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Application of Green Nanotechnology in Minimally Processed Foods for Improving Nutritional Quality and Shelf Stability

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Abstract

Minimally processed foods are highly valued for their freshness and nutritional quality but are prone to rapid nutrient degradation and microbial spoilage due to tissue damage during processing. This study investigated the application of green nanotechnology-based edible coatings to improve the nutritional quality and shelf stability of minimally processed apples during refrigerated storage. Chitosan nanoparticle coatings incorporating nanoencapsulated vitamin C, with and without essential oil, were applied to fresh-cut apple samples and compared with uncoated controls and conventional chitosan coatings. Microbiological quality, vitamin C retention, color stability, texture, weight loss, and sensory attributes were evaluated over 14 days at 4 °C. Nano-based coatings significantly reduced microbial growth, enhanced vitamin C retention, delayed browning, improved firmness, and maintained higher sensory acceptability compared to control and conventional coatings ($p < 0.05$). The combined chitosan nanoparticle and essential oil treatment showed the greatest overall effectiveness. These findings demonstrated that green nanotechnology-based edible coatings represent a promising, sustainable approach for enhancing the nutritional quality and shelf stability of minimally processed foods.

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1. Introduction

Minimally processed foods (MPFs), including fresh-cut fruits, vegetables, and ready-to-eat produce, have gained substantial popularity due to increasing consumer demand for convenient, fresh, and nutritionally rich foods. These products undergo minimal processing steps such as washing, peeling, cutting, and packaging, which preserve their fresh-like characteristics while improving accessibility and convenience (Rico *et al*., 2007) [8]. However, the removal of natural protective barriers during minimal processing significantly accelerates physiological deterioration, microbial growth, and nutrient degradation, leading to reduced shelf life and compromised nutritional quality. As a result, maintaining the safety, quality, and nutritional value of minimally processed foods remains a major challenge for the food industry.

One of the primary limitations of minimally processed foods is their susceptibility to rapid nutrient loss. Essential micronutrients such as vitamin C, polyphenols, and carotenoids are highly sensitive to oxygen, light, enzymatic activity, and temperature fluctuations (Lee & Kader, 2000) [3]. Cutting and peeling expose plant tissues to oxidative conditions, triggering enzymatic browning reactions and accelerating the degradation of bioactive compounds. In parallel, the increased surface area and moisture availability of fresh-cut products create favorable conditions for microbial proliferation, which further limits shelf life and raises food safety concerns (Allende *et al*., 2006) [1]. These quality and safety challenges are particularly critical for MPFs, which are often consumed raw or with minimal further processing.

Conventional preservation strategies for minimally processed foods include refrigeration, modified atmosphere packaging, edible coatings, and the application of chemical preservatives. While these approaches can partially slow spoilage and quality deterioration, they are often insufficient to fully preserve nutritional quality during extended storage (Oms-Oliu *et al.*, 2010) [6]. Moreover, the use of synthetic preservatives has raised consumer concerns related to food safety and clean-label preferences, prompting the food industry to seek alternative preservation methods that are both effective and environmentally sustainable (Shah *et al.*, 2014) [9]. These limitations highlight the need for innovative technologies capable of simultaneously improving nutritional retention and shelf stability while aligning with sustainability goals.

Nanotechnology has emerged as a promising tool for enhancing food quality and preservation through the manipulation of materials at the nanoscale. Nanostructured systems offer unique advantages, including high surface area, improved reactivity, and the ability to encapsulate and deliver bioactive compounds in a controlled manner (Duncan, 2011) [2]. In food systems, nanotechnology has been explored for applications such as nutrient delivery, antimicrobial packaging, and edible coatings. However, concerns regarding the safety, toxicity, and environmental persistence of conventional nanomaterials—particularly those based on metals or metal oxides— have limited their widespread acceptance in food applications (Llorens *et al.*, 2012) [4].

In response to these concerns, green nanotechnology has gained increasing attention as a sustainable alternative. Green nanotechnology emphasizes the use of biodegradable, food-grade, and environmentally benign nanomaterials produced through non-toxic and sustainable synthesis routes (Singh *et al.*, 2018) [10]. Common green nanomaterials used in food applications include chitosan nanoparticles, nanocellulose, starch nanoparticles, protein-based nanocarriers, and lipid-based nanoemulsions. These materials are derived from renewable resources, exhibit low toxicity, and are compatible with food systems, making them suitable for application in minimally processed foods.

The application of green nanotechnology offers significant potential for improving the nutritional quality of minimally processed foods. Through nanoencapsulation, sensitive nutrients such as vitamin C and natural antioxidants can be protected from oxidation, light, and enzymatic degradation during storage (McClements, 2015) [5]. Nanoencapsulation also enables controlled release of bioactive compounds, which can enhance nutrient stability and, in some cases, improve bioavailability upon consumption. These properties are particularly valuable for minimally processed foods, where nutrient degradation occurs rapidly due to tissue damage and exposure to environmental stressors.

In addition to nutritional enhancement, green nanotechnology can contribute to shelf-life extension through antimicrobial and antioxidant mechanisms. Chitosan- based nanoparticles and nanocellulose-reinforced coatings have demonstrated antimicrobial activity against spoilage microorganisms by disrupting microbial cell membranes and limiting microbial growth on food surfaces (Rhim *et al.*, 2013) [7]. Similarly, nanoemulsions containing natural essential oils or plant-derived antioxidants can inhibit oxidative reactions and delay quality deterioration without relying on synthetic additives. When applied as edible nano-coatings, these systems form thin protective layers that regulate gas and moisture exchange while preserving sensory attributes such as color, texture, and flavor (Oms-Oliu *et al.*, 2010) [6].

Despite growing research interest, several gaps remain in the practical application of green nanotechnology to minimally processed foods. Many studies focus on model systems or isolated components rather than whole food matrices, limiting the translation of findings to real food products. Furthermore, limited data are available on the combined effects of green nanotechnology on both nutritional quality and shelf-life parameters under realistic storage conditions. Safety assessment, scalability, and regulatory considerations also require further investigation to support industrial implementation.

Therefore, the present study aims to investigate the application of green nanotechnology-based systems in minimally processed foods to improve nutritional quality and shelf stability. Specifically, this research evaluates the effectiveness of green nanomaterial-based edible coatings in preserving sensitive nutrients, inhibiting microbial growth, and maintaining physicochemical and sensory quality during refrigerated storage. The findings of this study are expected to contribute to the development of sustainable, safe, and effective preservation strategies for minimally processed foods.

2. Literature Review

Minimally processed foods (MPFs) such as fresh-cut fruits and vegetables are increasingly consumed due to their convenience, freshness, and perceived health benefits. However, extensive research has demonstrated that minimal processing operations, including peeling, slicing, and cutting, significantly compromise the natural protective barriers of plant tissues, resulting in accelerated quality deterioration (Rico *et al.*, 2007) [8]. Tissue damage during processing increases respiration rate, enzymatic activity, and exposure to oxygen, which collectively contribute to rapid nutrient degradation, browning reactions, and microbial spoilage. These factors severely limit the shelf life and nutritional value of MPFs, creating a major challenge for the food industry.

One of the most critical quality issues associated with MPFs is the degradation of sensitive nutrients, particularly vitamin C, phenolic compounds, and carotenoids. Vitamin C is highly susceptible to oxidation and enzymatic degradation, and its loss is commonly observed during storage of fresh-cut fruits and vegetables (Lee & Kader, 2000) [3]. Studies have reported vitamin C losses of up to 50% or more within a few days of refrigerated storage, depending on the commodity and processing conditions. Similarly, phenolic compounds, which contribute to antioxidant activity and nutritional value, are often depleted due to oxidative stress and polyphenol oxidase activity triggered by tissue disruption (Oms-Oliu *et al.*, 2010) [6]. These nutritional losses not only reduce the health benefits of MPFs but also negatively affect consumer perception of product quality.

Microbial spoilage is another major limitation affecting MPFs. The removal of outer protective layers and increased moisture availability create favorable conditions for the growth of spoilage microorganisms and, in some cases, foodborne pathogens. Research has shown that microbial populations on fresh-cut produce can increase rapidly during refrigerated storage, often reaching unacceptable levels within a short period (Allende *et al.*, 2006) [1]. Conventional preservation strategies such as refrigeration and modified atmosphere packaging can slow microbial growth but are often insufficient to ensure extended shelf life without additional interventions. The use of chemical preservatives has been effective in some cases; however, growing consumer demand for clean-label and minimally processed products has driven the search for alternative, natural preservation methods (Shah *et al.*, 2014) [9].

Edible coatings based on natural polymers such as chitosan, alginate, starch, and cellulose derivatives have been widely studied as a means of improving the quality and shelf life of MPFs. These coatings act as semi-permeable barriers, reducing oxygen diffusion, moisture loss, and respiration rate, thereby slowing deterioration processes (Oms-Oliu *et al.*, 2010) [6]. Among these materials, chitosan has received particular attention due to its intrinsic antimicrobial properties and film-forming ability. Chitosan-based coatings have been shown to inhibit microbial growth and delay browning in various fresh-cut fruits and vegetables. However, conventional edible coatings often suffer from limited functional efficiency, poor mechanical stability, and inadequate control over nutrient degradation, highlighting the need for further technological enhancement.

Nanotechnology has emerged as a promising approach to overcome the limitations of conventional preservation methods. By manipulating materials at the nanoscale, it is possible to improve functional performance through increased surface area, enhanced reactivity, and controlled delivery of bioactive compounds (Duncan, 2011) [2]. In food systems, nanotechnology has been explored for applications including nutrient delivery, antimicrobial coatings, and active packaging. Nanoencapsulation techniques have been shown to protect sensitive nutrients from environmental stressors and improve their stability during storage (McClements, 2015) [5]. However, concerns regarding the safety and environmental impact of conventional nanomaterials, particularly those involving inorganic nanoparticles, have limited their acceptance in food applications.

Green nanotechnology has emerged as a response to these concerns, emphasizing the development and application of nanomaterials derived from renewable, biodegradable, and food-grade sources. Green nanomaterials such as chitosan nanoparticles, nanocellulose, starch nanoparticles, protein-based nanocarriers, and lipid-based nanoemulsions have been increasingly investigated for food applications (Singh *et al.*, 2018) [10]. These materials offer the functional advantages of nanotechnology while minimizing toxicity and environmental risks. Nanocellulose, for example, has demonstrated excellent mechanical properties, high biocompatibility, and the ability to enhance barrier performance when incorporated into edible coatings and films (Azeredo *et al.*, 2017) [11].

Several studies have reported the successful application of green nanotechnology in preserving the quality of MPFs. Nanoencapsulated antioxidants and vitamins have been shown to exhibit improved stability compared to their free counterparts, resulting in enhanced nutrient retention during storage (McClements, 2015) [5]. Chitosan-based nanoparticles have demonstrated strong antimicrobial activity against common spoilage microorganisms, contributing to extended shelf life of fresh-cut produce (Rhim *et al.*, 2013) [7]. Similarly, nanoemulsions containing essential oils or plant extracts have been reported to effectively inhibit microbial growth and oxidative reactions when applied as edible coatings, while maintaining acceptable sensory quality.

Despite these promising findings, the existing literature reveals several important gaps. Many studies have focused on model systems or simplified food matrices rather than whole minimally processed foods, limiting the applicability of results to real products. Furthermore, research often addresses either nutritional preservation or shelf-life extension in isolation, with limited studies evaluating both aspects simultaneously under realistic storage conditions. Data on the long-term stability, safety, and scalability of green nanotechnology-based systems remain scarce, particularly in relation to regulatory approval and consumer acceptance.

In summary, existing literature demonstrates the potential of green nanotechnology to enhance nutritional quality and shelf stability of minimally processed foods. However, there is a clear need for comprehensive, data-driven studies that evaluate the combined effects of green nanotechnology on nutrient retention, microbial safety, and physicochemical quality in real food systems. Addressing these research gaps will be essential for translating laboratory-scale innovations into practical, sustainable solutions for the food industry.

3. Materials and Methods

The study was conducted to investigate the application of green nanotechnology- based edible coatings in minimally processed foods for improving nutritional quality and shelf stability. A completely randomized experimental design was employed using fresh-cut apples as the model minimally processed food due to their high susceptibility to enzymatic browning, microbial spoilage, and nutrient degradation. Apples of uniform size, maturity, and free from visible defects were procured from a local market and stored at 4 °C prior to processing. Four treatment groups were prepared, including uncoated control samples, samples coated with conventional chitosan solution, samples coated with chitosan nanoparticles containing nanoencapsulated vitamin C, and samples coated with chitosan nanoparticles combined with nanoencapsulated vitamin C and essential oil. All samples were stored under refrigerated conditions at 4 °C and analyzed over a storage period of 14 days.

Food-grade chitosan with a degree of deacetylation of at least 85%, sodium tripolyphosphate, cellulose nanocrystals, ascorbic acid, and oregano essential oil were used as green nanomaterials and bioactive compounds. A 1% (w/v) chitosan solution was prepared by dissolving chitosan powder in 1% (v/v) acetic acid under continuous magnetic stirring for 24 h at room temperature until a clear solution was obtained. The solution was filtered to remove undissolved particles, and the pH was adjusted to approximately 5.5 using sodium hydroxide solution. This solution was used both as a conventional edible coating and as the base matrix for nanoparticle preparation.

Chitosan nanoparticles were prepared using the ionic gelation technique. A 0.25% (w/v) sodium tripolyphosphate solution was added dropwise to the chitosan solution under constant stirring to induce nanoparticle formation. Vitamin C solution was incorporated into the chitosan solution prior to tripolyphosphate addition to achieve nanoencapsulation. The mixture was stirred for 30 min and sonicated briefly to reduce aggregation and ensure uniform particle size distribution. The resulting nanoparticle suspension was stored at 4 °C until further use. A nanoemulsion of oregano essential oil was prepared separately by mixing the oil with a food-grade emulsifier and distilled water, followed by homogenization and probe sonication to obtain a stable nanoemulsion. This nanoemulsion was subsequently incorporated into the chitosan nanoparticle suspension for the combined active coating treatment.

Apple samples were washed, peeled, cored, and cut into uniform slices under hygienic conditions. The slices were rinsed with sterile distilled water and randomly assigned to the four treatment groups. Coating application was carried out by immersing the apple slices in the respective coating solutions for one minute, after which the samples were removed, allowed to drain excess coating solution, and air-dried at room temperature under aseptic conditions to allow film formation. The coated and uncoated samples were placed in sterile food-grade containers, sealed, and stored at 4 °C. Sampling was performed on days 0, 3, 7, 10, and 14 for physicochemical, microbiological, and nutritional analyses.

Microbiological quality was assessed by determining total aerobic plate counts and yeast and mold counts. Ten grams of each sample were aseptically homogenized in sterile peptone water, and serial dilutions were prepared. Appropriate dilutions were plated on plate count agar for total viable counts and on potato dextrose agar for yeast and mold enumeration. Plates were incubated under suitable conditions, and results were expressed as log colony-forming units per gram of sample. Vitamin C content was determined using high-performance liquid chromatography following extraction with an antioxidant-stabilizing solution. Quantification was performed using an external calibration curve, and results were expressed as milligrams of vitamin C per 100 g of fresh weight.

Color measurements were conducted using a colorimeter to record CIE L*, a*, and b* values, and total color difference was calculated relative to initial values. Texture analysis was performed using a texture analyzer equipped with a compression probe to determine firmness, expressed as peak force. Weight loss was calculated by measuring sample weight at each storage interval and expressing the results as a percentage of initial weight. Sensory evaluation was conducted by a trained panel using a nine-point hedonic scale to assess appearance, odor, texture, and overall acceptability, following institutional ethical guidelines.

All experiments were conducted in triplicate, and results were expressed as meanstandard deviation. Statistical analysis was performed using analysis of variance to evaluate the effects of treatment and storage time. Differences among means were considered statistically significant at $p < 0.05$.

4. Results

The effects of green nanotechnology-based edible coatings on the nutritional quality and shelf stability of minimally processed apples were evaluated through physicochemical, microbiological, nutritional, and sensory analyses during refrigerated storage at 4 °C for 14 days. The results obtained for nanoparticle performance, microbial growth, nutrient retention, color stability, texture, weight loss, and sensory acceptability are presented below.

4.1. Effect of Treatments on Microbiological Quality

Total aerobic plate counts (TAPC) increased progressively in all samples during storage; however, significant differences ($p < 0.05$) were observed among treatments. Uncoated control samples showed the most rapid microbial growth, exceeding the acceptable spoilage limit of 7 log CFU/g by day 10. Samples coated with conventional chitosan exhibited delayed microbial growth compared to the control. The chitosan nanoparticle coating with nanoencapsulated vitamin C significantly reduced microbial proliferation throughout storage, while the combined chitosan nanoparticle and essential oil treatment exhibited the strongest antimicrobial effect.

Table 4.1: Total aerobic plate counts (log CFU/g) of apple samples during refrigerated storage

Treatment	Day 0	Day 3	Day 7	Day 10	Day 14
Control	$3.02±0.18^a$	$4.85±0.22^a$	$6.42±0.31^a$	$7.86±0.29^a$	$8.92±0.34^a$
Chitosan	$3.05±0.20^a$	$4.20±0.25^b$	$5.78±0.28^b$	$6.94±0.26^b$	$7.82±0.30^b$
CH-NP-VitC	$3.01±0.16^a$	$3.92±0.19^c$	$4.96±0.23^c$	$6.12±0.21^c$	$6.98±0.27^c$
CH-NP-VitC+EO	$2.98±0.15^a$	$3.65±0.18^d$	$4.48±0.20^d$	$5.42±0.24^d$	$6.01±0.25^d$

Values are meanSD (n = 3). Different superscript letters within a column indicate significant differences (p < 0.05).

4.2. Vitamin C Retention during Storage

Vitamin C content decreased significantly in all samples over storage time; however, the rate of degradation differed among treatments ($p < 0.05$). Control samples exhibited rapid vitamin C loss, with more than 55% degradation by day 14. Chitosan-coated samples retained higher vitamin C levels than controls. Samples coated with chitosan nanoparticles containing nanoencapsulated vitamin C showed significantly greater nutrient retention, while the addition of essential oil further enhanced vitamin C preservation.

Table 4.2: Vitamin C content (mg/100 g fresh weight) of apple samples during storage

Treatment	Day 0	Day 3	Day 7	Day 10	Day 14
Control	$8.05±0.41^a$	$6.82±0.38^a$	$5.62±0.35^a$	$4.28±0.33^a$	$3.45±0.29^a$
Chitosan	$8.10±0.39^a$	$7.12±0.36^b$	$6.42±0.32^b$	$5.21±0.31^b$	$4.52±0.27^b$
CH-NP-VitC	$8.15±0.40^a$	$7.68±0.34^c$	$7.02±0.29^c$	$6.25±0.28^c$	$5.98±0.26^c$
CH-NP-VitC+EO	$8.08±0.42^a$	$7.75±0.36^c$	$7.18±0.30^c$	$6.48±0.27^c$	$6.32±0.25^c$

4.3. Color Stability

Color measurements revealed significant changes in L*, a*, and b* values during storage, particularly in control samples. Total color difference (ΔE) increased significantly over time in all treatments ($p < 0.05$). Nano-coated samples exhibited significantly lower ΔE values compared to controls, indicating better color preservation.

Table 4.3: Total color difference (ΔE) of apple samples during storage

Treatment	Day 3	Day 7	Day 10	Day 14
Control	4.85±0.41^{a}	8.62±0.56^{a}	12.78±0.72^{a}	16.34±0.85^{a}
Chitosan	3.92±0.38^{b}	6.45±0.49^{b}	9.28±0.63^{b}	12.56±0.78^{b}
CH-NP-VitC	3.25±0.34^{c}	5.42±0.44^{c}	7.65±0.58^{c}	9.92±0.71^{c}
CH-NP-VitC+EO	2.88±0.32^{c}	4.96±0.41^{c}	6.98±0.52^{c}	8.35±0.64^{c}

4.4. Texture and Weight Loss

Firmness decreased in all samples during storage, with control samples showing the most rapid softening. Nano-coated samples retained significantly higher firmness values throughout storage ($p < 0.05$). Weight loss increased over time in all treatments, with nano-coated samples exhibiting reduced moisture loss compared to controls.

Table 4.4: Firmness (N) and weight loss (%) of apple samples at day 14

Treatment	Firmness (N)	Weight loss (%)
Control	8.42±0.52^{a}	6.84±0.47^{a}
Chitosan	10.36±0.48^{b}	5.21±0.41^{b}
CH-NP-VitC	12.18±0.45^{c}	3.94±0.36^{c}
CH-NP-VitC+EO	13.04±0.43^{c}	3.21±0.34^{c}

4.5. Sensory Evaluation

Sensory scores for appearance, texture, odor, and overall acceptability declined during storage for all samples. Control samples received unacceptable sensory scores (<5) by day 10. Nano-coated samples maintained acceptable sensory quality throughout the 14-day storage period, with the combined nano-coating treatment receiving the highest overall acceptability scores.

Table 4.5: Overall acceptability scores of apple samples during storage

Treatment	Day 7	Day 10	Day 14
Control	6.1±0.4^{a}	4.8±0.5^{a}	3.6±0.6^{a}
Chitosan	6.8±0.3^{b}	5.9±0.4^{b}	4.7±0.5^{b}
CH-NP-VitC	7.5±0.3^{c}	6.8±0.4^{c}	6.1±0.4^{c}
CH-NP-VitC+EO	7.8±0.2^{c}	7.2±0.3^{c}	6.6±0.3^{c}

4.6. Statistical Summary

Two-way ANOVA revealed significant effects ($p < 0.05$) of treatment, storage time, and their interaction on microbial counts, vitamin C retention, color difference, firmness, and sensory acceptability. Nano-based treatments consistently outperformed control and conventional chitosan coatings across all evaluated parameters.

5. Discussion

The results obtained in this study demonstrated that the application of green nanotechnology-based edible coatings significantly improved the nutritional quality and shelf stability of minimally processed apples during refrigerated storage. The observed improvements in microbial control, vitamin C retention, color stability, texture preservation, and sensory acceptability confirmed that nano-enabled coatings were more effective than conventional chitosan coatings and uncoated controls. These findings supported the hypothesis that green nanomaterials can simultaneously enhance nutrient stability and delay spoilage processes in minimally processed foods.

Microbiological analysis revealed that nano-coated samples exhibited substantially reduced microbial growth compared to control and conventionally coated samples throughout storage. The strong antimicrobial performance of chitosan nanoparticle- based coatings was attributed to the increased surface area and enhanced interaction between positively charged chitosan nanoparticles and microbial cell membranes. This interaction likely disrupted cell membrane integrity, leading to leakage of intracellular components and inhibition of microbial proliferation. The further reduction in microbial counts observed in samples treated with the combined chitosan nanoparticle and essential oil coating suggested a synergistic antimicrobial effect, where nanoencapsulation improved the dispersion and controlled release of essential oil compounds on the food surface. These results were consistent with previous studies reporting enhanced antimicrobial activity of nano-structured chitosan systems compared to bulk chitosan formulations.

Vitamin C retention data clearly indicated that nanoencapsulation played a critical role in protecting this sensitive nutrient from degradation. Control samples showed rapid vitamin C loss, which was expected due to oxidative reactions and enzymatic activity following tissue disruption during minimal processing. Conventional chitosan coatings moderately reduced vitamin C degradation, likely by limiting oxygen diffusion. However, significantly higher vitamin C retention in nano-coated samples demonstrated that nanoencapsulation effectively shielded vitamin C from environmental stressors such as oxygen and light. The improved performance of nano-based coatings suggested that nanoscale carriers provided a protective microenvironment and slowed diffusion-driven degradation processes. These findings aligned with earlier research showing that nanoencapsulation enhances the stability of labile nutrients in food systems.

Color stability, as indicated by lower total color difference values in nano-coated samples, further supported the protective effect of green nanotechnology-based coatings. Enzymatic browning is a major quality defect in fresh-cut apples and is closely associated with polyphenol oxidase activity and oxygen availability. The reduced color change observed in nano-coated samples suggested that the coatings acted as effective semi-permeable barriers, limiting oxygen diffusion and reducing enzymatic browning reactions. Additionally, the antioxidant properties of vitamin C and essential oil components may have contributed to browning inhibition by scavenging reactive oxygen species and reducing quinone formation. The superior color preservation observed in nano-coated samples reinforced the multifunctional role of green nanotechnology in quality maintenance.

Texture analysis demonstrated that nano-coated samples retained higher firmness values compared to control and conventionally coated samples. Texture degradation in minimally processed fruits is commonly associated with moisture loss, cell wall degradation, and enzymatic softening during storage. The improved firmness retention observed in nano-coated samples suggested that the coatings effectively reduced moisture loss and slowed structural degradation. The presence of nanocellulose within the coating matrix may have further enhanced mechanical stability and moisture barrier properties, contributing to improved textural preservation. These findings were consistent with reports that nanostructured edible coatings provide superior mechanical reinforcement compared to conventional coatings.

Weight loss results also supported the effectiveness of nano-enabled coatings in reducing moisture migration. Lower weight loss in nano-coated samples indicated improved barrier properties, which likely contributed to better texture and sensory quality. Moisture retention is particularly important for minimally processed foods, as dehydration not only affects texture but also accelerates oxidative and microbial spoilage. The ability of nano-based coatings to regulate moisture transfer highlighted their potential to improve shelf-life stability without compromising freshness.

Sensory evaluation confirmed that improvements observed in physicochemical and microbiological parameters translated into enhanced consumer acceptability. Nano- coated samples maintained acceptable sensory scores throughout the storage period, whereas control samples became unacceptable at earlier stages. Importantly, the incorporation of essential oil in nanoemulsified form did not negatively affect sensory attributes, suggesting that nanoencapsulation successfully mitigated the strong aroma often associated with essential oils. This finding addressed a common limitation of natural antimicrobial agents and underscored the advantage of nano-based delivery systems in preserving sensory quality.

Overall, the results demonstrated that green nanotechnology-based coatings offered clear advantages over conventional preservation approaches by integrating nutritional protection, antimicrobial activity, and quality preservation within a single system. Unlike traditional methods that often address only one aspect of food deterioration, nano-enabled coatings provided a multifunctional solution aligned with clean-label and sustainability principles. However, despite the promising outcomes, further research is required to evaluate long-term safety, scalability, and regulatory compliance, as well as to assess performance across different types of minimally processed foods.

6. Conclusion

The present study demonstrated that green nanotechnology-based edible coatings effectively improved the nutritional quality and shelf stability of minimally processed apples during refrigerated storage. Nano-enabled chitosan coatings significantly reduced microbial growth, preserved vitamin C content, minimized color deterioration, and improved texture and sensory acceptability compared to uncoated and conventionally coated samples. The incorporation of nanoencapsulated vitamin C provided enhanced protection against oxidative degradation, while the addition of essential oil further strengthened antimicrobial performance without negatively affecting sensory quality. Overall, the results confirmed that green nanotechnology offers a multifunctional and sustainable strategy for addressing key challenges associated with minimally processed foods. These findings support the potential application of green nanomaterials as safe and effective alternatives to conventional preservation methods, contributing to improved food quality, extended shelf life, and reduced postharvest losses.

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