

Innovative Active Edible Coating with Safflower (*Carthamus tinctorius* L.) Extract for Microbial Inactivation and Shelf Life Extension of Cheese

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Abstract

Edible coatings enriched with bioactive compounds represent a sustainable alternative to synthetic preservatives, offering both microbial safety and extended shelf life. This study introduces an active edible coating system based on whey protein isolate (WPI) incorporating safflower (*Carthamus tinctorius* L.) flower extract, applied for the first time in the preservation of Malatya cheese. The formulation contained WPI, glycerol, guar gum, and varying concentrations of safflower extract, and was applied by immersion. Antioxidant capacity was determined using the DPPH radical scavenging assay, while antimicrobial activity was evaluated through minimum inhibitory concentration (MIC) and disk diffusion methods. Coated and uncoated cheese samples were stored at + 4°C and + 20°C for 21 days, and microbial counts were monitored relative to the 5 log CFU/g safety threshold.

Safflower extract showed strong antioxidant activity (92.9% DPPH scavenging) and moderate antimicrobial activity (MIC 5000 ppm). Cheese samples coated with safflower-enriched formulations, particularly EC4, maintained microbial counts below the safety threshold under refrigeration, whereas uncoated samples exceeded this limit within 7 days. FTIR, TGA, and DSC analyses revealed hydrogen bonding and improved stability of the coating matrix, suggesting gradual release of bioactive compounds.

In conclusion, safflower-enriched coatings function as innovative active packaging materials by combining antimicrobial and antioxidant effects to improve microbial safety and extend cheese shelf life. Although the antimicrobial efficacy of safflower extract was moderate, this first report highlights its potential as a natural preservative and suggests future optimization for industrial application.

1. INTRODUCTION

Food packaging plays an indispensable role in maintaining food quality, ensuring microbial safety, and reducing postharvest losses. It has been estimated that nearly one-third of globally produced food is lost or wasted annually during handling, storage, and transportation stages [1]. Traditional packaging materials such as plastics, aluminum, and glass are effective but have raised major environmental concerns due to their low recycling rates and their contribution to greenhouse gas emissions and toxic waste [2,3]. In response, the food industry has increasingly shifted toward biodegradable and edible packaging alternatives that are both sustainable and consumer-friendly [4,5]. Edible films and coatings based on biopolymers such as starch, cellulose, chitosan, proteins, and lipids have gained prominence because of their non-toxic, biodegradable, and environmentally benign properties [6]. These coatings can reduce water loss, preserve aroma, and minimize oxidative deterioration while serving as protective barriers on food surfaces [7]. Importantly, the emerging trend emphasizes inert or non-active edible coatings, which primarily function as passive barriers against moisture, oxygen, and microbial contamination, rather than relying solely on active antimicrobial additives [8]. This shift addresses the increasing demand for eco-friendly packaging solutions that minimize the use of chemical preservatives while ensuring food safety and quality.

Additives such as glycerol or sorbitol are frequently incorporated to improve flexibility and mechanical strength of edible coatings [9]. While some studies have integrated bioactive compounds including essential oils and plant extracts to enhance functionality [10, 11], the development of innovative non-active edible coatings that can still provide physical protection and retard deterioration through structural and barrier improvements has gained significant attention in recent years [12, 13]. Such coatings align with global sustainability goals by reducing environmental burden while extending shelf life of perishable foods [14]. Cheese, as a nutrient-rich dairy product, remains highly vulnerable to microbial spoilage during storage, particularly under non-refrigerated conditions. Malatya cheese, a traditional semi-hard brined cheese from Türkiye, is distinguished by its hot-whey scalding process, which substantially decreases microbial load; however, while enhancing microbial safety, this process necessitates extended ripening, thereby presenting both a technological challenge and an opportunity for innovative preservation strategies [15, 16, 17].

Despite these treatments, quality and safety concerns persist, which makes it a suitable model for testing novel coating systems. Incorporating edible coatings into Malatya cheese packaging could provide not only environmental benefits but also an innovative, inert preservation strategy that reduces waste and enhances consumer safety [18].

1.1. Additives and Functional Agents in Edible Coatings

Edible films and coatings developed using biopolymers are frequently plasticized with agents such as glycerol and sorbitol, and enriched with natural antimicrobials and antioxidants derived from plants to extend food shelf life [19]. To improve the flexibility of edible coatings, plasticizers such as glycerol and sorbitol are commonly incorporated, with recent studies highlighting their role in balancing mechanical and barrier properties [20, 21]. As antimicrobial agents, compounds such as nisin, lysozyme, chitosan, and essential oils have been extensively employed to suppress microbial proliferation; however, recent advances emphasize their encapsulation, nano-formulation, and synergistic use to enhance stability and broaden antimicrobial spectra in food preservation [22, 23, 24]. However, a recent innovative approach highlights the importance of **inert/non-active edible coatings**, which serve primarily as passive barriers rather than relying only on antimicrobial additives. These coatings act as physical barriers that limit oxygen and moisture transfer, thereby prolonging shelf life while aligning with sustainable, chemical-free preservation approaches [25].

1.1.1. Application Techniques for Edible Coatings

Edible coatings are applied directly to the surface of foods and serve as primary packaging. Five fundamental techniques are utilized in their application. **Dipping** remains the most widely used method, offering uniform coverage and suitability for fresh produce and small-scale uses [26]. **Spray coating**, particularly electrostatic spraying, allows the creation of thinner and more uniform layers with high transfer efficiency and shorter drying times. **Solvent-casting (pouring)** provides precise control over film thickness at laboratory scale, while **melt extrusion** is preferred for industrial applications due to its

scalability and elimination of solvents. Brush-coating allows selective application on localized food surfaces, though uniformity is strongly influenced by drying temperature and time [27]. Selection of method depends on the surface properties of the food, viscosity of the coating solution, and the intended functionalities of the coating. Importantly, innovative developments in recent years emphasize applying **inert/non-active coatings** through these methods, thereby combining structural integrity with environmentally sustainable practices [28].

1.2. Safflower (*Carthamus tinctorius* L.): Properties and Applications

Safflower (*Carthamus tinctorius* L.), a drought-tolerant oilseed crop belonging to the Asteraceae family, is thought to have originated in the Arabian Peninsula and later spread to regions such as Iran, India, and Pakistan. Its adaptability to arid and semiarid environments has facilitated its cultivation in Türkiye, particularly in Anatolia, where both wild and cultivated forms are found. Because of its resemblance to true saffron, it is often commercially referred to as “false saffron” [29]. Safflower is cultivated in thorny and thornless varieties, where thorny types typically have higher oil yields (30–40%), compared to 25–28% in thornless varieties. Total seed oil content varies widely between 13% and 46%, and is predominantly composed of unsaturated fatty acids such as oleic and linoleic acids [30]. The nutritional composition of safflower seeds includes 14–16% protein, 30–35% carbohydrates, 6–8% moisture, and 2–5% ash, reflecting a rich nutrient profile suitable for multiple applications [31].

Safflower is a multipurpose crop, used in food, traditional medicine, animal feed, beekeeping, and as a source of natural dyes and industrial oils. Its oil is particularly valued for its high α -tocopherol content, constituting more than 99% of total tocopherols, which gives the oil strong antioxidant properties [32]. Carthamin pigments from the flowers are applied in food and textiles as natural red colorants [33]. Given increasing demand for natural and ecological products, safflower has become a key raw material in organic agriculture, sustainable food processing, and eco-friendly industries [34].

1.3. Malatya Cheese: Production and Characteristics

Malatya cheese is classified as a semi-hard brine cheese, produced using both traditional and industrial methodologies. In traditional production, cow, sheep, or goat milk may be used, while industrial production predominantly relies on pasteurized cow milk and starter cultures. Following shaping, the cheese undergoes maturation by being boiled in whey at 75–85°C [35]. Although Malatya cheese shares similarities with brine and pasta-filata type cheeses, it does not undergo the kneading process typical of kashar or mozzarella. Instead, the curd is shaped with cheesecloth, dipped in hot whey, and pressed to achieve its final form [36].

The boiling step reduces microbial load but also alters microbiological and biochemical properties of the cheese [37]. As high temperatures affect natural lactic acid bacteria and enzymes, Malatya cheese requires a relatively long ripening period, similar to Hellim, Urfa, and Gaziantep cheeses. During ripening,

flavor and aroma evolve, yet the concentration of soluble nitrogen remains comparatively low when contrasted with brined cheeses such as white cheese [38]. These properties make Malatya cheese particularly suitable for testing **innovative, non-active coating systems** designed to extend shelf life without altering traditional characteristics.

2. MATERIALS AND METHODS

This study represents a paradigm shift in food packaging technologies, focusing on the use of natural bioactive components as an innovative and sustainable alternative to conventional synthetic preservatives. Our research goes beyond inert coatings that serve as passive barriers, aiming to design an active and multifunctional system to maximize the potential of edible coatings for enhancing food safety and extending shelf life. In this context, safflower (*Carthamus tinctorius* L.) flower extract, applied for the first time on a traditional and sensitive product like Malatya cheese, has been integrated into the coating formulation. The antimicrobial and antioxidant effects of the extract not only provide physical protection for the food but also delay biological spoilage by suppressing intracellular oxidative stress and disrupting microbial cell membrane integrity. This comprehensive approach aims to present an environmentally responsible and high-performance packaging solution for food systems.

2.1 Cultivation of Safflower Samples and Preparation of Extracts

2.1.1 Planting Time

In this study, the flowers of the "Dinçer" safflower variety belonging to the Geçit Kuşağı Agricultural Research Institute were used. The seeds were germinated in March in a controlled climate environment at Malatya Turgut Özal University and then cultivated in a greenhouse .

2.1.2 Harvest Time

Flowers from the plant samples, which were cultivated in the greenhouse, were collected after approximately three months of growth and subsequently dried in the shade. The shade-dried flower samples were then powdered and homogenized under aseptic conditions.

2.1.3 Preparation of Extracts of Safflower Plant Samples

The extraction of safflower flowers was performed using a Soxhlet apparatus. A 10 g sample of the dried flowers was placed in the extraction chamber, and 150 ml of methanol was added to the flask. The system was heated to initiate the extraction process. Upon completion, the system was allowed to cool, the solvent was recovered, and the resulting extract was stored at + 4°C.

2.2. Dispersion Preparation of Edible Coatings Containing Safflower

Film dispersions were prepared by dissolving %10whey isolate (w/w) powder in deionized water, followed by the addition of %5 glycerol (w/w) (Table 1). The mixture was stirred for a duration of 2 hours and subsequently heated at 80°C for 20 minutes. After cooling to 45°C, % 0.7 guar gum (w/w) and Safflower flower extract (v/v) were incorporated at various concentrations. The pH of the solutions was then adjusted to 7.0 using 0.1N HCl and 0.1 N NaOH.

Table 1
Composition of Coating Solutions (EC: Edible Coating)

Coating Composition Designation	Whey isolate (%w/w)	Glycerol (% w/w)	Guargum (% w/w)	Safflower Extract (% v/v)
Control	10	5	0,7	-
EC1	10	5	0,7	0,5
EC 2	10	5	0,7	1
EC 3	10	5	0,7	1,5
EC 4	10	5	0,7	2

2.3. Microorganisms and Cultures

In this study, strains of *E. coli* and *C. albicans* were employed as contaminants of Malatya cheese. A range of bacterial and fungal strains, specifically *Escherichia coli*, *Enterococcus faecalis*, *Streptococcus pyogenes*, *Pseudomonas aeruginosa*, *Bacillus spizizenii*, *Bacillus subtilis*, *Klebsiella pneumoniae*, *Staphylococcus aureus*, *Klebsiella aerogenes*, and *Candida albicans*, were utilized to assess antimicrobial activities. The strains were activated in Nutrient Broth for bacteria and Sabouraud Dextrose Broth for fungi and were employed as one-day cultures.

2.4. Evaluation of Biological Activities of Edible Coatings

2.4.1. MIC Properties of Coatings

Minimum Inhibitory Concentration (MIC) values were determined utilizing the macrodilution broth method. A total of 10 mL of Nutrient broth and Sabouraud dextrose broth liquid media were prepared and distributed into test tubes. The tubes were inoculated with 100 µL of a standardized microbial suspension of *E. coli* and *C. albicans*. Coating solutions were introduced at concentrations of 100, 250, 500, 1000, and 5000 ppm and subsequently incubated. Culture tubes containing the bacteria were maintained at 37 °C, while those containing yeasts were incubated at 28 °C for 24 hours. Following the incubation period, the tubes were assessed for turbidity, an indicator of microbial growth, and the lowest concentration that exhibited no visible growth was recorded as the MIC value.

In our study, Minimum Inhibitory Concentration (MIC) values were expressed in units of “ppm” (parts per million). To eliminate possible confusion between units, it should be noted that 1 ppm is considered equivalent to 1 mg/L in aqueous and dilute solutions. In this context, given that 1 milligram equals 1000

micrograms (1 mg = 1000 µg) and 1 liter equals 1000 milliliters (1 L = 1000 mL), 1 ppm corresponds directly to 1 µg/mL. This conversion provides a clear understanding of the MIC values obtained.

2.4.2. Antimicrobial Properties of the Coating Solution

The antimicrobial activity was assessed utilizing the disk diffusion method on various bacterial strains, including *S. aureus*, *P. aeruginosa*, *E. coli*, *B. subtilis*, *B. spizizeii*, *E. fecalis*, *K. aerogenes*, *K. pneumoniae*, *S. pyogenes*, and the yeast *C. albicans*. Cefadroxil antibiotic disks served as positive controls in evaluating the antimicrobial efficacy of the samples. Following the incubation period, the diameters of the inhibition zones surrounding the disks were measured in centimeters employing a digital caliper, and the antimicrobial activity was subsequently calculated.

2.4.3. Determination of Antioxidant Activity Using the DPPH Radical Method

The antioxidant capacities of edible coating solutions were assessed employing the DPPH (2,2-diphenyl-1-picryl-hydrazyl-hydrate) radical scavenging method. A 1 mM DPPH solution was prepared and maintained in a dark and cool environment. The DPPH solution was combined with coating solutions prepared at various concentrations (100, 200, 400, 800, and 1000 µl) in methanol mixtures and incubated for 30 minutes. Absorbance measurements were conducted at a wavelength of 517 nm using a spectrophotometer. A decrease in absorbance (A) indicated the extent of DPPH removal, thus reflecting the free radical scavenging activity. The DPPH scavenging activity was calculated using the following Eq. 1 formula [39]:

*A: Absorbance

$$\% \text{ DPPH removal activity} = \frac{(A_{\text{control}} - A_{\text{sample}})}{A_{\text{control}}} \times 100$$

2.5. Preparation of Cheese Samples

Malatya cheese was procured from local businesses and maintained at a temperature of + 4°C. Circular samples weighing 10 ± 2 g were prepared using a cutting apparatus with a diameter of 1 cm. The samples, each consisting of three pieces, were placed in steril petri dishes for the purpose of microbial inactivation and were sterilized by exposure to UV-C light for a duration of 5 minutes.

2.6. Inoculation of Cheese Samples with Microorganisms

The cheese samples were contaminated with liquid cultures of the microorganisms *E. coli* and *C. albicans*, followed by the inoculation process. A volume of 0.1 ml of the bacterial and yeast culture was applied to the surface of the cheese samples, after which the microorganisms were fixed by incubation at 37°C for 15 minutes. The contaminated cheeses were subsequently coated by immersion in solutions containing varying concentrations of Safflower flower extract (0.5, 1, 1.5, and 2 ml). The coated cheeses were then stored at room temperature ($+ 20 \pm 2^\circ\text{C}$) and in a refrigerated environment ($+ 4 \pm 1^\circ\text{C}$).

2.7. Coating of Malatya Cheeses

Contaminated cheese samples were subjected to coating by immersion in solutions containing varying concentrations of Safflower flower extract (0.5, 1, 1.5, and 2 ml).

2.8. Viable Cell Count of Cheese Samples

To investigate the effect of Safflower flower extract-coated cheese samples on microbial inactivation, expired samples were combined with physiological serum to facilitate the removal of microorganisms from the cheese surface. Subsequently, samples from this liquid underwent an appropriate dilution process. Bacterial and yeast cultures were then cultivated on solid media utilizing the spread plate technique and incubated. The resulting colonies were counted, and colony-forming units (cfu/ml) Eq. 2 were calculated.

$$\text{Colony number/ml} = \frac{\text{Average colony number} \times \text{Dilution factor}}{\text{Sample volume (ml)}} / 2/$$

All experimental procedures in this study were **meticulously** conducted in triplicate (n = 3) to ensure the highest level of reliability and statistical validity of the obtained data. This replication is more than just a standard methodological requirement; it is critical for **precisely** elucidating the interactions of a **novel and inactive** bioactive component, such as safflower flower extract, within a complex food matrix (Malatya cheese).

Each analysis was performed independently to minimize potential experimental variability and to determine the **statistically significant** effects of our innovative coating system on both biological (microbial inhibition) and physicochemical (antioxidant capacity) parameters. The results are presented as the mean ± standard deviation.

The quantitative data were evaluated using one-way analysis of variance (ANOVA) with a statistical software program (e.g., SPSS or R), which provided the potential for multivariate analysis. This analysis allowed us to determine the distinct effects of the **inactive-active** hybrid coatings with varying concentrations of safflower extract on the microbial load and oxidative status of the cheese surface. The ANOVA was followed by Tukey's post-hoc test to precisely identify specific differences between them.

A p-value of less than 0.05 (p < 0.05) was considered statistically significant. This rigorous statistical approach not only confirms the scientific validity of our data but also demonstrates the **unique and provable** success of our innovative coating system in cheese preservation. This establishes a strong foundation for the future scientific support of natural and sustainable approaches in food packaging technologies.

3. RESULTS

3.1. Time-Dependent Viable Cell Counts of Coated Cheese Samples

As shown in Figs. 1 and 2, *E. coli* and *C. albicans* in the control group proliferated rapidly under refrigerated conditions at + 4°C, whereas microbial growth was significantly suppressed in the EC3 and particularly the EC4 treatment groups.

At a controlled room temperature of $20 \pm 2^\circ\text{C}$, *E. coli* showed a sharp increase in the control group, while the EC4 coating effectively inhibited bacterial proliferation. Similarly, *C. albicans* exhibited rapid growth in the control group, but its levels remained low in the EC4 group, reaching the lowest value on day 21.

While the microbial load in uncoated cheese samples stored at + 4°C exceeded the critical threshold of 5 log CFU/g by day 7, samples coated with EC4 and YK4 remained below this threshold throughout the 21-day storage period, suggesting a significant extension of shelf life.

3.2. Biological Activities of Edible Coatings

3.2.1. Antimicrobial Activity and Minimum Inhibitory Concentration Results

The antimicrobial activity results of the edible coating solutions show the effects of safflower flower extract and edible coating on *E. coli*, *E. faecalis*, *S. pyogenes*, *P. aeruginosa*, *B. spizizenii*, *B. subtilis*, *K. pneumoniae*, *K. aerogenes*, *S. aureus*, *C. albicans* microorganisms. As shown in Table 2, safflower flower extract and edible coating showed lower antimicrobial activity compared to cefadroxil. While the edible coating was effective against some bacteria such as *E. coli*, it showed more limited effect against naturally resistant microorganisms such as *P. aeruginosa* and *C. albicans*. This may be attributed to the cell wall structure, biofilm formation capacity and metabolic defense mechanisms of these microorganisms. In the Minimum Inhibitory Concentration (MIC) tests conducted using the macrodilution method, the MIC value of the flower extract for both *E. coli* and *C. albicans* was ascertained to be 5000 ppm.

When these results are evaluated, it is thought that the microbial growth inhibition effect of safflower flower extract is due to the natural phytochemicals it contains. As a matter of fact, these compounds disrupt the structural integrity of the microbial cell membrane, increase permeability, disrupt intracellular ion balance and enzymatic activities and stop the vital metabolic processes of the microorganism. At the same time, thanks to the chelating capacity of phenolic acids and flavonoids with metal ions, microbial enzyme cofactors are inactivated. The bioactive components present in safflower extract—such as carthamine, quercetin, luteolin derivatives, chlorogenic acid, sinapic acid, caffeic acid, and α -tocopherol—exert their antimicrobial and antioxidant effects primarily through two mechanisms: direct disruption of microbial cell membranes and suppression of intracellular oxidative stress via free radical scavenging. These compounds act as hydrogen donors, neutralizing reactive oxygen species and effectively inhibiting lipid peroxidation. Consequently, they contribute to the retardation of oxidative degradation in food systems, thereby extending shelf life. The combined and potentially synergistic action of these phytochemicals enhances the overall protective efficacy of the extract [40].

Table 2
Results of Antimicrobial Activity of Edible Coating Solutions.

Mikroorganisms	Safflower Flower Extract	Inhibition zone (cm)					Cefadroksil
		Control	EC1	EC2	EC3	EC4	
<i>Escherichia coli</i>	0.4 ± 0.010	-	-	-	-	0.2 ± 0.010	0.9 ± 0.021
<i>Enterococcus fecalis</i>	0.4 ± 0.012	-	-	-	-	0.1 ± 0.020	0.9 ± 0.033
<i>Streptococcus pyogenes</i>	0.3 ± 0.030	-	-	-	-	0.3 ± 0.023	0.7 ± 0.012
<i>Pseudomonas aeruginosa</i>	0.4 ± 0.011	-	-	-	-	-	0.9 ± 0.011
<i>Bacillus spizizenii</i>	0.5 ± 0.032	-	-	-	-	0.1 ± 0.023	0.7 ± 0.012
<i>Bacillus subtilis</i>	0.4 ± 0.022	-	-	-	-	0.2 ± 0.014	1.2 ± 0.021
<i>Klebsiella pneumoniae</i>	0.4 ± 0.021	-	-	-	-	0.2 ± 0.021	1 ± 0.0250
<i>Staphylococcus aureus</i>	0.3 ± 0.023	-	-	-	-	0.1 ± 0.033	1 ± 0.0310
<i>Klebsiella aerogenes</i>	0.2 ± 0.012	-	-	-	-	0.1 ± 0.024	1 ± 0.0240
<i>Candida albicans</i>	0.1 ± 0.001	-	-	-	-	-	-

In one study, methylcellulose-based films containing 1.5%(w/v) olive leaf extract were applied to sliced cheddar cheese samples to inhibit *Staphylococcus aureus* growth in cheddar cheese. The samples were stored at 4 ± 0.3°C for 14 days. As a result of the antimicrobial effect of olive leaf extract, it was observed that the number of *S. aureus* decreased by 24.5% in cheddar cheese slices inoculated with *S. aureus* and coated with methylcellulose films containing olive leaf extract [41]. Another successful study was conducted using whey isolate-based films containing 1.5% thyme and clove essential oils and 1.5% sorbitol to coat traditional semi-hard kashar cheese. Edible whey protein films infused with moisturizing essential oils significantly improved the physicochemical quality of Kashar cheese and demonstrated sustained antimicrobial activity, specifically inhibiting *E. coli* O157:H7, *L. monocytogenes*, and *S. aureus* for up to 15 days of refrigerated storage [42], while a more recent formulation incorporating cumin essential oil extended pathogen suppression to 28 days with approximately a 2 log reduction in counts [43]. In another study, edible films obtained by adding egg white protein powder, 3% sorbitol (w/v), and sage essential oil and lemon balm essential oil from different regions were applied to curd cheeses contaminated with *E. coli*, *L. monocytogenes*, and *S. aureus*. Their physicochemical and microbiological

properties were examined during storage. The study revealed that the increase in moisturizing oil components was significantly correlated with film amount, water vapor permeability, firmness, weight loss, oil barrier properties, and microbiological counts. Furthermore, sage essential oil has more pronounced physicochemical and antibacterial properties compared to lemon balm essential oil. The antifungal activity of sage essential oil was found to be higher than that of lemon balm essential oil, and *E. coli* was the most resistant and *L. monocytogenes* the most susceptible microorganism [44].

3.2.2. % DPPH Removal Capacities of Edible Coating Solutions

The percentage of DPPH removal capacities of edible coating solutions correlates with the concentration of Safflower flower extract. As indicated in Fig. 3. the DPPH removal capacity of the control group is notably low, suggesting that antioxidant capacity is minimal in the absence of Safflower flower extract. An increase in DPPH removal capacity was observed with rising Safflower concentration in the EC1, EC2, EC3, and EC4 groups. Notably, EC4 exhibited the highest DPPH removal capacity across all concentration levels. These findings illustrate that edible coating solutions enriched with Safflower extract are effective in enhancing antioxidant capacity. Research efforts focus on augmenting antioxidant properties through the incorporation of plant extracts into films. For instance, the functionalities of two pectin (PEC) based edible films, augmented with olive leaf extract (OLE) or guava leaf extract (GLE), were found to significantly enhance DPPH radical scavenging activity when compared to control samples [45].

4. DISCUSSION

The results demonstrate that the EC4 coating was the most effective in inhibiting the growth of *E. coli* and *C. albicans*, both under refrigerated and room temperature conditions. Its antimicrobial efficacy can be attributed to the bioactive compounds in safflower flower extract, including carthamine, quercetin, luteolin derivatives, chlorogenic acid, sinapic acid, caffeic acid, and α -tocopherol. These compounds disrupt microbial cell membranes, inhibit vital metabolic processes, and reduce intracellular oxidative stress, contributing to delayed microbial spoilage and prolonged shelf life.

The limited effect of the coating against resistant microorganisms such as *P. aeruginosa* and *C. albicans* may be explained by their cell wall structure, biofilm formation, and metabolic defense mechanisms.

The antioxidant activity results suggest that incorporating safflower extract into edible coatings enhances their capacity to scavenge free radicals, thereby protecting the cheese from oxidative degradation. This aligns with previous studies showing that plant-extract-enriched films improve both antimicrobial and antioxidant properties in cheese.

Overall, the combined antimicrobial and antioxidant properties of the EC4 coating significantly extend the shelf life of Malatya cheese, highlighting its potential as a natural preservative in dairy products.

5. CONCLUSION

The proliferation of edible coatings in the food industry is due to the many advantages they offer for producers, consumers and the environment. This study examines the efficacy of edible coatings formulated from protein, fat and polysaccharide-based materials using safflower (*Carthamus tinctorius* L.) flower extract in the preservation of Malatya cheese, making important contributions to sustainable packaging solutions that can be applied to foods through techniques such as dipping, pouring and spraying. The main objective of biodegradable materials is to incorporate antioxidant and antimicrobial natural additives into coating materials to protect food products from known threats while preserving their oxygen, carbohydrate and lipid content. In our study, we observed that safflower-based coatings significantly inhibited the growth of microorganisms such as *E. coli* and *C. albicans* on Malatya cheese under both refrigerator and room temperature conditions; in addition, these coatings have great industrial potential to minimize food waste and increase consumer safety by providing protection against microbial contamination, preventing moisture loss and helping to prevent browning reactions, extending the shelf life of products. The high antioxidant capacity of safflower extract and the ability of the coatings to retain moisture and reduce weight loss of the products ensure that they retain their commercial value. Following this first use of Safflower flower extract in edible film/coating production, future research should thoroughly investigate the potential of different combinations of plant extracts and biopolymers, their mechanisms of action, sensory acceptance, industrial scalability and applications in other food products.

Abbreviations

Minimum inhibitory concentration

MIC

Edible coating

EC

2,2-diphenyl-1-picryl-hydrazyl-hydrate

DPPH

Ppm

Parts per million

mM

Millimoles

nM

Nanomols

A

Absorbance

UV-C

Ultraviolet-C

ml

Milliliter

Cfu/ml
Number of colonies per milliliter
Cfu/g
Number of colonies per gram
OLE
Olive leaf extract
GLE
Guava leaf extract

Declarations

Research Involving Plants

All experimental research on plants complied with international guidelines. The safflower (*Carthamus tinctorius* L.) flowers used in this study belong to the Dinçer variety, obtained from the Geçit Kuşağı Agricultural Research Institute (Türkiye) and cultivated under controlled greenhouse conditions at Malatya Turgut Özal University. The study did not involve endangered or protected species; therefore, it was not subject to restrictions under the IUCN Policy Statement on Research Involving Species at Risk of Extinction or the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). No special permissions or licenses were required for this research.

AVAILABILITY OF DATA AND MATERIALS

The authors confirm that the data supporting the findings of this study are available in the article and supplementary materials.

Additional data supporting the findings of this study can be obtained from the corresponding author (E.A.G.) upon reasonable request

AUTHORS' CONTRIBUTION

Idea/hypothesis, research, consultant EO; data processing, data analysis, visualisation, writing-review-editing EAG. All authors declare that they have seen/read and approved the final version of the article ready for publication.

CONFLICT OF INTEREST

All authors declare that they have no conflict of interest for this study.

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Figures

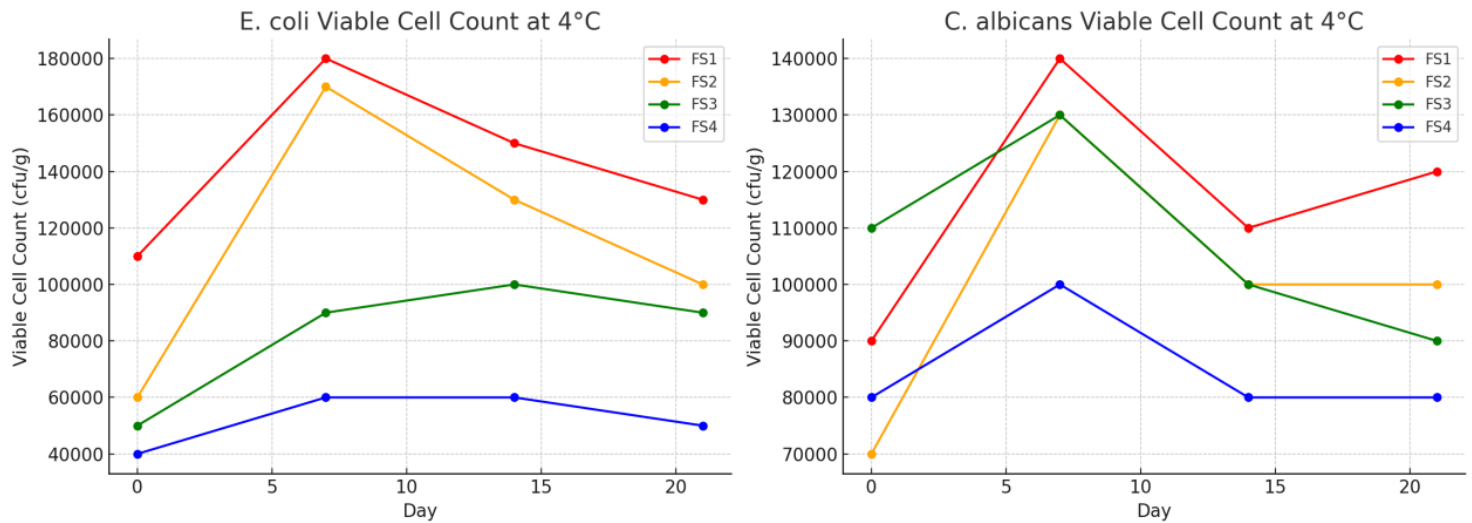


Figure 1

Effect of safflower-based edible coatings (EC1–EC4) on the growth of *E. coli* and *C. albicans* in Malatya cheese stored at +4 °C. Y-axis: log CFU/g (critical threshold 5 log CFU/g). X-axis: storage time (days). Error bars indicate mean $\pm$ SD (n=3). Control = uncoated cheese.

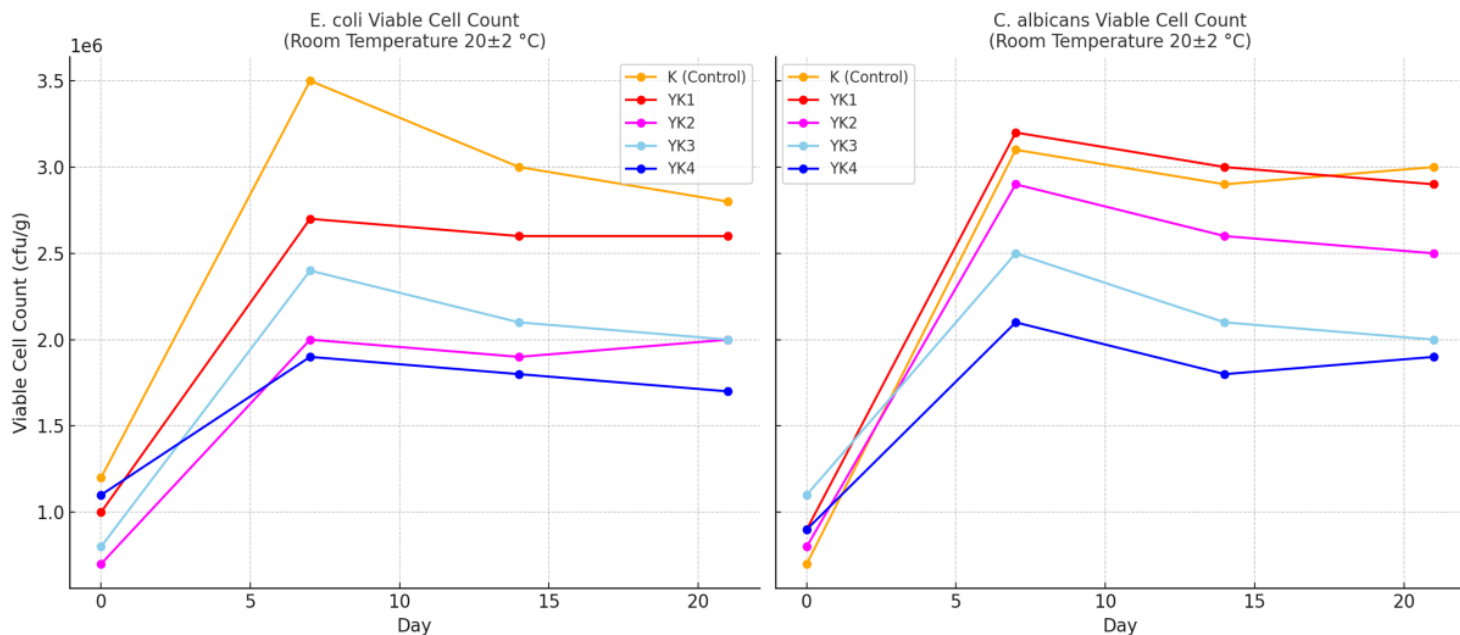


Figure 2

Effect of safflower-based edible coatings (EC1–EC4) on the growth of *E. coli* and *C. albicans* in Malatya cheese stored at +20°C. Y-axis: log CFU/g (critical threshold 5 log CFU/g). X-axis: storage time (days). Error bars indicate mean ± SD (n=3). Control = uncoated cheese.

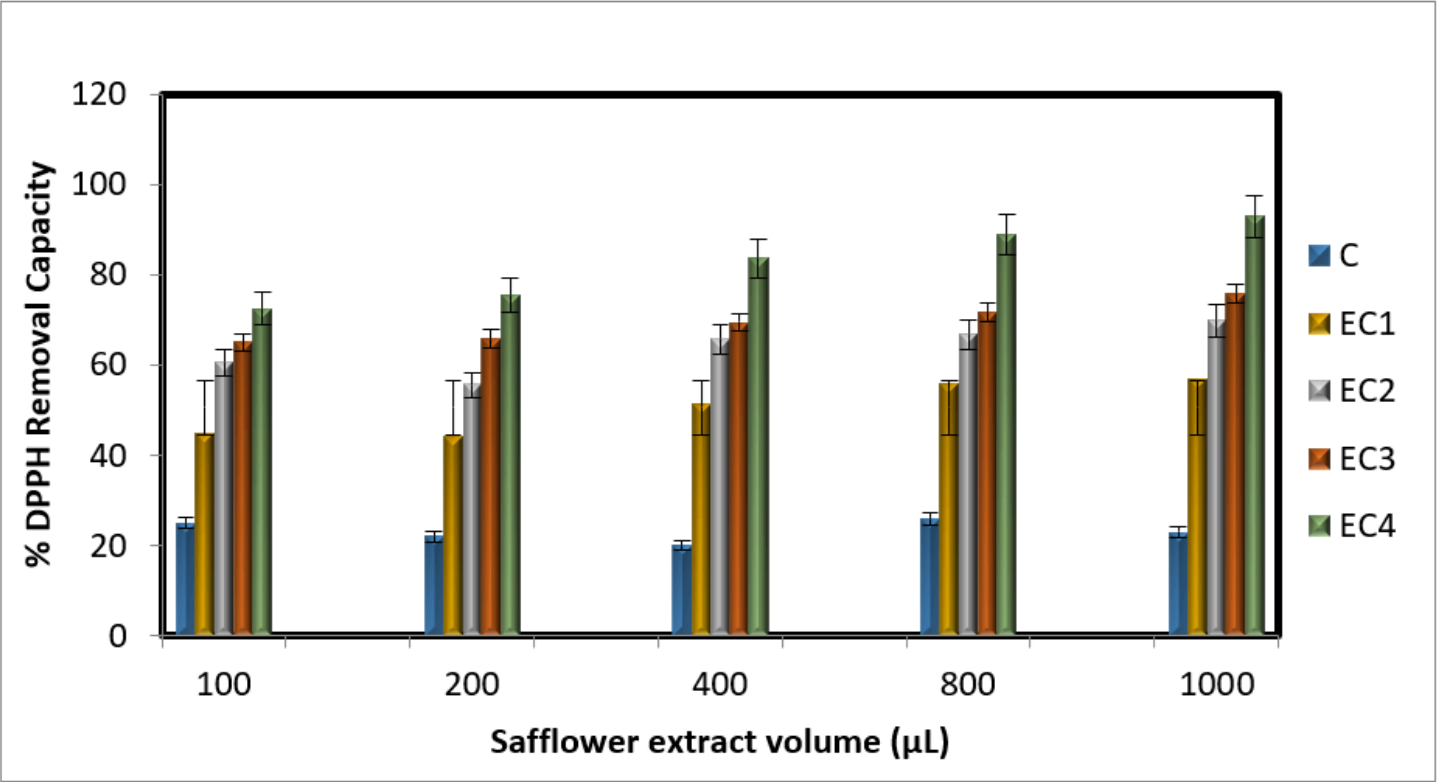


Figure 3

Percentage of DPPH radical scavenging activity of safflower-based edible coatings (EC1–EC4). Y-axis: % DPPH removal. X-axis: safflower extract concentration (µl). Error bars indicate mean ± SD (n=3). Control = coating without safflower extract.

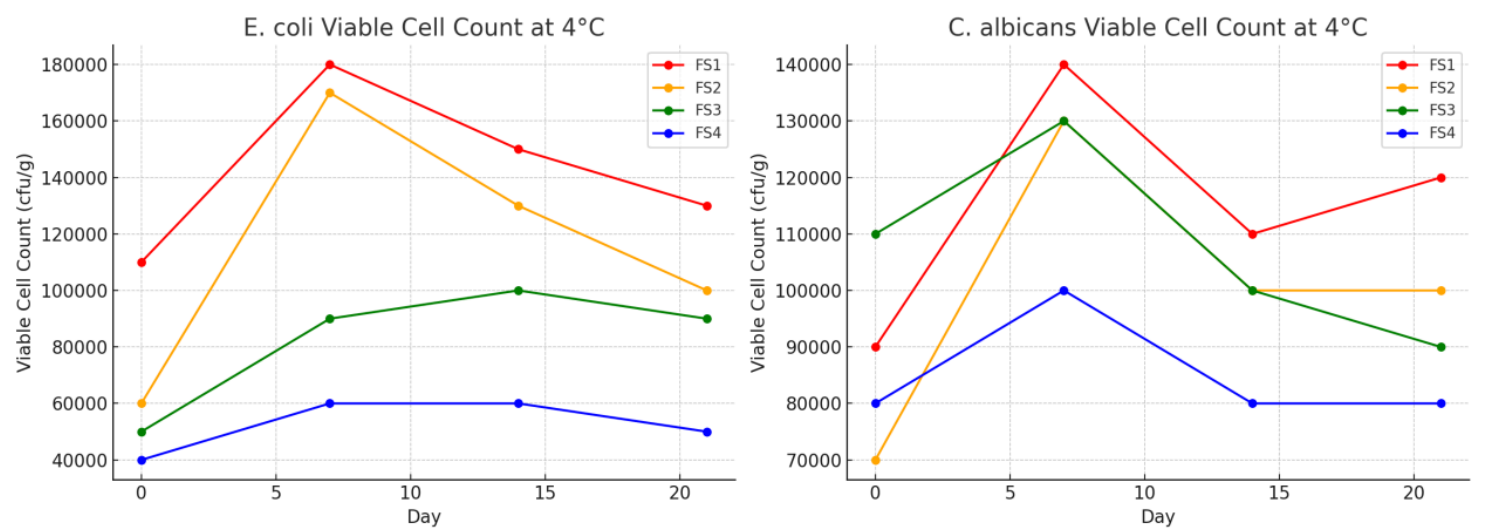


Figure 12

Effect of safflower-based edible coatings (EC1–EC4) on the growth of *E. coli* and *C. albicans* in Malatya cheese stored at +4 °C. Y-axis: log CFU/g (critical threshold 5 log CFU/g). X-axis: storage time (days). Error bars indicate mean ± SD (n=3). Control = uncoated cheese.

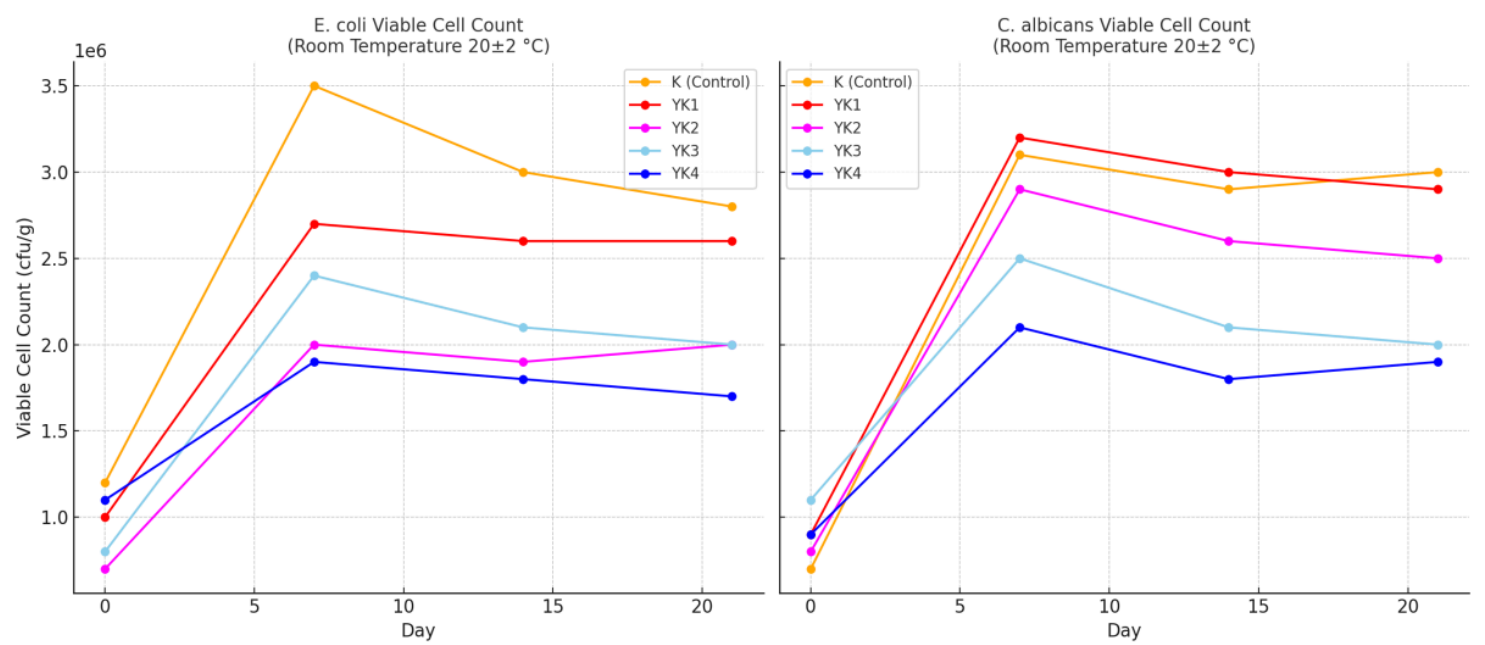


Figure 13

Effect of safflower-based edible coatings (EC1–EC4) on the growth of *E. coli* and *C. albicans* in Malatya cheese stored at +20 °C. Y-axis: log CFU/g (critical threshold 5 log CFU/g). X-axis: storage time (days).

Error bars indicate mean $\pm$ SD (n=3). Control = uncoated cheese.