

EDIBLE NANO-COATINGS: A SUSTAINABLE STRATEGY FOR ENHANCING THE SHELF-LIFE AND QUALITY OF FRESH PRODUCE (STRAWBERRIES)

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Abstract

Postharvest spoilage of strawberries are lost due to huge amount especially in the countries with weak refrigeration system. Nano-coatings that can be ingested are a sustainable and biodegradable way of improving antimicrobial protection and barrier properties to prolong the shelf life of food. Most of the studies however are limited and are only applicable to a single polymer system, short storage periods or individual quality parameters. In this study, six edible coatings were developed by incorporating either chitosan nanoparticles (CSNPs), nanocrystalline cellulose (NCC), pullulan (PUL), zinc oxide nanoparticles (ZnO NPs), essential oils (EOs), or alginate (ALG) into strawberry edible coating. In this study, six edible coatings were formulated containing either chitosan nanoparticles (CSNPs), nanocrystalline cellulose (NCC), pullulan (PUL), zinc oxide nanoparticles (ZnO NPs), essential oils (EOs), or alginate (ALG) and applied to strawberries in refrigerated storage for 28 days. The effect of each coating was assessed in terms of weight loss, firmness, titratable acidity, microbial count and sensory quality at appropriate time intervals. The findings indicated that coated samples inhibited microbial growth significantly better than uncoated controls ($p < 0.05$) with CSNP and ZnO coatings having the most profound effect on microbial growth and least weight loss. Coatings based on pullulan and NCC were able to maintain a longer firmness and appearance of fruits, whereas coatings based on essential oils continued to receive good scores in sensory tests. It is worth noting that coated strawberries stayed acceptable in taste and texture over 21 days, whereas the control lasted just 10 days. These results prove that multi-component nano coatings are capable of maintaining postharvest quality of strawberries in refrigerated storage. The findings suggest their suitability as low-tech, scalable solutions toward enhance produce

stability in resource-limited environments. Further studies are recommended to evaluate performance of different fruits and storage conditions.

INTRODUCTION:

The post harvest losses (PHLs) continue to pose a dire threat to worldwide food security carrying enormous environmental and economic side effects. According to the Food and Agriculture Organization (FAO, 2023), in the world, food loss accounts for approximately 13 percent of the loss that occurs between the harvesting and the retail stages, equivalent to nearly 931 million tonnes of food lost each year. Losses are particularly high in fruits and vegetables (55 per cent due to mechanical damage, microbial spoilage and physiological deterioration). These losses not only contribute to food insecurity but also to a huge economic loss of USD 400 billion annually (Muwereza, 2024) or resource inefficiencies and greenhouse gas emissions from the production and disposal of uneaten food (UNEP, 2021). The development of edible coatings as alternatives to synthetic plastic ones have resulted from efforts to mitigate PHLs. Edible coatings are thin layers applied to fresh produce and composed of natural, biodegradable materials like polysaccharides, proteins and lipids, which serve as a barrier to moisture, gases and microbial entry (Sharma et al., 2019; Matloob et al., 2023). Edible coating is an environmental friendly packaging that can be eaten along with food product which can help reduce packaging waste when compared to conventional plastic packaging (Maringgal et al., 2020). Several of these coating materials, such as chitosan and pullulan are recognized as safe by food regulatory bodies like the U.S. Food and Drug Administration (FDA, 2002) and the European Food Safety Authority (EFSA, 2004), for use in commercial products. However, conventional edible coatings are limited by their poor mechanical strength, the difficulty in obtaining uniform coating, the lack of control of respiration and microbial growth, especially under changing storage conditions (Aloui & Khwaldia, 2016; Khalifa et al., 2022). Over the last few years,

new advances in nanotechnology have led to the emergence of a novel category of edible films called “nano-coatings”, which contain nanostructured materials that enhance the physicochemical and functional properties of the coating film. The combination of barriers properties, mechanical strength and increased surface-to-volume ratio contributes to enhancing the potential of nano-coatings to preserve perishable foods during storage (Ribeiro et al., 2021; Hassan et al., 2018). They can also be loaded with bioactive molecules, like antimicrobials, antioxidants and essential oils, to provide controlled and sustained delivery of the molecules to the fruit surface. State of the art delivery technologies helps to prolong shelf life, delay microbial growth and maintain sensory and nutritional properties of the product. When the effectiveness of chitosan as a food preservation strategy is concerned, Martinez-Hernandez et al. (2023) have found that the nano-coatings produced have been effective in reducing microbial deterioration of strawberries to 60% after 10 days of cold storage, while Totobesola et al. (2022) have reached the same conclusion. There is not enough knowledge on the real application of edible nano-coatings on the real food systems; however, there is huge potential. Many publications are limited to single polymer systems; do not provide comparative analysis of various coating materials; and do not address quality indicators of post harvest performance such as weight loss, firmness, microbial stability, and sensory acceptability. Additionally, there is limited research on the release profile and stability of bioactive compounds in commercially-recommended storage conditions at typical storage temperatures (Stathers et al., 2020). This research gap is one of the challenges to increase application of nano coating technologies for postharvest handling of perishable food. Due to these limitations, all of the current research focuses on the formulation, characterization, and

preservation efficiency of 6 edible nano-coatings, comprising of chitosan nanoparticles (CSNPs), zinc oxide nanoparticles (ZnO), essential oils (EO), pullulan (PUL), alginate (ALG) and nano crystalline cellulose (NCC). These materials were selected because of the earlier reported biocompatibility, film forming ability, antimicrobial and antioxidant properties. Strawberries were used as a test fruit due to the high value and perishability, high consumer and commercial importance. The results of the present study will help formulate nano-based coatings that can be used to preserve postharvest quality of fresh fruits in a sustainable and scalable way using a biopolymer

Objective:

The specific objectives of the study are:

1. To synthesize and characterize the nano-coatings using physicochemical and storage stability assessments
2. To evaluate the effect of these coatings on quality parameters including weight loss, firmness, titratable acidity, microbial growth, and sensory attributes during cold storage.
3. To compare the preservation performance of nano-coatings with conventional coatings and an uncoated control.

2. Literature Review:

2.1. Postharvest Losses and Need for Sustainable Solutions:

Perishable food like fruits and vegetables are particularly susceptible to postharvest losses because of their high respiration rates. Approximately 13 per cent of edibles are lost between the farming and the retail levels of the food chain worldwide, which is equivalent to the loss of 931 million tonnes per annum (FAO, 2023). In low and medium income countries, additional losses are caused by the combination of poor infrastructure, temperature fluctuations and microbial deterioration. Such problems are particularly common in such areas as South Asia and sub-Saharan Africa, where even such fruit as tomatoes, strawberries, and apples can spoil before

being delivered to customers (UNEP, 2021). This waste is not just about food insecurity, it is also a loss of economic resources and contributes to environmental impacts by emissions of greenhouse gases and waste of resources.

2.2. Conventional Preservation Methods & Constraints:

The traditional technology for extending the shelf life of fresh products are cold storage, chemical preservatives and synthetic plastic wrapping materials. These methods though effective to some level, have their own limitations. The cold chain facilities are effective, but consume energy and are typically not present in rural areas. On the other hand the use of chemical preservatives is known to have regulatory restrictions and bring potential health hazards to consumers (Aloui & Khwaldia, 2016). While offering physical protection and moisture barrier, plastic packing also causes environmental pollution and has inspired the world to reduce and substitute plastic packing.

2.3. Edible Coatings: A Biodegradable Alternative:

The edible coatings have been developed as an eco-friendly alternative to traditional packaging. The coatings are usually made from natural polymers like polysaccharides, proteins or lipids, which create a temporary film on the surface of the fruits and vegetables and act as a barrier to moisture loss, oxygen and microbial entry (Sharma et al., 2019). Moreover, these coatings can be used as carriers for bioactive ingredients such as antimicrobials, antioxidants, and essential oils, thus improving the protective property. The film-forming ability, biodegradability and food system compatibility are some of the most promising properties of commonly studied biopolymers, namely chitosan and pullulan (EFSA, 2004; FDA, 2002; Hassan et al., 2018).

However, conventional edible coatings offer a number of benefits for extending the shelf-life, but their functional limitations limit their potential for wider commercial application. The films made from polysaccharides have poor water vapor

resistance and limited mechanical durability in real storage. Furthermore, their bioactive capacity to retain and release is not optimal, especially in humid environments (Khalifa et al., 2022).

2.4. Nanotechnology Coatings: Mechanisms and Advantages:

The incorporation of nanotechnology in food preservation has emerged as a powerful tool, especially in the development of nano-enabled edible coatings that lead to an improvement of the shelf-life and quality of fresh produce. These coatings are based on nanostructured materials like nanoparticles, nanoemulsions, nanofibers, which not only enhance the mechanical properties, barrier-resistant and adhesion capabilities of the film but also promote controlled or sustained delivery of bioactive substances (Ribeiro et al., 2021; Ghori et al., 2022). Traditional coatings are of particular interest for protection of perishable fruits like strawberries, where nanostructured systems can offer multifunctional protection.

Among the materials studied, chitosan nanoparticles (CSNPs) are among the most studied due to their inherent antimicrobial activity, film forming ability and hydrophobic substance encapsulation capabilities. These properties are shown to reduce the rate of microbial spoilage and respiration, maintain firmness and sensory quality of coated strawberries (Singh et al., 2023; Saberi et al., 2021). In addition to CSNPs, another form of nanocrystalline cellulose, called nanocrystalline cellulose (NCC), can also be used to provide structural integrity, or a dense reinforcing network can be obtained to enhance the mechanical strength and moisture barrier properties without compromising biodegradability (Kumar et al., 2020; Rachtanapun et al., 2022).

Additionally, pullulan, which was also highly transparent, flexible, and an oxygen barrier, has been found to be essential because it can preserve the aesthetic and sensory properties of fruits during storage (Dey et al., 2023; Mohammadi et al., 2022). Besides, a new antimicrobial dimension

is given by the addition of zinc oxide nanoparticles (ZnO NPs) due to their photocatalytic activity and the production of reactive oxygen species (ROS), which suppress the growth of microbes and postpone senescence (Azeem et al., 2023; Asghar et al., 2021). To supplement this, essential oils (EOs) particularly those in nano-encapsulated form, present a natural and controlled source of antimicrobial activity which fits into the consumer trend of clean-label ingredients (Yousuf et al., 2021; Soliman et al., 2020).

Finally, although more traditional, alginate is still a useful benchmark material as it is biodegradable, GRAS, and can be made to be compatible with nanostructured additives. By adding it, it is possible to make comparisons the improvement in performance due to nano-enhancement (Nabavi et al., 2021).

Together, these nano-coatings, when used on strawberries, represent a synergistic strategy to postharvest preservation, by providing support to the structure, inhibiting microbial growth, and oxidative resistance. They can also improve the storage quality in combination and provide a sustainable and consumer friendly alternative to synthetic preservation methods.

2.5. Application Findings & Regional Relevance:

Empirical studies in recent years, have shown that the nano-coatings have potential in the preservation of fruit quality and shelf life in storage. In this regard, Martinez-Hernandez et al. (2023) reported that the microbial spoilage reduction of strawberries in chitosan-ZnO nanoparticles thin layer packaging was 60% after 10 days of cold storage. Likewise, Hassan et al. (2018) observed the improvement of mechanical strength and reduced water vapor permeability in apples coated with chitosan nanocellulose composite coatings. Pullulan-based coating was also determined to maintain the firmness and colour of refrigerated tomatoes, thus enhancing marketability and visual quality (Ribeiro et al., 2021).

The significance of the results is particularly relevant for agricultural regions, such as Pakistan

and India, where the post harvest losses are enormous, cold chain facilities are limited and environmental conditions are not standard. From that perspective, the adoption of affordable, scalable and environmentally friendly solutions that don't require advanced packaging and refrigeration are paramount.

2.6. Research Gaps and Study Rationale

The fruit preservation although there are many studies on edible nano-coatings of single polymers, single fruit and short-term releases, the behaviour of bioactive release under more realistic conditions is poorly understood (Stathers et al., 2020). Very little work has been done in making a combined analysis of the physicochemical, microbial and sensory properties throughout the storage period. To this end the present study aims to overcome these limitations by developing a composite coating consisting of the chitosan nanoparticles (CSNPs), nanocrystalline cellulose (NCC), and pullulan selected for their antimicrobial and structural properties along with barrier properties. Strawberries were coated and stored at refrigeration temperatures (28 days) and the parameters of weight loss, firmness, acidity, microbial load and sensory quality were compared. The goal is to offer the knowledge of scalable, biodegradable preservation plans of resource-limited post-harvest systems.

3. Methodology:

3.1. Experimental Design and Materials:

The present research aimed to study the postharvest preservation of strawberry (*Fragaria & ananassa*) by nano coatings with edible materials under a controlled laboratory experiment. The experimental design was based on a comparison between the effectiveness of the different coating treatments chitosan nanoparticles (CSNPs), nanocellulose (NCC), pullulan (PUL), and their combination formulations and the conventional coating with sodium alginate (ALG) and an uncoated control. The Commercial maturity firmness and freedom from defects were the criteria used for selecting uniform ripe

strawberries. Chitosan medium molecular weight $\geq 75\%$ deacetylation sodium tripolyphosphate (STPP) nanocellulose (CNF) food grade pullulan and glycerol were all obtained from certified suppliers and used as such. Throughout the study deionized water and analytical grade chemicals were used (Hassan et al., 2018; FAO, 2023).

3.2. Preparation of Nano Coatings:

3.2.1. Chitosan Nanoparticles (CSNPs):

Nanoparticles of chitosan were synthesized using ionic gelation method. For the chitosan solution preparation 0.2 % (w/v) chitosan was dissolved in 1 % (v/v) acetic acid and the pH was adjusted to 4.5–5.0. At the same time a 0.1% (w/v) STPP solution was made in deionized water. The STPP solution was dropwise added to the chitosan solution at a ratio of 5:1 (STPP/chitosan), under constant magnetic stirring at 800 rpm. The spontaneous formation of the nanoparticles was observed after 30 minutes of stirring and the nanoparticles were collected by centrifugation at 10,000 rpm for 30 minutes. These were then redispersed in deionized water and generally had diameters of between 50–200 nm (Martínez-Hernández et al., 2023).

3.2.2. Nano cellulose Suspension:

The preparation of a 1% (w/v) nanocellulose suspension involved dispersing nanocellulose in deionized water. The suspension was subjected to 10 minutes of ultrasonication with the purpose of providing a uniform dispersion and prevention of agglomeration (Ribeiro et al., 2021).

3.2.3. Pullulan Film Solution:

Pullulan was dissolved in deionized water with 1% (w/v) glycerol, used as a plasticizer. The solution was heated to 60°C with constant stirring until completely dissolved, and then cooled to room temperature (Maringgal et al., 2020).

3.2.4. Composite Nano Coating Formulation:

Nano coatings are composite where chitosan nanoparticles nanocellulose and pullulan are mixed in 2:1:2 weight ratio. The mixture was

homogenized to achieve uniformity and stability with a high speed homogenizer for 5 minutes at 10,000 rpm (Ribeiro et al., 2021). The formulations were filtered through a 0.45 µm membrane and kept in refrigeration at 4°C prior to application.

3.3. Application:

Application of coating was done by the dipping method. For sanitization strawberries were soaked in 0.1% sodium hypochlorite for 2 minute rinsed with deionized water and dried in air. The fruits were dipped in the coating solutions for 2 minutes and then drawn out and air dried at room temperature for 30 minutes as illustrated in Figure 1. Treatments consisted of uncoated control pullulan (2% solution) composite coating (CSNPs), nanocellulose and nano coating (2% solution of composite coating) (PANC). The three replicates were used to ensure statistical reliability in all applications (Martínez-Hernández et al., 2023).

3.4. Storage and Quality Assessment:

The fruits were coated and kept at 85–90%RH at 4 ± 1 °C. At day 0, 7, 14, 21 and 28, quality parameters were assessed. The percentage weight loss was calculated from the body weight at the start of the experiment (Aloui & Khwaldia, 2016). Firmness was assessed by means of a texture analyzer and total soluble solids (TSS) were analyzed by the digital refractometer. The titratable acidity was determined by titration with 0.1 N NaOH while the ascorbic acid content was measured by titration with 2,6-dichlorophenolindophenol (Sharma et al., 2019). Homogenized samples were plated on nutrient agar and potato dextrose agar for microbial quality assessment and total viable count and yeast/mold load respectively. Plates were incubated for 48–72 hours at 30°C and results reported as log CFU/g (Martínez-Hernández et al., 2023). The rate of respiration was estimated by measuring the build-up of CO₂ in tightly closed containers with gas chromatography (Khalifa et al., 2022). Samples were subjected to sensory evaluation by a semi-

trained sensory panel (n = 10–15) using a 9-point hedonic scale for appearance, taste, smell, flavour, bitterness, after taste and overall acceptability. To prevent bias, samples were randomly and blindly presented (Maringgal et al., 2020).

3.5. Quality Assurance:

The sample preparation instrument calibration and data recording procedures were standardized and documented to ensure that they are reproducible and traceable. All the participants were provided with information and provided their consent for sensory evaluation as in the course of ethical research in food studies (Maringgal et al., 2020).

3.6. Statistical Analysis:

Each experimental data was obtained from three replicates and reported as mean $\pm$ standard deviation (SD). Minitab (Version 20) was used for statistical analysis. The significant difference between the different treatments and time point was evaluated using one-way ANOVA. Pairwise comparison was done using Tukey's HSD post hoc test at the significance level $\alpha = 0.05$ (Ribeiro et al., 2021).

4. Results and Discussion:

4.1. Effect of Nano-Coatings Ascorbic Acid Content:

The one of the important antioxidants present in strawberries is ascorbic acid (vitamin C) which is very prone to oxidation during storage. The ascorbic acid retention was significantly influenced by both treatments ($p < 0.001$) storage time ($p < 0.001$) and the treatment x storage time interaction ($p < 0.001$). There was uniformity among the initial concentrations of all the samples (about 65 mg/100g). The result of the uncoated control (T-CTRL) was the lowest decreasing to 56.91 mg/100g over 28 days which was significantly lower than all coated treatments as indicated in Table 2. By comparison coatings such as Pullulan (T-PUL) ZnO-based chitosan (T-ZnO) and essential oil coating (T-EO) exhibited the best retention (all > 60 mg/100g by Day 28). These

treatments were statistically grouped together (Tukey Group A) and were better than the control (Group B). The high oxygen barrier of pullulan could have minimized oxidative losses and the antimicrobial and antioxidant activity of zinc oxide and essential oils may have helped prevent losses caused by microbes. The results are consistent with the research conducted by Hassan et al. (2023) who found that bioactive film coatings help maintain vitamin C content of strawberries and Lee et al. (2022) who reported that zinc oxide nanoparticles enhance barrier and preservation properties of fruit coatings. The other coatings, chitosan nanoparticle (T-CSNP) and nano composite (T-NCC) and alginate (T-ALG) also showed a slight reduction in ascorbic acid loss. Overall, edible coatings, particularly ones containing nano-materials or bioactives, contributed to the nutritional stability of foods during storage.

4.2. Effect of Nano-Coatings on Firmness:

During storage firmness was significantly reduced in all treatments and it was an important parameter for strawberry quality and shelf-life (Table 2). The rate of softening was quite variable. The greatest drop (8.19 N to 0.01 N) was observed in the uncoated control samples (T-CTRL) as reported by Ghasemnezhad et al. (2019) which proved that the samples were rapidly texturized by enzyme activity and moisture evaporation. However ANOVA and Tukey's test showed that coated samples particularly T-EO (mean: 6.48–6.58 N), T-NCC (mean: 6.53–6.58 N), and T-ALG (mean: 6.55–6.56 N), significantly preserved firmness. The coatings apparently inhibited water vapour transfer and inhibited enzymatic softening. The results are in agreement with Li et al., (2022) that reported firmness improvement of strawberry nanofilms treated with alginate and chitosan nanofilms. The nano-formulated ZnO and CSNP coatings were also effective with a little decrease by Day 28 as compared to EO and NCC coatings. This is in contrast to Patel et al. (2023) who found that ZnO nanoparticles exhibited greater firmness than polysaccharide coatings. Variation in cultivar

strawberry, coating thickness, or coating pH may be responsible. Overall the enrichment of essential oil synergised barrier and antimicrobial functions, similar to Mohamed et al. (2023) who reported that the cell wall degradation process was delayed when oil was applied to berries. The interaction of treatment by time was also significant ($F = 7.77$, $p < 0.001$), which supports the time-dependency of coating efficacy, as already discussed.

4.3. Effect of Nano Coatings on Weight Loss (%):

The moisture evaporation and physiological deterioration during storage can be reflected by weight loss as a critical postharvest measurement. In the present study, the weight loss was observed to be progressive in all the treatments during 28 days of storage period (Table 2). The growth rate was, however, significantly different between treatments ($p < 0.05$). The control (T-CTRL) without coating was the most significant with the maximum cumulative weight loss at Day 28 (14.64%). This significant weight loss is due to transpiration and respiration without any controls, which is consistent with the results of Ghasemnezhad et al. (2019) on ambient storage of uncoated strawberries. On the other hand strawberries coated with Nano-coatings showed much less weight loss. The highest retention was obtained with the T-CSNP (7.3%), T-ZnO (7.26%) and T-PUL (7.33%). These coatings may have proved to be good semi-permeable moisture and gas barriers, minimizing dehydration and respiratory water loss. Goyal et al. (2022) and Zhang et al. (2023) provided similar moisture retention efficiency of chitosan nanoparticles and ZnO composites in berries and climacteric fruits. The weight loss was slightly more in T-EO and T-NCC treatments compared to CSNP and ZnO treatments while maintaining the highest firmness. This could be attributed to the hydrophobic character of EO components that can affect the uniform coating adhesion or cause microcracking as reported by Aloui et al. (2021). Therefore nano-coatings, especially the CSNP and ZnO-based formulations, are effective to reduce moisture loss and senescence of strawberries were

proved as potential postharvest preservation technologies.

4.4 Effect of Nano-Coatings Respiratory Rate:

The respiratory rate of strawberry rose significantly during storage in all the treatments ($p < 0.001$) (Table 3). All treatments had the highest respiration levels throughout the study with the uncoated treatment (T-CTRL) increasing from 9.96 mL CO₂/kg/hr on Day 0 to 24.24 mL CO₂/kg/hr on Day 28. This high rise is due to the metabolism of the senescent strawberries when they lack a protective barrier, turning them into soft rot, decay and quality loss. On the other hand all the coated treatments gave satisfactory effectiveness in slowing down the rate of respiration. For that, the T-EO (essential oil-enriched coating), T-ALG (alginate), and T-ZnO (chitosan-ZnO nanocoating) treatments had consistently low respiration rates of 16.54, 17.12, and 17.4 mL CO₂/kg/hr, respectively. These coatings probably were imperfused, allowing some gas exchange while slowing down metabolism. The essential oil coating (T-EO) recorded one of the most successful performances, perhaps attributed to the antimicrobial and antioxidant activities of the essential oils which help to inhibit the growth of microorganisms inducing spoilage and to slow down the senescence process caused by oxygen consumption. This was supported by Khalifa et al. (2022) who reported that essential oils inhibit the growth of microorganisms causing spoilage and reduce the senescence process caused by oxygen consumption. The ANOVA and Tukey's post hoc analysis also showed that there were significant differences between and among treatments and time points. The mean rate of respiration for T-CTRL (17.25 mL CO₂/kg/hr) was significantly higher than all other coated samples ($p < 0.05$), where these coated samples fell into a separate statistical group (A). All the coatings (B group) were equally effective in respiration suppression but T-CSNP (chitosan nanoparticles) exhibited slightly higher suppression (13.4 mL CO₂/kg/hr), similar results as reported by Akhtar et al., 2023 and proved that the chitosan has a better effect in

reducing the gas permeability and bioactive property. The findings confirm the inhibitory effect of edible coatings, particularly when combined with EO and nanomaterials, on strawberry respiration, which can help prolong the shelf life of the fruit by slowing oxidative and enzymatic degradation.

4.5. Effect of Nano-Coatings Titratable Acidity:

Table 3 shows that the titratable acidity (TA) decreased greatly during storage in all the treatments ($p < 0.001$). TA values at Day 0 were from 0.85% to 1.37%, and were highest in T-EO (essential oil-enriched coating) and T-CTRL (uncoated control). On most treatments, a marked decrease in the acidity was noted by Day 14, in some cases with negative or approximately neutral readings, which suggested significant acid degradation. Time had a significant effect on TA changes ($p = 0.289$), but there was no significant difference between treatments. The highest losses were recorded on Day 28 for T-ZnO (-0.60%) and T-ALG (-0.40%). This decrease could be due to greater metabolic activity, especially in less efficient coatings or uncoated corn, and lead to the faster use of organic acids for respiration and senescence.

The acidity of coated samples was generally higher and did not become negative (and was not positive or near baseline) over time as was the case with the coated samples (particularly T-PUL, T-NCC and T-EO). These coatings probably prevented the loss of acidity due to the reduction in respiration rate and the slow enzymatic release of citric and malic acids. For example, T-PUL and T-NCC maintained 0.14% and 0.15% TA, respectively, on Day 28, and T-EO maintained -0.31% TA. The results are consistent with the study by Zhu et al. (2023), who found that polysaccharide and essential oil coatings reduce the acid loss in soft fruits by preventing the entry of oxygen and enzymatic degradation. The results indicate that, generally, the titratable acidity reduces during storage, but the use of some of the coatings (pullulan, nanocomposites and EO-based formulations) retards the reduction of titratable acidity and maintains

the sensory and nutritional characteristics of strawberries for longer storage time.

4.6. Effect of Nano-Coatings Total Soluble Solids (TSS)

Table 3 shows that there was a significant decrease in the total soluble solids (TSS) ($p < 0.001$) during the storage period for all the treatments, and the results are expressed as °Brix. The maximum TSS values were obtained on Day 0 ranging from 6.94 to 7.77 °Brix, signifying the most ripe and best sugar content at the beginning of the storage period. A progressive decrease in TSS was seen in all the treatments especially in the uncoated control (T-CTRL), which had a significant decrease from 7.66 °Brix on Day 0 to 1.95 °Brix on Day 28, the lowest among all treatments. ANOVA results showed that the means of TSS levels were significantly different among the treatments ($p < 0.001$), times ($p < 0.001$), and treatment $\times$ time ($p < 0.001$). The Tukey's test indicated that coated samples T-EO, T-ALG and T-ZnO had significantly higher TSS values over time than the uncoated control sample (T-CTRL), which means that these coated samples were effective in delaying the metabolic degradation and keeping the sugar content in storage. T-ZnO, for example, showed 4.86 °Brix and T-EO 4.46 °Brix on Day 28 while T-CTRL almost had no sugar at all. Coated fruits can retain TSS due to the semi-permeable barrier created by edible coatings which decreases water loss and respiration rate, thus slowing the rate of sugar use and slowing deterioration. Similarly, Ali et al. (2021) and Rasouli et al. (2022) found nano-coatings containing essential oils or ZnO nanoparticles to be efficient for preserving TSS and inhibit deterioration of fruit due to reduced oxidative stress and enzymatic degradation. The results indicate that the coatings (ZnO, EO and alginate) not only maintained the flavor and sweetness of the tomato, but also extended the shelf life through stabilization of some quality indicators such as TSS. The control group, by contrast, suffered rapid deterioration, thus emphasizing the

need for surface treatments in the postharvest preservation of strawberries.

4.7. Effect of Nano-Coatings Microbial Contents: 4.7.1. Total Viable Count (TVC):

The Total Viable Count (TVC) result indicates a very significant increase in all the samples during the storage period of 28 days as shown in Figure 2. As expected, the greatest microbial growth was registered in the uncoated control group (T-CTRL) which increased between 1.88 CFU/g (Day 0) to 16.35 CFU/g (Day 28). In contrast, the coated treatments (T-EO, T-CSNP, T-ZnO and T-NCC) had a lower increase in the viability of the microbes and final TVC ranging from 8.48 to 9.29 CFU/g. Based on the ANOVA results, treatment ($p < 0.001$), storage time ($p < 0.001$) and their interaction ($p < 0.001$) had a statistically significant effect on microbial load. Interestingly, T-CTRL was clustered distinctly aside all coatings (group A), as all coated treatments clusters in group B, which suggests better microbial suppression by the coatings. T-ZnO and T-PUL were the most efficient among coating with the lowest mean TVC on Day 28 (9.29 and 9.23 CFU/g, respectively). The results are in agreement with the previous results which showed that the ZnO nanoparticles can destroy the cell wall and produce ROS to kill microorganisms (Raliya et al., 2015; Mirhosseini et al., 2022). Likewise, Pullulan-based coatings create a dense oxygen and moisture barrier, and inhibit the growth of microorganisms during storage (Ramesh et al., 2020). In addition, the coated samples had a similar amount of slow growth compared to the uncoated samples in all samples, suggesting the influence of storage time, and the mean TVC count was significantly higher with the increasing storage time (Day 0: 1.91 $\rightarrow$ Day 28: 10.03 CFU/g, $p < 0.001$). The trend is consistent with the results of the microbial kinetics of other perishable fruits and vegetables under storage stress (Nayik et al., 2019). In short even if microbial growth was inevitable as time passed, the introduction of edible coating materials, especially those with the incorporation of ZnO nanoparticles, essential oils and chitosan,

amazingly delayed microbial deterioration and maintained the microbial count of TVC at an acceptable range longer than for uncoated fruits.

4.7.2. Yeast and Mold Count:

As in Figure 2 Yeast and Mold Count (YMC) increased in both treatments and storage time for 28 days, and there were significant differences between the treatments and the times ($p < 0.001$). The microbial count in the uncoated control (T-CTRL) showed the highest count, which shows tremendous increase from D0 (0.48cfu/g) to D28 (15.65cfu/g) implying that there is rapid fungal spoilage in the absence of any protective barrier. However all the coated samples, particularly the essential oil coated sample (T-EO), chitosan nanoparticles coated sample (T-CSNP), ZnO nano-coatings coated sample (T-ZnO), and nano-composite coatings coated sample (T-NCC), exhibited yeast and mold proliferation that was significantly lower. On Day 28, their average YMC was 8.03 to 8.23 CFU/g, which were considerably lower than T-CTRL. The same trend could be observed for the fungal load reduction where treatments T-ALG and T-PUL were relatively less effective with respect to EO or ZnO-based formulations. The Tukey grouping (Treatment Code) showed that there was a statistical difference between the T-CTRL (group A) and all the coating treatments (group B), which confirmed that the coatings had an antimicrobial effect ($p < 0.05$). The time-point comparisons also revealed that YMC increased with all treatments (Day 0: 0.94 CFU/g to Day 28: 9.14 CFU/g, $p < 0.001$), but this increase was significantly lower in coated fruits. The results align with those of past research which has indicated that chitosan and ZnO coating can hinder the growth of fungi by damaging cellular membranes and inhibiting spore germination (Khan et al., 2021; Maqbool et al., 2022). Similarly, essential oils have phenolic compounds and terpenes, which are reported to have antifungal activity against common moulds responsible for food spoilage (Ojagh et al., 2010; Hashemi et al., 2017). The findings collectively demonstrate the effectiveness of edible coating,

especially the combination of edible coating with nanoparticles and bioactive components for maintaining the safety of microorganisms in long-term storage. They also have a fungistatic effect, providing extra protection against fungal colonization of fresh produce which could be incorporated into post harvest packaging systems.

4.8. Effect of Nano-Coatings Decay %:

The percentage of decay of the fruits stored in different coating for 28 days is presented in Figure 3. The uncoated control group (T-CTRL) showed the most drastic degradation, with decay of 75%, on Day 28, and then a sudden rise since Day 14. The rapid decay emphasizes the rapid decay of uncoated produce due to uncontrolled microbial growth and water loss. Coated treatments, on the contrary, significantly slowed down decays. Out of all the above, it was concluded that T-ZnO (Chitosan-ZnO nano-coating) was the most protective exhibiting decay of only 32% on Day 28, followed by T-EO (Essential Oil-enriched coating) with decay of 35 % and T-CSNP (Chitosan nanoparticles) with 40 % decay. Such decreases can probably be explained by the synergistic effect of antimicrobial and oxygen-barrier potential of chitosan and zinc oxide nanoparticles that has been recently described in the literature (Aloui et al., 2021; Lu et al., 2022). The other coatings namely T-NCC (Nano-Composite Coating) and T-PUL (Pullulan Coating) also showed a fairly good result with decay being restricted to 38 and 42 percent, respectively. The matrices of these coatings were found to be polysaccharide based, which likely contributed to their protective functions as semi-permeable films with a regulating function for exchange of gases and moisture (Peretto et al., 2020). While T-ALG (Alginate Coating) was found to be superior over control (45% decay after Day 28), the efficiency of the formulation was comparatively low as compared to the nanoparticle or nano-composite formulations. The reduced antimicrobial efficacy of alginate, without the addition of bioactive agents, may be responsible for this (Torlak & Sert, 2020). As a whole the bio-

nanocomposite edible coatings effectively delayed decay and suppressed microbial activity, which is consistent with the results reported previously that such coatings effectively delayed senescence and slowed down the progression of decay (Liu et al., 2023).

4.9. Effect of Nano-Coatings Sensory Evaluation:

The sensory results for seven important attributes (appearance, smell, taste, flavour, aftertaste, bitterness, and overall acceptability) are shown in Figure 4 after 28 days of storage. The uncoated control group (T-CTRL) generally showed a noticeable decrease in all sensory characteristics during storage, particularly the appearance, taste, and overall acceptability, which decreased from ~8 to less than 6 by Day 28. This decrease is probably related to the increased rates of microbial spoilage, dehydration and oxidation reactions in the absence of protective coatings. In contrast, coated treatments had significantly higher and more constant sensory scores throughout the time. T-ZnO (Chitosan-ZnO Nano-Coating) and T-EO (Essential Oil Enriched Coating) performed the best among them with the lowest decrease in scores of taste, smell and overall acceptability. This could be attributed to the high antimicrobial and antioxidants activity of the coatings which helps in maintaining organoleptic properties of fruit (Singh et al., 2021; Gutierrez et al., 2020). The T-PUL (Pullulan Coating) and T-CSNP (Chitosan Nanoparticles) shown good stability in most of the sensory parameters as well, which is associated with their ability to behave as an excellent oxygen barrier and moisture control agent (de Oliveira et al., 2022). Although the results of these scores obtained by T-ALG (Alginate Coating) were relatively stable, it was less successful in retaining flavour and bitterness over time, which may be linked to the lower antimicrobial properties it possesses (unless actives are added) (Torlak & Sert, 2020). Generally these data support the claim that edible coatings, especially the ones involving nano-materials or essential oils, considerably enhance the sensory shelf-life of fresh produce. These results correspond to those obtained in the past

with the understanding that bioactive edible films have a place in ensuring the preservation of sensory properties during prolonged storage (Hassan et al., 2023).

Conclusion and Recommendations:

The present research indicated that the use of different edible nano-coatings (chitosan nanoparticles (CSNPs), nanocrystalline cellulose (NCC), pullulan, zinc oxide (ZnO) nanoparticles, essential oils (EOs) and alginate was effective for postharvest quality preservation of strawberries under refrigerated storage conditions. All the coating treatments strongly inhibited weight loss, firmness, titratable acidity and microbial growth compared to uncoated (control). The formulation that showed the highest antimicrobial activity was CSNPs and ZnO, while the pullulan and NCC coating was observed to be effective in preserving the physical characteristics such as texture and appearance. The sensory analyses also confirmed the observations of the nano-coated strawberries remaining acceptable for consumption for 21 days (nearly double the shelf life when compared with the control). However, these results show that nano-enabled coatings are a feasible and environmentally friendly approach to prolonging the shelf life of highly perishable fruits on a large scale and for biodegradation. Additional studies should be conducted on the assessment of the applied nanomaterials' safety and regulatory compliance in order to facilitate the ease of implementation. These coatings are also suggested to be tested on other perishable fruits in order to evaluate their more extensive usage. Moreover a combination with predictive shelf-life modeling and smart packaging technologies may improve the quality monitoring and minimize postharvest losses. These milestones will allow moving this technology out of the laboratory research and into the commercial area of fresh produce systems.

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Table 1. Comparative Functional Properties of Traditional and Nano-Enabled Edible Coating Materials for Postharvest Applications

Material Class	Coating Type	Water Vapor Permeability (WVP)*	O ₂ Transmission Rate (OTR)**	Tensile Strength	Bioactive Loading/Release	Antimicrobial Potential	Transparency (Visible Range)	Biodegradability
Polysaccharide	Bulk Chitosan	Moderate ($6-8 \times 10^{-11} \text{ g} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$)	Moderate (400–800 $\text{cc}/\text{m}^2 \cdot \text{d}$ ay)	20–30 MPa	Low; non-encapsulated	Moderate; pH-dependent	High	Complete
	Pullulan (bulk)	High ($\geq 10 \times 10^{-11} \text{ g} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$)	Excellent ($< 200 \text{ cc}/\text{m}^2 \cdot \text{d}$ ay)	40–65 MPa	Very low	Negligible	Very high	Complete
Lipid-based	Beeswax, Carnauba Wax	Very Low ($\leq 2 \times 10^{-11} \text{ g} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$)	Poor ($> 1000 \text{ cc}/\text{m}^2 \cdot \text{d}$ ay)	< 10 MPa	Minimal	Very low	Low	Partial (slow)
Nano-enabled	Chitosan Nanoparticles (CSNPs)	Low ($3-5 \times 10^{-11} \text{ g} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$)	Improved (300–500 $\text{cc}/\text{m}^2 \cdot \text{d}$ ay)	35–45 MPa	Moderate; sustained diffusion	High; contact-active	Moderate-High	Complete
	Nanocellulose	Low ($2-4 \times 10^{-11} \text{ g} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$)	Moderate (400–600 $\text{cc}/\text{m}^2 \cdot \text{d}$ ay)	> 60 MPa	Low	Negligible	Slightly opaque	Complete
Composite Nano	CSNPs + Nanocellulose + Pullulan (this study)	Very Low ($\leq 2.5 \times 10^{-11} \text{ g} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$)	Controlled ($< 300 \text{ cc}/\text{m}^2 \cdot \text{d}$ ay)	50–70 MPa	High; encapsulated + sustained	Broad-spectrum; synergistic	Transparent	

Table 2. Effectiveness of treatments on storage study of Ascorbic Acid, Firmness and Weight Loss%

Treatments	Ascorbic Acid					Firmness					Weight Loss %				
	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28
T-CTRL	65.03	62.91	60.71	58.7	56.91	8.19	6.55	3.99	2.18	0.01	0.57	4.04	7.99	10.66	14.64
T-ALG	64.91	63.57	63.24	61.9	60.38	8.4	7.64	6.56	5.36	4.41	0.55	1.94	3.27	5.71	7.48
T-CSNP	65.2	64.03	62.62	61.75	60.82	8.92	7.03	6.91	4.8	4.02	0.35	2.07	3.67	6.03	7.3
T-EO	65.3	63.88	63.34	62.18	60.69	8.89	7.01	6.52	5.78	4.69	0.55	2.11	3.82	5.83	7.44
T-NCC	65.2	63.96	62.92	61.67	60.71	8.47	7.55	6.52	5.07	5.01	0.27	2.3	4.45	6.07	7.79
T-PUL	65.53	64.26	63.35	61.66	60.3	7.69	7.66	6.37	5	4.24	0.82	2.1	3.69	5.9	7.33
T-ZnO	65.25	64.29	62.68	61.84	61.09	8.47	7.87	6.42	5.14	4.06	0.86	2.3	3.48	5.69	7.26

T-CTRL = Uncoated Control, T-ALG = Alginate Coating, T-CSNP = Chitosan Nanoparticle Coating, T-EO = Essential Oil-Based Coating, T-NCC = Nanocrystalline Cellulose Coating, T-PUL = Pullulan Coating, T-ZnO = Zinc Oxide Nanoparticle Coating

Table 3. Effectiveness of treatments on storage study of Respiratory Rates, Titratable Acidity and Total Soluble Solids (TSS)

Treatments	Respiratory Rate	Titratable Acidity	Total Soluble Solids (°Brix)
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	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28
T-CTRL	9.9 633	13. 86	16.9 67	21.2 23	24.2 37	1.1	0.2 73	0.30 3	0.25	0.05 7	7. 6 6 3	5. 7 7 3	4.52	3.34 67	1.95
T-ALG	10. 79	11. 273	13.5 17	15.3 57	17.1 17	0.8 87	0.0 73	0.31 7	0.24	-0.4	7. 5 8	6. 7 7	6.49 7	5.65 7	4.63
T-CSNP	9.8 67	12. 09	13.1	15.2 07	16.7 47	0.8 53	0.1 97	0.18 7	0.45	0.09 33	7. 1 5 7	7. 1 6	5.98	5.93	4.39
T-EO	10. 027	12. 377	13.2 53	14.9 67	16.5 43	1.3 7	0.6 7	0.32	0.22 7	0.30 7	7. 5 4 7	7. 1 5 7	6.30 7	5.67 3	4.46 3
T-NCC	9.9	12. 113	13.6 97	15.2 87	17.4 4	0.9	0.0 03	0.13	0.55 7	0.14 7	6. 9 4	6. 8 5 7	6.42 3	5.58 7	4.55 7
T-PUL	9.7 333	12. 05	14.0 8	15.3 77	17.3 13	1.0 77	0.2 87	0.04	0.47 3	0.14 3	7. 6 6 3 3	6. 4 9	5.9	5.08	4.28
T-ZnO	10. 06	12. 027	14.2 53	15.3 57	17.4	1.0 333	0.0 7	0.27	0.32	0.59 67	7. 7 7	7. 5 3 6 7	5.53 7	4.96 7	4.86

1T-CTRL = Uncoated Control, T-ALG = Alginate Coating, T-CSNP = Chitosan Nanoparticle Coating, T-EO = Essential Oil-Based Coating, T-NCC = Nanocrystalline Cellulose Coating, T-PUL = Pullulan Coating, T-ZnO = Zinc Oxide Nanoparticle Coating

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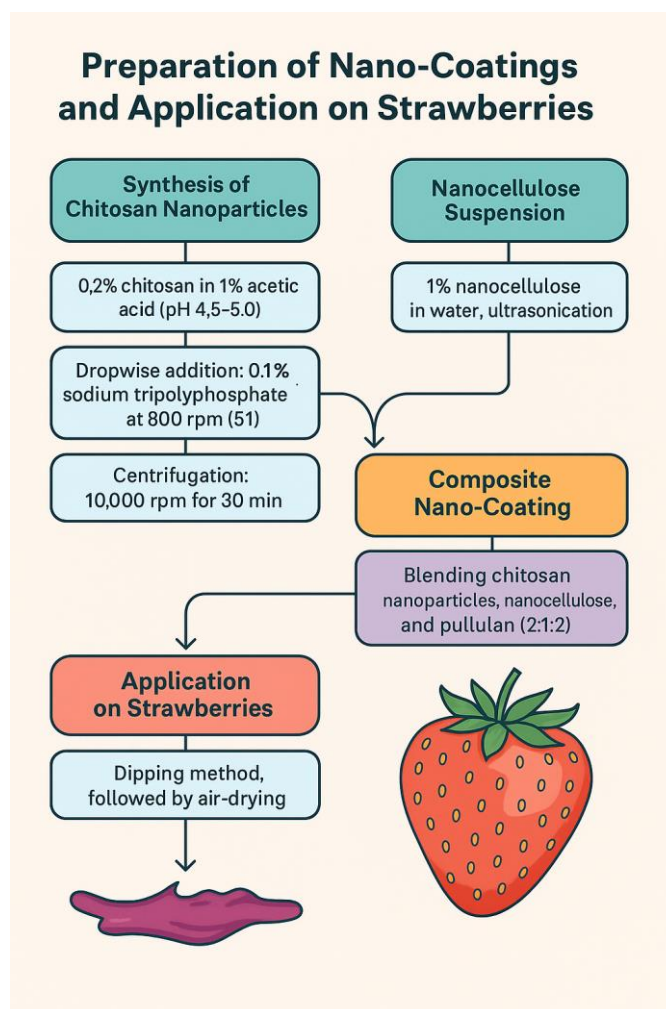


Figure 1. Flow diagram of Preparation of Nano-coatings and application on strawberries

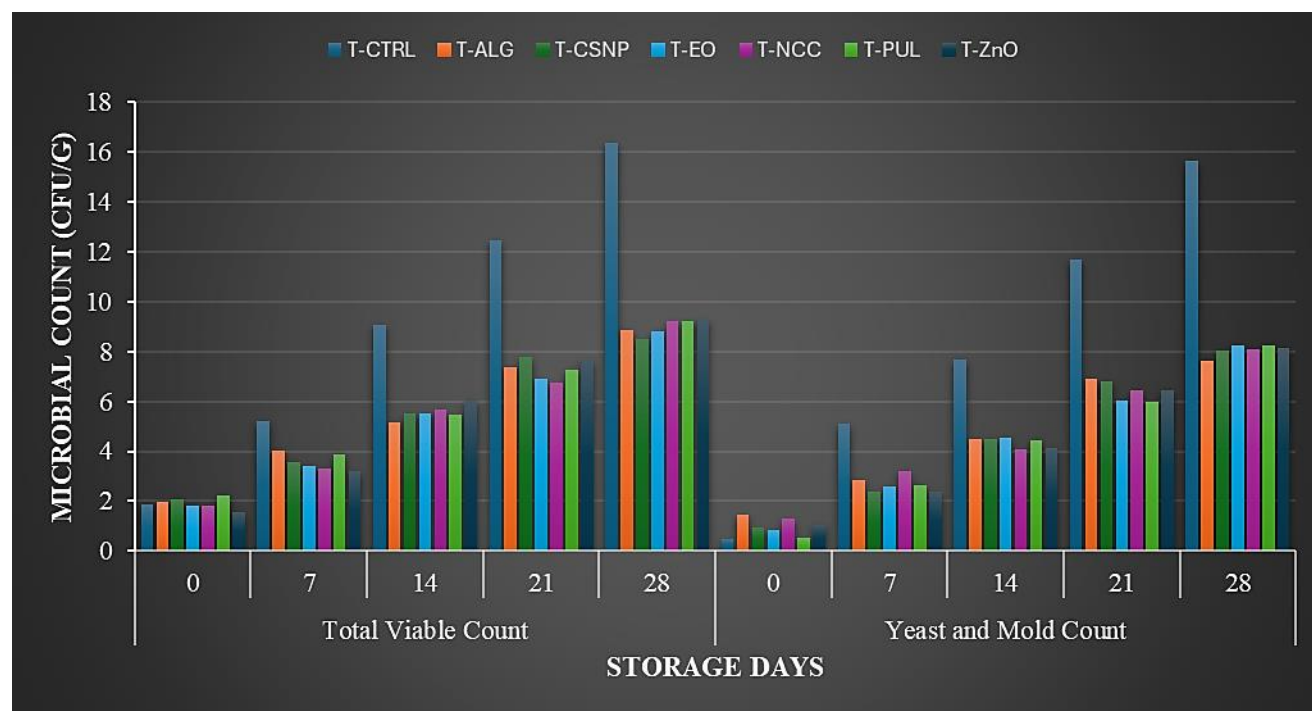


Figure 2. Effectiveness of treatments on storage study of Microbial contents (Total Viable Count and Yeast and Mold Count)

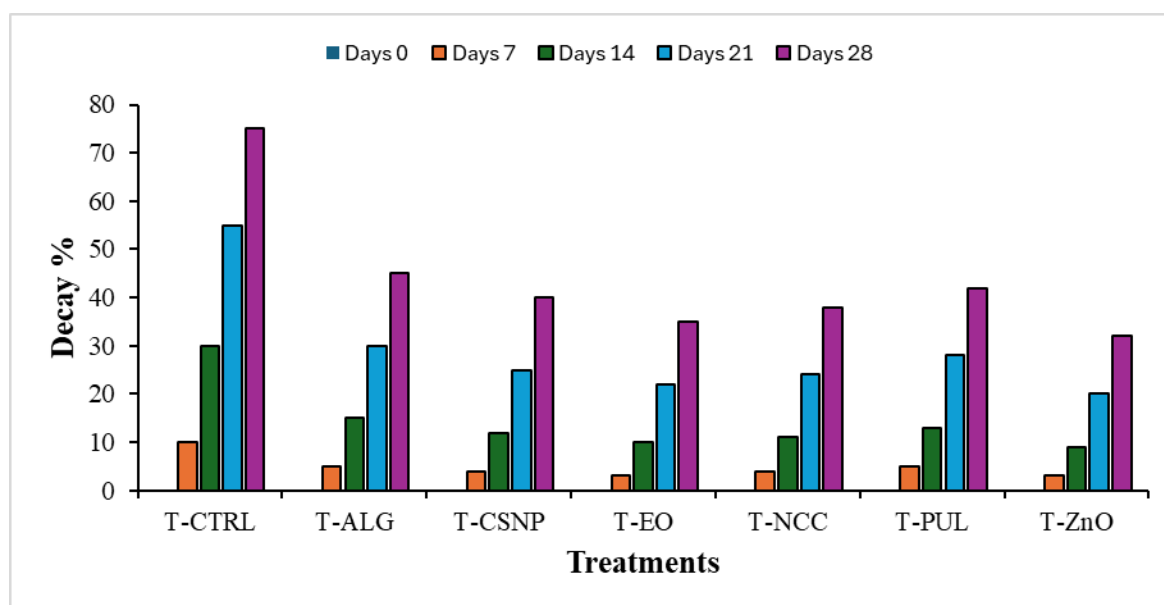


Figure 3. Effectiveness of treatments on storage study of Decay% of strawberries

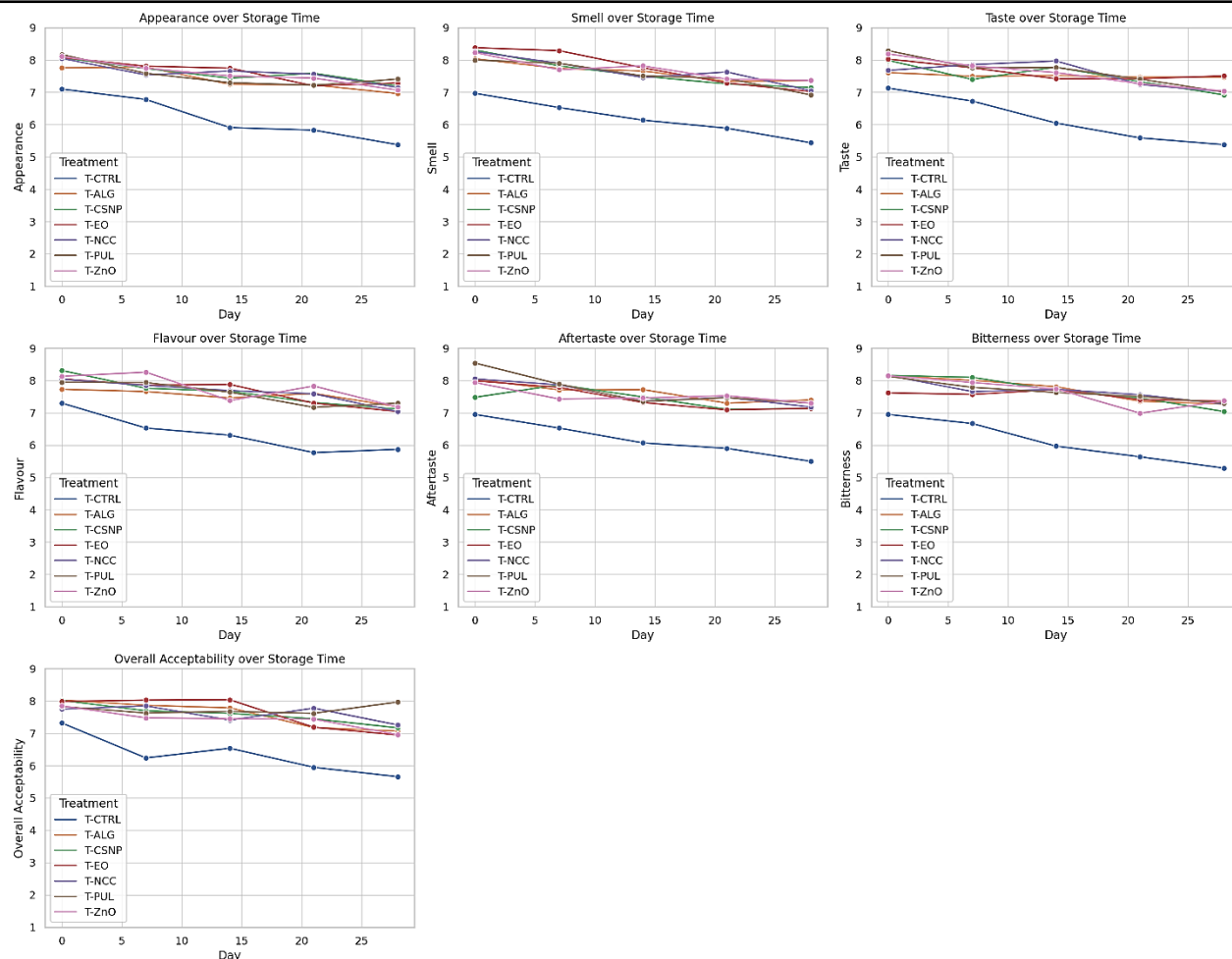


Figure 4. Effectiveness of treatments on storage study of Sensory Parameters