International Journal of Nutrology
(Official Journal of the ABRAN - Brazilian Association of Nutrology)

ORIGINAL ARTICLE

DOI: 10.54448/ijn26S316

Modification of citric acid on whey proteins: a novel approach to modify functional properties and reduce oil content in potato strips

Anaam S. Al-khafaje[1], Jasim M. S. Al-Saadi[1,*]

[1] Al-Qasim Green University. College of Food Science, Babylon, Iraq.

*Corresponding author: Jasim M. S. Al-Saadi.
Al-Qasim Green University. College of Food Science,
Babylon, Iraq.
E-mail: jasim_salih@fosci.uoqasim.edu.iq
DOI: https://doi.org/10.54448/ijn26S316
Received: 02-02-2026; Revised: 04-06-2026; Accepted: 04-13-2026; Published: 07-31-2026; IJN-id: e26S316

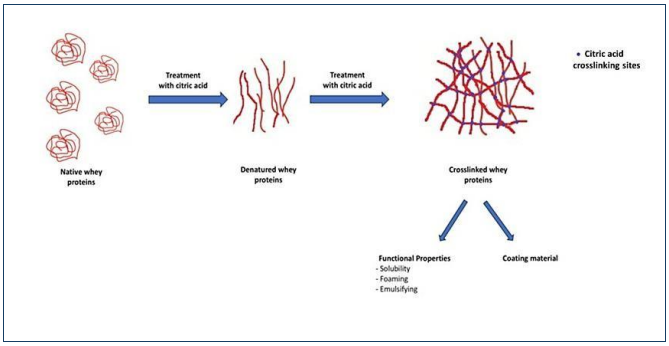
Editor: Dr. Carla Maria Barreto da Silva de Sousa Rego, MD, MsD, Ph.D.

Abstract

Introduction: Functional properties and coating behaver of a whey proteins modified with citric acid were investigated. **Objective:** Citric acid modification was carried out by incubating whey protein with 0.67 mol/L citric acid at 50°C for 4 hours. **Methods:** The functional properties assessment demonstrated that citric acid alteration had a considerable impact on protein behavior. Solubility dropped significantly across all pH values (3-10), notably at pH 3-4, due to lower surface charge from crosslinking. Foaming capabilities and emulsifying activity index were similarly reduced. **Results:** The effect of using modified whey proteins as a coating material on potato strips properties was studied. Potato strips coated with 5% modified whey proteins had the maximum moisture retention (72.8%) compared to the uncoated control (62.3%) and dramatically reduced oil content to 10.32%, a 70.6% reduction over the control (35.1%). **Conclusion:** Texture study revealed that the 5% modified coating generated softer potato strips. Sensory test found that samples coated with 5% modified protein had the highest overall acceptability scores, combining health advantages (lower fat) with a pleasurable eating quality.

Keywords: Chemical modification. Whey protein. Citric acid. Protein coatings. Potato strips.

Graphical Abstract



Note: Crosslinking of whey proteins using citric acid. Source: Own authorship.

Introduction

Whey proteins are the proteins that remain in whey following the separation of caseins, accounting about 20% of total milk proteins. Whey proteins are extremely important because of their unique functional qualities and application in food processing, as well as their high concentration of essential amino acids, which has piqued consumers' interest [1].

Protein modification can achieve using three methods: physical modification (such as heat treatment and ultrasound), enzymatic modification (using enzymes like transglutaminase), and chemical modification including processes such as esterification, phosphorylation, and crosslinking [2]. Modification can lead to crosslinking between protein units which effect the functional, nutritional and processing properties of proteins. Chemical crosslinking agents, such as formaldehyde and glutaraldehyde, can be harmful for human, therefore, finding safe and non-toxic crosslinking agents can be useful to modify proteins

properties [3]. Citric acid is an excellent substitute for typical chemical crosslinking agents since it is affordable, non-toxic, and safe, and it is extensively used in the food sector citric acid is found naturally in fruits and vegetables and has been categorized by the US. The Food and Drug Administration (FDA) classifies it as a Generally Recognized As Safe (GRAS) direct food additive [3].

Citric acid unique carboxyl structure (tricarboxylate) and outstanding bonding capabilities make it a safe, effective, and inexpensive crosslinking agent [3]. The binding mechanism of citric acid is based on a nucleophilic substitution process in which free amino groups in the protein attack the partly positive carbon atoms of citric acid carboxyl groups, resulting in the creation of new amide bonds [3,4]. When more than one carboxyl group in the citric acid molecule participates in the process, crosslinking occurs between or within protein molecules, forming protein networks with improved functional characteristics [4,5]. This approach has been used successfully to improve the mechanical characteristics of several proteins, such as soy protein, gliadin, and zein [5] It has also been utilized to convert hydrolyzed whey protein peptides into gallic acid carrier particles [6]. Whey proteins molecular structure, which includes reactive free amino groups, makes them suitable for covalent cross-linking [7]. This cross-linking process has been demonstrated to greatly improve the functional and structural characteristics of WPI. For example, CA inclusion increases the barrier characteristics, storage stability, and thermal resistance of WPI-based edible films [8]. Coating solution is often characterized as a liquid solution that produces a film and is applied directly to the food surface by spraying, dipping, washing, or brushing. When the coating dries, it generates a thin layer of edible material that may be mixed with or ingested alongside the meal [9].

In the present time, customers are becoming increasingly aware of the need of a healthy diet containing low fat ratio. French fries are among the most popular dishes in the world because they are tasty, inexpensive, and widely available. Deep frying is a popular and regularly used way of food preparation ،It induces heat and mass transfer processes that result in surface browning, fast water evaporation, and oil absorption or degradation.

However, because of their high fat content, fried foods are frequently seen as part of an unhealthy diet. The purpose of the present work was to prepare citric acid modified whey proteins and study their functional properties and their role as a coating material for reducing oil uptake in fried potato strips.

Materials and methods

Materials

Whey protein concentrate (WPC, 80% protein content) was procured from Kalleh Dairy Company (Iran). Sunflower oil was supplied by AL Dar Oil Company (Iraq). Fresh potatoes of the Hormoz variety were sourced from Khayrat Abi Al Ahrar Company (Iraq). Hydrochloric acid, citric acid and ascorbic acid were procured from Oxoid (UK). Sodium hydroxide, glycerol and hexane was obtained from BDH (UK).

Methods

Cross-Linking of Whey Protein Isolate with Citric Acid

Citric acid-modified whey protein was prepared according to [10]. Whey protein concentrate (5 g) was dissolved in 200 mL of 0.67 mol/L citric acid solution, and the pH was adjusted to 6.8. The mixture was incubated in a water bath at 50°C for 4 hours under continuous stirring to facilitate cross-linking. At the end of the reaction, the solution was freeze-dried to obtain the modified protein powder.

Turbidity

Change in turbidity of the WPI solutions during cross-linking at 50°C with citric acid was determined by measuring absorbance at 500 nm in spectrophotometer according to [11].

SDS-PAGE

SDS-PAGE was carried out following the method described by [12]The separating gel was prepared at a concentration of 12% and the stacking gel at 6%. Electrophoresis was performed at a constant voltage of 200 V for 3.5 hours. After separation, the gel was stained with Coomassie Brilliant Blue G-250 and destained with a 5% acetic acid solution to visualize protein bands. Protein profiles were identified by comparison with previous studies [13].

Functional properties and antioxidant activity of whey proteins modified with citric acid

Solubility

The solubility of both native and citric acid-modified whey protein concentrate (WPC) samples was evaluated across a range of pH values according to the method described by [14].

Foaming Properties

The foaming characteristics of both native and citric acid-modified whey protein concentrate (WPC) samples were assessed using the gas-sparging method as described by [15] A volume of 15 mL of protein

solution (0.1% (w/v) prepared in 0.15 M sodium chloride, pH 7.0) was placed in a glass column (1.6 cm internal diameter × 70 cm height). Air was introduced into the solution from the bottom of the column at a constant flow rate of 30 mL/min for a duration of 2 minutes. The height of the foam column formed was measured immediately after the airflow was stopped. Subsequently, the foam height was recorded at 0.5-minute intervals until complete foam collapse was observed.

Emulsifying Activity Index (EAI)

The emulsifying activity of the protein samples was assessed according to the turbidimetric method described by **[16]**.

Preparation of Citric Acid-Crosslinked WPI Edible Films

Coating solutions were prepared according to the method described by **[17]** with modifications. A volume of 80 mL of distilled water was used to dissolve whey protein (both citric acid-modified and unmodified forms, separately) at concentrations of 2.5% and 5% (w/v). The pH of the mixture was initially adjusted to 8.0-8.5 using 2 M sodium hydroxide (NaOH) under continuous stirring until complete dissolution was achieved. Subsequently, the pH was precisely adjusted to 8.0, and glycerol was added as a plasticizer at a concentration of 5.0% (v/v). The volume of each solution was then made up to 100 mL with distilled water. The coating solutions were heated to 85°C for 20 min and the samples were homogenized using an electric blender for 3 min, filtered through multiple layers of muslin cloth, and subsequently degassed under vacuum for 40 min **[17]**.

Potato Sample Preparation

Fresh Hormoz potato tubers were thoroughly washed under tap water to remove surface impurities, manually peeled, and cut into uniform strips (approximately 1 cm × 1 cm × 5 cm). To prevent enzymatic browning, the potato strips were immediately immersed in a 0.05% ascorbic acid solution at a ratio of 2:10 (potato strips:ascorbic acid solution, w/v) for 15 min, following the method described by **[17]**. After the immersion period, the potato strips were removed and placed on a clean cloth to drain excess surface solution prior to subsequent coating applications.

Application of Edible Coatings to Potato Strips

The prepared potato strips were systematically allocated into five distinct experimental groups to evaluate the efficacy of the coating treatments. These groups comprised: uncoated control sample, (T1) strips coated with unmodified whey protein at a concentration of 2.5% (w/v), (T2) strips coated with unmodified whey protein at a concentration of 5% (w/v), (T3) strips coated with citric acid-modified whey protein at a concentration of 2.5% (w/v), and (T4) strips coated with citric acid-modified whey protein at a concentration of 5% (w/v).Coating was carried out following the procedure described by Rimac-Brnčić et al. (2004), wherein each group of potato strips was immersed in its corresponding coating solution for 15 s to ensure uniform surface coverage. Upon completion of the immersion period, the strips were retrieved and placed onto absorbent paper to facilitate the removal of excess coating material. Subsequently, the coated strips were allowed to air-dry under a fan at ambient temperature for 45-55 min to ensure adequate surface drying prior to further processing, in accordance with the method outlined by **[18]**.

Frying Process

The frying procedure was conducted according to the method described by **[19]**, with minor modifications. Potato strips from each experimental group were immersed in sunflower oil at a ratio of 1:2 (potato strips :oil w/v). Frying was performed at 180°C for 10 min. The oil was replaced after frying each group to prevent cross-contamination and maintain consistent frying conditions. Following frying, the potato strips were removed from the oil and allowed to cool at ambient temperature. The fried samples were subsequently evaluated for sensory attributes, textural properties, as well as oil and moisture content.

Texture Profile Analysis

Hardness of fried potato strips, including both coated and uncoated samples, were evaluated using a CT3 (4500) Brookfield Engineering texture analyzer. Measurements were conducted using a 4 mm diameter cylindrical probe with a trigger load of 0.2 kg. The probe penetrated the samples to a depth of 5 mm at a constant test speed of 1 mm/s.

Determination of Oil Content

The oil content of fried potato strips was determined using the Soxhlet extraction method as described by A.O.A.C. (2008). Hexane was employed as the extraction solvent. Samples were subjected to continuous extraction for approximately 6 h, after which the solvent was evaporated and the residual oil content was determined gravimetrically.

Moisture Content Determination

Moisture content of the fried potato samples was

determined using the oven-drying method according to **[20]**. Samples were placed in a pre-weighed dish and dried in an air oven at 105°C for 24 h until a constant weight was achieved. The moisture content was expressed as a percentage of the initial sample weight.

Sensory Evaluation

Sensory evaluation of fried potato samples, including uncoated strips, strips coated with unmodified whey protein, and strips coated with citric acid-modified whey protein, was conducted according to the method described by **[21]**. The evaluation was performed by a panel of eight trained assessors, all staff members from the College of Food Sciences, Al-Qasim Green University, Iraq, aged between 21 and 55 years. Panelists evaluated the samples based on five sensory attributes: appearance, color, taste, texture, and overall acceptability. A nine-point hedonic scale was employed for scoring, where 1 represented "dislike extremely" and 9 represented "like extremely".

Statistical analysis

All experiments were conducted in triplicate, and results were expressed as mean ± standard deviation (SD). Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by Duncan's multiple range test to determine significant differences between means at a confidence level of $p < 0.05$. All statistical analyses were conducted using SPSS software (Version **[2018]**, IBM Corp., USA).

Ethical Approval and Safety Considerations

The study protocol, including the sensory evaluation, was reviewed and approved by the Institutional Ethics Committee of the College of Food Science, Al-Qasim Green University, Babylon, Iraq. All experimental procedures were conducted in accordance with standard laboratory safety regulations. Chemical handling and protein modification processes were performed under controlled laboratory conditions to ensure safety. Food preparation and coating applications followed strict hygiene and food safety standards. Sensory evaluation involved voluntary participants who were informed about the objectives of the study and provided informed consent prior to participation. All samples were safe for consumption, and participants were free to withdraw from the evaluation at any time without penalty.

Results and Discussion

Modification of whey proteins with citric acid

Turbidity was used to follow changes in the size of protein aggregates during modification with citric acid based on light scattering (Figure 1). Absorbance at 500 nm was increased from 0.425 to 0.564 after 4 h of modification. The gradual increase in turbidity gives unambiguous quantitative proof of intermolecular interactions between cross-linked entities, which drive their growth into enormous protein aggregates **[22]**. The cross-linking process relies on the formation of covalent bonds between the carboxylate groups of citric acid and the hydroxyl groups of proteins **[23]**.

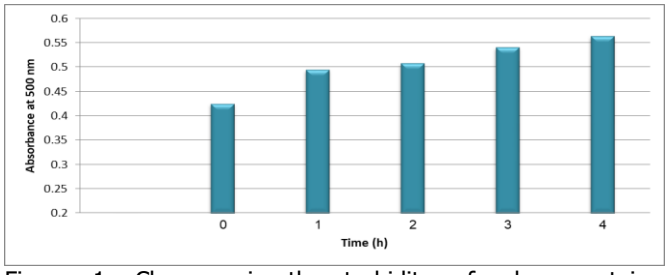


Figure 1. Changes in the turbidity of whey proteins concentrate during treatment with citric acid. Source: Own authorship.

The electrophoretic profiles (Figure 2) show a significant difference in migratory behavior between native and changed proteins, giving molecular proof for the structural alterations outlined previously. Lane (2) depicts natural whey proteins with distinct bands for β-lactoglobulin and α-lactalbumin. Lane (1), which corresponds to citric acid-modified whey proteins, shows a severe alteration; these separate bands vanish completely, replaced by a dense protein aggregation that remains at the stacking gel interface. According to **[22]**, this electrophoretic shift provides solid evidence for significant intermolecular cross-linking. The creation of covalent amide bonds results in macromolecular complexes with molecular weights that surpass the resolving gel's fractionation capacity, limiting their migration into the separation matrix.

Furthermore, Lane (1) shows widespread blurring that extends throughout the gel lane, which **[24]** ascribe to the production of a heterogeneous population of protein polymers with a wide size distribution. Citric acid acts as a polyfunctional cross-linking agent in this situation, randomly connecting polypeptide chains to form polydisperse complexes with varying molecular weights. This polydispersity is owing to the nonspecific nature of the interaction between citric acid carboxyl groups and accessible amine residues on protein surfaces.

Critically, the retention of these protein assemblies at the top of Lane (1) aligns perfectly with the previously documented increases in turbidity and absorbance**[3]** establish that such supramolecular aggregates act as efficient light scattering centers in solution.

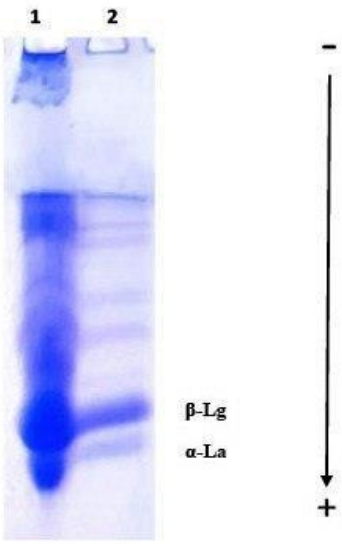


Figure (2) SDS-PAGE of whey proteins modified with citric acid (line 1) compared to normal whey proteins (line 2). Source: Own authorship.

Functional properties of whey proteins modified with citric acid :

Solubility

The solubility study demonstrates a significant pH-dependent difference between native and modified whey proteins, emphasizing the importance of chemical derivatization on surface charge architecture (Figure 3). Citric acid-modified whey protein exhibits relatively poor solubility over the pH range of 3-10, with the lowest solubility seen in the range between pH 3-4, while native whey proteins have exceptionally good solubility at pH values between 3-10. This behavioral disparity provides solid evidence for a shift in the modified protein's which altered surface charge distribution. This decrease in whey proteins solubility after modification with citric acid is related to the ability of citric acid to form crosslinking between proteins units witch reduce the surface charge on protein and decrease their ability to contact with water **[23]**.

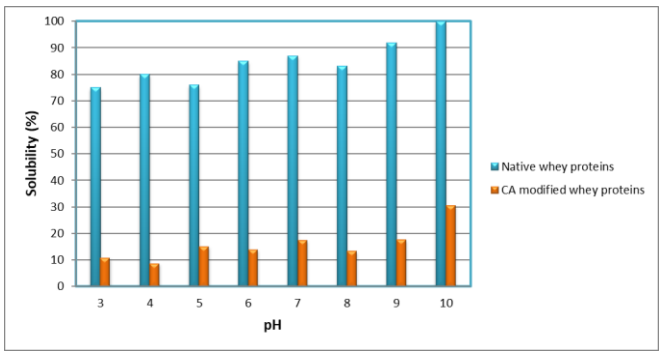


Figure 3. Effect of pH on the solubility of CA modified whey proteins and native whey proteins. Source: Own authorship.

Foaming properties

Protein surface activity and film-forming qualities are necessary for the formation of a protein foam, which is a liquid-protein-containing phase encircling a gas bubble phase. The foaming behavior of modified whey proteins demonstrates a complex interaction between foam generation capability and subsequent stability, revealing that chemical alteration significantly changes interfacial adsorption kinetics. The modified protein shows fast decrease in foam volume from 10 to 0 mL over 0.5 min (Figure 4),while foaming volume of native whey protein was 118 mL at zero time, and this volume decreased gradually to zero after 2.5 min. These results suggests that covalent crosslinking caused by citric acid modification, reducing foaming ability and stability of whey proteins and this maybe related to the decrease in the solubility of CA modified protein which make these proteins unable to bond water and reduce their foaming properties **[25]**.

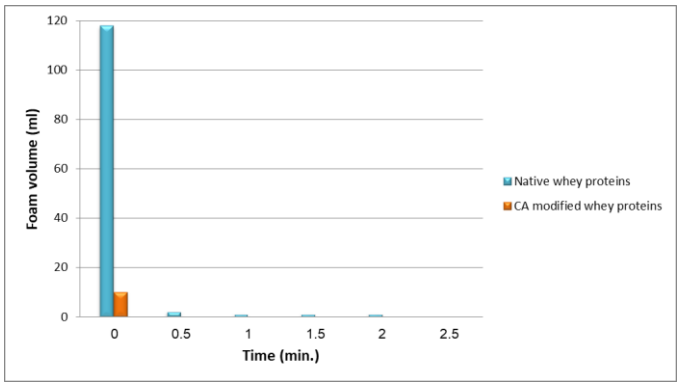


Figure 4. Foam volume of CA modified whey proteins and native whey proteins. Source: Own authorship.

Emulsification

Protein emulsifying capabilities are primarily determined by their ability to adsorb and unfurl at the oil-water interface, where hydrophobic moieties interact with the oil phase while hydrophilic areas retain touch with the aqueous environment **[26]**. Figure 5 showed that native whey protein's emulsifying behavior is pH-dependent, with a significant decrease in capacity near the isoelectric point of the predominant whey protein fractions, particularly β-lactoglobulin, typically range between pH 4.5 and 5.2. At the pI, the net electrostatic charge approaches neutrality, which reduces electrostatic repulsion between protein molecules. This charge neutralization enhances protein aggregation and precipitation, resulting in significantly lower solubility **[27]**. In general the EAI of native whey proteins was higher than EAI of CA modified whey proteins throughout a wide pH range.

The chemical modification with citric acid induces a shift in the effective isoelectric point of the protein through the incorporation of additional carboxyl groups from citric acid, thereby altering the surface charge

architecture; beside that the covalent crosslinking generates modified protein polymers [28]. As a result, these changes decrease the ability of whey proteins to adsorb at the oil-water interface which caused EAI decrease [29].

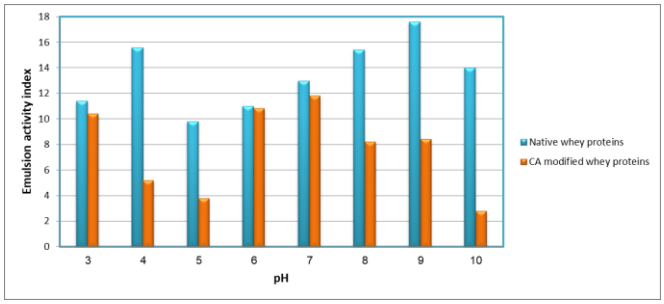


Figure 5. Effect of pH on the emulsion activity index of CA modified whey proteins and native whey proteins. Source: Own authorship.

Effect of coating with CA modified whey proteins on the properties of potato strips

Estimating the moisture content of potato strips

Figure 6 showed that moisture ratio in potato treatments varies depending on coating type.Moisture in control (uncoated) potato stripes was 62.3 % while its ratio was 65.8, 63,68.7 and 72.8 % in T1,T2,T3 and T4 respectively. This result supports the moisture-barrier properties of whey protein-based edible coatings. During deep-frying, the protein matrix creates a physical barrier that effectively retards water vapor evaporation from the product into the surrounding hot oil medium, improving moisture retention and extending the sense of crispness [30]. This result agrees with the findings of [31]. Who found that an edible coating with milk proteins was effective in reducing moisture loss during the heat process.

Although both 2.5% and 5% native whey protein coatings retained more moisture than the control (65.8% and 63.0%, respectively), increasing the protein content from 2.5% to 5% resulted in a small decrease in residual moisture. This negative association shows that higher native protein content, under the harsh heat conditions typical of deep-frying, may damage film integrity claimed that excessive protein content might cause film brittleness or microcracking at high temperatures, reducing barrier performance and allowing for marginally higher moisture leakage. This event emphasizes the vital need of adjusting coating concentration to balance film thickness and structural integrity under heat stress [32].

Surprisingly, the 5% citric acid-modified whey protein coating had the maximum moisture retention of any treatment (72.8%), indicating excellent efficiency in building a robust and functional barrier during deep-frying. This better performance is mechanistically attributed to the structural changes provided by the citric acid treatment. Chemical modification increases the heat stability of the protein matrix [32], allowing for the formation of a more cohesive, less permeable film that keeps structural integrity even under the extreme conditions of deep-frying. This enhanced thermal stability effectively prevents water vapor from escaping, resulting in much greater moisture retention.

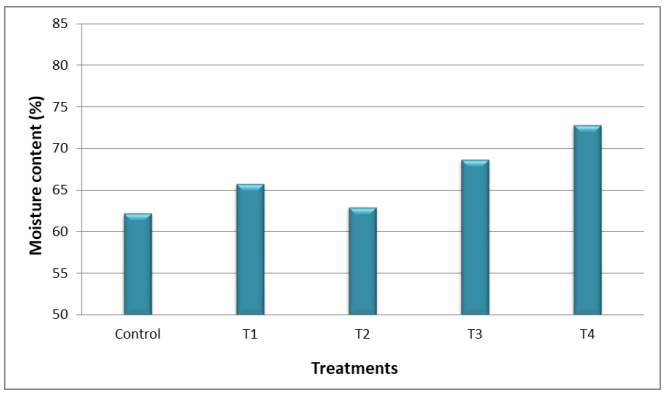


Figure 6. Moisture content in potato strips after frying process at 180°C for 10 min. (T1) strips coated with unmodified whey protein at a concentration of 2.5%, (T2) strips coated with unmodified whey protein at a concentration of 5%, (T3) strips coated with CA-modified whey protein at a concentration of 2.5% and (T4) strips coated with CA-modified whey protein at a concentration of 5%. Source: Own authorship.

Estimating the fat content of potato strips

The lipid content of fried potato strips was measured using Soxhlet extraction after treatment with different protein-based coating formulations, demonstrating the effectiveness of whey protein coatings as functional barriers against oil absorption during deep-frying. Minimizing oil absorption constitutes a significant target in fried food product creation, because lower lipid content immediately increases the nutritional profile and health compatibility. The fundamental principle underlying edible coating application is the formation of a hydrophobic barrier on the product surface, which physically prevents oil penetration during thermal processing; thus, lower residual lipid content is a direct indicator of improved coating barrier efficiency [31]. The untreated control samples had a lipid content of 35.1%, which served as the baseline for measuring coating effectiveness.

All coating treatments significantly decreased oil absorption compared to the control. This decrease is due to whey protein's ability to create a cohesive film network on the potato surface when applied and then dried. This layer acts as a physical barrier, reducing moisture loss while also restricting hot oil penetration

through surface pores during the frying process [33].

The results show that oil content in T1, T2,T3 and T4 were 23.34, 21.73,23.23 and 10.32 respectively (Figure 7). Raising the coating concentration from 2.5% to 5% improves oil barrier performance for both native and modified protein formulations. The lipid content of natural whey protein fell from 23.34% at 2.5% to 21.73% at 5% concentration. Citric acid-modified protein showed a more significant drop, with lipid content falling from 23.23% at 2.5% to 10.32% at 5%. This concentration-dependent response is consistent with the fundamental principles of coating technology, where greater biopolymer concentration results in thicker, denser film development, improving barrier functioning and lowering oil permeability [33].

The most astonishing discovery comes from comparing native and modified proteins at equal doses. The 5% citric acid-modified whey protein coating decreased lipid content to 10.32%, which is less than half of the oil absorption reported with the 5% natural protein coating (21.73%) and a 70.6% reduction compared to the uncoated control (35.1%). This better barrier performance demonstrates the substantial effect of chemical modification on protein interfacial functioning.

The significant difference in oil absorption between native and modified coatings is mechanistically due to the improved film-forming properties caused by citric acid treatment. As previously stated, chemical treatment enhances surface hydrophobicity by structural unfolding and covalent cross-linking. This increased hydrophobicity increases beneficial protein-oil interactions at the interface, allowing for the creation of a cohesive, impermeable layer during frying, effectively preventing oil penetration into the food matrix [22]. Furthermore, citric acid modification is expected to affect the surface charge distribution of protein molecules, allowing for orderly aggregation and the development of more structured, strong protein networks. This structural rearrangement enables the modified protein film to retain its integrity, density, and barrier functioning even under the severe heat conditions associated with deep-frying [34].

These findings confirm the well-known negative link between moisture retention and oil absorption in fried food systems [30]. The treatment with the highest moisture retention (72.8% for 5% modified protein) matches identically to the treatment with the lowest oil uptake (10.32%, as mentioned in the fat analysis section). This reciprocal connection demonstrates that good moisture barrier construction not only retains product moisture but also limits oil penetration into the food matrix during frying. The citric acidmodified protein coating thus provides a very successful technique for concurrently enhancing both quality characteristics, with substantial promise for the production of low-fat fried items with improved sensory features.

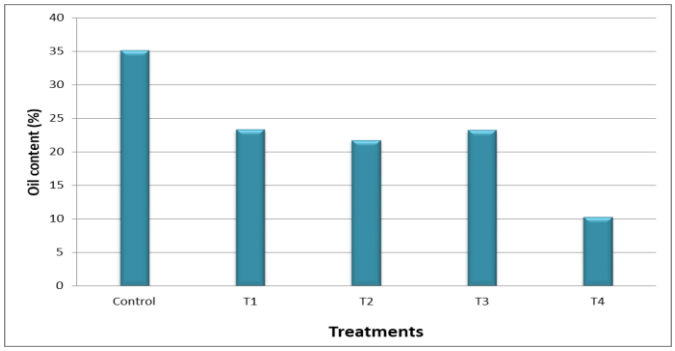


Figure 7. Oil content in potato strips after frying process at 180°C for 10 min. (T1) strips coated with unmodified whey protein at a concentration of 2.5%, (T2) strips coated with unmodified whey protein at a concentration of 5%, (T3) strips coated with CA-modified whey protein at a concentration of 2.5% and (T4) strips coated with CA-modified whey protein at a concentration of 5%. Source: Own authorship.

Hardness of potato strips

Hardness is a significant quality trait that indicates the coating's mechanical effect and efficacy in keeping product texture after heat processing, particularly deep frying. In fried items, hardness is an important textural indicator, representing the strength and brittleness of the outer crust. This textural property is the result of a complicated interaction between decreased oil absorption, moisture retention, and the protein film's intrinsic mechanical characteristics.

The results (Figure 8) show that hardness in control was 111.8 g while in T1, T2,T3 and T4 were 271.1, 119.8,138.2 and 44.3 g respectively. The 2.5% natural whey protein coating had the greatest hardness value. The significant decrease in hardness found for the 5% natural protein coating (119.8 g) compared to its 2.5% counterpart (271.1 g) indicates a concentration-dependent textural shift.

The 2.5% modified whey protein coating displayed increased hardness (138.2g) compared to the untreated control (111.8 g), showing that citric acid modification improves mechanical characteristics at this dose. However, the 5% modified coating had the lowest hardness value of all treatments (44.3 g), offering an intriguing paradox: this formulation displayed higher oil barrier effectiveness (10.32% lipid content) while producing the weakest mechanical texture. This seeming contradiction highlights the intricate structure-function interactions that affect modified protein film performance.

As previously stated, the citric acid modification increases film flexibility via covalent cross-linking. At higher concentrations (5%), this increased flexibility may become excessive, resulting in a coating that is too flexible or rubbery rather than crisp and firm. While the cross-linked network provides an efficient barrier against oil penetration, it may lack the brittleness necessary for the typical crispy feel of fried items.The modified protein film is anticipated to absorb mechanical stress via deformation rather than fracture, resulting in lower experimental hardness values despite enhanced barrier performance **[22]**.

The findings show that citric acid modification does not evenly improve all functional parameters; rather, it significantly enhances lipid barrier performance and moisture retention at high concentrations while potentially impairing hardness at the same concentration. Native whey protein, on the other hand, has the best mechanical texture when used at the recommended concentration (2.5%).

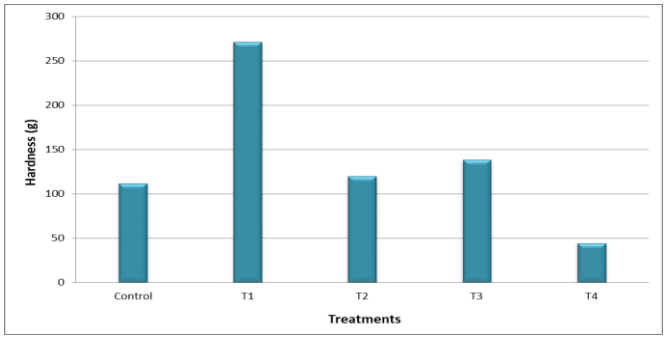


Figure 8. Hardness of potato strips after frying process at 180°C for 10 min. (T1) strips coated with unmodified whey protein at a concentration of 2.5%, (T2) strips coated with unmodified whey protein at a concentration of 5%, (T3) strips coated with CA-modified whey protein at a concentration of 2.5% and (T4) strips coated with CA-modified whey protein at a concentration of 5%. Source: Own authorship.

Sensory Evaluation of potato strips

The application of whey protein as an edible coating significantly improved the sensory attributes of fried potato strips. The 5% citric acid-modified whey protein coating received the highest scores (approximately 42), followed by the 2.5% modified protein formulation (Figure 9). The increased sensory acceptance of modified protein-coated samples is due to citric acid-induced covalent cross-linking, which results in minimizing oil penetration into the potato tissue and a limiting moisture loss, retaining interior softness against surface crispness. This dual functioning is consistent with **[22]** observations on the impact of cross-linked protein assemblies in improving the mechanical quality of edible films.

Sensory data shows that raising modified protein concentration from 2.5% to 5% leads to proportionate gains in assessment scores, indicating a positive concentration-dependent connection. This dose-responsive augmentation suggests that greater protein film density provides improved sensory attribute protection, such as color, taste, and texture. According to the extensive review by **[30]**. Protein-based colloidal films improve moisture retention and texture quality in deep-fried meals, which explains why panelists preferred samples coated with 5% modified protein, which received the highest acceptance ratings compared to the uncoated control (around 37).

The modified protein structure, shown by SDS-PAGE and the creation of high-molecular-weight polymers, creates a protective layer that resists drainage and bubble collapse when frying. This structural integrity gives the potato strips an appealing look and maintains textural cohesiveness after heat processing **[32]**. Sensory assessment scores show that citric acid modification goes beyond altering biochemical attributes and successfully translates these enhancements into the final product. The enhanced whey protein coating fulfills the crucial goal of creating healthier fried potato strips (lower fat content) while still providing higher sensory quality. This dual optimization establishes citric acid-modified whey protein as an exemplary formulation for applications requiring both nutritional enhancement and consumer acceptability, with significant commercial potential in the development of low-fat fried products with uncompromised sensory properties.

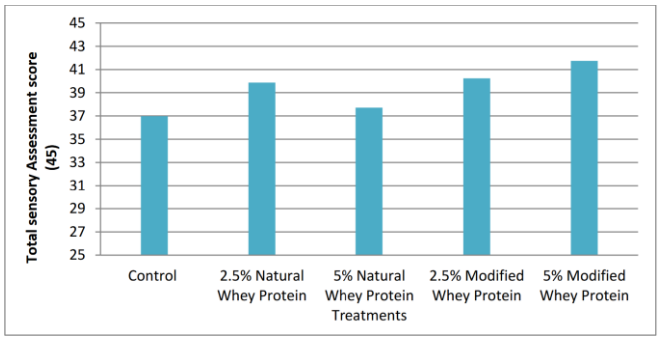


Figure 9. Total sensory evaluation score of potato strips after frying process at 180°C for 10 min. (T1) strips coated with unmodified whey protein at a concentration of 2.5%, (T2) strips coated with unmodified whey protein at a concentration of 5%, (T3) strips coated with CA-modified whey protein at a concentration of 2.5% and (T4) strips coated with CA-modified whey protein at a concentration of 5%. Source: Own authorship.

Conclusion

Citric acid effectively crosslinks whey proteins by forming covalent bonds, resulting in high-molecular-weight polymers with changed functional

characteristics. Although the change affects solubility, foaming, and emulsifying capacity, it improves the protein's ability to create thermally stable, efficient barrier coatings. The 5% citric acid-modified whey protein coating is particularly efficient in reducing oil absorption in fried potato strips while retaining moisture and providing great sensory acceptability. This technique provides a safe, cost-effective, and commercially feasible alternative for creating healthier fried foods without sacrificing quality.

CRediT

Conceptualization; Data Curating; Formal Analysis; and Investigation: Anaam S. Al-khafaje, Project Administration; Supervision; Writing - Original Draft: Jasim M. S. Al-Saadi

Acknowledgment

The authors wish to express their gratitude to all individuals and institutions that provided support during the course of this study. Special thanks are extended to those who contributed to the study design, data collection, and analysis.

Ethical Approval

The study was approved by the Institutional Ethics Committee of the College of Food Science, Al-Qasim Green University, Babylon, Iraq.

Informed Consent

Informed consent was obtained from all participants involved in the study, with all procedures explained in detail before participation.

Funding

Not applicable.

Data Sharing Statement

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request, and all data is stored following privacy and ethical guidelines.

Conflict of Interest

The authors declare no competing interests.

Similarity Check

It was applied by Ithenticate®.

Application of Artificial Intelligence (AI)

Not applicable.

Peer Review Process

It was performed.

References

1. Amin M. Whey proteins and their importance in food industry. International Journal of Dairy Science, 2014, 9(3), 45-52.
2. Zhu T, Wu B. Repurposing Amide Bond-Forming Enzymes for Non-native Protein Modification. ACS Catalysis, 2024, 14(21), 15811–15826.
3. Li X, Zhang H, Chen Y. Citric acid as a safe crosslinking agent for protein modification: A review. Food Chemistry, 2018, 245, 678-685.
4. Xu H, Shen L, Xu L, Yang Y. Low-temperature crosslinking of proteins using citric acid for food packaging applications. Journal of Agricultural and Food Chemistry, 2015, 63(4), 1183-1190.
5. Reddy N, Li Y, Yang Y. Citric acid cross-linking of protein films for biomedical and food applications. Biotechnology Progress, 2009, 25(5), 1418-1424.
6. Nourbakhsh H, Madadlou A, Emam-Djomeh Z, Wang YC, Gunasekaran S. Citric acid cross-linking of heat-set whey protein hydrogel for delivery of gallic acid. Food Chemistry, 2016, 197, 136-143.
7. Jasim AA, Al-Saadi JM. Study the effect of adding iron salts on the physiochemical and sensory properties of yoghurt. Indian Journal of Forensic Medicine & Toxicology, 2020, 14(4), 2771-2778.
8. Azevedo VM, Dias MV, Borges SV, Costa ALR. Whey protein isolate edible films cross-linked with citric acid: Physical, mechanical, and barrier properties. Food and Bioprocess Technology, 2015, 8(8), 1739-1748.
9. Garcia Anaya MC, Sepulveda DR, Contreras-Esquivel JC. Edible coatings and films: A review on materials, application techniques, and future perspectives. Food Packaging and Shelf Life, 2023, 35, 101023.
10. Li X, Zhang H, Chen Y. Citric acid cross-linking of whey protein for improved functional properties. Food Chemistry, 2020, 305, 125-133.
11. Munialo CD, van der Linden E, de Jongh HH. Turbidity measurement for monitoring protein cross-linking. Food Hydrocolloids, 2013, 30(1), 123-130.

12. Laemmli UK. Cleavage of structural proteins during the assembly of the head of bacteriophage T4. Nature, 1970, 227(5259), 680-685.
13. Mulakhudair AR, Al-Bedrani DI, Al-Saadi JM, Kadhim DH, Saadi AM. Improving chemical, rheological and sensory properties of commercial low-fat cream by concentrate addition of whey proteins. Journal of Applied and Natural Science, 2023, 15(3), 998.
14. Al-Saadi JMS, Deeth HC. Cross-linking of proteins and other food components. In Encyclopedia of Dairy Sciences, 2011, 2nd ed., pp. 789-795.
15. Waniska RD, Kinsella JE. Foaming properties of proteins: Evaluation of a column aeration apparatus using ovalbumin. Journal of Food Science, 1979, 44(5), 13981402.
16. Pearce KN, Kinsella JE. Emulsifying properties of proteins: Evaluation of a turbidimetric technique. Journal of Agricultural and Food Chemistry, 1978, 26(3), 716-723.
17. De Grandi Castro Freitas D, Berbari SA, Prati P, Faria J. Reducing oil uptake in fried potato strips using edible coatings. Food Science and Technology, 2009, 29(3), 532-537.
18. Han JH, Gennadios, A. Edible films and coatings: A review. In Innovations in Food Packaging, 2004, pp. 239-262. Academic Press.
19. Rimac-Brnčić S, Lelas V, Rade D, Šimundić B. Decreasing of oil absorption in potato strips during deep fat frying. Journal of Food Engineering, 2004, 64(2), 237-241.
20. AOAC. Official Methods of Analysis (18th ed.). Association of Official Analytical Chemists, Washington, DC, USA, 2008.
21. Amerine MA, Pangborn RM, Roessler EB. Principles of Sensory Evaluation of Food. Academic Press, New York, 1965.
22. Wang Y, Zhang L, Chen H. Cross-linked protein aggregates: Formation, characterization, and functional properties. Food Hydrocolloids, 2018, 82, 312-321.
23. Azeredo HMC, Waldron KW, Kirby AR. Cross-linking of polysaccharides and proteins with citric acid for food applications. Food Research International, 2016, 88, 218-225.
24. Luo Y, Pan K, Zhong Q. Physical, chemical and biochemical properties of whey protein cross-linked with citric acid. International Journal of Food Science & Technology, 2017, 52(3), 732-740.
25. Siamand RN, Al-Saadi JMS. Functional properties of cow milk proteins co-precipitate. Journal of Garmian university, 4(ICBS Conference), 2017, 340-356.
26. Lam RSH, Nickerson MT. Food proteins: A review on their emulsifying properties using a structure-function approach. Food Chemistry, 2013, 141(2), 975-984.
27. Damodaran S. Amino acids, peptides, and proteins. In S. Damodaran & K. L. Parkin (Eds.), Fennema's Food Chemistry, 2017, 5th ed., pp. 235-356. CRC Press.
28. Dudeja S, Chauhan AK, Singh RRB. Protein modification for improved functionality: A comprehensive review. Journal of Food Science and Technology, 2023, 60(2), 451-465.
29. Al-Saadi JMS. Effect of heat treatment on whey proteins denaturation in the presence and absence of lactose. Journal of Zankoy Sulaimani-Part A, Special Issue, 2014, 16, 271-279.
30. Bansal V, Jindal N. Edible coatings for deep-fried foods: A review. Journal of Food Science and Technology, 2019, 56(4), 1705-1715.
31. Mohammed NK, Muhialdin BJ, Meor Hussin AS. Milk proteins as edible coatings: A review of their application in food preservation. Food Reviews International, 2021, 37(6), 651-672.
32. Raikos V. Effect of heat treatment on milk protein functionality at emulsion interfaces: A review. Food Hydrocolloids, 2010, 24(4), 259-265.
33. Ziai M, Alaei F. Application of edible coatings for reduction of oil uptake in fried foods: A review. Journal of Food Processing and Preservation, 2018, 42(2), e13482.
34. Dickinson E. Mixed biopolymers at interfaces: Competitive adsorption and multilayer structures. Food Hydrocolloids, 2011, 25(8), 1915-1921.
35. Fonger GC, Hakkinen P, Jordan S, Publicker S. The National Library of Medicine's (NLM) Hazardous Substances Data Bank (HSDB): background, recent enhancements and future plans. Toxicology, 2014, 325, 209–216.