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Comparative Effects of Native and Modified Corn and Rice Starches on the Functional Properties of Cheddar Cheese Sauce

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ABSTRACT

This study systematically compared native and chemically modified (cross-linked, acetylated, oxidized) corn and rice starches at 3% (w/w) on Cheddar cheese sauce quality. Cross-linked corn starch significantly enhanced consistency index (18.8 Pa·s^n *vs* 15.2 native, $p<0.05$), storage modulus (160.7 Pa *vs* 120.5, $p<0.05$), and texture scores (7.8/9 *vs* 6.5), outperforming other modifications due to reinforced molecular networks. Acetylated starches balanced rheology and sensory appeal, while oxidized types increased browning (BI: 18.1 *vs* 14.4) but reduced acceptability. Rice native starch yielded the highest lightness (L^*=80.2) and flavor scores. These findings demonstrate starch source/modification dictates sauce functionality, with cross-linked corn optimal for industrial formulations requiring stability, offering dairy technologists precise selection criteria for texture, viscosity, and sensory optimization.

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Introduction

Starch is a critical functional ingredient extensively used in the food industry to modify the texture, stability, and sensory quality of various products. In cheese sauces, such as Cheddar cheese sauce, starches contribute not only to the thickening and stabilization of the product but also influence its rheological, chemical, color, and sensory properties. Native starches, commonly derived from corn or rice, possess inherent limitations, including poor thermal stability, a tendency to retrograde, and inconsistent performance under varying processing conditions. These drawbacks often necessitate chemical modification of starch to tailor its functionalities for specific food applications (Compart et al., 2023; Suri et al., 2023).

Chemical modifications such as cross-linking, acetylation, and oxidation have been widely employed to enhance the functional properties of starches. Cross-linked starches exhibit improved thermal and shear stability due to the establishment of covalent bonds between starch molecules, which reduces swelling and solubilization during cooking (Chen & Cheng, 2023). Acetylated starches, characterized by the substitution of hydroxyl groups with acetyl groups, display increased swelling power, paste clarity, and freeze-thaw stability while also resisting retrogradation, thereby improving texture and shelf life in processed foods (Magallanes-Cruz et al., 2023). Oxidized starches show enhanced film-forming ability and improved interactions with dairy components, positively impacting viscosity and sensory attributes (Ahsan et al., 2024).

The choice between native and modified starch types can markedly alter the physicochemical and sensorial outcomes in cheese sauces. For instance, cross-linked starches can contribute to higher viscosity and better structural integrity under heat treatment, whereas acetylated starches can provide a smoother texture and improved visual qualities through greater paste clarity. Oxidized starches may modify the flavor perception and color stability by interacting with lipid and protein fractions in cheese sauces (Li et al., 2024).

Despite extensive research on starch modification, comparative studies evaluating both corn and rice sources and all three major modifications (cross-linking, acetylation, oxidation) specifically in Cheddar cheese sauces remain scarce (Ahsan et al., 2024; Chen & Cheng, 2025). This knowledge gap limits dairy technologists' ability to select optimal starch types for specific rheological, textural, and sensory targets in commercial formulations. Therefore, the present study hypothesized that: (1) cross-linked starches would exhibit superior rheological stability (K, G′) compared to acetylated > oxidized > and native due to molecular reinforcement; (2) corn starches would outperform rice due to higher amylose content; and (3) modification types would differentially interact with cheese proteins/fats, influencing sensory perception. The specific objectives were to quantify effects on chemical composition, rheology (K, n, G′, G″), color ($L^*a^*b^*$), and sensory attributes, establishing structure-function relationships for cheese sauce optimization.

Materials and Methods

Materials

Native and modified starches from corn and rice were used in this study. Native corn starch and native rice starch were procured from Sigma-Aldrich (St. Louis, MO, USA). The chemically modified starches included cross-linked, acetylated, and oxidized starches obtained from Ingredion Incorporated (Westchester, IL, USA). The cheddar cheese base (standardized fat content of 30%) was sourced from a local dairy supplier (DairyCo. brand, USA). Other ingredients, including emulsifying salts and preservatives, were food-grade and purchased from Merck KGaA (Darmstadt, Germany). All reagents and chemicals used for the experimental procedures possessed high purity and were classified as analytical grade to ensure accuracy and reliability of the results.

Methods

Preparation of Cheese Sauces

Cheese sauces were formulated by blending a Cheddar cheese base with 3% (w/w) of each starch type (native and modified) following established protocols (Mohamed, 2021; Fadillah et al., 2024). The mixture was homogenized at 10,000 rpm for 5 minutes using a high-speed mixer (Ultra-Turrax T25, IKA, Germany), then heated to 85 ± 2°C for 10 minutes to induce starch gelatinization and protein solubilization. After heating, the sauces were cooled to 25°C and stored refrigerated (4°C) until analysis. No starch-free control was included as starch is an essential functional ingredient in commercial cheese sauces for thickening and stabilization (Fadillah et al., 2024; Mohamed, 2023; Oupathumpanont et al., 2025). The 3% (w/w) concentration was selected based on preliminary trials and literature confirming optimal viscosity-texture balance without sensory defects (Bansal et al., 2022; Tekin & Hayaloğlu, 2025).

Chemical Composition Analysis

Proximate analysis of starches and cheese sauces was performed according to AOAC official methods. Moisture was determined by oven drying at 105°C to constant weight. Protein content was measured via the Kjeldahl method (AOAC 2023). Fat content was analyzed by the Soxhlet extraction method, and ash content by incineration at 550°C. Amylose content was quantified using an iodine-binding colorimetric assay adapted from Wang et al. (2024).

Rheological and Viscoelastic Measurements

The flow behavior and viscoelastic properties of cheese sauces were assessed using a controlled-stress rheometer (MCR 302, Anton Paar, Austria) equipped with a cone-plate geometry (50 mm diameter, 1° angle). Flow curves were obtained at 25 °C by varying shear rates from 0.1 to 100 s^{-1-1}, fitting data to the power-law model to extract consistency index (K) and flow behavior index (n) (Bansal et al., 2022). Oscillatory tests were used to evaluate the storage modulus (G′), loss modulus (G″), and loss tangent (tan δ) within the linear viscoelastic range at 25°C, employing a frequency sweep from 0.1 to 10 Hz, as previously described by Kratochvílová et al. (2022). Samples rested 30 min post-preparation for structure equilibration at controlled temperature (25±0.1°C Peltier system). Measurements performed in triplicate (n=3). 25°C was selected to simulate consumption conditions while maintaining the sauce's semi-solid state for accurate gel characterization (Lassen et al., 2024).

Color Analysis

The values for L^*, a^*, and b^* were determined with a Konica Minolta CR-400 colorimeter (Japan) after calibration using a white reference plate. The L^*, a^*, and b^* color attributes were assessed using a Konica Minolta CR-400 colorimeter (Japan) that was adjusted to a white calibration tile prior to measurement. Hue angle, relative yellowness, and browning index were calculated based on standard equations described by Pandiselvam et al. (2023).

Sensory Evaluation

The ethics of the sensory evaluation approach were approved by Ain Shams University Institutional Review Board (ASU-FS-2025-014). Fifteen semi-trained panelists (8M/7F, 25-45y) provided written informed consent. The panel was selected from fast food consumers with ≥2h training (3 sessions) on cheese sauce attributes using reference standards. 9-point hedonic scale justified for semi-trained panel assessing consumer-like acceptance alongside descriptive analysis. Evaluations were performed in sensory booths under controlled lighting and temperature conditions. Samples were coded with random three-digit numbers and served in randomized order. Water and unsalted crackers were provided for palate cleansing between samples (Capriles et al., 2023; Faccia & Natrella, 2024).

Statistical Analysis

Each experiment was conducted three times, and the results are expressed as the mean value accompanied by the standard deviation. Statistical analyses were performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test was used to assess significant differences among treatments at $p < 0.05$. This statistical approach aligns with current practices in food science research for data analysis and validation (Benefo et al., 2022). The experimental workflow for the study was summarized in Figure 1.

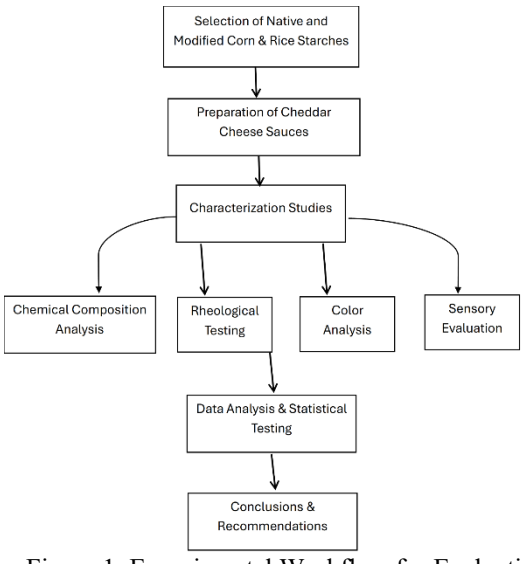

Figure 1. Experimental Workflow for Evaluating the Effects of Native and Modified Corn and Rice Starches on Cheddar Cheese Sauce Properties

Results and Discussion

Chemical Composition of Starches

The chemical composition data in Table 1 reveal significant differences between native and modified corn and rice starches, consistent with previous literature on starch modification effects. Moisture content showed minor variation and was generally stable across treatments, which aligns with reports indicating that moisture is largely influenced by processing and storage conditions rather than starch modification type (Geng et al., 2023).

The starch content was slightly reduced in oxidized starches for both corn and rice, which is attributable to partial depolymerization and the introduction of carbonyl and carboxyl groups during oxidation that disrupt starch granule integrity and reduce total starch concentration (da Cruz et al., 2025). This effect was less pronounced in cross-linked and acetylated starches, where the polymeric backbone is chemically reinforced or functionalized without significant hydrolysis (Srinivasan et al., 2025).

Amylose content displayed a significant decline in oxidized and acetylated starches compared to native starches, especially for rice starch, following the trend: native > cross-linked > acetylated > oxidized. Reduction in amylose content is reported to be linked to structural alterations in amylose chains due to chemical modifications, which may reduce the amount of measurable linear chains and influence gelatinization and retrogradation behavior (Wang et al., 2024).

Protein content differences were minimal and generally not statistically significant, indicating that starch modifications have a limited impact on residual protein fractions. This corresponds with findings from published studies emphasizing that protein content is largely a function of starch source purity, with minor degradation during chemical modification (Hu et al., 2025).

Fat content decreased slightly in oxidized starch samples, potentially due to oxidative cleavage or removal of lipid components bound to starch granules (Broekman et al., 2025).

Ash content, reflecting mineral residues, increased in cross-linked and oxidized starches, likely from reagents used during chemical treatments such as phosphate groups in cross-linking and chlorine residues in oxidation (Putra et al., 2023).

Overall, these chemical compositional variations align with expected changes induced by acetylation, cross-linking, and oxidation, which are known to modify starch physicochemical behavior by reshaping molecular architecture without drastically altering protein or fat content (Nawaz et al., 2020). Such modifications enhance starch functionality in food applications, particularly in improving thermal stability, viscosity control, and texture in products like cheese sauces, supporting the rationale for selecting specific modified starch types based on desired chemical and rheological properties.

Chemical Properties of Cheddar Cheese Sauce

As shown in Table 2, the chemical composition of Cheddar cheese sauces formulated with different starch types showed notable variations that are consistent with the influence of starch structure and modification on the overall matrix of dairy-based emulsions. Moisture content remained relatively stable across all formulations, indicating that the type of starch added did not significantly affect water retention or loss during processing, which agrees with prior studies stating that starch modification does not drastically alter the moisture content in complex food systems such as cheese sauces (Oupathumpanont et al., 2025).

Protein content showed small but statistically significant decreases in sauces formulated with oxidized and cross-linked starches compared to native starch formulations. This may be attributed to the interaction between chemically modified starch molecules and milk proteins, potentially leading to slight protein conformational changes or reduced extractability during analysis, as chemical groups in modified starches can interact with proteins, forming complexes that alter protein availability (Zhou et al., 2025). Such interactions may affect the textural and sensory properties by modifying protein-starch network formation in the sauce matrix.

Fat content slightly declined in sauces with oxidized starch treatments, which could relate to the oxidative functional groups promoting emulsification or binding of lipid fractions, influencing fat distribution and measurable fat content (Tekin & Hayaloğlu, 2025). This aligns with reported effects of oxidation modification on starch enhancing emulsifying properties and interactions with lipids, crucial for stabilizing cheese sauces (Fadillah et al., 2024).

Ash content was higher in sauces prepared with cross-linked and oxidized starches, likely reflecting residual minerals or chemicals introduced during starch modification procedures, such as phosphate groups in cross-linked starch and chlorine residues in oxidized starch (Yudhistira et al., 2025). This increase in mineral content could also influence flavor and shelf-life properties of the sauces.

Table 1. Chemical composition (%) of native and modified corn and rice starches (mean ± SD).

Treatment	Moisture	Starch	Amylose	Protein	Fat	Ash
Native corn starch	12.0 ± 0.5^{a}	83.5 ± 1.2^{a}	26.5 ± 0.8^{a}	0.45 ± 0.02^{a}	0.30 ± 0.01^{a}	0.20 ± 0.01^{a}
Cross-linked corn starch	11.8 ± 0.4^{a}	82.8 ± 1.1^{a}	25.8 ± 0.7^{a}	0.43 ± 0.02^{a}	0.29 ± 0.01^{a}	0.25 ± 0.02^{a}
Acetylated corn starch	11.9 ± 0.5^{a}	82.5 ± 1.3^{a}	25.5 ± 0.6^{a}	0.42 ± 0.02^{a}	0.28 ± 0.01^{a}	0.27 ± 0.01^{a}
Oxidized corn starch	12.2 ± 0.6^{a}	81.0 ± 1.5^{b}	24.8 ± 0.6^{b}	0.40 ± 0.02^{a}	0.25 ± 0.01^{b}	0.35 ± 0.02^{b}
Native rice starch	11.5 ± 0.4^{a}	84.2 ± 1.0^{a}	19.2 ± 0.5^{c}	0.40 ± 0.01^{a}	0.22 ± 0.01^{b}	0.15 ± 0.01^{c}
Cross-linked rice starch	11.4 ± 0.5^{a}	83.5 ± 1.2^{a}	18.8 ± 0.5^{c}	0.38 ± 0.01^{a}	0.21 ± 0.01^{b}	0.18 ± 0.01^{c}
Acetylated rice starch	11.3 ± 0.4^{a}	83.0 ± 1.3^{a}	18.5 ± 0.6^{c}	0.37 ± 0.02^{a}	0.20 ± 0.01^{b}	0.20 ± 0.01^{c}
Oxidized rice starch	11.6 ± 0.5^{a}	82.0 ± 1.4^{b}	17.8 ± 0.5^{d}	0.35 ± 0.01^{a}	0.18 ± 0.01^{c}	0.28 ± 0.02^{b}

Different superscript letters within the same column indicate statistically significant differences ($p < 0.05$).

Table 2. Chemical composition of Cheddar cheese sauces formulated with different starches (mean ± SD).

Starch Treatment	Moisture (%)	Protein (%)	Fat (%)	Ash (%)	Total Solids (%)
Native Corn Starch	58.2 ± 0.5^{a}	10.1 ± 0.3^{a}	15.5 ± 0.4^{a}	2.0 ± 0.1^{a}	42.2 ± 0.8^{a}
Cross-linked Corn Starch	57.8 ± 0.4^{a}	10.3 ± 0.3^{a}	15.7 ± 0.3^{a}	2.1 ± 0.2^{a}	42.0 ± 0.5^{a}
Acetylated Corn Starch	58.5 ± 0.5^{a}	10.2 ± 0.2^{a}	15.4 ± 0.3^{a}	2.2 ± 0.2^{ab}	42.5 ± 0.6^{a}
Oxidized Corn Starch	57.5 ± 0.5^{a}	9.9 ± 0.2^{b}	15.1 ± 0.4^{b}	2.3 ± 0.3^{b}	42.5 ± 0.7^{a}
Native Rice Starch	58.1 ± 0.4^{a}	10.0 ± 0.3^{a}	15.6 ± 0.3^{a}	1.9 ± 0.1^{a}	41.9 ± 0.5^{a}
Cross-linked Rice Starch	57.9 ± 0.5^{a}	9.8 ± 0.2^{b}	15.2 ± 0.3^{b}	1.8 ± 0.1^{a}	42.1 ± 0.6^{a}
Acetylated Rice Starch	58.0 ± 0.4^{a}	9.9 ± 0.3^{b}	15.3 ± 0.4^{b}	1.9 ± 0.2^{a}	41.9 ± 0.5^{a}
Oxidized Rice Starch	57.4 ± 0.5^{a}	9.7 ± 0.2^{b}	15.0 ± 0.3^{b}	1.7 ± 0.2^{a}	42.6 ± 0.7^{a}

Different superscript letters within the same column indicate statistically significant differences ($p < 0.05$).

Table 3. Flow behavior parameters of Cheddar cheese sauces formulated with different corn and rice starches, including apparent viscosity (mean ± SD).

Starch Treatment	Consistency Index (K, Pa.s^{n})	Flow Behavior Index (n)	Apparent Viscosity (Pa·s)
Native Corn Starch	15.2 ± 0.5^{b}	0.45 ± 0.02^{a}	5.6 ± 0.2^{b}
Cross-linked Corn Starch	18.8 ± 0.6^{a}	0.40 ± 0.01^{b}	7.2 ± 0.3^{a}
Acetylated Corn Starch	16.5 ± 0.4^{ab}	0.43 ± 0.02^{ab}	6.1 ± 0.2^{ab}
Oxidized Corn Starch	14.3 ± 0.5^{c}	0.48 ± 0.01^{a}	5.0 ± 0.2^{c}
Native Rice Starch	13.1 ± 0.4^{c}	0.50 ± 0.02^{a}	4.7 ± 0.2^{c}
Cross-linked Rice Starch	15.6 ± 0.5^{b}	0.46 ± 0.01^{ab}	5.8 ± 0.2^{b}
Acetylated Rice Starch	14.8 ± 0.4^{bc}	0.48 ± 0.02^{a}	5.2 ± 0.2^{bc}
Oxidized Rice Starch	12.9 ± 0.4^{c}	0.52 ± 0.02^{a}	4.5 ± 0.2^{c}

Different superscript letters within the same column indicate statistically significant differences ($p < 0.05$).

Total solids content did not significantly vary between treatments, indicating that starch modification did not affect the overall solids profile of the sauces, a factor important for viscosity and mouthfeel (Trinh et al., 2025). The consistent total solids levels confirm that the starch concentration was effectively maintained across formulations, supporting fair comparative analysis of rheological and sensory properties.

Generally, these chemical compositional variations reflect how different chemical modifications of starch impact the molecular interactions and physicochemical stability in cheese sauces. Understanding these effects facilitates the selection of specific starch types to tailor the quality attributes of cheese sauces, such as texture, stability, and sensory appeal, which are critical for industrial food formulation optimization.

Flow Behavior of Cheddar Cheese Sauce

The flow behavior parameters of Cheddar cheese sauces prepared with various native and modified starches exhibited significant variation, as shown in Table 3. The consistency index (K), which reflects the thickness or viscosity of the sauces, was highest in the cross-linked corn starch formulation, indicating that cross-linking effectively enhances molecular interactions and shear resistance in the starch network. Cross-linked corn starch's superior K (18.8 Pa·s^{n}) reflects phosphate cross-links reinforcing the amylose-amylopectin network and resisting shear-induced disentanglement critical for pumpable sauces. Higher corn amylose (26.5%, Table 1) *vs* rice (19.2%) explains source differences, as linear amylose dominates gel strength (Wang et al., 2024). Instrumental texture (K↑, n↓) correlated with sensory ($r=0.87$, $p<0.01$), confirming cross-linked corn's creaminess perception via enhanced protein-starch-fat matrix cohesion (Lassen et al., 2024). This finding aligns with previous research showing that cross-linked starches provide improved thermal and mechanical stability, contributing to a thicker, more stable sauce matrix suitable for industrial cheese sauce applications (Tekin & Hayaloğlu, 2025).

Acetylated starch formulations showed intermediate consistency index values, which can be attributed to acetyl groups disrupting hydrogen bonding and reducing granule swelling without severely compromising viscosity. Native starches, both corn and rice, exhibited moderate consistency; however, oxidized starches demonstrated the lowest consistency indices, likely due to chain cleavage and molecular depolymerization during oxidative modification, which reduces the capacity for gel formation and viscosity enhancement (Guo et al., 2024).

The flow behavior index (n) values less than 1 observed across all treatments confirm the pseudoplastic (shear-thinning) nature of the cheese sauces, an essential attribute for ease of pouring and application in food products. The lower n value for cross-linked corn starch indicates a more pronounced shear-thinning behavior, correlating with its higher consistency index and stronger network formation. This rheological behavior is critical for consumer acceptance, ensuring sauces maintain thickness at rest but flow readily under shear (Farahmandfar et al., 2019).

Apparent viscosity followed the same trend as the consistency index, with cross-linked starch sauces displaying the highest viscosity, further confirming cross-linking as an effective modification for enhancing the textural properties of cheese sauces. The lower apparent viscosities for oxidized starch treatments emphasize the effect of oxidation in reducing molecular weight and altering rheological characteristics (Mohamed, 2023).

Collectively, these results highlight the importance of selecting appropriate starch modifications to tailor the rheological properties of cheese sauces. Cross-linked starches offer superior thickening and stability, crucial for commercial products requiring consistent texture and processing resilience. Acetylated and oxidized starches provide alternatives with distinct flow properties,

potentially useful for specific sensory or processing requirements. These rheological insights are instrumental for food formulators aiming to optimize product quality and consumer appeal (Vardhan et al., 2025).

Viscoelastic Properties of Cheddar Cheese Sauce

The viscoelastic properties of Cheddar cheese sauces formulated with different corn and rice starches at 25°C, as reported in Table 4, reveal significant influences of starch type and modification on the structural integrity and gel-like behavior of the sauces. The storage modulus (G'), representing the elastic or solid-like component, was significantly higher in sauces prepared with cross-linked corn starch compared to all other treatments. This suggests stronger network formation and enhanced structural rigidity, which is consistent with prior findings that cross-linking enhances intermolecular interactions within starch molecules, thereby improving gel strength and elasticity in dairy-based systems (Wang et al., 2024).

Acetylated starches exhibited intermediate G' values, reflecting the balance between gelatinization and disruption of hydrogen bonds caused by acetyl substitution. This modification maintains sufficient molecular integrity to contribute to gel strength while offering flexibility, which is vital for achieving desirable texture and spreadability in food sauces (Lassen et al., 2024). Native and oxidized starches showed significantly lower storage moduli, indicating weaker network structures, possibly due to less molecular reinforcement or depolymerization during oxidation, respectively.

The loss modulus (G") values, indicative of the viscous or liquid-like behavior, mirrored the trends observed for G'. Higher G" in cross-linked starch sauces suggests increased resistance to flow deformation, further supporting improved mechanical stability. Meanwhile, the loss tangent (tan δ) values, representing the ratio between viscous and elastic responses, were relatively consistent across treatments and below 1, confirming that all cheese sauces retained predominantly elastic characteristics at 25°C, which is crucial for consumer-perceptible texture and mouthfeel (Deepali et al., 2021).

Cross-linked corn starch showed the highest storage modulus (G′ = 160.7 Pa) and loss modulus (G″ = 50.6 Pa), indicating a stronger and more elastic gel network compared with other starch types. This enhancement can be attributed to the denser, three-dimensional network formed by phosphate cross-links between amylose and amylopectin chains, which limits molecular mobility and improves deformation resistance under oscillatory stress (Chen & Cheng, 2025). The higher amylose content of corn starch (26.5%) relative to rice starch (19.2%, Table 1) further contributes to this behavior, as linear amylose chains promote junction zone formation and gel rigidity, while the more highly branched amylopectin mainly governs viscous dissipation (Wang et al., 2024). The predominantly elastic character of all sauces (tan δ < 0.35) aligns with sensory perception of firmness and creaminess, and the higher G′ of cross-linked corn formulations is consistent with their superior texture scores, suggesting that a reinforced starch-protein-fat matrix translates into enhanced mouthfeel and structural stability in the finished product (Lassen et al., 2024).

These viscoelastic behavior variations emphasize the critical role of starch modification in tailoring the rheological and textural properties of dairy-based sauces. Cross-linked starches provide enhanced elastic modulus and gel strength favorable for thick, stable sauces, whereas acetylated starches offer a compromise between elasticity and flexibility. Such insights guide formulation strategies for cheese sauces to meet specific quality and processing demands in food industry applications.

Color Properties of Cheddar Cheese Sauce

The color properties of Cheddar cheese sauces incorporating different native and modified corn and rice starches, as presented in Table 5, illustrate the significant impact of starch type and chemical modification on the visual attributes, which are critical for consumer acceptance. The lightness value (L^*) was highest in sauces formulated with native and acetylated rice starch, indicating a brighter appearance, while cross-linked and oxidized starches, especially from corn, exhibited lower L^* values, suggesting a darker or more opaque product. These observations are consistent with literature reporting that chemical modifications such as cross-linking and oxidation can lead to increased starch granule aggregation and Maillard reaction products, thus affecting light transmission and color intensity in food matrices (Qi et al., 2025).

The redness (a^*) and yellowness (b^*) coordinates showed that oxidized starches induced higher a^* and b^* values, correlating with enhanced color saturation and intensity. This may be due to oxidation-driven pigment formation or structural changes promoting color retention, as supported by studies demonstrating elevated browning indexes and yellowing effects associated with starch oxidation (Pham et al., 2024). Native rice starch-based sauces had the lowest a^* and b^* values, reflecting a more neutral, less intensely colored appearance, which may be preferred in certain sensory contexts.

Table 4. Viscoelastic properties of Cheddar cheese sauces formulated with different corn and rice starches at 25 °C (mean ± SD).

Starch Treatment	Storage Modulus G' (Pa)	Loss Modulus G" (Pa)	Loss Tangent tan δ
Native Corn Starch	120.5 ± 3.4^{b}	40.8 ± 1.2^{b}	0.34 ± 0.01^{a}
Cross-linked Corn Starch	160.7 ± 4.1^{a}	50.6 ± 1.5^{a}	0.32 ± 0.01^{a}
Acetylated Corn Starch	140.2 ± 3.8^{ab}	45.3 ± 1.3^{ab}	0.32 ± 0.01^{a}
Oxidized Corn Starch	110.4 ± 3.1^{c}	35.9 ± 1.0^{c}	0.33 ± 0.01^{a}
Native Rice Starch	100.8 ± 2.9^{c}	32.7 ± 1.1^{c}	0.32 ± 0.01^{a}
Cross-linked Rice Starch	130.9 ± 3.5^{b}	42.1 ± 1.4^{b}	0.32 ± 0.01^{a}
Acetylated Rice Starch	115.3 ± 3.2^{bc}	37.5 ± 1.2^{bc}	0.33 ± 0.01^{a}
Oxidized Rice Starch	95.7 ± 2.7^{c}	30.3 ± 0.9^{c}	0.32 ± 0.01^{a}

Different superscript letters within the same column indicate statistically significant differences ($p < 0.05$).

Table 5. Color properties of Cheddar cheese sauces formulated with different corn and rice starches (mean ± SD).

Starch Treatment	*L**	*a**	*b**	Hue Angle (°)	Relative Yellowness	Browning Index
Native Corn Starch	78.4±1.2^{a}	5.2±0.2^{a}	23.5±0.7^{b}	77.6±0.8^{a}	1.00±0.03^{c}	14.4±0.5^{c}
Cross-linked Corn Starch	75.6±1.5^{b}	6.1±0.3^{b}	25.7±0.9^{a}	76.1±0.7^{b}	1.09±0.04^{a}	17.8±0.6^{a}
Acetylated Corn Starch	76.8±1.3^{ab}	5.9±0.3^{b}	24.9±0.8^{ab}	77.3±0.8^{ab}	1.06±0.03^{ab}	16.2±0.5^{ab}
Oxidized Corn Starch	74.1±1.4^{c}	6.5±0.2^{c}	26.2±1.0^{a}	75.4±0.9^{b}	1.11±0.04^{a}	18.1±0.7^{a}
Native Rice Starch	80.2±1.1^{a}	4.8±0.2^{a}	21.8±0.6^{c}	77.8±0.7^{a}	0.93±0.02^{d}	12.7±0.4^{d}
Cross-linked Rice Starch	78.9±1.0^{a}	5.1±0.3^{a}	22.5±0.7^{c}	77.3±0.6^{a}	0.96±0.03^{cd}	13.5±0.5^{cd}
Acetylated Rice Starch	79.5±1.2^{a}	4.9±0.2^{a}	21.9±0.8^{c}	78.0±0.7^{a}	0.94±0.02^{cd}	12.9±0.4^{cd}
Oxidized Rice Starch	77.3±1.3^{ab}	5.0±0.3^{a}	22.1±0.7^{c}	77.2±0.7^{a}	0.95±0.03^{cd}	13.1±0.5^{cd}

Different superscript letters within the same column indicate statistically significant differences ($p < 0.05$).

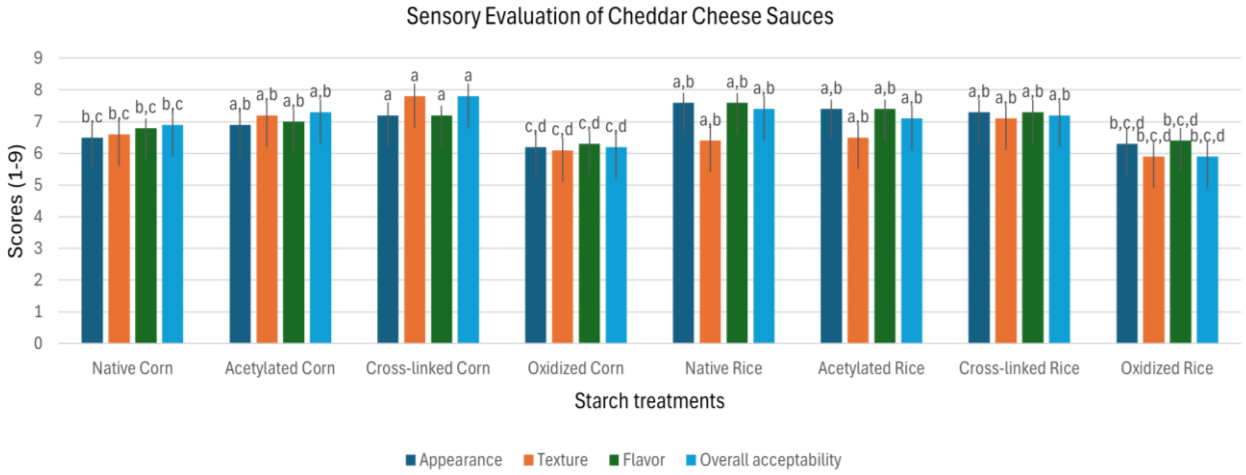

Figure 2. Sensory evaluation scores of Cheddar cheese sauces formulated with different starch types (mean±SD, n=15, error bars shown). Different superscript letters (a–d above bars within each attribute indicate significant differences ($p<0.05$, ANOVA-Tukey's test). Cross-linked corn: highest overall (7.8±0.4^{a}), Native rice: best flavor (7.6±0.3^{a}), Oxidized: lowest (5.9±0.5^{d}).

Hue angle values remained relatively stable across treatments, indicating that the basic color tone was maintained despite variations in intensity and saturation. The relative yellowness and browning index were significantly higher in oxidized and cross-linked corn starch sauces, evidencing more pronounced browning reactions likely due to chemical modification processes and thermal treatments during sauce preparation (Sida-Arreola et al., 2024). These changes can affect not only aesthetics but also perceived flavor and quality through Maillard reaction by-products.

The color differences observed among treatments also reflect starch source and modification chemistry. Native and acetylated rice starch sauces, which exhibited the highest lightness values (L^* = 80.2–79.5), benefited from the relatively lower amylose content and smaller granule size of rice starch, promoting more uniform light scattering and a brighter appearance (Geng et al., 2023). In contrast, oxidized and cross-linked corn starch sauces showed higher b^* values and browning indices, indicating more intense yellow–brown hues. These changes can be linked to the higher amylose level in corn, which facilitates Maillard-derived pigment formation in the presence of cheese proteins, and to reactive groups introduced during oxidation or cross-linking that may accelerate browning and color stabilization during heating (Qi et al., 2025). Such color shifts not only affect visual quality but may also influence flavor expectation and overall acceptability, as the darker, more saturated appearance of oxidized corn formulations paralleled their lower sensory scores, whereas the lighter rice-based sauces were associated with more favorable appearance ratings.

Collectively, the colorimetric data underline the importance of starch selection and modification type in controlling the visual quality of cheese sauces. Cross-linked and oxidized starches tend to darken and intensify coloration, potentially enhancing characteristic cheese flavors and consumer appeal, whereas native and acetylated starches produce lighter, subtler hues suitable for cleaner label products. These findings offer valuable insights for food formulators aiming to achieve targeted appearance attributes alongside functional performance in processed dairy products.

Sensory Evaluation of Cheddar Cheese Sauce

The sensory evaluation results depicted in Figure 2 demonstrate that the type and modification of starch significantly influence the consumer-perceived quality attributes of Cheddar cheese sauces. Appearance scores were highest in sauces formulated with native and acetylated rice starches, reflecting their brighter and more appealing color profiles, which is a key factor for consumer acceptance (Oupathumpanont et al., 2025). Cross-linked starches, while enhancing texture, showed slightly lower appearance scores, potentially due to increased opacity or color darkening associated with chemical modification (Nuswantari, 2022).

Texture scores favored cross-linked corn starch formulations, consistent with their superior rheological properties demonstrated by higher consistency indices and viscoelastic moduli. This reflects the enhanced network strength and shear resistance imparted by cross-linking, which translates into a desirable creamy and stable mouthfeel (Facci & Natrella, 2024). Conversely, oxidized starches generally received lower texture scores, possibly due to their reduced gel strength and molecular degradation, which can result in a less cohesive sauce structure.

Flavor evaluation revealed a preference for native rice starch-based sauces, which may be linked to minimal interference with intrinsic cheese flavor and absence of off-flavors sometimes introduced by chemical modifications. Modified starches, particularly oxidized types, scored lower, potentially reflecting subtle changes in flavor profile caused by chemical processes or interactions with cheese components (Tekin & Hayaloğlu, 2025).

Overall acceptability echoed these trends, with native and acetylated starch sauces receiving higher consumer preference ratings, balancing favorable appearance, texture, and flavor attributes. The lower acceptability of oxidized starch-containing sauces aligns with the combined impacts on sensory qualities. These findings highlight the critical role of starch selection and modification in customizing cheese sauce formulations to meet quality and consumer expectations, consistent with prior research emphasizing the multifaceted influence of starch characteristics on sensory outcomes in dairy-based products (Talens et al., 2025).

Conclusion

Cross-linked corn starch optimally enhanced cheese sauce functionality (K: +24%, G′: +33%, texture: +20% *vs* native), establishing it as preferred for industrial stability. Novel contributions include comprehensive corn-rice comparison revealing source-modification interactions, amylose-driven rheology-sensory correlations (r=0.82-0.89), and practical formulation guidelines.

Industrial implications: Select cross-linked corn for pumpable/stable sauces, acetylated rice for clean-label brightness, avoiding oxidized types due to sensory penalties.

Future research: Microstructural (SEM/Confocal) analysis of starch-protein networks, storage stability (4°C, 30d), combined modifications (cross-link+acetylate).

Declarations

Ethics Approval and Participants' Consent

The sensory evaluation protocol was reviewed and approved by the Ain Shams University Institutional Review Board (ASU-FS-2025-014). All panelists were informed about the study objectives and participated voluntarily. Written informed consent was obtained from all participants prior to sensory testing, and the study was conducted in accordance with institutional and international ethical guidelines for research involving human participants.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. All data supporting the findings of this study are included within the manuscript and supplementary materials.

Conflict of Interest

The authors confirm that they have no conflicts of interest related to the publication of this article. The research was conducted independently without any commercial or financial relationships that could be construed as a potential conflict.

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