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Research Article

Extending Shelf Life of Strawberry Using Dill Seeds Powder Edible Coating Film

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Abstract

This study aimed to develop and evaluate a bioactive edible coating based on polyvinyl alcohol (PVA) incorporated with dill seed powder (DSP) to enhance the quality and shelf life of fresh strawberry during cold storage (4 ± 1 °C). DSP was characterized for its antioxidant capacity, phytochemical composition, and antimicrobial activity, revealing substantial levels of phenolics and flavonoids as well as strong inhibitory effects against major foodborne pathogens. Composite DSP/PVA films were prepared using the solution-casting method and assessed for mechanical, physical, and optical properties. The incorporation of DSP significantly improved film thickness, tensile strength, elongation at break, water vapor barrier performance, and UV-blocking capacity. Scanning Electron Microscope further confirmed the formation of a heterogeneous composite matrix containing well distributed phytochemical rich particles. When applied as a coating, DSP/PVA films effectively reduced moisture loss, maintained higher firmness, and better preserved titratable acidity, soluble solids, and anthocyanin content compared with the other with PVA. Microbiological assessments demonstrated that DSP/PVA coatings substantially suppressed total viable counts, psychrophilic bacteria, and mold and yeast populations throughout storage. Overall, the incorporation of dill seed powder into PVA-based films enhanced the functional properties of the edible coating filme and significantly improved the physicochemical stability and microbial quality of strawberries. These findings that DSP/PVA promising as natural and eco-friendly packaging alternative for extending the shelf life of highly perishable fruits.

Keywords: Edible Coating; Dill Seed Powder; Strawberry Shelf Life; Antioxidant and Antimicrobial Activity

Introduction

Processing, storage, and distribution, it is necessary to maintain stable environmental and chemical food storage parameters. Therefore, food must limit interaction with the external environment, which could lead to deterioration and loss of initial characteristics. Fruits, vegetables, cheese, processed meat, and fish products present a high risk of contamination by microorganisms due to high moisture, optimal pH, and features that promote microbial growth. In addition, lipid oxidation can change the concentration of certain chemical compounds in products, affecting nutritional and organoleptic characteristics [61].

Fresh strawberries (*Fragaria ananassa*) exhibit quality attributes that are largely determined by their colour, soluble solids

content, acidity, and characteristic flavour. Owing to their attractive sensory properties and the beneficial health effects associated with their bioactive compounds, strawberries possess considerable commercial value. However, the fruit has not achieved its expected economic prominence due to its inherently high respiration rate, which renders it highly perishable. Consequently, undesirable physicochemical alterations often occur during postharvest handling and storage, leading to a decline in overall quality and marketability [9].

The use of active components in edible films and coatings has been shown to improve the keeping quality of food products by modifying the internal atmosphere and enhancing sensorial characteristics. Natural compounds are preferred as additives instead of synthetic ones, which may result in toxic effects upon human consumption. Natural antioxidants derived from herbs, spices, fruits, vegetables, and plants are considered suitable alternatives for incorporation into films and coatings, as they help to retard deterioration processes associated with oxidative damage occurring in food products exposed to heat, light, or oxygen [47].

Several researchers have successfully incorporated naturally derived active components, such as caffeic acid, essential oils, propolis, ash gourd wax, whey protein, and green tea leaf extract, into biopolymer-based film-forming materials. These active components, possessing antimicrobial efficacy, contribute to antifungal effects, colour improvement, shelf-life extension, enhanced phytochemical potential, prevention of oxidation, and increased antioxidant activity. Bioactive components, including vitamins, minerals, polyphenols, fatty acids, volatile compounds, and pigments, are naturally present in many food products and are also extracted using suitable techniques from their natural sources for utilization as functional additives in edible films and coatings [34].

Anethum graveolens L. (dill) is a notable source of essential oils, particularly rich in D-carvone and D-phellandrene. These compounds constitute a major proportion of dill oil; however, when aerial parts are harvested prior to flowering, carvone may not be a predominant constituent. Dill essential oil has wide applications in pharmaceutical, health, and food industries due to its antioxidant, antimicrobial, and anti-inflammatory properties 333333. Nevertheless, the application of essential oils in food systems is limited by their instability under environmental conditions such as elevated temperature and light, which may lead to degradation of these bioactive compounds [37].

Dill seed essential oil, along with its polar and non-polar fractions and isolated compounds, has been evaluated for antioxidant potential using various *in vitro* assays [11]. In addition, seed oil and aqueous extracts exhibit antimicrobial and antifungal activities against several pathogenic microorganisms, including *Escherichia coli*, *Staphylococcus aureus*, *Shigella flexneri*, *Pseudomonas aeruginosa*, *Salmonella typhimurium*, and *Salmonella typhi*. Dill has long been used in Ayurvedic medicine for the treatment of rheumatic conditions, joint swelling, abdominal discomfort, and digestive disorders, and recent studies have demonstrated its hypoglycemic and cholesterol-lowering properties [40].

Therefore, the utilization of herbs, spices, and agricultural or forestry wastes as packaging materials and natural antioxidant sources for the development of antioxidant-active packaging films may represent a feasible and sustainable strategy for lipid preservation.

Materials and Methods

Materials

- Dill (*Anethum graveolens L.*) seeds were obtained from IMTENAN company and was separately beaten in the mill, and the sieved well to obtain the powder and it was stored in a tightly closed container before the start of the study.
- Fresh strawberry (*Fragaria ananassa*) used in the study was collected from local markets in El-Mansoura city, El-Dakahlya Governorate, Egypt.
- All chemicals were purchased from the SIGMA corporation on in Cairo, Egypt.

Methods

Technical methods

Preparation of bio-coating film

Polyvinyl alcohol (PVA) and dill seed powder (DSP)/PVA composite films were prepared using the solution casting method according to [62] with slight modifications. Two film-forming solutions were prepared: PVA film and DSP/PVA composite film, both containing the same concentration of sodium alginate. 2% (w/v) PVA film solution was prepared by dissolving PVA in 1% (m/v) acetic acid using a magnetic stirrer at 50 °C with continuous stirring for 2 h. 1% DSP/PVA solution was prepared by gelatinizing DSP at 50 °C for 15 min under constant stirring. The prepared PVA and DSP solutions were plasticized with 0.98% glycerol (m/v, based on total film solution volume) and mixed at a mass ratio of 1:1 (DSP/ PVA).

Coating method

Dipping is one of the most extensively used methods for edible coating of fresh fruits, achieving uniform coverage. The method involves immersing fruits in the coating solution for a specified period, typically ranging from 5 s to 3 min, followed by drying under ambient conditions and storage at 4 ± 1 °C [59].

Thickness and mechanical properties of all prepared films:

Film thickness

Film thickness was measured at five random positions using a handheld micrometer with a precision of 0.01 mm. The average thickness value was used for water vapor permeability calculations [16].

Tensile strength and elongation at break (EAB)

Mechanical properties were determined using a creep meter (RE-3305S, Yamaden, Tokyo) according to the method described by [10]. Film strips (20 mm × 30 mm) were fixed vertically between two grips set 17 mm apart and stretched at a constant rate of 0.5 mm s^{-1} until rupture. Measurements were conducted in triplicate

Physical characteristics of all prepared films

Film water vapor transmission rate analysis

WVTR was determined following the method described by [49]. Film samples (5 cm diameter) were sealed onto cups containing silica gel and placed in a desiccator maintained at 75% RH using NaCl solution at 25 °C. Weight gain was recorded every 24 h for six days. WVTR was calculated as:

$$WVTR = \frac{\Delta W}{t \times A}$$

Note: Δ *W* = Change in film weight after 24 hours

t = Times (24 hours)

A = Surface area (cm^2)

Colour

Film colour parameters (L*, a*, b*) were measured using a portable colorimeter (CR-300, Minolta, Osaka, Japan) against a white standard plate. Measurements were carried out in triplicate and the yellowness index (YI) was calculated according to Babak and Hadi [6]: All measurements were performed in three replicates. The Yellowness index (YI) was calculated as:

YI=142.86 b/L

Optical property

Optical properties were evaluated using a UV–Vis spectrophotometer. Film samples (1 × 3 cm) were scanned from 200–800 nm to determine light transmittance and UV barrier properties at 300, 360, and 390 nm [35].

Characterization of the film

Film morphology was examined using scanning electron microscopy (SEM), while functional groups were analyzed in ATR mode according to [63].

Antioxidant Activity, Phytochemicals content and Antimicrobial activity of dill seeds powder

Antioxidant assay DPPH radical scavenging method 2, 2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging: Antioxidant activ-

ity was determined using the DPPH radical scavenging method as described by [31]. Absorbance was measured at 517 nm, with ascorbic acid used as a standard.

Percentage inhibition (%) =

$$\frac{\text{Absorbance of control - Absorbance of sample}}{\text{Absorbance of control}} \times 100$$

Phytochemical content of dill seeds powder

Determination of total phenolic compounds (TPC)

TPC was determined using the Folin Ciocalteu method according to [31].

Determination of total flavonoids compounds (TFC)

TFC was determined according to the method described by [44].

Antimicrobial activity of dill seeds powder

Six microbial strains were selected to evaluate the antimicrobial activity of dill seed powder according to the method described by [30].

Determination of strawberry quality

The moisture content

Moisture content was determined by vacuum drying at 70 °C according to [1].

Fruit firmness

The firmness of fresh fruit was determined by measuring the compression force of the samples using a Fruits Hardness Tester Cat.

Total soluble Solids (TSS) Content and Titratable Acidity (TA)

TSS was measured using a hand refractometer according to [2]. Titratable acidity was determined following the method described by [20].

Measurement of anthocyanin content

Anthocyanin was extracted following the method of [23] and quantified according to [60].

Microbiological analysis

The microbiological analysis comprised the determination of total colony count, psychrophilic bacterial count and molds and yeasts was carried out as follows.

Preparation of sample for microbiological analysis

Under aseptic conditions, 50 grams of each sample were added to 450 ml of sterilized peptone water (1 gm/liter) in sterilized glass blender jar. The weighed samples were blended for 5 min. They provided a dilution of 10. appropriate serial dilution was made, and then samples were plated by standard microbiological pour plat technique for enumeration [15].

Total plate count (TPC)

Total plate count of bacteria was determined as (CFU/g) using plate count agar medium according to the procedures, described [15].

Psychrophilic bacterial count

Psychrophilic bacterial count was determined as (CFU/g) described in typical procedure of the total colony count method, except incubation was carried out at 7ºC for 5-7 days in refrigerator according to [12].

Molds and yeasts count

The mold and yeast were determined using the methods for the microbiological examination of foods described by [3].

Results and Discussion

Thickness and mechanical properties of films formulas

The mechanical properties of the tested samples in Table 1 demonstrated clear variations in thickness, tensile strength, and elongation at break, indicating differences in their structural integrity and internal polymer network arrangement. DSP/PVA film, which exhibited a greater thickness (1.30 mm), recorded higher tensile strength (1143 g) and elongation at break (45.8%) compared with PVA film (1.15 mm thickness, 990 g tensile strength, and 33.6% elongation). This trend suggests that increased thickness may con-

tribute to improved mechanical resistance due to enhanced intermolecular interactions and denser film matrix formation, as previously reported in biopolymer-based films [13].

The increase in tensile strength observed in DSP/PVA film reflects a more cohesive and strongly bonded internal network, which could be attributed to higher solid content, improved polymer chain entanglement, or the presence of reinforcing agents. Similar behavior has been documented for starch, protein-, and polysaccharide-based films, where enhanced matrix density led to improved tensile strength values [42].

Table 1: Thickness and Mechanical Properties of films formulas.

Formulas	Thickness (mm)	Tensile Strength (g)	Elongation at Break (%)
PVA	1.15	990	33.6
DSP/PVA	1.30	1143	45.8

PVA: Poly phenyl alcohol film, DSP/PVA: dill seeds powder and poly phenyl alcohol film.

Furthermore, the elongation at break followed the same increasing trend, indicating that DSP/PVA possesses greater flexibility and ductility. A higher elongation percentage typically signifies that the film can withstand greater deformation before rupture, which may result from increased moisture content, presence of plasticizers, or improved polymer compatibility [57]. These findings are consistent with earlier studies showing that thicker films tend to retain more moisture and exhibit higher extensibility [5].

Overall, the combined increase in tensile strength and elongation at break in DSP/PVA film indicates a more balanced mechanical behavior, achieving both strength and flexibility. Such mechanical profiles are desirable in applications such as food packaging, biodegradable films, and edible coatings, where structural durability and flexibility enhance performance and processing characteristics [50].

Physical characteristics of edible film

Film water vapor transmission rate and colour

Film Water Vapor Transmission Rate (WVTR) for edible films refers to the rate at which water vapor passes through the edible film material. WVTR is an important parameter that indicates the film's effectiveness as a moisture barrier, which is crucial in food packaging to maintain product quality and shelf life [24].

Following this, we analyzed the water vapor transmission properties and colour of PVA films Table 2. The control film (without dill powder) exhibited a water vapor transmission rate (WVTR) of 35 g/(d·cm^2), while the DSP/PVA film showed a reduced WVTR of approximately 22 g/(d·cm^2), demonstrating its effectiveness as a barrier to water vapor. Notably, the water vapor barrier properties of the DSP-PVA films were further enhanced through cross-linking with gallic acid and lysozyme, which significantly decreased the WVTR, indicating improved resistance to moisture permeation.

Similar improvements in WVTR have been observed in PVA-based films modified with cross-linking agents like gallic acid, where higher crosslinking reduces water uptake and swelling by forming ester bonds and limiting polymer chain mobility. These modifications align with established findings on chemically cross linked PVA membranes, confirming their efficacy in enhancing barrier properties for applications such as food packaging [51].

The colour of edible films serves as the primary visual cue for consumers evaluating their appearance and physical attributes, while also influencing the perceived quality of packaged products. The L* value quantifies lightness (0 = black, 100 = white), positive a* values indicate redness (increasing toward red), and positive b*

values denote yellowness (increasing toward yellow) [48]. The results in Table 2 showed an interaction ($p \leq 0.05$) between both factors on the brightness (L) of edible film. The highest L value indicates a brighter film, obtained in the control one 42.50 while the low L value signifies an increasingly dark film, derived at DSP/PVA that has 40.16. These results indicate that with the addition of dill seed powder can decrease the bright value of edible film. The measurement results by using the color reader show a positive value against all the samples indicating that the edible film is reddish. A positive value obtained 0.2 and 0.6. The results also showed an interaction ($p \leq 0.05$) between concentrations of yellow sweet potato starch and glycerol against a positive value of a.

Table 2: Physical Characteristics of films formulas.

Formulas	WVTR of Edible Film g/(d·cm^2)	Color Intensity of Edible Film		
		L	a *	b *
PVA	35	42.50^a	0.2^a	3.5^b
DSP/PVA	22	40.16^a	0.6^a	4.6^b

The added concentration of dill seeds powder and polyvinyl alcohol increases the redness of the edible film. The positive B value of all samples showed that the edible film is yellowish that records 3.5 and 4.6. The results also showed an interaction ($p \leq 0.05$) between both factors on a positive B value. The decrease in the L (brightness) is followed by an increase in the value of a+ and b+ along with the addition of dill seeds powder. It is related to the existence of carotenoids in dill seeds powder that can provide reddish color. Carotenoids are a group of natural pigments and antioxidants that lead to orange and red, yellow in plants [43].

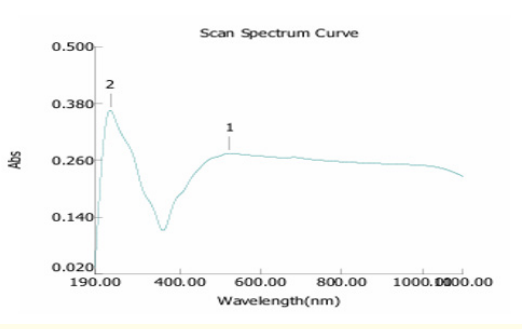

Figure 1: UV–Vis scan of film formulas (No.1: PVA, No.2: DSP/PVA).

Optical property of film

In figure 1 the UV–Vis scan spectrum curve was recorded to characterize the electronic absorption behavior of the sample over the wavelength range 190–1100 nm and to identify the most suitable wavelength for quantitative analysis. The spectrum exhibits an intense absorption band in the nearUV region with a maximum absorbance of approximately 0.38 and a broader, less intense band in the lowerenergy visible region with an absorbance of about 0.26, separated by a pronounced minimum around 350–400 nm. This pattern indicates the presence of at least two distinct electronic transitions or chromophoric centers in the molecule, supporting the use of the corresponding values as analytical wavelengths and as spectroscopic markers for probing the structural and environmental changes of the studied compound.

The presence of two wellresolved absorption bands provides a distinctive spectral fingerprint that can be used for qualitative identification of the compound and for monitoring structural or environmental changes (e.g., pH, complexation, binding). The absorbance values around 0.2–0.4 lie in the optimal range for applying the Beer–Lambert law, allowing accurate construction of calibration curves and reliable quantitative determination of concentration. Recording the spectrum from the deep UV to the nearIR reduces the risk of missing additional bands or interferences and supports confident selection of an appropriate λ_{max} away from noisy or overlapping regions. Because the spectrum is well defined and reproducible, it can be exploited in later work for kinetic studies,

stability monitoring, or method development (pharmaceutical, environmental, or materials analysis), increasing the scientific value of the data set.

Scanning electron microscope (SEM)

The surface morphologies of the edible films plasticized with dill seeds powder and PVA observed using SEM are depicted in Figure 2. The surface morphological structures of the films plasticized with sorbitol and glycerol affected their mechanical properties and WVTR. The SEM micrograph of the polyvinyl alcohol (PVA)-based edible film at ×500 magnification reveals a heterogeneous and semi-crystalline surface morphology, which is characteristic of PVA films depending on formulation parameters and drying behavior. The image displays irregular agglomerated particles and rounded polymeric domains dispersed within the matrix. Such surface features are typically attributed to polymer chain aggregation during solvent evaporation, leading to localized accumulation of PVA clusters. Similar aggregation phenomena have been reported in PVA films incorporating bioactive compounds or plasticizers, where intermolecular hydrogen bonding drives micro-scale clustering [4]. Several needle-like and plate-like crystalline structures are clearly visible, indicating the presence of highly ordered regions within the film. These crystalline domains arise from the ability of PVA chains to form strong intermolecular hydrogen bonds between hydroxyl groups, which enhance crystalline when the film undergoes controlled drying or limited plasticization [29]. The coexistence of amorphous agglomerates and ordered crystalline structures supports the classification of PVA as a semi-crystalline polymer, consistent with previous observations in food-grade PVA composites and biodegradable packaging films.

The SEM micrograph of the PVA/dill seeds powder composite film at ×200 magnification reveals a heterogeneous and highly textured microstructure, reflecting the interaction between the polyvinyl alcohol (PVA) matrix and the suspended plant powder particles. The surface morphology exhibits large irregular plate-like structures, angular fragments, and finely dispersed particulates, which are characteristic of films containing unextracted plant powders or phytochemical-rich particulates. The plate-like particles visible across the image correspond to the insoluble fibrous and lignocellulosic components naturally present in dill seeds powder. These particles typically include cellulose, hemicellulose, proteins, minerals, and crystalline phytochemical residues that remain intact during the film-casting and drying process. Their distribution within the matrix indicates partial but not complete integration into the PVA polymer network. Similar particle morphology has been documented for plant powder-loaded PVA biofilms [45].

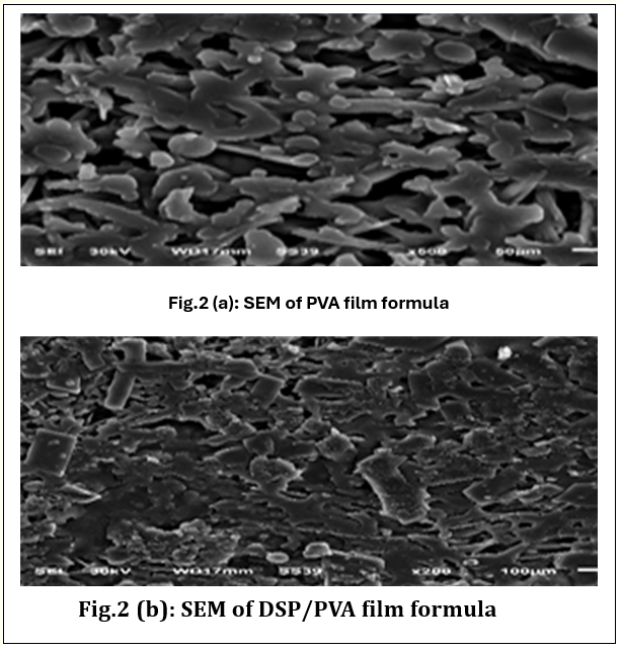

Fig.2 (a): SEM of PVA film formula

Fig.2 (b): SEM of DSP/PVA film formula

Figure 2: The morphologies of PVA and DSP\PVA films.

Overall, the SEM image confirms that the incorporation of dill seeds powder into PVA results in a composite edible film with a non-uniform, particulate rich morphology, where plant-derived crystalline and fibrous particles are embedded within the polymer structure. This microstructure is consistent with previous findings on PVA films reinforced with crude botanical powders, indicating partial miscibility and the formation of a composite network governed by particle–matrix interactions.

Evaluation of dill seeds powder

Dill seeds powder was evaluated for several properties namely Antioxidant Activity, Phytochemicals content and Antimicrobial activity. Results in Table 3 obtained that dill showed strong DPPH radical scavenging activity. The DPPH radical-scavenging assay demonstrated that dill extract possesses notable antioxidant activity, which increased in a concentration-dependent manner from 0.125 to 1.0 mg/mL (74–88%). Both vitamin C and BHT showed stronger scavenging activities at all concentrations, with BHT exhibiting the highest inhibition (80–95%) and vitamin C intermediate values (75–90%). The lower activity of dill relative to BHT and vitamin C may be attributed to the comparatively lower content of phenolic and flavonoid compounds in the extract, which are primarily responsible for hydrogen-donating and electron-transfer mechanisms in free radical neutralization [32]. Despite this, the substantial antioxidant potential of dill suggests that it could serve as a natural source of bioactive compounds for functional foods or nutraceutical applications. The observed concentration-dependent increase in activity aligns with previous studies reporting that higher concentrations of plant extracts correlate with enhanced radical-scavenging capacity due to a greater availability of electron-donating molecules [55]. Overall, the antioxidant efficacy of dill extract, though lower than standard antioxidants, highlights its potential as a natural and safe alternative to synthetic antioxidants.

Table 3: Antioxidant Activity, Phytochemicals content and Antimicrobial activity of Dill Seed Powder.

(A) Antioxidant activity (DPPH) of different concentrations of dill, BHT, and Vitamin C			
	Dill	Vit C	BHT
Concentration (mg/ml)	80	82	85
0.500 1.00	88	90	95
(B) Phytochemicals content Dill seeds powder			
TPC (mg GAE)	26.09 ± 0.16		
TFC (mg QE)	1.07 ± 0.28		
(C) Antimicrobial activity	Dill seeds powder	Antibiotic (Amoxicillin)	
Microorganism	Inhibition zone diameter, mm		
Escherichia coli	45.0 ± 1.50	27.0 ± 0.84	
Staphylococcus aureus	81.0 ± 2.16	28.0 ± 0.97	
Salmonella enteritids	30.0 ± 0.97	32.0 ± 0.96	
Listeria monocytogenes	25.0 ± 0.83	36.0 ± 0.72	
Bacillus subtilis	52.0 ± 1.38	38.0 ± 0.59	
Candida albicans	22.0 ± 0.57	N.T	

BHT: butylated hydroxytoluene, TPC: Total phenolic compounds, TFC: Total flavonoids compound, GAE: milligrams of Gallic Acid Equivalent, QE: milligrams of Quercetin Equivalent.

The dill seed powder analyzed in this study exhibited a total phenolic content (TPC) of 26.09 ± 0.16 mg GAE g^{-1} and a total flavonoid content (TFC) of 13.07 ± 0.28 mg QE g^{-1}. These levels indicate a considerable abundance of phenolic and flavonoid compounds, which align with the phytochemical profile typically reported for dill. Phenolic constituents in dill seeds are known to contribute significantly to antioxidant capacity and overall bioactivity [52].

Previous studies have reported wide variability in the phenolic content of dill seed extracts, generally ranging from 16 to 46 mg GAE g^{-1}, depending on the extraction solvent and procedure. Ethanolic extracts have shown TPC values like those obtained in the present study (around 26–30 mg GAE g^{-1}), suggesting that the extraction conditions applied here were effective in recovering phenolic compounds [8]. Likewise, the TFC value obtained (13.07 mg QE) falls within the range reported in earlier investigations, where dill seed TFC typically ranges between 13 and 20 mg QE [27].

The antimicrobial activity of dill seed powder demonstrated a pronounced inhibitory effect against a broad range of pathogenic microorganisms. The strongest activity was recorded against *Staphylococcus aureus* (81.0 ± 2.16 mm), followed by *Bacillus subtilis* (52.0 ± 1.38 mm) and *Escherichia coli* (45.0 ± 1.50 mm). These values were markedly higher than those produced by the antibiotic amoxicillin, indicating a superior natural antimicrobial potential of dill seeds. Showing that dill seed essential oil exhibits strong antibacterial activity, particularly against Gram-positive bacteria. It is found that *S. aureus* was the most sensitive strain to dill essential oil, presenting larger inhibition zones compared to *E. coli* and *Salmonella.* This aligns with the current observation where *S. aureus* showed the highest susceptibility among all tested strains [58].

Similarly, [17] reported that methanolic and ethanolic dill seed extracts effectively inhibited *S. aureus*, *L. monocytogenes*, *E. coli*, and *Salmonella spp.*, with the authors attributing this activity to phenolic compounds and monoterpenes. The strong inhibition observed in the present study against *E. coli* (45 mm) is comparable to those recorded for dill extracts in previous experiments, confirming the broad-spectrum antimicrobial efficacy of the seed constituents.

Chemical profiling studies showed that dill seeds are rich in carvone, limonene, anethofuran, dill apiole, and anethole which are known to disrupt microbial membranes and interfere with metabolic processes [46].

These findings provide mechanistic support for the strong inhibitory effects observed here. Additionally, recent work by [27] demonstrated that phenolic compounds in *A. graveolens* act synergistically, significantly enhancing antimicrobial potency. Such synergistic interactions may explain the unusually large inhibition zone recorded against *S. aureus* (81 mm), which exceeded both cephalexin (27 mm) and amoxicillin (28 mm) by a large margin.

In contrast, *Listeria monocytogenes* showed greater susceptibility to amoxicillin (36 mm) compared to dill powder (25 mm). A similar pattern was reported by [58] who noted that *Listeria* expresses moderate resistance to hydrophobic phytochemicals due to its thick peptidoglycan layer and adaptive stress response. Thus, the lower inhibition in this study is consistent with its known resilience toward plant-derived antimicrobials.

For *Salmonella enteritidis*, the dill seed powder produced an inhibition zone of 30 mm, comparable to amoxicillin (32 mm). Previous studies also reported moderate susceptibility of *Salmonella* to dill extracts [17], supporting the present findings. The dill seed powder demonstrated significant antifungal activity against Candida albicans (22.0 ± 0.57 mm).

These results support previous findings and further demonstrate that dill seed powder is a promising natural antimicrobial agent with potential applications in food preservation, pharmaceuticals, and natural therapeutic formulations. Its ability to outperform conventional antibiotics against certain pathogens highlights its relevance in combating antimicrobial resistance.

Effect of coating process on physio-chemical properties of strawberry fruits during cold storage at (4 ± 1 °C)

Fruits and vegetables continue to respire and transpire after harvesting as living organisms. They are characterized by a high

respiration rate and reducing the respiration and transpiration rates can extend their shelf life. This reducing can be done by controlling some factors such as temperature, relative humidity, light and mechanical damage, using some treatments as waxing and irradiation [9].

The moisture content

The results of moisture content have been shown in Figure 3 demonstrated the effects of various coatings on moisture content of strawberry during the storage time. Moisture decreased when the PVA was mixed with DSP, while maintaining firmness and soluble solids content.

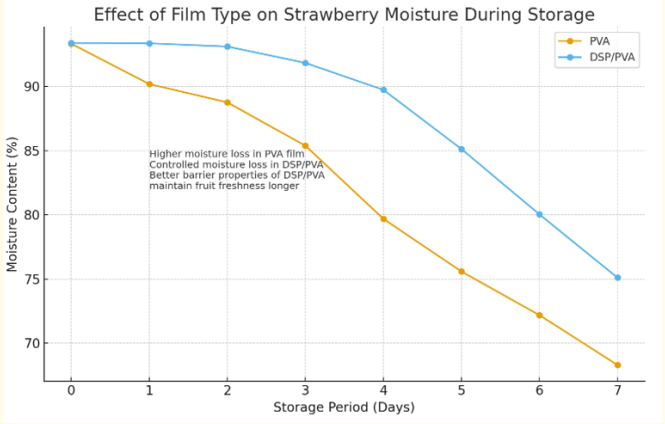

Figure 3: Change of coating process on moisture of strawberry under cold storage (4 ± 1 ºC).

The obtained results in Figure 3 clearly demonstrate that moisture content decreased progressively with increasing storage period. However, the rate of moisture loss was highly dependent on the type of coating film used, namely Polyvinyl Alcohol (PVA) and the DSP/PVA composite film. Strawberry exhibited a pronounced decline in moisture content from 93.32% at day 0 to 68.30% after 7 days. Strawberries are known to be highly perishable due to their elevated respiration and transpiration rates, which explains the rapid moisture loss observed during storage. This behavior agrees with the postharvest physiology described by [25], which indicates that strawberries are extremely susceptible to moisture loss and softening during refrigerated storage. When coated with DSP/PVA film, moisture content dropped more slowly from 93.38% to 75.10% over 7 days, demonstrating significantly better moisture retention compared to PVA alone. This confirms the enhanced barrier efficiency of the composite film, which effectively limits transpiration and vapor diffusion. These results strongly support the conclusions of [56] who reported that Multilayer and composite edible films provide significantly lower water vapor permeability compared to single-layer films.

Fruit firmness (Ib/inch2)

The effect of PVA and DSP/PVA coatings on the firmness of ° strawberry stored under refrigeration (4 ± 1 °C) is presented in Table 4. A continuous decline in firmness was observed in all treatments during storage; however, the rate of softening differed markedly between coating formulations.

Table 4: Changes of firmness(Ib/inch2) of coated strawberry samples during cooling storage (4ºC ±1).

Storage period (day)	Strawberry samples	
	PVA	DSP/PVA
0	228	228
1	215	228
2	213	228
3	208	220
4	208	217
5	200	217
6	195	210
7	190	208

For strawberries stored at 4 ± 1 °C, firmness decreased from 228 to 190 in PVA-coated samples after seven days (≈16.7% loss), while DSP/PVA-coated fruits retained higher firmness, decreasing only to 208 (≈8.8% loss). This demonstrates that the DSP/PVA coating provided nearly double the firmness preservation compared with PVA alone. These findings are consistent with those of [26], who reported that PVA-based edible coatings enriched with grape pomace extract significantly slowed textural degradation in strawberries during cold storage. Likewise, [19] observed improved mechanical stability and firmness retention in strawberries treated with mul-

tifunctional biopolymer coatings due to reduced water vapor permeability and delayed pectin solubilization.

Although the present study confirms the superior performance of DSP/PVA over PVA alone, it should be noted that the specific abbreviation "DSP" is not yet widely standardized in the literature. Nevertheless, the general trend observed here strongly agrees with previous studies showing that the incorporation of bioactive or reinforcing additives into PVA matrices markedly enhances coating efficiency in maintaining fruit firmness. This improvement is mainly associated with the formation of a denser polymeric network, which limits gas exchange, retards moisture migration, and suppresses the activity of cell wall degrading enzymes such as polygalacturonase and pectin methyl esterase. Therefore, the notable firmness preservation achieved by DSP/PVA in strawberry demonstrates its strong potential as an advanced edible coating for extending postharvest quality under both ambient and refrigerated storage conditions.

Total soluble Solids (TSS) Content and Titratable Acidity (TA)

Total soluble solids (TSS) play an important role in affecting fruit quality and consumer acceptability. TSS content of fruits samples as affected by coatings with DSP\PVA during storage at room and cold temperatures throughout the storage period are presented in Table 5.

Table 5: Changes of Total Soluble Solids of coated strawberry samples during cooling storage (4ºC ±1).

Storage period (day)	Strawberry samples	
	PVA	DSP/PVA
0	10.2	10.2
1	10.2	10.2
2	10.0	10.2
3	9.5	10
4	9.5	10
5	9.2	9.8
6	8.8	9.8
7	8.2	8.2

The results show that coating strawberry fruits with PVA and DSP/PVA affected the pattern of total soluble solids (TSS) during storage at cooling storage (4ºC ± 1). Strawberry, exhibited a smaller fluctuation in TSS, although DSP/PVA maintained slightly higher values than PVA as storage progressed. An increase in TSS during ripening is generally associated with enzymatic hydrolysis of starch and complex carbohydrates into simple sugars, a well-established phenomenon in climacteric fruits, particularly bananas [32]. In addition, moisture loss during storage concentrates soluble solids; therefore, even when metabolic sugar synthesis slows down, dehydration can still contribute to elevated TSS values [22].

Edible coatings such as PVA are known to function as semi-permeable barriers that reduce respiration rate and delay ripening by limiting gas exchange and water vapor transmission [39]. Studies on bananas coated with PVA or PVA-based composites have demonstrated delayed starch degradation and improved maintenance of soluble sugars compared with uncoated fruit [64]. This aligns with the pattern seen here, where DSP/PVA-coated bananas recorded the highest TSS values by the end of storage.

Composite coatings, particularly those incorporating bioactive compounds or additional polymers, generally possess enhanced antioxidant and barrier properties, which further retard senescence and sugar depletion [36]. This supports the superior performance of DSP/PVA over PVA alone in your results, suggesting that the DSP component likely strengthened the coating matrix and contributed to reduced respiration and moisture loss.

Overall, the results indicate that DSP/PVA is more effective than PVA in maintaining or enhancing soluble solid content in strawberry during storage, likely due to improved barrier properties and delayed metabolic degradation. These findings are consistent with literature highlighting the advantages of composite edible coatings for preserving postharvest quality.

The titratable acidity of fruits plays a key role in their taste. The organic non-volatile acids are among the most important components and represent the second most important component of fruits flavor, after soluble sugars [28].

The effect of coatings by PVA and DSP\PVA on Titratable acidity content for strawberry fruits is presented in Table 6. The Titratable acidity (TA) value strawberry showed a gradual decline during storage, with DSP/PVA coated samples maintaining higher acidity compared to PVA alone in fruits. This pattern is consistent with known postharvest physiological changes in climacteric and non-climacteric fruits.

Table 6: Changed of Titratable acidity (%) of coated strawberry samples during cooling storage (4ºC ± 1).

Storage period (day)	Strawberry samples	
	PVA	DSP/PVA
0	7.25	7.25
1	7.25	7.22
2	7.22	7.22
3	7.10	7.18
4	6.96	7.18
5	6.90	6.95
6	6.33	6.54
7	5.84	6.10

For strawberry, a non-climacteric fruit, TA also showed a downward trend from 7.25% to 5.84% in PVA-coated samples and 7.25% to 6.10% under DSP/PVA. Strawberries typically lose acidity during storage due to the conversion of acids into sugars and CO_2 via respiratory pathways, as well as structural degradation of tissues [53]. Studies confirm that edible coatings help maintain acidity for longer periods by reducing respiratory metabolism and slowing senescence [21]. The present results align with this, as the DSP/PVA coating slowed the decline in TA compared with the PVA coating, particularly after day 3.

Furthermore, maintenance of acidity is often correlated with delayed softening and improved sensory quality, since organic acids contribute to flavor and postharvest freshness [54]. The higher TA in DSP/PVA-coated fruits suggests that this composite coating provided stronger protection against moisture loss and oxidative reactions, thereby prolonging the biochemical stability of organic acids during storage.

Overall, the TA data demonstrates that DSP/PVA is more effective than PVA in slowing acid degradation in both banana and strawberry.

Anthocyanin content

Colour is the most important factor which describes the fruit general quality. The effect of coating on anthocyanin content for fruits treated by PVA and DSP\PVA at different levels was studied and the results are presented in Table 7.

Table 7: Changed of Anthocyanin content of coated strawberry samples during cooling storage (4ºC ± 1).

Storage period (day)	Strawberry	
	PVA	DSP/PVA
0	42.50	42.50
1	44.78	46.12
2	48.54	50.33
3	50.12	54.12
4	46.50	49.88
5	44.12	48.21
6	40.44	46.42
7	38.51	45.81

The total anthocyanin content of strawberry exhibited a characteristic initial increase during the early storage period (0–3 days), followed by a gradual decline thereafter. Such early increases have been documented in coated fruits and attributed to stress induced biochemical activity and improved pigment extractability due to modified micro-atmosphere created by edible coatings [26]. In the present study, both coating systems showed this trend; however, fruits treated with DSP/PVA consistently recorded higher anthocyanin values than those coated with PVA alone.

The superior performance of DSP/PVA became evident at day 3, where DSP/PVA coated strawberry reached 54.12 mg/100 g, values higher than their PVA counterparts. This enhancement can be explained by the incorporation of phenolic rich date seed powder

(DSP) into the PVA matrix. DSP contains abundant phenolic antioxidants capable of scavenging reactive oxygen species and protecting anthocyanin from oxidative degradation.

During mid-to-late storage (days 4–7), anthocyanin content declined in all treatments due to natural oxidative, enzymatic, and structural degradation pathways common in postharvest fruit systems. Nonetheless, DSP/PVA markedly slowed pigment loss. Notably, DSP/PVA-coated strawberries maintained anthocyanin levels above their initial baseline at day 7, indicating a strong protective effect.

In contrast, only PVA forming a good mechanical barrier does not supply additional antioxidant capacity and therefore shows limited ability to inhibit oxidative degradation, as also reported in previous studies on neat PVA films [7]. This explains the more pronounced decline in anthocyanin values in PVA treatments toward the end of storage. Collectively, the results highlight a synergistic interaction between PVA and DSP. While PVA controls transpiration and gas exchange, DSP contributes phenolic antioxidants that intercept free radicals and delay anthocyanin decomposition. This synergism aligns with established mechanisms describing the stabilization of monomeric anthocyanin and the protective influence of natural antioxidants embedded in edible coatings [18].

Microbiological evaluation

Controlling the microbial load is a fundamental prerequisite for maintaining the overall quality of food products throughout processing and storage. Effective microbial management not only delays spoilage and extends shelf-life but also preserves key physicochemical and sensory attributes that are highly sensitive to microbial deterioration. Moreover, strict regulation of microbial contamination represents a critical factor in ensuring the hygienic integrity and safety of the final product, thereby safeguarding consumer health and meeting international quality standards [65].

The changes of TBC, mold and yeast count during storage for uncoated and coated fruits are exhibited in Tables 8,9,10.

Total count of bacteria (TC)

Results in table 8 show a clear change in the total number of bacteria observed in covered and exposed samples during storage refrigeration (strawberry samples), as it was found that the total number of bacteria increased gradually with increasing storage period, but the results in the covered samples with DSP\PVA were better than the covered ones with PVA only.

The microbiological evaluation of coated strawberry samples revealed clear differences in total viable counts (TVC; CFU/g) as a function of coating type and storage period. At the beginning of storage (day 0), all samples exhibited similarly low microbial loads ($\sim 10^2$ CFU/g), reflecting the natural background flora of freshly harvested fruits. As storage progressed, TVC increased in all treatments; however, the magnitude of increase varied substantially between PVA and DSP/PVA coatings and fruit matrices.

Table 8: Total count of bacteria of coated strawberry samples during cooling storage (4 ± 1 ˚C).

Storage period (day)	Strawberry samples	
	PVA	DSP/PVA
0	2.18 ×10 (CFU/g)	2.18 ×10 (CFU/g)
1	2.76 ×10 (CFU/g)	2.18 ×10 (CFU/g)
2	3.11 ×10^2 (CFU/g)	3.00 ×10^2 (CFU/g)
3	2.18 ×10^3 (CFU/g)	3.34 ×10^2 (CFU/g)
4	4.54 ×10^3 (CFU/g)	2.20 ×10^3 (CFU/g)
5	5.01 ×10^4 (CFU/g)	3.90 ×10^3 (CFU/g)
6	5.56 ×10^4 (CFU/g)	2.18 ×10^4 (CFU/g)
7	5.89 ×10^4 (CFU/g)	3.43 ×10^4 (CFU/g)

For strawberry, using PVA, microbial counts reached 2.18 × 10^3 CFU/g by day 3 and increased further to 5.89 × 10^4 CFU/g by day 7. The DSP/PVA coating consistently maintained lower TVC across storage, with values of 3.34 × 10^2 CFU/g on day 3 and 3.43 × 10^4 CFU/g on day 7. These differences correspond to reductions of 0.82 log10 on day 3 and 0.24 log10 on day 7.

The enhanced antimicrobial performance of DSP/PVA coatings is likely attributable to both chemical and physical protective mechanisms. Dill seed powder contains phenolic compounds and other bioactive constituents with documented antimicrobial properties against foodborne and spoilage microorganisms. Incorporation of these phytochemicals into the PVA matrix enables a gradual migration or surface interaction that suppresses microbial viabil-

ity, consistent with previous demonstrations of antimicrobial activity in date-seed extracts [13].

Additionally, DSP particles may modify the structural and barrier characteristics of the PVA film by reducing oxygen permeability, altering surface hydrophobicity, and limiting moisture availability thereby creating a less favorable microenvironment for microbial growth. Similar effects have been reported in other plant extract enriched PVA coatings applied to fresh fruits, including strawberries [26].

From a practical standpoint, total viable counts approaching 10^7–10^8 CFU/g typically indicate the onset of spoilage or loss of acceptable hygiene quality in fresh produce.

Psychrophilic bacterial count

The microbial enumeration for plate-count bacteria (PBC) illustrated distinct differences between coating treatments (PVA vs. DSP/PVA) over the storage period in both banana and strawberry Table 9. At day 0, strawberry exhibited low counts (≈ 10^2 CFU/g), indicating good initial microbiological quality. However, over storage time, a marked increase in bacterial load was observed, with differences in the rate of growth depending on the type of coating used.

Table 9: Psychrophilic bacterial count of coated strawberry samples during cooling storage (4 ± 1 °C).

Storage period (day)	Strawberry samples	
	PVA	DSP/PVA
0	2.10 ×10 (CFU/g)	2.10 ×10 (CFU/g)
1	2.88 ×10 (CFU/g)	2.18 ×10 (CFU/g)
2	2.54 ×10^2 (CFU/g)	2.18 ×10 (CFU/g)
3	3.18 ×10^3 (CFU/g)	3.34 ×10^2 (CFU/g)
4	4.22 ×10^3 (CFU/g)	2.55 ×10^3 (CFU/g)
5	5.10 ×10^4 (CFU/g)	3.94 ×10^3 (CFU/g)
6	5.50 ×10^4 (CFU/g)	2.48 ×10^4 (CFU/g)
7	6.80 ×10^4 (CFU/g)	3.76 ×10^4 (CFU/g)

For strawberry, PVA-coated samples showed moderate bacterial increases: from ~2.10 × 10^2 CFU/g at day 0 to ~3.18 × 10^3 CFU/g at day 3, 4.22 × 10^3 CFU/g at day 4, and 5.10 × 10^4 CFU/g by day 5. The DSP/PVA coating again demonstrated an inhibitory effect maintaining lower counts throughout storage 2.10 × 10^2 CFU/g (day 0), ~2.18 × 10^2 CFU/g (day 2), ~3.34 × 10^2 CFU/g (day 3), ~2.55 × 10^3 CFU/g (day 4), and ~3.94 × 10^3 CFU/g by day 5. By day 5 the difference is roughly about one log lower (≈ 10^3 vs. 10^4 CFU/g) compared to PVA alone.

This consistent suppression of microbial growth in DSP/PVA treated fruits suggests that the DSP/PVA coating provides more effective microbial control than PVA alone. The likely mechanisms are twofold. First, incorporation of dill seed (or date-derived) phenolic compounds into PVA matrix may impart antimicrobial activity. Plant phenolics derived polyphenols are well documented to inhibit or reduce growth of spoilage and pathogenic bacteria by disrupting membrane integrity, interfering with enzyme systems, or generating oxidative stress to microbes. Indeed, formulations combining PVA with natural phenolic extracts have shown improved microbial inhibition in fresh produce.

Physical barrier effect of the DSP/PVA coating likely reduces oxygen permeability and surface moisture two key factors that affect microbial growth on fruit surfaces. Edible coatings are known to modulate gas exchange and water loss, thereby creating a less favorable microenvironment for bacterial proliferation [41].

This combined chemical (antimicrobial phenolics) and physical (barrier) mechanisms can explain the observed delayed bacterial growth in DSP/PVA-coated banana and strawberry samples. From a shelf-life and food-safety standpoint, the difference is practically significant. In contrast, DSP/PVA coatings kept counts lower (≈ 10^3–10^4 CFU/g) over the same period, indicating a possible extension of shelf life by at least several days under similar storage conditions.

Molds and yeasts count

Mold and yeast growth is a critical indicator of fruit spoilage, as these microorganisms rapidly proliferate under high-moisture

and high-sugar conditions typical of fresh produce. In the present study, strawberry samples exhibited a progressive increase in mold and yeast counts during storage; however, the rate and extent of microbial development differed markedly depending on the applied coating material.

Table 10: Mold and Yeast count of coated strawberry samples during cooling storage (4 ± 1˚C).

Storage period (day)	Strawberry	
	PVA	DSP/PVA
0	0 ×10 (CFU/g)	0 ×10 (CFU/g)
1	0 ×10 (CFU/g)	0 ×10 (CFU/g)/g)
2	2.94 ×10 (CFU/g)	0 ×10 (CFU/g)
3	3.58 $\times 10^3$ (CFU/g)	2.34 $\times 10^2$ (CFU/g)
4	4.12 $\times 10^3$ (CFU/g)	3.55 $\times 10^3$ (CFU/g)
5	5.33 $\times 10^4$ (CFU/g)	3.94 $\times 10^3$ (CFU/g)
6	6.50 $\times 10^4$ (CFU/g)	4.48 $\times 10^4$ (CFU/g)
7	6.14 $\times 10^5$ (CFU/g)	4.90 $\times 10^4$ (CFU/g)

At day 0, all samples recorded non-detectable levels of mold and yeast, confirming good initial hygienic quality. By day 1, strawberries remained free of contamination. In strawberries, for which DSP/PVA coatings significantly inhibited fungal proliferation (2.34 $\times 10^2$ CFU/g) compared to PVA alone (3.58 $\times 10^3$ CFU/g). This reduction strongly suggests that incorporating date seed powder (DSP) into PVA enhances the antimicrobial efficacy of the coating. These findings agree with previous evidence demonstrating that plant-derived phenolics and flavonoids possess strong antifungal properties. For example, [26] reported that integrating grape pomace extract into PVA-based edible coatings markedly suppressed mold and yeast growth on strawberries throughout cold storage, attributing the effect to the high phenolic content and antioxidant activity of the incorporated plant material. The parallel behavior observed in the present study reinforces the hypothesis that DSP contributes antifungal bioactive compounds capable of disrupting fungal cell walls and inhibiting spore germination. By the end of the storage period, the performance gap between treatments widened considerably. Strawberry results showed that although fungal proliferation increased in all samples, DSP/PVA coated fruits consistently displayed the lowest microbial loads (e.g., 4.90 $\times 10^4$ CFU/g at day 7 versus 6.14 $\times 10^5$ CFU/g in the PVA group). Overall, the results demonstrate that DSP/PVA coatings provided superior protection against mold and yeast growth in both fruits compared to PVA alone. The enhanced antimicrobial activity is likely due to the synergistic effect between the structural barrier properties of PVA and the bioactive phytochemicals naturally present in DSP. This aligns closely with previously published findings on plant-enhanced edible coatings, supporting the use of such materials for extending shelf life and improving the microbiological stability of perishable fruits.

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