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DEVELOPMENT OF WHEY PROTEIN AND PECTIN-BASED FILM ENRICHED WITH LEMON ESSENTIAL OIL FOR FOOD PACKAGING: EFFECTS ON MECHANICAL PROPERTIES, ANTIOXIDANT, AND BIODEGRADABILITY

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ABSTRACT: The employment of conventional plastics in food packaging has been demonstrated to exert a detrimental effect on the environment, owing to the fact that these plastics are non-biodegradable. Furthermore, there is a possibility that microplastics will accumulate within the food chain. The objective of this study is to develop an edible film that has been enriched with lemon essential oil and glycerol. The aim of the enrichment is to improve the film's mechanical properties, antioxidant content and biodegradability. The present study was conducted experimentally, employing a completely randomized factorial design with five replicates. Factor A consisted of control film; film with added lemon essential oil; and film with added encapsulated lemon essential oil. Factor B consisted of glycerol concentrations (5%; 10%; and 15%). The findings demonstrated that the incorporation of lemon essential oil and varying glycerol concentrations exerted a substantial impact ($P < 0.01$) on the tensile strength, elongation, and antioxidant content of whey-pectin-based edible films. The tensile strength values ranged from 4.23 to 7.54 MPa, the elongation ranged from 62.49 to 68.76%, and the antioxidant content ranged from 20.84 to 42.25%. The biodegradability of the film was demonstrated by the observation of a satisfactory degradation rate over a 30-day period following burial in soil. The edible film, composed of whey-pectin and fortified with encapsulated lemon essential oil and 10% glycerol, exhibited optimal tensile strength, elongation, antioxidant properties, and biodegradability. This renders it a sustainable and environmentally friendly solution for food packaging.

Keywords: Biodegradable, Essential Oil, Glycerol, Packaging, Whey.

INTRODUCTION

The primary issue associated with the utilization of conventional plastic for food packaging pertains to its deleterious impact on the environment, a consequence of its non-biodegradable nature. Furthermore, it has been demonstrated that plastic contains reactive and toxic chemicals that have the potential to accumulate in the food chain in the form of microplastics (Butler et al., 2023). A solution that has been extensively developed is the creation of eco-friendly packaging made from natural materials (Fahrullah et al., 2022, 2024). A widely considered approach is the use of edible films based on natural biopolymers, such as proteins, polysaccharides, and lipids (Motelica et al., 2020; Reis & Gomes, 2023). Edible films have been shown to function not only as protective coatings for food products but also to carry active compounds that act as antioxidants and antimicrobials, thereby extending the shelf life of food items (Barbosa et al., 2021). This approach offers the ability to preserve food products by preventing microbial contamination and oxidative damage (Qian et al., 2021).

The combination of whey protein and pectin is considered to be a promising biopolymer matrix system, exhibiting the capacity to yield films that demonstrate favorable mechanical characteristics and intercomponent compatibility. A substantial body of research has been published on the use of whey protein as a film, and the results are very promising in terms of its potential as a barrier against moisture, aroma, lipids, and oxygen (Kumar et al., 2022). Lemon by-products have been identified as a potential alternative source of natural components for the manufacture of active packaging. This phenomenon can be attributed to the high concentration of functional compounds present in lemons, including vitamin C, fibre, carotenoids, essential oils, phenolic compounds, and pectin. The pectin content of lemons is a particularly attractive option in packaging formulations due to its superior physical and functional properties. Pectin's capacity to form gels, in conjunction with its biocompatibility and biodegradability, renders it a highly suitable biomaterial for a range of applications. Moreover, pectin is an excellent polymer matrix for film production because it is easily biodegradable (Karim et al., 2022; Aleksanyan, 2023; Djerri et al., 2025). Pectin also has water solubility, good flexibility, and effective barrier properties, which play an important role in inhibiting the oxidation process in food products during storage (Dobrucka et al., 2024).

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Essential oils are natural compounds derived from aromatic plants and have been used in food packaging (Anuradha and Bharadvaja, 2023). These compounds have been shown to enhance resistance to oxidation and mitigate the occurrence of mechanical degradation in biopolymer-based materials. However, not all types of essential oils are suitable for food packaging applications due to migration issues, as well as undesirable tastes and odours (Rehman et al., 2020; Suri et al., 2021). A potential solution to this issue could be the research and development of innovations such as encapsulation techniques. Encapsulation has been demonstrated to play a pivotal role in enhancing the stability of bioactive compounds (Kadmiri et al., 2021; Bae et al., 2022). This process effectively protects the compounds from external factors that can cause degradation, thereby maintaining their functionality. The incorporation of bioactive compounds into a protective matrix has been demonstrated to enhance stability, regulate release, control solubility, and augment bioavailability (Riseh et al., 2021; Zabot et al., 2022).

Beyond mechanical and functional aspects, the biodegradability of an edible film is a crucial parameter in assessing its environmental sustainability. Films derived from renewable biopolymers such as starch, protein, or chitosan have been shown to undergo microbial degradation and reduce plastic waste accumulation (Molavi et al., 2015; Gupta et al., 2022). Recent reviews also indicate that the sustainability of food films is not only related to materials and barrier properties, but also to their compostability and biological recyclability potential (Oliveira et al., 2025). In light of the mounting cognizance of the significance of environmental sustainability, the evolution of environmentally friendly and biodegradable edible films emerges as a pivotal stratagem for curtailing plastic waste within the food industry. The present study focuses on the development of natural-based edible films, with a particular emphasis on biodegradability. The objective is to enhance comprehension and to explore potential applications in a food packaging industry that is more environmentally friendly.

Whey, as a major by-product of the dairy industry, represents a significant component of livestock-based agro-industrial systems. The valorization of whey into biodegradable films not only addresses environmental concerns but also contributes to sustainable livestock production by converting dairy waste into value-added biomaterials. In livestock and animal feed industries, biodegradable and edible films have potential applications in the packaging of animal-derived products (Kandasamy et al., 2021), as well as in the protection of functional feed additives such as probiotics, enzymes, organic acids, and phytogenic compounds. The development of active films enriched with essential oils may also support hygienic handling, extended shelf life, and reduced contamination risk in feed and feed supplement distribution systems. Therefore, this technology is relevant not only to food packaging but also to sustainable livestock and feed-related industries (Chaudary et al 2025). The present study aims to evaluate the effect of the incorporation of lemon essential oil, in both free and encapsulated forms, and varying glycerol concentrations, on the physical properties, antioxidant activity, and biodegradability of whey–pectin-based edible films.

MATERIALS AND METHODS

Materials

This study employed a range of materials for analysis, encompassing whey derived from cow's milk (Sigma-Aldrich, Germany), lemon, glycerol (Merck, Germany), gelatin (Greenara, Indonesia), silica gel, maltodextrin (Lihua Starch, China), distilled water, Tween 80, NaOH, ethanol, sodium tripolyphosphate, HCl, and CH_3COOH.

Sample preparation

The preparation of the whey-pectin-based film was undertaken through the utilization of a casting method. A total of 15 grams of whey and 1 gram of pectin were dissolved in 100 ml of distilled water. The solution is then subjected to continuous stirring at a temperature of 60°C for a duration of 30 minutes, employing a hot plate stirrer. Subsequently, lemon essential oil and lemon essential oil encapsulation are introduced, with each constituting 5% of the total solution. In order to enhance the mechanical properties of the film, solutions of glycerol in the proportions of 5, 10, and 15% have also been incorporated. The resulting mixture solution was then transferred to a Petri dish and levelled. The film was then subjected to a drying process at a temperature of 50°C for a duration of 24 hours, with the objective of achieving a hardened state. Subsequent to this, the film was stored within a desiccator at ambient temperature for a period of 24 hours prior to testing. Modification (Fahrullah et al., 2020).

Extraction of lemon essential oil

The extraction of lemon essential oil was accomplished through the utilization of a Heidolph Rotary Evaporator Hei-VAP Value Digital G3 (Heidolph Instruments GmbH & Co. KG, Germany). The grated lemon was subsequently placed in a rotating vessel containing ethanol. Subsequently, the vessel was attached to the evaporator unit, with the temperature maintained between 40-60°C using a water bath. The utilization of a vacuum pump serves to reduce the pressure, thereby accelerating the evaporation process and facilitating more efficient separation of the essential oil. It is during this process that the solvent undergoes evaporation, with the resultant essential oil being collected in a suitable container. The essential oil obtained is then stored in dark glass bottles in a cool place to maintain its quality.

Extraction of pectin

Pectin was extracted from the waste residue produced during the lemon essential oil extraction process using an acidification method with an acid solution. The extraction process was conducted within a controlled environment, utilizing a hot hydrochloric acid solution at a temperature of 45°C and a pH of 1.25, with the objective of achieving the desired hydrolysis and dissolution of the pectin. Following the conclusion of the extraction process, an ethanol solution is introduced with the objective of reducing the solubility of pectin in the acid solution. This results in the pectin precipitating and separating from the liquid phase. The precipitated pectin is then collected through filtration, washed with ethanol to remove impurities, and then dried.

Lemon essential oil encapsulation

The encapsulation process, as outlined in the extant literature (Bezerra et al., 2016; Manaf et al., 2018), involves a two-stage procedure. The initial stage of the process is the preparation of an essential oil emulsion with a gelatin and maltodextrin solution. A total of 100 ml of gelatin solution was mixed with 8 ml of a lemon essential oil mixture and 6 ml of Tween 80, then homogenized at room temperature at a speed of 700 revolutions per minute for 30 minutes. Subsequently, 100 ml of maltodextrin solution was added and the homogenization process was repeated for a duration of 30 minutes. The second stage of this process was complex coacervation, which commenced with the addition of 2 ml of a 10% CH_3COOH solution until the pH had decreased to 4. Thereafter, the homogenization process was continued for a period of 60 minutes. The emulsion was left at a temperature of ±10ºC for 30 minutes. Subsequently, 20 ml of sodium tripolyphosphate solution is introduced as a cross-linking agent, and the mixture is subjected to homogenization for a duration of 60 minutes. Subsequently, the pH is adjusted by the addition of a 20% NaOH solution until the pH reaches 9. Following this adjustment, the homogenization process is carried out for a period of 2 hours. The emulsion is then left at a temperature of ±10°C for 16 hours prior to being dried using a freeze dryer.

Measurement of tensile strength and elongation film

The tensile strength testing method, utilizing a Universal Testing Machine (UTM) (ASTM, 2018).

Antioxidant

The antioxidant content was analyzed using UV-Vis spectrophotometry and the DPPH method. A total of 1 g of sample was added to 9 ml of methanol, then vortexed. The sample was left for 24 hours to ensure optimal extraction. Subsequently, the sample underwent filtration using Whatman filter paper to facilitate the separation of the residue. Thereafter, 1 ml of the filtrate was collected and added to 2 ml of a 0.1 mM DPPH solution. Subsequently, the mixture was subjected to agitation until the desired homogeneity was achieved. Subsequently, the mixture was covered with aluminium foil and placed in an incubator in a dark environment for a period of 30 minutes. The rationale behind this procedure was to mitigate the potential for light interference, which could compromise the precision of the results. Subsequent to the incubation period, the absorbances were measured at a wavelength of 517 nm, employing a UV-Vis spectrophotometer. The results of the measurement of the degree of light absorption by the sample were recorded and utilized to calculate the antioxidant content in the sample using the following formula:

$$\text{Antioxidant (\%)} = ((\text{A blank} - \text{A sample}))/(\text{A blank}) \times 100\% \quad (1)$$

Biodegradability testing

The biodegradability of the film was assessed by evaluating the physical changes that occurred in the composting environment. The samples were buried at a depth of 12–15 cm in the soil for a period of 30 days. Following a 30-day period, more in-depth observations were made to evaluate the level of film degradation. The samples were meticulously extracted from the soil to circumvent any potential disruption to the ongoing degradation process. A visual inspection of the films was conducted to ascertain any substantial alterations in their physical integrity, including damage, decomposition, or dissolution.

Statistical analysis

The present study employed a completely randomized design with a factorial pattern and five repetitions. The treatments comprised Factor A (control film; film with added lemon essential oil; film with added encapsulated lemon essential oil) and Factor B (5% glycerol; 10% glycerol; 15% glycerol). The data obtained were analyzed using Analysis of Variance (ANOVA), and if there were differences, they were followed up with Duncan's Multiple Range Test using SPSS 25 software.

RESULTS AND DISCUSSION

Tensile Strength

Tensile strength is a pivotal mechanical property in the assessment of material resistance to applied loads, particularly in the context of film and plastic materials. This property is defined as the capacity of a material to resist tensile forces prior to the occurrence of damage or rupture. The tensile strength values of films with the addition of lemon essential oil and different glycerol concentrations are presented in Figure 1. The mean tensile strength values obtained ranged from 5.61 to 7.03 MPa. Glycerol, a hydrophilic plasticizing agent utilized in the production of this film, interacts with whey and pectin polymer chains through the formation of hydrogen bonds. It has been demonstrated that the presence of glycerol results in an increased mobility of the polymer chains, consequently leading to the formation of a more flexible film. However, this process concomitantly reduces the tensile strength, thereby rendering the material softer. Furthermore, the presence of a polar group in glycerol contributes to the stabilization of the dispersion of lemon essential oil within the water polymer matrix. In addition, lemon essential oil has been observed to aggregate (clump) into larger droplets. These substantial aggregates function as weak points within the film structure, thereby substantially diminishing the tensile strength of the material.

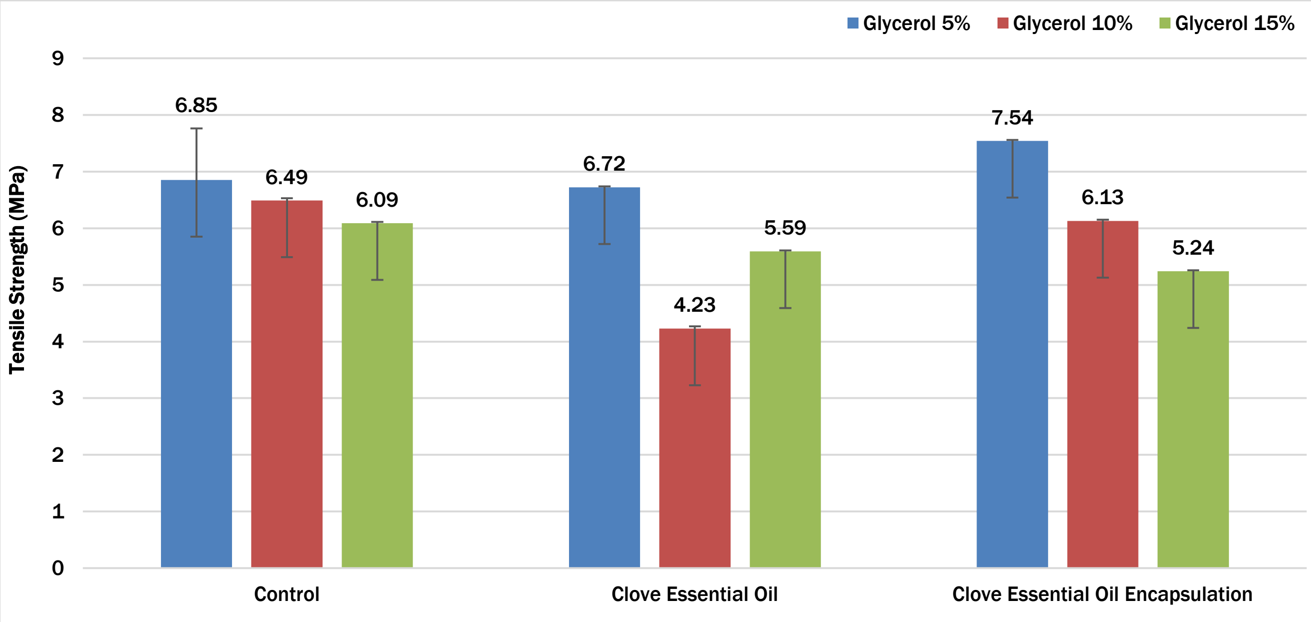

Figure 1 - Tensile strength (Mpa) of whey-pectin film with the addition of lemon essential oil and different glycerol concentrations

Whey-pectin films have been shown to possess the highest tensile strength in comparison to other treatments, a property attributable to the formation of a cohesive and dense polymer matrix through strong intermolecular interactions. It has been established that whey protein and pectin form a stable network through hydrogen bonds, electrostatic interactions and disulphide bonds (in whey protein). This results in the creation of a film that is resistant to external tensile forces (Pires et al., 2024). The addition of lemon essential oil resulted in a decline in tensile strength, which can be ascribed to the essential oil's role as a hydrophobic dispersed phase within a hydrophilic matrix (Sharma et al., 2021; Fahrullah et al., 2024, 2025). These oil droplets have the capacity to disrupt the continuity of the polymer network, and the oil also has a tendency to coat the polymer chains, thereby reducing the number of hydrogen bonds. Consequently, the internal cohesion of the film is reduced, rendering it more vulnerable to fracture under pressure, which in turn decreases its tensile strength (Atarés and Chiralt, 2016; Šuput et al., 2016). It has been demonstrated that the process of essential oil encapsulation leads to an enhancement in tensile strength, with a recorded maximum of 6.30 MPa being attained. It has been demonstrated that, by means of this technique, the primary whey-pectin matrix is capable of reconfiguring itself into a robust polymer-polymer interaction network (Akachat et al., 2025 a). The process of physical encapsulation involves the isolation of the hydrophobic oil core from the whey-pectin polymer matrix. Furthermore, the presence of these fillers within the film matrix has been shown to result in a more even distribution and improved integration into the overall polymer network (Reis and Gomes, 2023). This reduction in tensile strength is indicative of a decrease in the film's ability to withstand pressure when the glycerol content is increased. As demonstrated in Figure 2, elevated glycerol concentrations have been shown to diminish the intermolecular forces that facilitate mobility between molecular chains, consequently resulting in augmented elongation values (Akachat et al., 2025 b). It has been demonstrated that high tensile strength is obtained from lower glycerol concentrations, possibly due to the dominance of strong hydrogen bonds formed through polymer interactions that are greater than the tensile forces between polymers and glycerol (Geleta et al., 2020). This decline in tensile strength can be attributed to the weakening of intermolecular bonds and the reduction in internal cohesion. This results in an increase in the stretchability and flexibility of the film, accompanied by a decrease in its tensile strength (Butt et al., 2023).

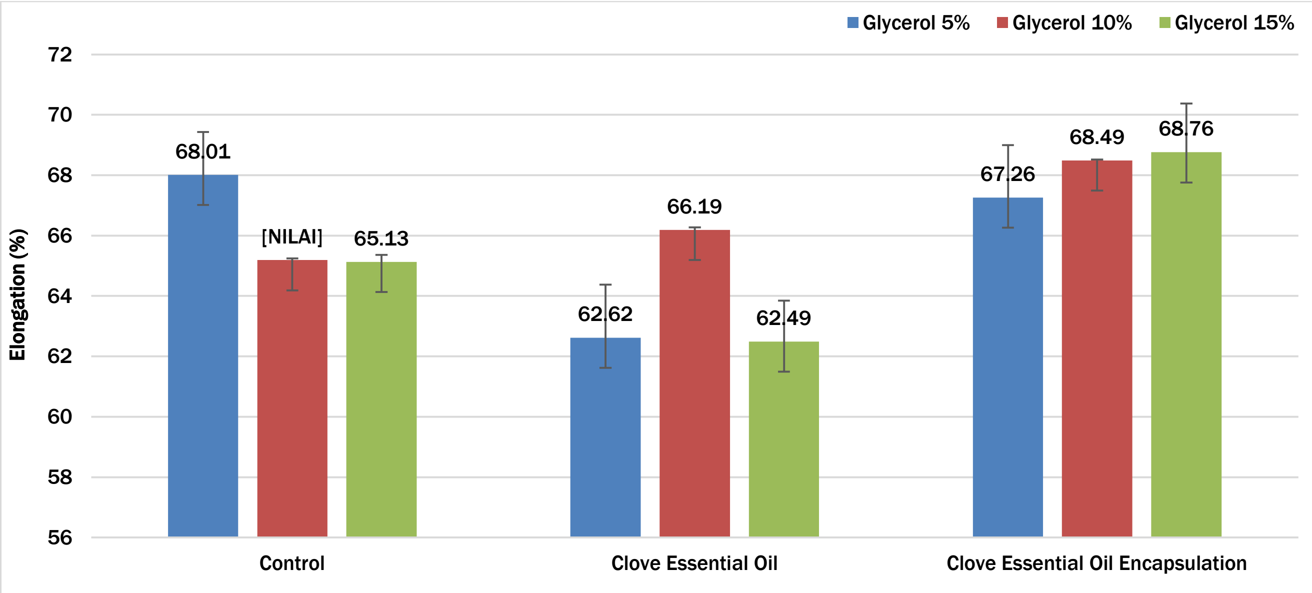

Figure 2 - Elongation (%) of whey-pectin film with the addition of lemon essential oil and different glycerol concentrations

Elongation

Film elongation is defined as the ability of a material to stretch or lengthen when subjected to tensile stress before breaking or rupturing. This property is significant in the assessment of materials' flexibility and resistance to mechanical deformation. The film elongation values resulting from the incorporation of lemon essential oil and varying glycerol concentrations are illustrated in Figure 2. The mean elongation value produced ranged from 63.76 to 68.17%. The interaction between glycerol and polymers can be influenced by essential oils, which have been shown to reduce the amount available for hydrogen bonding between glycerol and polymers, thereby facilitating more even dispersion of glycerol across multiple domains. The range of elongation values produced is indicative of a balance between the plasticizing effect of glycerol and the structural modification caused by the dispersion of lemon essential oil in the whey-pectin matrix. It has been demonstrated that specific interactions at certain concentrations optimize polymer chain mobility, resulting in films with significant stretchability (Lina et al., 2023). Lemon essential oil is hydrophobic and not fully soluble in the hydrophilic whey-pectin matrix; the oil tends to form large droplets that are not evenly dispersed in the polymer matrix. These oil droplets have the capacity to interfere with the bonds between polymer chains and to reduce the density of cross-links. This, in turn, can inhibit the uniform transfer of tension throughout the film when it is pulled. This phenomenon has been shown to result in the film's increased susceptibility to breakage, thereby reducing the overall elongation when compared to whey-pectin film (Ghadetaj et al., 2018). The utilization of encapsulated lemon essential oil has been demonstrated to result in an augmentation of the elongation value. This phenomenon can be attributed to the encapsulation process, which generates minute essential oil droplets that are uniformly dispersed throughout the polymer matrix (Mehta et al., 2022). This uniform dispersion enhances the compatibility between the hydrophobic phase (oil) and the hydrophilic phase (whey-pectin), thereby enabling the film matrix to undergo greater elastic stretching and to absorb pressure more effectively prior to rupture. This, in turn, leads to the attainment of the highest elongation value (Amjadi et al., 2021).

Glycerol, a hydrophilic polyol, functions as a plasticizer in the film matrix by reducing interactions between polymers. Glycerol has been shown to interact with whey and pectin through hydrogen bonds, thereby replacing the strong hydrogen bonds between polymer chains and increasing the distance between chains and the free volume in the matrix (Akachat et al., 2025 b). This increase in flexibility is accompanied by a corresponding decrease in rigidity, resulting in an enhancement of the elongation value, defined as the film's capacity to stretch prior to breaking (Hachity-Ortega et al., 2024). The dense whey-pectin film matrix is characterized by the presence of numerous hydrogen bonds and robust van der Waals forces between polymer chains. The presence of these bonds contributes to the film's rigidity and fragility. The incorporation of glycerol has been demonstrated to occur between the polymer chains, thereby increasing the distance between them. This has been shown to result in an increase in the free volume present within the film matrix. The polymer chains become freer to move (increased mobility) when the film is subjected to pressure (Asfaw et al., 2023; Agustin et al., 2024), due to the extra space and weaker interactions.

Antioxidant

The results of the study demonstrate that the antioxidant content of the film with the addition of lemon essential oil and different glycerol concentrations can be observed in Figure 3. This finding suggests that lemon essential oil is a significant source of bioactive compounds, and that glycerol functions as a plasticizer capable of regulating the antioxidant activity it produces. Lemon essential oil, which contains main components such as limonene and geraniol, provides natural antioxidants (Bof et al., 2016; Song et al., 2018). In addition, glycerol affects the physical properties of the film, such as homogeneity, flexibility (Lau and Sarbon, 2022), and the distribution of active compounds in the whey-pectin polymer matrix. The control film (whey-pectin) exhibited an antioxidant content of 21.12%, while the addition of lemon essential oil to the film matrix resulted in a significant increase to 36.28%, thereby underscoring the role of bioactive compounds (limonene and geraniol) in neutralizing free radicals (Budiarto et al., 2024). Furthermore, formulations incorporating encapsulated lemon essential oil exhibited a 32.62% increase in antioxidant content. This discrepancy is presumably attributable to the controlled release mechanism of lemon essential oil in encapsulated form, which results in the active compounds being less available in the initial stages but more stable over the storage period (Himed et al., 2019). Research related to the effectiveness of using encapsulated lemon essential oil in films as a sustainable controlled release antioxidant strategy (Akachat et al., 2025 b) demonstrates that pectin-based films with encapsulated lemon essential oil not only increase antioxidant activity but can also improve the film's structural resistance to biological and water degradation. The encapsulation of essential oils represents a technological advancement that has the potential to address issues of volatility and enhance the release efficiency of antioxidant compounds (Khan et al., 2023).

As demonstrated in Figure 1, the incorporation of elevated levels of glycerol into whey-pectin films has been observed to result in a concomitant reduction in the antioxidant content. This phenomenon can be attributed, at least in part, to the indirect impact of glycerol on the rate of diffusion and release of active compounds, thereby influencing the overall antioxidant content of the films. It has been established that elevated glycerol concentrations have the capacity to diminish tensile strength and modulus. Conversely, they have been observed to augment elongation and water vapor permeability. This condition has been observed to accelerate the release of antioxidants, but it has also been demonstrated that excess glycerol can cause a rapid decline in their stability (Hachity-Ortega et al., 2024; Lau and Sarbon, 2022; Tafa et al., 2023).

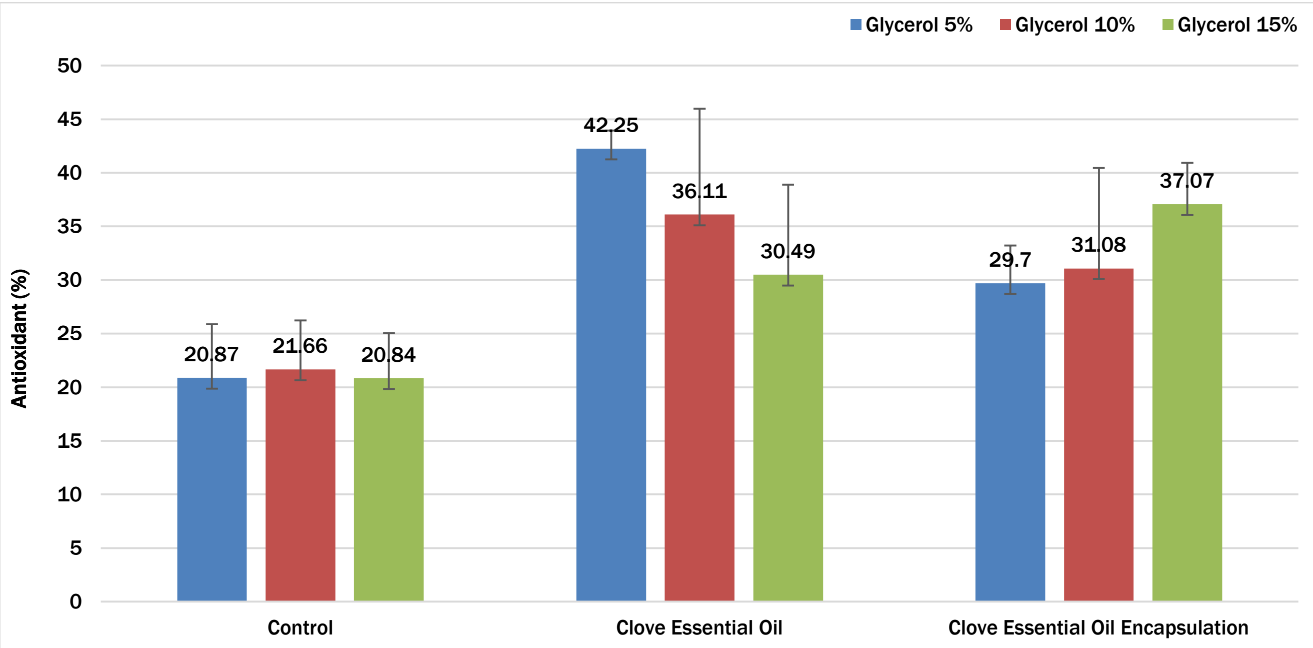

Figure 3 - Antioxidant (%) of whey-pectin film with the addition of lemon essential oil and different glycerol concentrations

Film biodegradability

The biodegradability of whey-pectin-based edible films was investigated to ascertain their capacity to undergo natural degradation through microbial activity in the environment. The findings of this investigation offer a comprehensive overview of the environmental sustainability of the film produced and its degradation rate when compared to conventional materials. The findings of the biodegradability test demonstrate that whey-pectin-based edible films exhibit favorable degradability within natural environments. The degradation process was observed through physical appearance, with the samples being exposed to weathering conditions for a period of 30 days in the soil. The biodegradability of whey-pectin edible film is demonstrated in Figure 4,


Before
Planted in soil for 30 days
(a)
(b)
(c)
(d)


(e)
(f)
(g)
(h)

Figure 4 – (a) whey-pectin film with 5% glycerol; (b) whey-pectin film with 10% glycerol; (c) whey-pectin film with 15% glycerol; (d) whey pectin film with lemon essential oil and 5% glycerol; (e) whey pectin film with lemon essential oil and 10% glycerol; (f) whey pectin film with lemon essential oil and 15% glycerol; (g) whey pectin film with encapsulated lemon essential oil and 5% glycerol; (h) whey pectin film with encapsulated lemon essential oil and 10% glycerol; (i) whey pectin film with encapsulated lemon essential oil and 15% glycerol

The utilization of glycerol as a plasticizer in biopolymer films, including those derived from whey protein and pectin, has been demonstrated to enhance the flexibility (i.e. the elongation at break) of the resultant films. Concurrently, this increase in flexibility is accompanied by a reduction in film stiffness (Young's modulus), a phenomenon that can be attributed to the capacity of glycerol to disrupt the intermolecular bonds between polymer chains. This disruption leads to an augmentation in the openness and accessibility of the film structure to water and microorganisms. For instance, research on whey-based films indicates that the incorporation of glycerol leads to a reduction in inter-protein chain forces and an enhancement in film flexibility (Fahrullah et al., 2020; Pires et al., 2024). In a similar manner, pectin films fortified with glycerol have demonstrated that the glycerol concentration exerts an influence on the mechanical properties and permeability of the film (Akachat et al., 2025 b). It can be deduced that the increased flexibility and susceptibility to water and microorganism penetration of films with elevated glycerol levels (15%) results in a faster rate of biodegradation in comparison to films with lower glycerol concentrations (5%).

Furthermore, the incorporation of essential oils into the biopolymer film matrix exerts a dual effect: firstly, EOs can enhance the antimicrobial and antioxidant activity of the film, thereby reducing microbial contamination; however, secondly, from a structural standpoint, the addition of EOs frequently compromises the integrity of the film matrix due to the formation of droplets or dispersions within the oil phase, resulting in the creation of pores or channels. In films containing lemon essential oil, the rate of biodegradation tends to be slower in the early stages, as soil microbes require a longer time to attack the polymer structure of the film. However, over time and with increasing degradation of the encapsulation matrix, the essential oil begins to be released and its antimicrobial properties gradually decrease, allowing the biodegradation process to continue until the film is almost completely decomposed.

The process of essential oil encapsulation introduces an additional factor: namely, that the encapsulated essential oil is released in a controlled or gradual manner. This can increase the interaction of the film with environmental conditions (humidity, microbes) over a longer period of time, while also changing the structure of the film. Encapsulation can form a more heterogeneous microstructure and increase the interface area between the film, oil and environment, causing the film to degrade more quickly due to the many 'entry points' for degradation. The analysis of biopolymer films incorporating essential oils and plasticizers has revealed a correlation between the degree of porosity and the rate of degradation. It has been demonstrated that a more porous or disturbed film structure is associated with an accelerated rate of degradation. As demonstrated by (Anis et al., 2021), the utilization of biopolymer-based films, incorporating a combination of plasticizers and essential oils, results in a reduction of film compactness and an escalation in the rate of mass loss (weight loss) during biodegradation tests.

From an environmental and biodegradation perspective, protein- and polysaccharide-based films offer inherent advantages due to the natural composition of their polymer chains, which are susceptible to biodegradation through microbial enzymes or through processes such as oxidation and hydration (Nikbakht et al., 2025). The combination of these polymers produces a more flexible, porous film that is open to the environment, facilitating the interaction of degradation microorganisms with the film. Consequently, visual changes show a reduced, damaged, partially lost film structure after 30 days, in line with active biodegradation expectations.

CONCLUSION

This study demonstrates that whey-pectin-based edible films incorporated with lemon essential oil and glycerol possess the potential to serve as an eco-friendly packaging solution. The incorporation of lemon essential oil has been demonstrated to enhance the antioxidant content and barrier effectiveness of the film, thereby mitigating its susceptibility to oxidation and microbial contamination. The utilization of glycerol as a plasticizer has been demonstrated to enhance the flexibility of the resultant film. The optimal treatment is a film comprising encapsulated lemon essential oil and 10% glycerol, which offers an optimal balance between tensile strength, elongation, antioxidant activity, and biodegradability. This film also exhibits good biodegradability, is more environmentally friendly than conventional plastics, and can be used for more sustainable food packaging. Future studies are recommended to evaluate the performance of this edible film under real food storage conditions using different food matrices, investigate its long-term storage stability and controlled release behavior of the encapsulated essential oil, and assess its scalability and economic feasibility for commercial food packaging applications.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Authors' contribution

FF, DK, BRDW: designed the research; FF, DK, BRDW, AN: investigation the research; FF, AN: conducted the research and analyzed data; All authors wrote the manuscript, had primary responsibility for final content and approved the final manuscript.

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Consent to Publish

The publication of this manuscript has been approved by all authors.

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Competing Interest

The authors have not declared any competing of interests.

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