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Comparative physical evaluation of adhesive properties in modified gluten

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ABSTRACT

The development of eco-friendly adhesives is essential to reduce reliance on petroleum-based products in the wood industry. In this study, wheat gluten was modified through enzymatic hydrolysis, heat treatment, and chemical reactions, including deamidation and acetylation, to improve its adhesive properties. The modified formulations were applied to bond Russian birch plywood (*Betula pendula*), and the tensile shear strength was evaluated under dry and wet conditions. Results showed that enzymatic hydrolysis provided the highest performance, with shear strength reaching about 6.4 MPa under dry conditions and 5.1 MPa under wet conditions, compared to other modifications. Heat treatment and deamidation with acetic acid or sodium hydroxide also improved properties, achieving values up to 3.5 MPa. In contrast, acetylation and deamidation with concentrated hydrochloric acid resulted in lower strength, around 2.0 MPa, particularly under wet conditions. These effects were attributed to structural alterations and new functional groups that enhance intermolecular interactions. Overall, targeted modifications of gluten can produce durable, eco-friendly adhesives suitable for wood applications.

1. Introduction

Wheat is a primary source of gluten, a plant-based protein mainly composed of glutenin and gliadin. Glutenin contributes to elasticity and structural integrity, whereas gliadin enhances extensibility, enabling the formation of a cohesive and stable gluten network during hydration and mechanical processing. This protein matrix underpins a range of industrial applications [1,2], particularly gluten-based adhesives and biodegradable packaging materials [3]. From a surface and interface science perspective, the ability of gluten to form continuous networks and interact with solid substrates highlights its potential as a bio-based interfacial adhesive material. Accordingly, the wood industry has shown increasing interest in bio-based adhesives as alternatives to petrochemical systems. Gluten-based adhesives can effectively bond wood substrates while reducing environmental impact [4]; however, their industrial application remains limited by poor water resistance, high viscosity, and insufficient bonding performance [5]. These limitations are closely associated with interfacial phenomena, including protein aggregation, surface wetting, penetration into wood microstructures, and joint stability under humid conditions.

To overcome these challenges, various modification strategies have been explored to tailor the molecular structure and interfacial behavior of gluten. Covalent and non-covalent cross-linking using agents such as tannin, glycerol, and polyethyleneimine enhances network cohesion and adhesion performance [6], while reactions with urea–glyoxal resin further improve mechanical and bonding properties [7]. Enzymatic hydrolysis has also proven effective by improving solubility, emulsifying capacity, and molecular mobility—key factors for interfacial adhesion [8,9]. Standard methods for determining the degree of hydrolysis [10] and analytical techniques such as HPLC and NMR have been employed to characterize hydrolyzed and thermally treated gluten systems [11] Nordqvist et al., 2013.

Chemical modification has attracted growing attention due to its ability to systematically alter protein conformation and aggregation behavior Abedi & Pourmohammadi, 2021. β-Elimination of cystine and subsequent lanthionine formation significantly influence gluten functionality [12], while acid-induced deamidation enhances solubility and emulsifying properties by promoting more extended protein conformations [13]. The effects of acid and alkaline pretreatments on gluten aggregation under hydrothermal conditions have been extensively studied Jansens et al., 2013; [14], and electrochemical deamidation has recently emerged as an alternative modification route [15]. Collectively, these studies highlight gluten aggregation as a key factor governing functional and interfacial properties [16–18]. Additionally, acetylation improves water solubility, emulsification, and foaming capacity by disrupting hydrogen bonding and enhancing protein–water interactions,

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particularly in glutenin Majzoobi & Abedi, 2014.

Despite these advances, a systematic comparison of physical, chemical, and enzymatic modification strategies with respect to adhesion strength and water resistance at the wood–adhesive interface remains limited. Therefore, this study systematically investigates the adhesive performance of wheat gluten–based formulations on wooden substrates using different modification approaches. Quantitative evaluation of bonding strength and interfacial water resistance provides new insights into the relationships among gluten molecular structure, aggregation behavior, and interfacial performance, supporting the development of high-performance, sustainable gluten-based adhesives in line with the scope of Results in Surfaces and Interfaces.

2. Experimental

2.1. Materials

Wheat gluten, obtained from Faradaneh Starch Co. (Shiraz, Iran), was used in this study. It contained protein (approximately 80–82%), moisture (8–10%), and ash (1.2–1.4%), all reported on a dry basis. The product was light yellow, with a pH of 6.0–6.4. The hydrolysis of wheat gluten was performed using the enzyme Protease (Neutral protease from *Aspergillus niger*-derived, ≥900,000 U/g, VemoHerb, Bulgaria). Russian birch plywood panels (*Betula pendula*) were purchased from the local wood market (Tehran, Iran). Sodium dodecyl sulphate (SDS) and Trinitrobenzene sulfonic acid (TNBS) were of analytical grade and were obtained from Sinopharm Co Ltd (China). All other chemicals used in this study were of analytical grade and were purchased from Merck (Germany).

2.2. Modification of wheat gluten

Wheat gluten was modified using thermal treatment, acetylation, enzymatic hydrolysis, and deamidation under acidic or alkaline conditions. All procedures were adapted from previously reported methods, with modifications in processing conditions and parameters specifically tailored to the objectives of the present study.

2.2.1. Thermal treatment

The thermal treatment of wheat gluten was performed based on the method reported by Nordqvist et al. [8], with modifications in treatment duration and stirring conditions tailored to our study. Wheat gluten (10 g) was suspended in 50 mL of deionized water and incubated in a static oven at 50 °C, 70 °C, or 90 °C for 1 h. None of the mixtures were stirred during the thermal treatment. In a separate experiment, a sample was heated at 90 °C for 1 h in an oil bath under continuous stirring with a magnetic stirrer. All samples were subsequently vacuum-dried at 25 °C for 24 h. The dried residues were ground and sieved using an industrial grinder (Model Regina KD-150, Dessini, China).

2.2.2. Acetylation

The acetylation procedure was developed based on the approach described by Majzoobi and Abedi [19], with deliberate adjustments to pH control, reagent dosage, and reaction time. Wheat gluten (10 g) was suspended in deionized water (40 g) and adjusted to pH 8.5 using 2N NaOH. After gradually adding 0.5 g of acetic anhydride and readjusting the pH, the mixture was stirred overnight at room temperature using a magnetic stirrer. The mixture was centrifuged at 10000 g for 10 min, washed with 2-propanol until a clear supernatant was obtained, and both the precipitate and supernatant were collected and dried under vacuum at room temperature for 24 h. The solid residue was ground and sieved by an Industrial Grinder.

2.2.3. Enzymatic hydrolysis

A slightly modified procedure based on the method developed by Kong et al. [9] was used for the enzymatic hydrolysis of gluten. The enzyme-to-substrate ratio was 1:100 (w/w). Gluten (5 g) was suspended in deionized water (100 mL) and stirred at room temperature for 30 min. Protease (0.05 mg) was then added. The pH was adjusted to 7.0 using 1 M NaOH. The mixture was incubated at 50 °C for 6 h in a water bath under constant magnetic stirring. Throughout this incubation period, the pH was continuously maintained at 7.0 by adding 1 M NaOH as needed. To inactivate the enzyme, the mixture was heated at 90 to 95 °C for 10 min. The resulting hydrolysate was dried under vacuum at room temperature for 24 h. The dried residue was ground and sieved using an industrial grinder. The degree of hydrolysis was determined using the pH-STAT titration method.

2.2.4. Deamidation under acidic and alkaline conditions

Deamidation under acidic and alkaline conditions was conducted using a modified protocol based on Jansens et al. [20]. Solutions of hydrochloric acid or sodium hydroxide (25 mM) were prepared in 70% (v/v) ethanol. Gluten powder was added at a concentration of 10% (w/v), and the suspensions were stirred at room temperature for 16 h using a magnetic stirrer. Subsequently, the mixtures were heated to 35 °C under continuous stirring to remove ethanol. The resulting concentrated products were collected and used for adhesive preparation and characterization.

2.2.5. Deamidation of gluten by acetic acid

Deamidation using acetic acid was performed following the general approach reported by Liao et al. [21], with modifications to treatment temperature and reaction time. Acetic acid (0.4 mL, 0.14 mol/L) was added to 50 mL of a wheat gluten suspension (100 g/L) prepared in deionized water. The mixture was heated at 120 °C for 15 min under continuous stirring. Immediately after treatment, the samples were cooled in an ice bath for 5 min to terminate the reaction.

2.3. Determination of the degree of hydrolysis

The degree of hydrolysis (DH) was determined using the pH-stat titration method. During hydrolysis, the pH was maintained by continuous addition of NaOH, and the volume of base consumed was used to calculate DH according to Eq. (1).

$$DH = \frac{B \times N_B \times 100}{\alpha \times M_P \times h_{tot}} \% \quad (1)$$

Where B is the volume of base consumed (mL); N_B is the normality of base (mol/L); $\alpha = 0.89$ (average degree of dissociation of α-amino groups at pH 7.0 and 50 °C); M_P is the mass of protein in the reaction mixture (g); and h_{tot} is total number of peptide bonds in wheat gluten (meq/g protein).

For samples treated with acetic acid, DH was additionally evaluated using the TNBS method. Absorbance was measured at 340 nm, and L-leucine was used to construct the calibration curve.

2.4. Preparation of adhesive dispersions

Modified gluten samples obtained from the treatments described above were used to prepare adhesive systems according to their physical state after modification. For thermally treated, acetylated, and enzymatically hydrolyzed samples, the dried and ground powders were dispersed in 0.1 M NaOH at a solid-to-liquid ratio of 1:5 (w/v), following the general methodology reported by Nordqvist et al. [11]. The pH was adjusted to 13 using 1 M NaOH, and the dispersions were stirred continuously for 1 h. In contrast, gluten samples subjected to acidic or alkaline deamidation, as well as acetic acid deamidation, were used directly in their liquid or semi-liquid form after completion of the modification process.

2.5. Viscosity measurements

Viscosity measurements were performed 24 h after sample preparation using a Brookfield viscometer (Model Visco Star-R, J.P. Selecta S. A., Spain) operated at 25 °C. A TR11 spindle was used at rotational speeds of 2, 5, 10, and 20 revolutions per minute (rpm). Each measurement was conducted in triplicate, and the mean value was reported as the final result.

2.6. Wood bonding and mechanical testing

Birch plywood specimens (3 mm thick, 25 mm wide, and 100 mm long) were coated on one side with the prepared adhesive to obtain a uniform adhesive layer approximately 0.1 mm in thickness. The specimens were hot-pressed at 110 °C for 15 min under a pressure of 0.7 MPa (Fig. 1a). Bonded samples were conditioned and tested in accordance with modified EN 204 and EN 205 standards. Two conditioning series were applied prior to mechanical testing:

The first series: Specimens were conditioned at room temperature (approximately 25 °C) for 7 days before tensile shear testing.

The second series: Specimens were conditioned at room temperature for 7 days, immersed in water at 20 ± 5 °C for 3 h, and then conditioned again at room temperature for 7 days before tensile shear testing.

Tensile shear strength was measured using a universal testing machine (Model STM-20, SANTAM Co., Iran) at a crosshead speed of 5 mm/min (Fig. 1b). For each conditioning sequence, five specimens were tested. Shear strength was calculated using Eq. (2), and results are reported as mean ± standard deviation (SD).

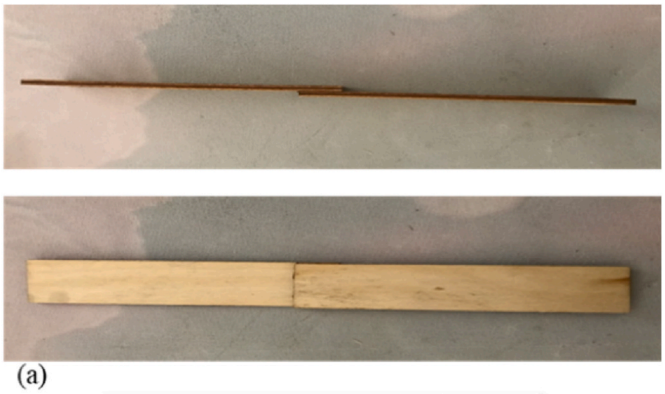




Fig. 1. Preparation and evaluation of wood substrates (a) Bonded wood panels (b) universal testing machine.

$$\tau_{max} = \frac{F_{max}}{A} \quad (2)$$

Where F_{max} is the maximum applied shear force (N), A is the bonded area (mm^2), and τ is the calculated shear strength (N/mm^2).

3. Results and discussions

3.1. Effect of thermal treatment on gluten adhesive performance

Thermal treatment significantly improved the dispersibility of gluten under alkaline conditions, particularly in 0.1 M NaOH. This behavior is attributed to the deprotonation of acidic amino acid residues, such as glutamic and aspartic acids, which increases the net negative charge of protein molecules. The resulting electrostatic repulsion enhances protein solubility and dispersion. As shown in Fig. 2, adhesive strength increased consistently with rising treatment temperature.

Thermal processing is known to induce structural modifications in gluten proteins through the rearrangement and partial cleavage of disulfide bonds Abedi & Peyghambardoust, 2021. These changes promote partial protein unfolding, thereby exposing reactive functional groups capable of forming hydrogen bonds and possible covalent interactions with hydroxyl groups on lignocellulosic surfaces. Consequently, improved interfacial bonding and enhanced adhesive durability were achieved, explaining the observed increase in shear strength with increasing thermal treatment temperature.

3.2. Impact of enzymatic hydrolysis on adhesive strength

Enzymatic hydrolysis of gluten using protease resulted in an unexpected increase in adhesive strength, reaching 2099 ± 156.5 N (Fig. 3a). In general, extensive hydrolysis reduces adhesion by disrupting the protein network; however, in this study, the degree of hydrolysis determined by the pH-STAT method was relatively low (0.611%). This indicates that enzymatic treatment caused only limited peptide bond cleavage. Such mild hydrolysis likely enhanced the exposure of hydrophilic and reactive functional groups while preserving the integrity of the gluten matrix. As a result, intermolecular interactions within the adhesive and interfacial interactions with the wood substrate were improved, leading to enhanced adhesive performance.

3.3. Effects of deamidation on gluten adhesion

Deamidation induced substantial changes in gluten structure and adhesive performance. Although both deamidation and enzymatic hydrolysis involve cleavage of amide bonds, the deamidated sample exhibited lower adhesive strength (1291 ± 61.4 N; Fig. 3b) compared with the enzymatically hydrolyzed sample. This difference can be attributed to a higher degree of structural disruption during deamidation, particularly affecting gliadin fractions that are more susceptible to acidic conditions. Consistent with this interpretation, the degree of hydrolysis following deamidation (1.12%) was notably higher than that observed after enzymatic treatment (0.611%), indicating more extensive bond cleavage.

Deamidation using hydrochloric acid resulted in pronounced protein degradation and the lowest adhesive strength (781 ± 161.5 N; Fig. 3c). In contrast, alkaline deamidation with NaOH led to improved adhesion (1273 ± 259.2 N; Fig. 3d), reflecting less severe peptide bond cleavage and partial preservation of the gluten network. Deamidation using acetic acid produced intermediate adhesion values, suggesting that milder organic acids can balance structural modification with retention of

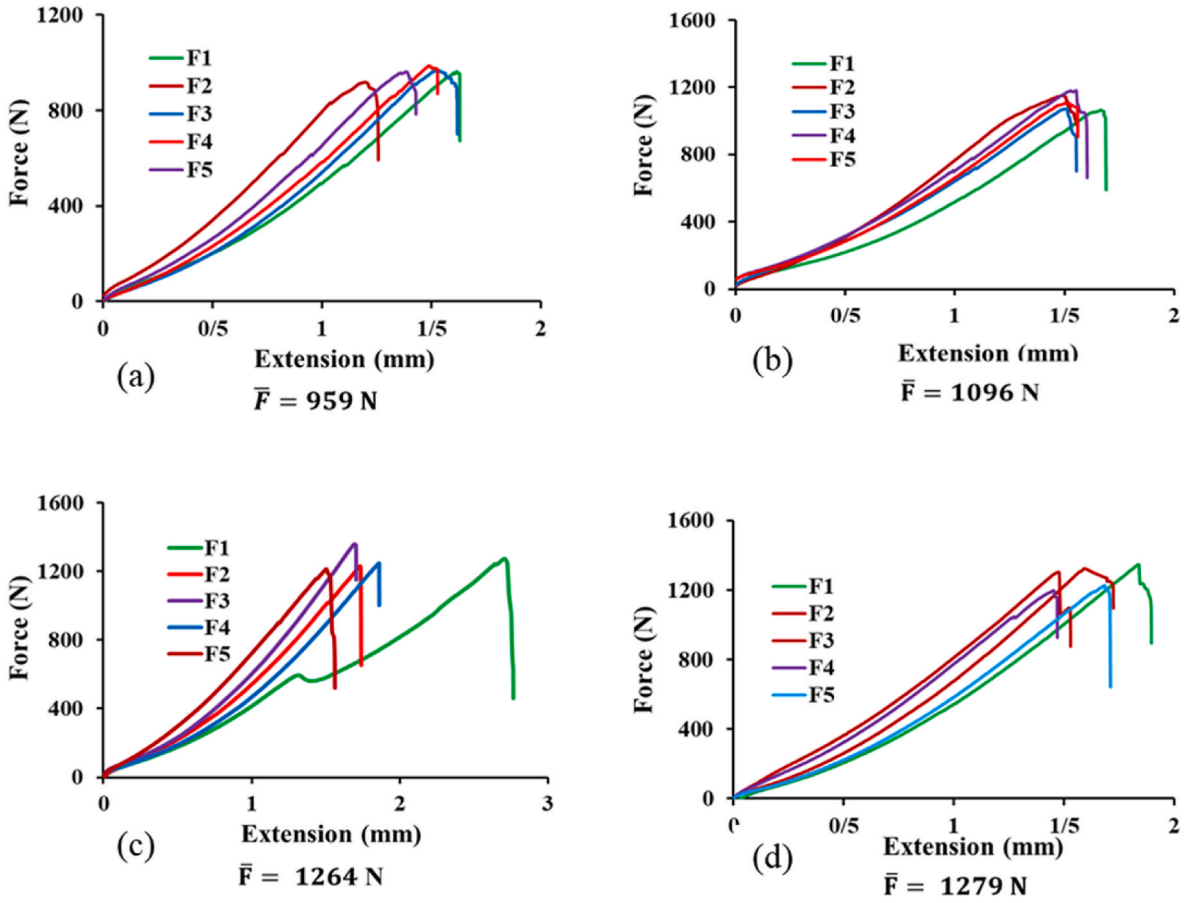


Fig. 2. Shear strength test results of samples subjected to heat treatment at (a) 50 °C, (b) 70 °C, (c) 90 °C without stirring, and (d) 90 °C with stirring.

protein integrity.

Alkaline conditions are also known to promote rearrangement or disruption of disulfide bonds, thereby altering gluten viscoelasticity and adhesive behavior [1,2,22]. These molecular-level changes collectively explain the observed differences in adhesive performance among the deamidation treatments.

3.4. Influence of acetylation on adhesive performance

Acetylation chemically modifies gluten proteins by converting free amino groups (–NH_2) into acetamide groups (–NH–CO–R), thereby reducing the availability of hydrogen-bonding and ionic interaction sites. This modification alters the structural conformation of gluten, particularly within the glutenin fraction, which plays a critical role in intermolecular networking.

As a result, acetylation led to a clear decline in adhesive performance, with a measured shear force of 865 ± 197.0 N (Fig. 3e). The reduced bonding strength confirms that acetylation diminishes the interaction potential of gluten proteins with hydroxyl-rich lignocellulosic substrates by attenuating essential hydrogen bonding and electrostatic interactions.

3.5. Comparative analysis of adhesive strength across treatments

Fig. 4 compares the shear force values of gluten-based adhesives subjected to different modification treatments under two conditioning series. Among all samples, enzymatic hydrolysis consistently resulted in the highest adhesive strength, exceeding 2000 N in Series 1 and 1600 N in Series 2. This outcome highlights the effectiveness of controlled enzymatic modification in enhancing functional group availability while maintaining protein network integrity.

Samples thermally treated at 90 °C, either in a static oven or in an oil bath with stirring, also exhibited high adhesive strength (approximately 1300–1400 N). These improvements are attributed to enhanced protein unfolding and disulfide bond rearrangement at elevated temperatures. In contrast, samples treated at lower temperatures (50 °C and 70 °C) showed reduced adhesive strength, indicating insufficient conformational modification.

Deamidation effects were strongly dependent on the chemical agent. Alkaline deamidation maintained adhesion comparable to high-temperature treatments, whereas mineral acid deamidation resulted in the poorest performance due to extensive protein degradation. Acetic acid deamidation and acetylation exhibited intermediate and reduced adhesion, respectively, emphasizing the importance of preserving protein network cohesion during chemical modification.

3.6. Statistical considerations and adhesive classification

For several samples, relative standard deviation (RSD) values exceeded 20%, indicating variability in measured shear forces. Exclusion of one or two outlier values reduced RSD to below 10% without significantly altering mean values, confirming the reliability of the reported data.

Shear strength values (Tables 1 and 2) were calculated and classified according to EN 204 and EN 205 standards. Most samples in the first conditioning series were classified as D3, indicating suitability for use under humid conditions. After moisture exposure in the second series, thermally treated, enzymatically hydrolyzed, and alkali-deamidated adhesives retained D3 classification, whereas acetylated and mineral acid–deamidated samples fell below D3 thresholds, demonstrating limited moisture resistance.

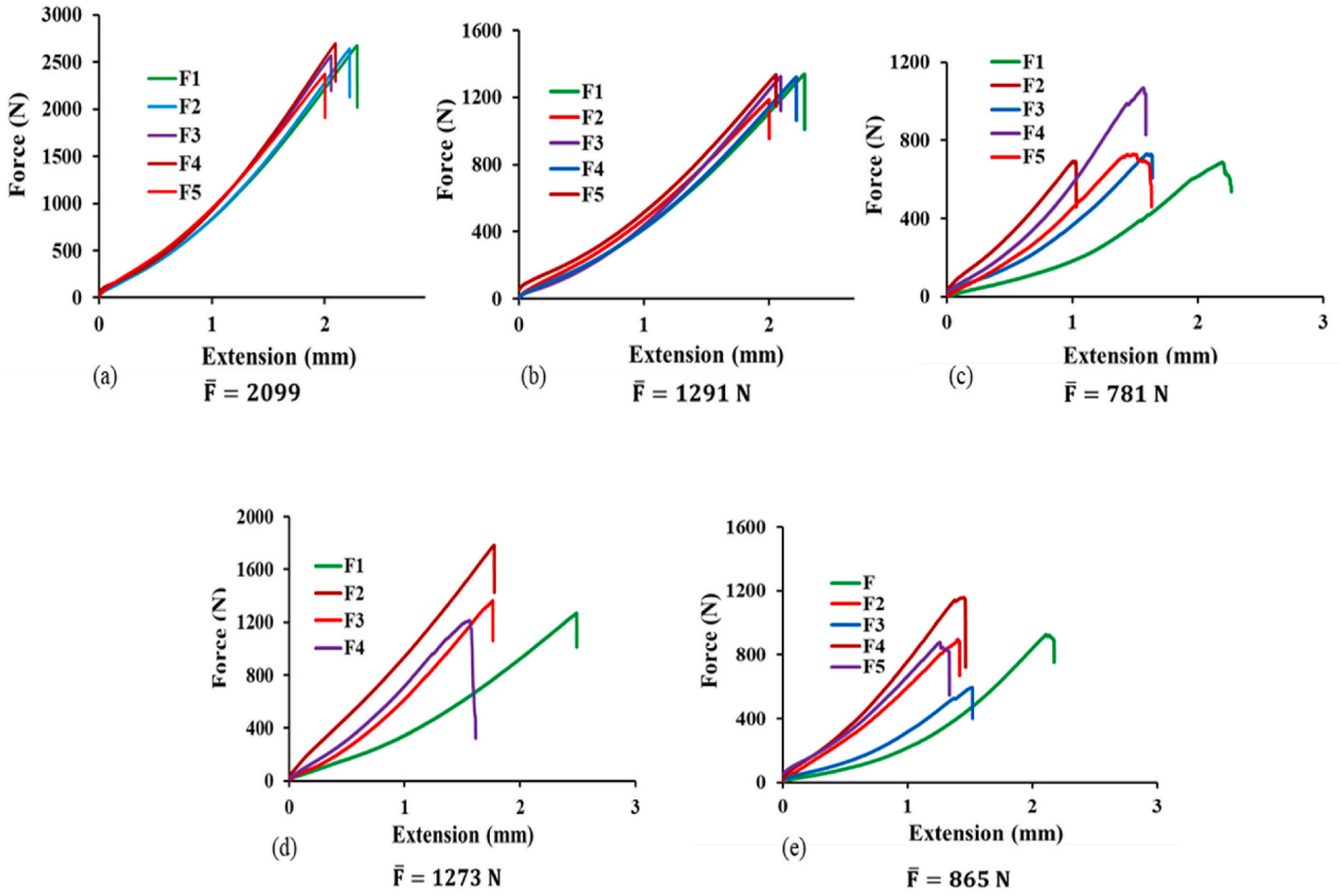


Fig. 3. Shear strength test results of (a) hydrolyzed enzyme with protease (b) deamidation with acetic acid (c) deamidation with HCl (d) deamidation with NaOH (e) acetylation with anhydride acetic.

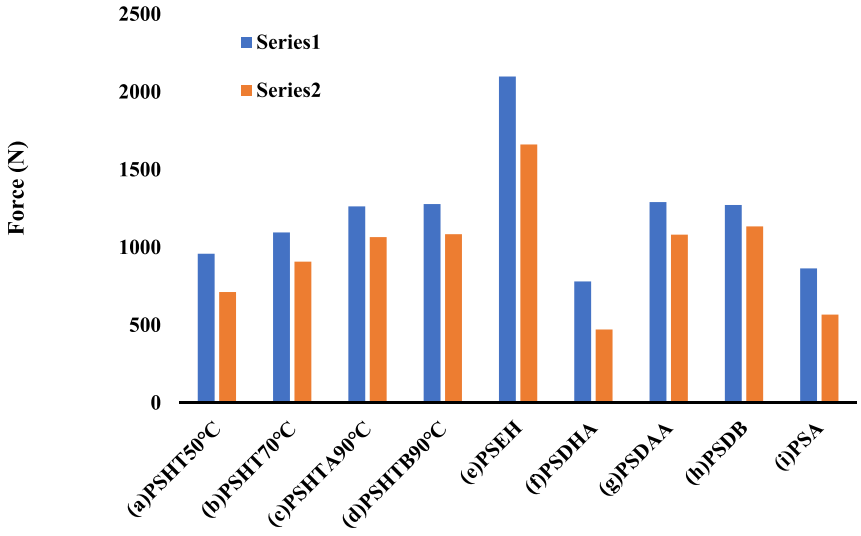


Fig. 4. Comparison chart of shear forces for the first series (The first series was conditioned at room temperature for 7 days) and second series (The second series was conditioned at room temperature for 7 days, immersed in 20 ± 5 °C water for 3 h, and then conditioned again at room temperature for 7 days) of test specimen. (a) Prepared Sample by Heat-Treated at 50 °C in an oven (b) Prepared Sample by Heat-Treated at 70 °C in an oven (c) Prepared Sample by Heat-Treated at 90 °C in an oven (d) Prepared Sample by Heat-Treated at 90 °C in an oil bath with stirring (e) Prepared Sample by Enzymatic Hydrolyses (f) Prepared Sample by Deamidation with HCl (g) Prepared Sample by Deamidation with Acetic Acid (h) Prepared Sample by Deamidation with NaOH (i) Prepared Sample by Acetylation.

Table 1
Shear strength and classification of the first series of gluten-based adhesive samples under dry conditions. F_{max} represents the maximum applied shear force (N), A is the bonded area (325 mm^2), and τ denotes the calculated shear strength (N/mm^2).

[a] Samples	F_{max} (N)	SD (N)	(%) RSD	A (mm^2)	(N/ mm2) τ	Durability classes
PSHT50 °C	959	24.9	2.59	325	2.95	D3
PSHT70 °C	1096	44.6	4.07	325	3.37	D3
PSHTA90 °C	1264	57.3	4.53	325	3.89	D3
PSHTB90 °C	1279	64.7	5.06	325	3.93	D3
PSEH	2099	156.5	7.46	325	6.45	D3
PSDHA	781	161.5	20.68	325	2.40	D3
PSDAA	1291	61.4	4.76	325	3.97	D3
PSDB	1273	259.2	20.36	325	3.92	D3
PSA	865	197.0	22.77	325	2.66	D3

[a] PSHT50 °C: prepared sample heat-treated at 50 °C in an oven; PSHT70 °C: heat-treated at 70 °C in an oven; PSHTA90 °C: heat-treated at 90 °C in an oven; PSHTB90 °C: heat-treated at 90 °C in an oil bath with stirring; PSEH: enzymatically hydrolyzed sample; PSDHA: deamidated with HCl; PSDAA: deamidated with acetic acid; PSDB: deamidated with NaOH; PSA: acetylated sample; SD: Standard Deviation; RSD: The relative standard deviation.

Table 2
Shear strength and classification of the first series of gluten-based adhesive samples under dry conditions. F_{max} represents the maximum applied shear force (N), A is the bonded area (325 mm^2), and τ denotes the calculated shear strength (N/mm^2).

Samples	F_{max} (N)	SD (N)	(%) RSD	A (mm^2)	(N/ mm^2) τ	Durability classes
PSHT50 °C	713	40.3	5.65	325	2.19	D3
PSHT70 °C	908	67.4	7.42	325	2.79	D3
PSHTA90 °C	1066	37.9	3.56	325	3.28	D3
PSHTB90 °C	1085	62.5	5.76	325	3.34	D3
PSEH	1662	101.3	6.09	325	5.11	D3
PSDHA	472	113.2	23.98	325	1.45	-
PSDAA	1082	31.5	2.91	325	3.34	D3
PSDB	1135	94.6	8.33	325	3.49	D3
PSA	568	121.5	21.39	325	1.75	-

3.7. Rheological properties and their relation to adhesive performance

Viscosity measurements (Table 3) showed that all adhesive formulations exhibited values within acceptable limits according to INSO 3262 (2016). Viscosity strongly influenced application performance: excessively low viscosity promoted over-penetration into wood pores, reducing interfacial bonding, while excessively high viscosity impaired flowability and spreading.

Structural modifications induced by thermal treatment, enzymatic hydrolysis, and chemical modification altered molecular interactions among protein chains, leading to changes in viscosity. These rheological variations correlate with adhesive performance and reflect the balance between flow behavior and interfacial interaction required for effective wood bonding Nordqvist et al., 2013.

3.8. Limitations and future directions

Despite the systematic evaluation of multiple gluten modification strategies, this study has certain limitations. In-depth molecular characterization techniques, such as spectroscopic analyses, were not employed to directly confirm structural changes. Long-term durability under diverse environmental conditions was not extensively investigated, and direct comparisons with commercial synthetic adhesives were not performed.

Future studies should incorporate advanced analytical tools and expanded durability testing to further validate the structure–performance relationships identified here. Such efforts will strengthen the practical relevance and industrial applicability of gluten-based adhesive systems.

Table 3
The viscosity test results of the prepared samples.

Samples	Viscometer spindle	Speed (rpm)	μ (CP)	%SP	T°C
PSHT50 °C	TR11	20	35000	70.1	25
PSHT70 °C	TR11	20	37200	75.1	25
PSHTA90 °C	TR11	20	37500	75.7	25
PSHTB90 °C	TR11	20	38800	78.6	25
PSEH	TR11	20	41400	84.2	25
PSDHA	TR11	2	467900	93.5	25
PSDAA	TR11	20	40800	83	25
PSDB	TR11	2	459500	91.9	25
PSA	TR11	20	43400	87.9	25

4. Conclusions

Applying thermal treatment, increasing alkalinity above pH 8, and introducing physical agitation such as stirring constitute practical and readily implementable approaches for modulating the cross-linking behavior of gluten proteins, particularly disulfide bonds, which play a critical role in determining gluten structure. These treatments promote protein loosening and enhanced dispersion of the gluten matrix, ultimately resulting in improved adhesion to wood surfaces.

In addition, this study demonstrated that specific chemical modifications, including alkaline and carboxylic acid (e.g., acetic acid) deamidation, selectively target particular amino acid residues. These reactions induce controlled physical and structural alterations within the gluten network, thereby improving its processability and suitability for use as a wood adhesive.

Among all investigated treatments, enzymatic hydrolysis yielded the highest adhesive performance. The enzyme-hydrolyzed sample exhibited a low degree of hydrolysis (0.611%), indicating a controlled modification that primarily affected surface interactions and cross-linking behavior while largely preserving the integrity of peptide bonds. As a result, the adhesive system displayed increased fluidity with an optimal viscosity range, while maintaining a coherent polypeptide framework. This balance facilitated effective interfacial bonding with the wood substrate and enhanced overall adhesion performance.

From a sustainability perspective, and in response to the growing emphasis on green chemistry and biodegradable materials, the utilization of natural and renewable resources is gaining increasing importance. Although substantial research efforts are currently underway in this area, further investigations are necessary to fully explore and validate the practical applications of bio-based adhesive systems. Gluten, as demonstrated by its promising adhesive performance in this study, represents a viable renewable alternative and is expected to attract continued scientific and industrial interest for future adhesive applications.

CRediT authorship contribution statement

Atefeh Mousavi: Writing – original draft, Methodology, Data curation. **Javad Safaei-Ghomi:** Writing – review & editing, Supervision, Methodology.

Data availability statement

The data generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] Wieser, H., 2007. Chemistry of gluten proteins. Food Microbiol. 24 (2), 115–119. https://doi.org/10.1016/j.fm.2006.07.004.
[2] Wieser, H., Koehler, P., Scherf, K.A., 2023. Chemistry of wheat gluten proteins: qualitative composition. Cereal Chem. 100 (1), 23–35. https://doi.org/10.1002/cche.10572.
[3] Zhang, M., Jia, R., Ma, M., Yang, T., Sun, Q., Li, M., 2023. Versatile wheat gluten: functional properties and application in the food-related industry. Crit. Rev. Food Sci. Nutr. 63 (30), 10444–10460. https://doi.org/10.1080/10408398.2022.2078785.
[4] Lei, H., Pizzi, A., Navarrete, P., Rigolet, S., Redl, A., Wagner, A., 2010. Gluten protein adhesives for wood panels. J. Adhes. Sci. Technol. 24 (8-10), 1583–1596. https://doi.org/10.1163/016942410X500963.
[5] Nordqvist, P., Khabbaz, F., Malmström, E., 2010. Comparing bond strength and water resistance of alkali-modified soy protein isolate and wheat gluten adhesives. Int. J. Adhesion Adhes. 30 (2), 72–79. https://doi.org/10.1016/j.ijadhadh.2009.09.002.
[6] Cheng, Z., Ye, R., Shi, X., Lai, C., Gao, S., Zhang, D., Chu, F., 2024. A multiple cross-linking strategy to develop an environment-friendly and water resistance wheat gluten protein wood adhesive. Int. J. Biol. Macromol. 257, 128712. https://doi.org/10.1016/j.ijbiomac.2023.128712.
[7] Du, X., Li, Z., Zhang, J., Li, X., Du, G., Deng, S., 2024. Development of environmentally friendly glyoxal-based adhesives with outstanding water repellency utilizing wheat gluten protein. Int. J. Biol. Macromol. 273, 133081. https://doi.org/10.1016/j.ijbiomac.2024.133081.
[8] Nordqvist, P., Lawther, M., Malmström, E., Khabbaz, F., 2012. Adhesive properties of wheat gluten after enzymatic hydrolysis or heat treatment–A comparative study. Ind. Crop. Prod. 38, 139–145. https://doi.org/10.1016/j.indcrop.2012.01.021.
[9] Kong, X., Zhou, H., Qian, H., 2007. Enzymatic hydrolysis of wheat gluten by proteases and properties of the resulting hydrolysates. Food Chem. 102 (3), 759–763. https://doi.org/10.1016/j.foodchem.2006.06.062.
[10] Navarrete del Toro, M.A., García-Carreño, F.L., 2003. Evaluation of the progress of protein hydrolysis. Curr. Protoc. Food Anal. Chem. 10 (1).
[11] Nordqvist, P., Johansson, E., Khabbaz, F., Malmström, E., 2013. Characterization of hydrolyzed or heat treated wheat gluten by SE-HPLC and 13C NMR: correlation with wood bonding performance. Ind. Crop. Prod. 51, 51–61. https://doi.org/10.1016/j.indcrop.2013.08.057.
[12] Lagrain, B., De Vleeschouwer, K., Rombouts, I., Brijs, K., Hendrickx, M.E., Delcour, J.A., 2010. The kinetics of β-elimination of cystine and the formation of lanthionine in gliadin. J. Agric. Food Chem. 58 (19), 10761–10767. https://doi.org/10.1021/jf102575r.
[13] Wang, Y., Gan, J., Zhou, Y., Cheng, Y., Nirasawa, S., 2017. Improving solubility and emulsifying property of wheat gluten by deamidation with four different acids: effect of replacement of folded conformation by extended structure. Food Hydrocoll. 72, 105–114. https://doi.org/10.1016/j.foodhyd.2017.04.013.
[14] Li, T., Guo, X.N., Zhu, K.X., Zhou, H.M., 2018. Effects of alkali on protein polymerization and textural characteristics of textured wheat protein. Food Chem. 239, 579–587. https://doi.org/10.1016/j.foodchem.2017.06.155.
[15] Dai, Y., Zhong, W., Hu, X., Ji, X., Sun, Q., Wang, R., Wang, L., 2023. Conformational and functional changes from deamidation of wheat gluten with electrochemical treatment. J. Sci. Food Agric. 103 (12), 5677–5686. https://doi.org/10.1002/jsfa.12702.
[16] Liao, L., Liu, T.X., Zhao, M.M., Zhao, H.F., Cui, C., 2011. Aggregation behavior of wheat gluten during carboxylic acid deamidation upon hydrothermal treatment. J. Cereal. Sci. 54 (1), 129–136. https://doi.org/10.1016/j.jcs.2011.01.017.
[17] Liao, L., Han, X.Y., Zhao, M.M., Ni, L., Liu, Z.B., Zhang, W., 2016. Effect of native aggregation state of soluble wheat gluten on deamidation behavior in a carboxylic acid/heat water solution. J. Cereal. Sci. 72, 1–9. https://doi.org/10.1016/j.jcs.2016.09.011.
[18] Cui, C., Hu, Q., Ren, J., Zhao, H., You, L., Zhao, M., 2013. Effect of the structural features of hydrochloric acid-deamidated wheat gluten on its susceptibility to enzymatic hydrolysis. J. Agric. Food Chem. 61 (24), 5706–5714. https://doi.org/10.1021/jf400281v.
[19] Majzoobi, M., Abedi, E., 2014. Effects of pH changes on functional properties of native and acetylated wheat gluten. Int. Food Res. J. 21 (3).
[20] Jansens, K.J., Lagrain, B., Brijs, K., Goderis, B., Smet, M., Delcour, J.A., 2013. Impact of acid and alkaline pretreatments on the molecular network of wheat gluten and on the mechanical properties of compression-molded glassy wheat gluten bioplastics. J. Agric. Food Chem. 61 (39), 9393–9400. https://doi.org/10.1021/jf403156c.
[21] Liao, L., Zhao, M., Ren, J., Zhao, H., Cui, C., Hu, X., 2010. Effect of acetic acid deamidation-induced modification on functional and nutritional properties and conformation of wheat gluten. J. Sci. Food Agric. 90 (3), 409–417. https://doi.org/10.1002/jsfa.3830.
[22] Abedi, E., Pourmohammadi, K., 2021. Chemical modifications and their effects on gluten protein: an extensive review. Food Chem. 343, 128398. https://doi.org/10.1016/j.foodchem.2020.128398.