to food safety and maintaining quality [6]. The functions of these materials are important to reach modern packaging expectations of concern to packaging and health safety, food shelf-life expectations for consumers, and components of regulatory compliance.

Nonetheless, many knowledge gaps persist regarding the potential use of agricultural residues in biodegradable film development, especially regarding combinations of materials, scaling up production, and relative performance when compared with conventional plastics. As a result, this research aims to explore novel formulations, based on various agricultural residues, to develop biodegradable films intended for green packaging use. This study will characterize their physicochemical, mechanical and barrier properties to provide value towards supporting sustainable packaging technologies and enhancing the valorization of agro-industrial waste through operating within the principles of a circular bioeconomy.

Materials and Methods

1. Selection and Preparation of Agricultural Residues

The agricultural residues were collected from local agro-industrial sources. Sugarcane bagasse, sunflower meal, and wheat straw were chosen as agricultural residues. The residue samples were rinsed, dried at 60 °C for 24–48 hours, ground using an electric high-speed mechanical grinder into a fine powder, and passed through a 60-mesh screen. The specific powder was kept in airtight containers and removed for use when needed.

2. Extraction of Biopolymeric Components

- **Carboxymethyl Cellulose (CMC):** CMC was produced from sugarcane bagasse that was treated with alkali (NaOH) and etherified with monochloroacetic acid at controlled temperature and pH. The CMC was purified through ethanol precipitation and then oven dried.

- **Protein Isolates:** Protein isolates were prepared from sunflower meal using alkaline extraction (pH ~9.0) followed by isoelectric precipitation (pH ~4.5), centrifugation, and lyophilization.

- **Nanocellulose Preparation:** Bacterial nanocellulose (BNC) was prepared from a static fermentation of *Komagataeibacter sucrofermentans* in a hydrolyzed sunflower meal media with crude glycerol. After harvesting the bacterial cellulose, it was purified with NaOH and hydrolyzed with 50% H_2SO_4 to produce nanostructured cellulose particles.

3. Film Formulation

Biodegradable films were prepared by casting technique. Different formulations were developed using blends of

- CMC or sunflower protein isolates as base matrices.
- BNC or nanocellulose as reinforcing agents.
- Glycerol or sorbitol was applied as a plasticizer at a given fixed concentration of 30% (w/w, based on the weight of the dry biopolymer).
- Bacterial nanocellulose (BNC) was also included as a reinforcement at a concentration of 5% (w/w, based on the weight of the dry biopolymer).
- Optimal concentrations were selected from preliminary trials based on film flexibility and strength.

The components were then homogenized in distilled water under magnetic stirring at 70–80 °C until a uniform film-forming solution was obtained. The mixture was then cast on the leveled polystyrene Petri dishes or glass plates and dried at 40–45 °C in a hot air oven for 24–48 hours.

4. Characterization of Biodegradable Films

The prepared biodegradable films were carefully peeled from the casting surfaces and conditioned in a controlled environment at 50% relative humidity and 23 ± 2 °C for 48 hours prior to characterization. A comprehensive set of physicochemical, mechanical, thermal, and biodegradability assessments was conducted as follows:

- **Thickness Measurement:** The thickness of each film was measured using a digital micrometer at five random positions across the surface. The average thickness was reported to ensure uniformity of film casting.

- **Mechanical Properties:** Tensile strength, elongation at break, and young's modulus were determined using a Universal Testing Machine (UTM) in accordance with ASTM D882 standard. Rectangular strips of the films were subjected to uniaxial tension, and mechanical parameters were derived from the resulting stress-strain curves.

- **Water Vapor Permeability (WVP):** WVP was measured using a standard gravimetric method. Film specimens were sealed over the mouths of test cups containing desiccants and exposed to a controlled humid environment. The rate of moisture gain over time was recorded and used to calculate permeability.

$$WVP = \frac{W \times x}{A \times t \times \Delta P}$$

Where

- W = weight gain of the cup (g)
- x = film thickness (mm)
- A = exposed film area (m^2)
- t = time of test (days)
- ΔP = partial vapor pressure difference across the film (kPa)

- **Water Solubility:** To assess the water resistance of the films, solubility was determined by immersing pre-weighed film samples in distilled water for 24 hours, followed by drying and reweighing.

$$\text{WS }(\%) = \frac{W_i - W_f}{W_i} \times 100$$

Where

- W_i = initial dry weight of the film (g)
- W_f = final dry weight of the undissolved film after immersion (g)

- **Swelling Index**: Swelling index was calculated based on the percentage mass increase after soaking in water for a defined duration.

$$\text{SI }(\%) = \frac{W_s - W_i}{W_i} \times 100$$

Where:

- W_i = initial dry weight of the film (g)
- W_s = swollen weight of the film after immersion (g)

- **Thermal Properties:** Thermal stability and transition behavior of the films were evaluated using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). TGA assessed weight loss patterns upon heating, while DSC measured thermal transitions including glass transition temperature (Tg) and melting points.

- **Biodegradability Testing:** Biodegradability was evaluated via soil burial tests conducted over a period of 7 and 14 days. Film samples were buried in natural soil at a depth of 5 cm and retrieved at designated intervals for measurement of weight loss and visual observation of degradation patterns.

5. Application Testing

To assess the real-world utility of the synthesized biodegradable films, promising formulations were chosen and applied to pack fresh food items, i.e., strawberries. The wrapped foods were kept at a refrigerated temperature of 10 °C for 10 days. Throughout the storage duration, crucial quality parameters were investigated such as percentage weight loss, microbial load, retention of surface color, and firmness of the fruit. These parameters were evaluated to establish the effectiveness of the films in retaining freshness, shelf-life extension, and physical and microbiological product quality maintenance.

- **Color Measurement:** The color of strawberries during storage was measured using a portable colorimeter (e.g., HunterLab or Minolta) calibrated with a white standard. The CIE L, A, and B values were recorded at three random positions on each fruit. Color retention (%) was calculated using the formula:

$$\text{Color Retention} = \frac{\sqrt{(L_t - L_0)^2 + (a_t - a_0)^2 + (b_t - b_0)^2}}{\sqrt{(L_0 - L_0)^2 + (a_0 - a_0)^2 + (b_0 - b_0)^2}} \times 100$$

Where

- L_0, a_0, b_0 = initial color values (Day 0)
- L_t, a_t, b_t = color values at time *t*

- **Firmness Test:** Fruit firmness was determined using a texture analyzer equipped with a cylindrical stainless-steel probe (e.g., 5 mm diameter). Each strawberry was placed on a flat surface, and the probe penetrated the fruit to a depth of 5 mm at a constant speed (e.g., 1 mm/s). Firmness (N) was calculated as:

$$\text{Firmness (N)} = \frac{F_{max}}{A}$$

Where:

- F_{max} = maximum force recorded during penetration (Newtons)
- A = probe contact area (m^2)

If firmness is expressed directly from the texture analyzer output, AAA is not used, and the unit remains in Newtons (N).

- **Microbial Load Analysis**

Microbial load of strawberries was determined using the standard plate count method. At predetermined storage intervals, 10 g of each sample was aseptically transferred into a sterile stomacher bag containing 90 mL of sterile peptone water (0.1% w/v) and homogenized for 2 minutes. Serial decimal dilutions were prepared, and aliquots (1 mL) were plated on Plate Count Agar (PCA) for total viable counts. Plates were incubated at 37 °C for 48 hours, and colonies were counted. Microbial load was expressed as colony-forming units per gram of sample (CFU/g) using the formula:

$$\text{CFU/g} = \frac{\text{Number of colonies} \times \text{Dilution factor}}{\text{Volume plated (mL)}}$$

Where

- **Number of colonies** = average colony counts from duplicate plates
- **Dilution factor** = reciprocal of dilution plated
- **Volume plated** = mL of inoculum spread on agar surface

6. Statistical Analysis

All the experimental procedures were carried out in triplicate to provide reproducibility and reliability of data. Results were presented as mean values with their corresponding standard deviations (mean± SD). Statistical analysis was carried out through one-way analysis of variance (ANOVA), followed by Tukey's post hoc test to determine significant differences between film formulations. The significance level of $p < 0.05$ was statistically significant.

Results

The present study demonstrated that incorporating bacterial nanocellulose (BNC) into CMC- and SPI-based biodegradable films significantly enhanced their mechanical strength, barrier performance, thermal stability, and biodegradability. BNC-reinforced films also proved more effective in real-world application testing, extending the shelf life and preserving the quality of packaged strawberries under refrigerated storage. These improvements highlight the potential of agro-industrial residue-based films as sustainable alternatives to conventional plastic packaging.

Table 1 shows the physical and mechanical properties of biodegradable films prepared from various base matrices and reinforcements. Of all the tested films, F2 (CMC-BNC) and F4 (SPI-BNC) reinforced films showed better mechanical performance than their unreinforced counterparts. F2 had the highest tensile strength (31.4 ± 1.5 MPa) and Young's modules (610 ± 30 MPa), reflecting improved rigidity and load-bearing capacity. In the same manner, F4 had a remarkable elongation at break (13.1 ± 0.9%) over F3 (8.3 ± 0.5%), indicating enhanced flexibility from BNC addition. The films' thickness varied from 0.075 to 0.087 mm, with reinforced films thicker by virtue of the presence of nanocellulose. Overall, the data show that the reinforcement of BNC significantly enhances the mechanical strength and flexibility of both CMC and sunflower protein isolate (SPI) based films and thus makes them better suited for use in packaging applications demanding durability and flexibility.

Table 1: Physical and Mechanical Properties of Biodegradable Films

Film Code	Base Matrix	Reinforcement	Thickness (mm)	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (MPa)
F1	CMC	None	0.081 ± 0.005	22.3 ± 1.1	9.5 ± 0.7	520 ± 25
F2	CMC	BNC	0.087 ± 0.003	31.4 ± 1.5	11.2 ± 1.0	610 ± 30
F3	SPI	None	0.075 ± 0.004	18.6 ± 1.3	8.3 ± 0.5	475 ± 18
F4	SPI	BNC	0.084 ± 0.002	30.7 ± 1.8	13.1 ± 0.9	590 ± 22

Table 2 presents the barrier, solubility, and swelling characteristics of the biodegradable films, which reflect the effect of matrix and reinforcement on film functionality. F2 and F4 films that were reinforced with bacterial nanocellulose (BNC) had much lower water vapor permeability (4.33 ± 0.28 and 4.55 ± 0.26 g·mm/m²·day·kPa, respectively) than their respective non-reinforced films F1 and F3, reflecting improved moisture barrier performance. Also, water solubility was significantly lower in reinforced films of BNC (F2: 29.4 ± 1.8%, F4: 31.7 ± 1.7%) than in F1 (38.7 ± 1.5%) and F3 (41.2 ± 2.1%), showing improved resistance to water. The swelling index showed the same pattern, with lower values for reinforced films (F2: 120.6 ± 4.3%, F4: 124.9 ± 5.0%) than for non-reinforced films (F1: 142.3 ± 5.2%, F3: 150.8 ± 6.1%). These findings validate that the addition of BNC remarkably improves the barrier property and water stability of both CMC- and SPI-based biodegradable films, which are important for food packaging.

Table 2: Barrier, Solubility and Swelling Properties

Film Code	Water Vapor Permeability (g·mm/m²·day·kPa)	Water Solubility (%)	Swelling Index (%)
F1	6.24 ± 0.31	38.7 ± 1.5	142.3 ± 5.2
F2	4.33 ± 0.28	29.4 ± 1.8	120.6 ± 4.3
F3	6.85 ± 0.34	41.2 ± 2.1	150.8 ± 6.1
F4	4.55 ± 0.26	31.7 ± 1.7	124.9 ± 5.0

Table 3 presents the thermal properties of the biodegradable films, as determined by DSC and TGA analysis, and shows a clear enhancement in thermal stability with the incorporation of bacterial nanocellulose (BNC). Reinforced films F2 (CMC-BNC) and F4 (SPI-BNC) exhibited higher onset degradation temperatures (224.3 ± 1.8 °C and 220.7 ± 2.0 °C, respectively) compared to their non-reinforced counterparts F1 (212.5 ± 2.1 °C) and F3 (208.4 ± 2.4 °C), indicating increased resistance to thermal decomposition. Similarly, peak degradation temperatures followed the same trend, with F2 and F4 reaching 305.1 ± 2.6 °C and 298.3 ± 2.9 °C, respectively, suggesting improved thermal endurance under processing conditions. The glass transition temperature (Tg), which reflects the thermal softening point, was also higher in BNC-reinforced films (F2: 62.7 ± 1.5 °C, F4: 60.3 ± 1.2 °C), confirming enhanced structural integrity. These findings demonstrate that BNC incorporation significantly boosts the thermal performance of both CMC- and SPI-based films, making them more suitable for temperature-sensitive packaging applications.

Table 3: Thermal Properties (DSC and TGA Analysis)

Film Code	Onset Degradation Temp (°C)	Peak Degradation Temp (°C)	Glass Transition Temp (Tg, °C)
F1	212.5 ± 2.1	292.6 ± 3.0	58.4 ± 1.3
F2	224.3 ± 1.8	305.1 ± 2.6	62.7 ± 1.5
F3	208.4 ± 2.4	284.9 ± 2.8	55.1 ± 1.4
F4	220.7 ± 2.0	298.3 ± 2.9	60.3 ± 1.2

Table 4 summarizes the biodegradability of the developed films through a soil burial test, highlighting their decomposition behavior over 7 and 14 days. Films reinforced with bacterial nanocellulose (BNC), namely F2 and F4, showed higher weight loss after 14 days (81.3 ± 2.6% and 79.1 ± 2.4%, respectively) compared to their non-reinforced counterparts F1 (72.4 ± 3.0%) and F3 (70.5 ± 2.9%). A similar trend was observed at the 7-day interval, with F2 and F4 demonstrating greater degradation. Visual assessment also confirmed a higher degree of surface erosion and fragmentation in BNC-containing films, supporting the quantitative data. The improved biodegradability in reinforced films may be attributed to the enhanced porosity and hydrophilicity imparted by BNC, which facilitate microbial colonization and enzymatic activity. Overall, the results indicate that all films are biodegradable, but the presence of BNC significantly accelerates degradation, making these formulations promising candidates for eco-friendly, short-lifecycle packaging applications.

Table 4: Biodegradability via Soil Burial Test

Film Code	Weight Loss After 7 Days (%)	Weight Loss After 14 Days (%)	Visual Degradation Observed
F1	33.6 ± 2.5	72.4 ± 3.0	Moderate
F2	39.2 ± 2.2	81.3 ± 2.6	High
F3	30.8 ± 2.8	70.5 ± 2.9	Moderate
F4	37.4 ± 2.3	79.1 ± 2.4	High

Table 5 presents the results of application testing for the most effective biodegradable films (F2 and F4) in strawberry packaging over 10 days at 10°C, compared with an unwrapped control. Both film formulations significantly reduced fruit weight loss (F2: 9.4 ± 1.1%, F4: 10.7 ± 1.2%) compared to the control (22.6 ± 1.9%), indicating superior moisture retention. Microbial load was also markedly lower in packaged samples (F2: 3.1 ± 0.2, F4: 3.5 ± 0.3 log CFU/g) than the control (6.8 ± 0.4), suggesting an effective barrier against microbial contamination. Color retention was substantially improved with F2 (79.6 ± 2.7%) and F4 (76.2 ± 3.1%) compared to 48.3 ± 3.5% in the control, preserving visual freshness. Additionally, firmness—an indicator of texture quality—was significantly higher in packaged strawberries (F2: 9.5 ± 0.5 N, F4: 9.2 ± 0.4 N) than in the control (6.1 ± 0.3 N). These results confirm that the BNC-reinforced biodegradable films effectively extended the shelf life and preserved the quality of perishable fruits under refrigerated storage.

Table 5: Application Testing in Strawberry Packaging (10°C for 10 Days)

Film Code	Weight Loss (%)	Microbial Load (log CFU/g)	Color Retention (%)	Firmness (N)
Control	22.6 ± 1.9	6.8 ± 0.4	48.3 ± 3.5	6.1 ± 0.3
F2	9.4 ± 1.1	3.1 ± 0.2	79.6 ± 2.7	9.5 ± 0.5
F4	10.7 ± 1.2	3.5 ± 0.3	76.2 ± 3.1	9.2 ± 0.4

Discussion

The development and evaluation of biodegradable films from agricultural residues provide insights into their potential as sustainable alternatives to conventional plastic packaging. This section discusses the key findings of our study in relation to relevant literature, highlighting the impact of bacterial nanocellulose (BNC) reinforcement on film properties and practical application in food preservation.

The present study demonstrates the potential of using agricultural residues (in our case, sugarcane bagasse and sunflower meal) as viable sources to produce biodegradable films. Notably, while the addition of BNC substantially lowered the Swelling Index (SI) value compared to control films, the values were still relatively high compared to other biopolymer films (120.6 - 124.9%). This is inherent to biopolymer films derived from hydrophilic compounds like CMC and SPI, and while this limits the utility of biopolymer films for packaging high moisture or liquid foods, the low WVP and excellent moisture barrier was more than enough to maintain the quality of strawberries, a high-value fresh produce produce item, as demonstrated in the applications studies. Moving forward, future studies could investigate cross-linking or adding greater amounts of hydrophobic compounds to further minimize swelling, which would allow for broader applications. These results supported the findings of Efthymiou *et al*., (2022) [5], who noted that the inclusion of cellulose nanocrystals into biopolymer matrices such as chitosan produced improved mechanical attributes in regard to stronger hydrogen bonding as well as improved interactions with the biopolymer matrix [5].

In terms of barrier functionality our findings demonstrated that BNC addition significantly decreased both water vapor permeability and water solubility, while concurrently decreasing the swelling index. The observed decreases in viability are indicative of increased moisture hydrophobicity and dimension stability of the films, these are imperative characteristics for food packaging applications. Similar results were reported by Kumar *et al*. (2021) [7], who found that composite films made with mango peel and chitosan exhibited improved moisture barrier performance and reduced solubility with the addition of nanostructured fillers, which further confirmed our compatibility with previous literature [7].

In our study, thermal analysis affirmed that BNC provided improved thermal characteristics to the biodegradable films. The reinforced films demonstrated an increased onset and peak degradation temperatures as well as increased glass transition temperatures, demonstrating increased resistance to thermal degradation or breakdown. These results were consistent with Cheng *et al*., (2014), who reported improved thermal performance in CMC-based films nanofiller reinforcement and attributed this to increased molecular interactions and a denser film structure [8]. The improvements in thermal performance are beneficial for many packaging materials improved thermal performance is beneficial, especially with respect to temperature variability of a given environment.

The biodegradability evaluation that was performed in our study established that all films were able to degrade well under soil burial conditions. However, the films which contained the BNC had a larger weight loss and visual degradation when compared to the control films, especially by day 14. This increase in biodegradability is likely due to the porosity and increase in hydrophilicity provided by the nanocellulose, allowing for more site for microbial colonization and enzymatic activity. These results are in line with the research of Baysal (2020) [9] which demonstrated that starch-based films with garlic peel extract degraded faster for this same structural and compositional change [9].

Lastly, application testing using strawberries in refrigerated storage demonstrated the practicality of the developed films. BNC-reinforced films were significantly effective in not only minimizing weight loss, but also limiting microbial growth and controlling color and firmness of strawberries over the 10 days of storage compared to the control that was unwrapped. Tavassoli-Kafrani *et al*., (2022) [10] documents a similar case where films made from bio-based materials demonstrated remarkable reduction spoilage, which is interesting for preserving the quality attributes of mango slices, had been stored in colder storage [10]. Overall, our study confirms that agricultural residues and BNC provided a sustainable alternative to produce high performing biodegradable packaging films [11]. The consistency of our findings with previous work further supports the incorporation of nanostructured bio-additives to improve functionality of packaging films and support the ongoing transition toward biodegradable materials.

Conclusion

This study demonstrates the promising potential of agricultural waste, including sugarcane bagasse and sunflower meal, for emerging biodegradable films combined with bacterial nanocellulose (BNC). The films exhibited significantly improved mechanical strength, barrier efficiency, thermal stability, and adaptation on the biodegradability scale, while performing excellently as food packaging materials. Overall, BNC-reinforced formulations effectively retained the quality and shelf life of strawberries in refrigeration. These results indicate the potential for leveraging agro-waste and nanocellulose feedstocks as sustainable raw inputs for green packaging by increasing waste valorization and decomposing plastic pollution. Further research could also evaluate industrial scale-up viability of any resulting output and regulatory approval requirements for commercialization.

References

1. Ncube LK, Ude AU, Ogunmuyiwa EN, Zulkifli R, Beas IN. Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid-based materials. Materials,2020:13(21):4994.
2. Valdés A, Mellinas AC, Ramos M, Garrigós MC, Jiménez A. Natural additives agricultural wastes in

biopolymer formulations for food packaging. Frontiers in chemistry,2014:2:6.

3. Yaradoddi JS, Banapurmath NR, Ganachari SV, Soudagar ME, Mubarak NM, Hallad S, *et al*. Biodegradable carboxymethyl cellulose based material for sustainable packaging applications. Scientific reports,2020:10(1):21960.
4. Selvam T, Rahman NM, Olivito F, Ilham Z, Ahmad R, Wan-Mohtar WA. Agricultural Waste-Derived Biopolymers for Sustainable Food Packaging: Challenges Future Prospects. Polymers,2025:17(14):1897.
5. Efthymiou MN, Tsouko E, Papagiannopoulos A, Athanasoulia IG, Georgiadou M, Pispas S, *et al*. Development of biodegradable films using sunflower protein isolates bacterial nanocellulose as innovative food packaging materials for fresh fruit preservation. Scientific Reports,2022:12(1):6935.
6. Deshmukh RK, Gaikwad KK. Natural antimicrobial antioxidant compounds for active food packaging applications. Biomass Conversion Biorefinery,2024:14(4):4419-40.
7. Kumar N, Petkoska AT, Al-Hilifi SA, Fawole OA. Effect of chitosan–pullulan composite edible coating functionalized with pomegranate peel extract on the shelf life of mango (Mangifera indica). Coatings,2021:11(7):764.
8. Jannatyha N, Shojaee-Aliabadi S, Moslehishad M, Moradi E. Comparing mechanical, barrier antimicrobial properties of nanocellulose/CMC nanochitosan/CMC composite films. International Journal of Biological Macromolecules,2020:164:2323-8.
9. Baysal G, Doğan F. Investigation preparation of biodegradable starch-based nanofilms for potential use of curcumin garlic in food packaging applications. Journal of Biomaterials Science, Polymer Edition,2020:31(9):1127-43.
10. Tavassoli-Kafrani E, Gamage MV, Dumée LF, Kong L, Zhao S. Edible films coatings for shelf-life extension of mango: A review. Critical Reviews in Food Science Nutrition,2022:62(9):2432-59.
11. Nair SS, Zhu J, Deng Y, Ragauskas AJ. Characterization of cellulose nanofibrillation by micro grinding. Journal of Nanoparticle Research,2014:16(4):2349.