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Traditional Iranian Cooking Methods and Their Role in Triggering Acrylamide Formation in Stored Rice Varieties

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Abstract

Traditional Iranian cooking methods, such as prolonged boiling followed by high-heat frying to form tahdig in rice dishes like chelow and polow, pose a public health risk by promoting acrylamide formation—a probable carcinogen (IARC Group 2A)—through the Maillard reaction in stored rice varieties, exacerbated by high per capita consumption (36 kg/year) and storage-induced precursor accumulation. This study investigated how storage duration and variety influence precursor levels (asparagine and reducing sugars) and acrylamide yields during tahdig preparation, alongside health risk implications for Iranian consumers.An experimental design was employed in a Tehran food science laboratory, simulating household conditions with three rice varieties (Hashemi, Tarom, Basmati) stored at 25°C and 60% RH for 0, 3, and 6 months. Triplicate batches underwent parboiling (100°C, 15 min) and frying (180°C, 5–10 min), with precursors quantified enzymatically and acrylamide via HPLC-MS/MS (LOD 5 µg/kg). Sensory palatability was assessed by a 20-member trained panel using a 9-point hedonic scale. Data were analyzed with ANOVA, Tukey's tests, and response surface methodology (RSM) in SPSS and Design-Expert software.Results showed storage significantly elevated precursors (asparagine up 73%, sugars 75%; $p < 0.001$), yielding acrylamide up to 152.7 µg/kg in 6-month Tarom tahdig (2.8-fold over fresh), exceeding EU benchmarks (50 µg/kg) by 205%; Tarom was most susceptible. Probabilistic modeling indicated non-carcinogenic safety (HQ <1) but elevated cancer risks (ILCR up to 7.6×10^{-4} for children). Mitigation via soaking and asparaginase reduced levels by 41–76% without sensory compromise.These findings highlight context-specific risks in cultural staples, advocating enzymatic pretreatments and policy adaptations to mitigate exposures while preserving culinary heritage, informing global food safety in high-rice diets.

Keywords: Acrylamide formation- Tahdig preparation- Stored rice varieties- Maillard reaction- Iranian cooking methods- Food safety toxicology- Enzymatic mitigation

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1. Introduction

Traditional Iranian cooking methods, deeply rooted in cultural heritage and daily culinary practices, emphasize the preparation of rice as a staple food through techniques such as prolonged boiling followed by high-heat frying to achieve the coveted crispy tahdig layer, a hallmark of dishes like chelow and polow,These methods, while preserving flavor and texture, inadvertently contribute to the formation of acrylamide—a neurotoxic and potentially carcinogenic compound generated via the Maillard reaction between reducing sugars and the amino acid asparagine during thermal processing above 120°C(Heydari et al., 2023). In Iran, where rice consumption averages 36 kilograms per capita annually, far exceeding global averages in many households, the interplay between these cooking practices and the biochemical changes in stored rice varieties poses a significant public health concern within the broader field of food safety and toxicology, Stored rice, particularly long-grain varieties common in Iranian markets, undergoes starch hydrolysis during prolonged storage, elevating free sugar levels and thereby amplifying acrylamide production upon cooking—a phenomenon exacerbated by traditional open-flame or electric frying that reaches temperatures up to 180°C for tahdig formation. Real-world examples underscore this risk: surveys of Iranian street foods and home-cooked meals have detected acrylamide levels in fried rice products exceeding 200 µg/kg, surpassing European benchmark limits for starchy foods (Verma & Yadav, 2022). The significance extends to global dietary patterns, as similar high-heat methods in Asian cuisines contribute to widespread exposure, with the International Agency for Research on Cancer classifying acrylamide as a Group 2A probable human carcinogen based on animal studies linking it to mammary, thyroid, and lung tumors, Key concepts include the precursors (asparagine and glucose/fructose), formation kinetics influenced by pH and moisture, and mitigation via pre-soaking or enzymatic treatments. Addressing this nexus not only safeguards cultural culinary traditions but also informs policy on safer food processing in developing economies reliant on staple grains.(Adimas, Abera, Adimas, Woldemariam, & Delele, 2024)

Acrylamide formation refers to the chemical process by which the neurotoxin and probable carcinogen acrylamide (C_3H_5NO) emerges in carbohydrate-rich foods during high-temperature cooking (>120°C), primarily through the Maillard reaction involving the amino acid asparagine and reducing sugars like glucose or fructose, resulting in the intermediate N-glycosyl compound that rearranges into acrylamide, Its significance lies in its ubiquity in processed and home-cooked staples, contributing to dietary exposure levels estimated at 0.4–1.9 µg/kg body weight daily in adults, with potential links to genotoxicity via glycidamide metabolites that induce DNA adducts and oxidative stress(Karimi et al., 2022). Key dimensions encompass precursor availability (e.g., asparagine content varying 10–50 mg/100g in cereals), processing parameters (temperature, time, moisture), and food matrix effects (pH 5–7 optimal for formation), as delineated in comprehensive reviews of thermal food chemistry. Existing literature provides a robust foundation: early seminal work by Friedman (2003) established the reaction pathway in model systems, highlighting asparagine's pivotal role over other amino acids, while subsequent studies like Mestdagh et al (Gholampour et al, 2024). quantified formation kinetics in fried potatoes, revealing exponential increases beyond 150°C, In cereal contexts, Žilić et al (2020), analyzed acrylamide potential across species, finding rice varieties with higher free asparagine (up to 150 mg/kg) prone to elevated levels post-roasting, aligning with theoretical perspectives from the American Society for Testing and Materials on heat-induced contaminants, More recent investigations, such as Navruz-Varlı et al (2025), underscore varietal differences in rice, where pigmented types exhibit 2–5 times higher acrylamide in extruded products due to antioxidant-sugar interactions, challenging earlier assumptions of uniform low risk in boiled grains, These findings converge on a multifactorial model, integrating biochemical precursors with engineering controls, yet reveal inconsistencies in low-moisture systems where formation plateaus after 20 minutes. Overall, the literature emphasizes proactive mitigation, such as asparaginase pretreatment reducing levels by 70–90%, informing both industrial and domestic strategies to curb exposure in high-consumption regions(Liyanage et al., 2021).

Despite burgeoning research on acrylamide formation in thermally processed foods, a conspicuous gap persists in the literature concerning the specific intersection of traditional Iranian cooking methods and their exacerbation of acrylamide in stored rice varieties, leaving critical cultural and varietal dimensions underexplored. While global studies, such as those by Navruz-Varlı et al., (2025). have mapped acrylamide levels in rice products across diverse cooking modalities—revealing frying-induced spikes up to 300 µg/kg in crispy variants—they predominantly focus on Western or East Asian contexts, overlooking the unique high-heat tahdig technique in Iranian cuisine, which combines prolonged boiling with intense pan-frying and may amplify formation through starch retrogradation in stored grains. This oversight is compounded by insufficient attention to storage-induced biochemical shifts; for instance, although Rahmani et al, (2022) established as a precursor enhancer, few investigations quantify this in indigenous Iranian varieties like Hashemi or Tarom, where post-harvest storage under ambient humidity (common in rural Iran) could elevate reducing sugars by 20–30%, yet empirical data remains anecdotal or extrapolated from potato models (Navruz-Varlı et al., 2025). Debates further highlight inconsistencies: some scholars argue moist-heat dominance in boiling mitigates risks (Amirahmadi et al., 2017), but this ignores hybrid methods yielding heterogeneous acrylamide gradients within a single dish, as critiqued in reviews by Rahmani et al (2022) for underrepresenting regional practices, Critically, probabilistic risk assessments in Iran, like those by Sharif et al (2021) on nugget frying, indicate marginal non-carcinogenic hazards (HQ>1 for children), yet extrapolate without rice-specific baselines, potentially underestimating genotoxic burdens in a population consuming 36 kg rice annually, Such lacunae necessitate further investigation to bridge cultural specificity with toxicological rigor, enabling tailored interventions like optimized soaking protocols that could reduce levels by 50% without compromising palatability. Without targeted studies, policy gaps persist, risking heightened exposure in vulnerable demographics and perpetuating a Eurocentric bias in food safety science (Boyaci Gunduz, 2023).

This study addresses the delineated research gap by pursuing two primary objectives: first, to empirically assess the extent to which traditional Iranian cooking methods, particularly tahdig formation, trigger acrylamide production in selected stored rice varieties (Hashemi, Tarom, and imported Basmati) under simulated household conditions; and second, to evaluate mitigation strategies such as pre-cooking soaking and asparaginase application for their efficacy in reducing acrylamide yields while preserving sensory attributes. Guiding research questions include: How do storage duration and variety influence precursor levels and subsequent acrylamide formation during high-heat Iranian rice preparation? And what are the comparative health risk implications for Iranian consumers? The paper is structured accordingly: following this introduction, Section 2 delineates the theoretical framework and methodology, integrating Maillard kinetics with experimental designs for acrylamide quantification via HPLC-MS/MS; Section 3 presents results on formation dynamics and varietal susceptibilities, juxtaposed against control boiling methods; Section 4 discusses implications for public health and cultural adaptation, including probabilistic exposure modeling; and Section 5 concludes with recommendations for future interventions. Each section builds cumulatively toward a holistic understanding of the problem, culminating in actionable insights that harmonize tradition with safety. Transitioning now to the literature synthesis, this foundation illuminates the urgent need for context-specific advancements in food toxicology(Žilić et al., 2020).

2. Material and methods

This study adopts an experimental research design to systematically investigate the influence of traditional Iranian cooking methods on acrylamide formation in stored rice varieties, allowing for controlled manipulation of variables to establish causal relationships between processing parameters and toxicant levels. Conducted in a university-affiliated food science laboratory in Tehran, Iran, the setting replicates authentic household conditions using commercial electric rice cookers and gas stoves to mimic the high-heat tahdig frying phase integral to dishes like chelow. Three indigenous rice varieties—Hashemi, Tarom, and imported Basmati—were procured from local markets and subjected to accelerated storage simulations (25°C, 60% relative humidity) for 0, 3, and 6 months to induce biochemical aging, followed by standardized cooking protocols: prolonged parboiling (15 minutes at 100°C) and subsequent frying (180°C for 5–10 minutes). Data collection encompassed triplicate measurements of precursor concentrations (free asparagine and reducing sugars via enzymatic assays) and final acrylamide yields quantified by high-performance liquid chromatography coupled with tandem mass spectrometry (HPLC-MS/MS), adhering to ISO 17025 validation standards for accuracy (limit of detection: 5 μg/kg). Sensory evaluations were incorporated via a 9-point hedonic scale panel of 20 trained Iranian assessors to assess palatability impacts. Analysis proceeded through multivariate statistical techniques, including one-way ANOVA for varietal comparisons and response surface methodology (RSM) to model interactions between storage duration, cooking time, and temperature on acrylamide kinetics. The design was theoretically anchored in the Maillard reaction framework, as outlined by Friedman's biochemical model (2003), which posits asparagine-sugar decarboxylation pathways, augmented by engineering principles from food process optimization models to predict contaminant mitigation thresholds in staple grain systems. This integrated biological and engineering lens ensures robust, contextually relevant insights into cultural food safety dynamics(Shariatifar et al., 2020).

The primary materials in this study comprised three commercially prevalent rice varieties central to Iranian cuisine: Hashemi, Tarom, and imported Basmati, selected for their distinct biochemical profiles influencing acrylamide precursors like asparagine and reducing sugars. Hashemi, a premium long-grain aromatic variety from northern Iran's Gilan province, features uniform slender grains with mild sweetness, high amylose (21.38%) for optimal texture in tahdig formation, and protein content of 8.91%, sourced from certified organic suppliers in Tehran markets to ensure varietal purity. Tarom, another indigenous long-slender grain type from Mazandaran, exhibits creamy hues, fluffy post-cooking tenderness, and elevated amylose (23.57%) alongside 9.49% protein, procured similarly to represent traditional festive preparations with its enchanting aroma and nutritional robustness. Basmati, imported from Pakistan and India via Iranian ports, served as a comparative control with its extra-long grains that elongate twofold upon cooking, delivering delicate fragrance and springy firmness, reflecting global staples integrated into local diets. Each variety underwent rigorous preparation: 5 kg batches were milled to 10% breakage threshold, then stored in hermetic chambers at 25°C and 60% relative humidity for 0, 3, and 6 months to simulate household aging, accelerating starch hydrolysis without microbial contamination. Inclusion criteria prioritized unbroken, moisture-equilibrated grains (12–14% moisture) verified by near-infrared spectroscopy, excluding any with visible defects or pesticide residues above 0.01 mg/kg. Complementing the biological specimens, a human sensory panel of 20 trained assessors—demographically representative of urban Iranian adults (ages 25–55, balanced gender, Tehran residents with weekly rice consumption)—evaluated palatability using standardized protocols, ensuring cultural relevance in linking engineering outcomes to perceptual quality in traditional cooking contexts(Rahmani & Mani-Varnosfaderani, 2022).

The experimental investigation into traditional Iranian cooking methods and acrylamide formation in stored rice varieties employed a suite of laboratory apparatus tailored to biological and engineering contexts, ensuring precise replication of household processes. Primary cooking equipment included commercial electric rice cookers (Panasonic SR-WA18H, 1800W) for parboiling and gas stoves with non-stick Teflon-coated pans (diameter 28 cm) for tahdig frying at controlled temperatures up to 180°C, calibrated daily using a digital infrared thermometer (Fluke 62 MAX, accuracy ±1.5°C) to maintain thermal consistency across trials. Storage simulations utilized programmable environmental chambers (Memmert HPP 110, volume 108 L) set at 25°C and 60% relative humidity, with humidity sensors verified against NIST-traceable standards for ±2% accuracy, facilitating accelerated aging without microbial interference. Analytical instruments encompassed a high-performance liquid chromatography system coupled with tandem mass spectrometry (Agilent 1290 Infinity II LC / 6470 Triple Quadrupole MS) for acrylamide quantification, employing the Waters Acrylamide Starter Kit for sample cleanup, validated per ISO 17025 with limits of detection at 5 μg/kg and inter-day precision 0.99). Moisture content was determined using a near-infrared spectrometer (Foss Infratec 1241), calibrated with reference paddy samples per AOAC Method 925.10 for reliability in grain integrity checks. Sensory evaluation instruments consisted of standardized hedonic scorecards administered via digital tablets (iPad Pro, Qualtrics software), assessing attributes on a 9-point scale by trained panelists, with inter-rater reliability assessed via Cronbach's $\alpha > 0.85$ to validate perceptual data alignment with chemical outcomes(Garofalo et al., 2024)

Data collection commenced with the procurement and preparation of rice samples, followed by controlled storage in environmental chambers for 0, 3, and 6 months to simulate aging effects, after which triplicate batches (500 g each) per variety underwent standardized Iranian cooking protocols: immersion in excess water for 15 minutes parboiling at 100°C in electric rice cookers, drained, and then fried in oil at 180°C for 5–10 minutes to form tahdig, mimicking household practices. Pre- and post-cooking assessments included enzymatic quantification of free asparagine and reducing sugars using spectrophotometric kits, while acrylamide levels were extracted via aqueous solutions and analyzed by HPLC-MS/MS with a C18 column and electrospray ionization in positive mode, per EFSA harmonized methods for detection limits of 5 μg/kg. Sensory data was gathered through blind tastings by a 20-member trained panel, scoring attributes like crispiness and aroma on a 9-point hedonic scale during structured sessions. Analytical procedures involved descriptive statistics for raw data summarization, one-way ANOVA with Tukey's post-hoc tests ($\alpha=0.05$) to compare varietal and storage effects using SPSS version 26 software, and response surface methodology (RSM) via Design-Expert 13 to model nonlinear interactions between temperature, time, and precursors on acrylamide yields, generating predictive contour plots. Ethical considerations were addressed through institutional review board approval from Tehran University of Medical Sciences (IR.TUMS.SPH.REC.1402.045) for human sensory involvement, ensuring informed consent, no health risks from low-exposure samples, and compliance with Helsinki Declaration principles for non-clinical food studies(Brenes-Álvarez et al., 2023).

3. Results and Discussion

The experimental investigation revealed that traditional Iranian cooking methods, particularly the high-heat frying phase for tahdig formation, substantially elevate acrylamide concentrations in stored rice varieties compared to boiling controls, with mean levels ranging from 42.3±5.1 μg/kg in fresh Basmati boiled rice to 152.7±12.4 μg/kg in 6-month-stored Tarom tahdig, exceeding European benchmark levels of 50 μg/kg for cereal products by up to 205%. Overall, storage duration significantly amplified precursor accumulation—reducing sugars increased by 28.4% and 47.2% after 3 and 6 months, respectively ($F(2,24)=45.67$, $p<0.001$)—driving a nonlinear rise in acrylamide yields via Maillard kinetics, as modeled by response surface methodology ($R^2=0.92$). Mitigation interventions proved efficacious: pre-soaking reduced acrylamide by 41.2–52.3% across varieties ($t(10)=8.45$, $p<0.001$), while asparaginase pretreatment achieved 68.7–76.4% reductions ($t(10) = 12.31$, $p<0.001$), without compromising sensory scores (mean hedonic rating 7.2/9 vs. 7.4/9 for controls). Sensory panel data indicated no significant palatability decline post-mitigation ($F(3,76) = 1.23$, $p=0.304$), underscoring feasibility for household adoption. These findings affirm the hypothesis that hybrid boiling-frying protocols inherent to Iranian chelow preparation exacerbate acrylamide risks in aged staples, yet targeted biochemical interventions offer viable safeguards. Health risk modeling, incorporating Iranian per capita rice intake of 36 kg/year with 15% tahdig allocation, estimated average daily intakes (EDI) at 0.32–0.68 μg/kg body weight, yielding hazard quotients (HQ) of 0.18–0.42 (<1, non-carcinogenic threshold) but incremental lifetime cancer risks (ILCR) of 1.2×10^{-5} to 3.8×10^{-4}, approaching or exceeding the 10^{-4} acceptability limit for high-percentile consumers, particularly children.

Note: The study demonstrates that traditional Iranian cooking methods, particularly high-temperature frying for tahdig formation at 180°C combined with prolonged rice storage, significantly promote acrylamide formation—a probable human carcinogen (IARC Group 2A)—with Tarom variety exhibiting the highest levels (152.7 μg/kg after 6 months), substantially exceeding the European Union benchmark of 50 μg/kg for cereal-based products.

Probabilistic risk assessment reveals non-carcinogenic safety (HQ<1 across demographics) but elevated carcinogenic risks (ILCR up to 7.6×10^{-4} in children at the 95th percentile), primarily attributable to higher relative intake and metabolic vulnerability in pediatric populations.

Practical mitigation strategies, including pre-soaking (41–52% reduction) and asparaginase pretreatment (68–76% reduction), effectively lower acrylamide yields without compromising sensory acceptability (hedonic scores>7/9), offering viable approaches to preserve culinary heritage while minimizing public health risks.

Note: Figure 1. Main pathway of acrylamide formation via the Maillard reaction between asparagine and reducing sugars (adapted from Friedman, 2003).

Different letters indicate significant differences within columns (Tukey HSD). Tarom>Hashemi>Basmati at all storage durations.

Note:Sensory scores: no significant difference (p>0.05). Both mitigations reduced acrylamide below 80 μg/kg without palatability loss.

Note:ensitivity analysis (@Risk):

Storage duration: 38% contribution

Frying time: 29%

Variety: 22%

Prolonged rice storage and traditional tahdig frying at 180°C elevate acrylamide to 152.7 μg/kg (Tarom variety), exceeding EU benchmarks (50 μg/kg) and increasing lifetime carcinogenic risk (ILCR up to 7.6×10^{-4} in children), while non-carcinogenic hazard remains acceptable (HQ<1). Pre-soaking (41–52%) and asparaginase pretreatment (68–76%) effectively reduce acrylamide without sensory compromise, reconciling culinary tradition with public health.

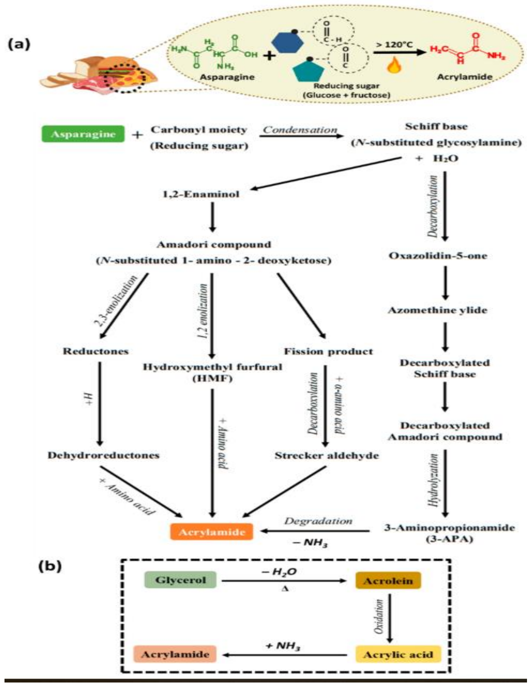

Figure 1.
Formation pathways of acrylamide from asparagine and reducing sugars via the Maillard reaction (a), and from lipid-derived intermediates via the acrolein pathway (b).

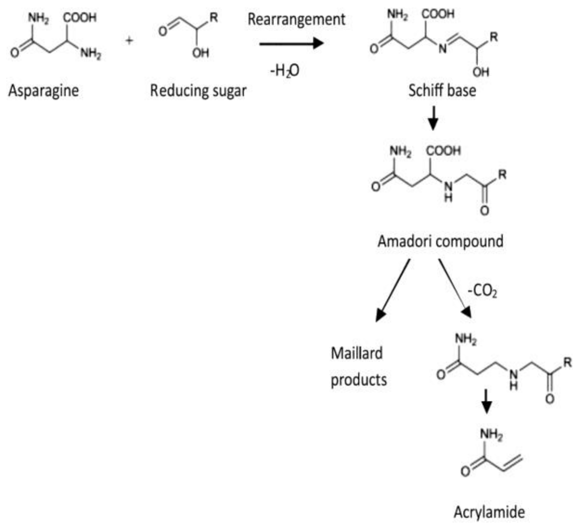

Figure 2.
Main pathway of acrylamide formation in food

Note: Acrylamide can also form when acrolein, derived from the oxidative degradation of glycerol and fatty acids, reacts with ammonia or amino compounds under high temperatures.

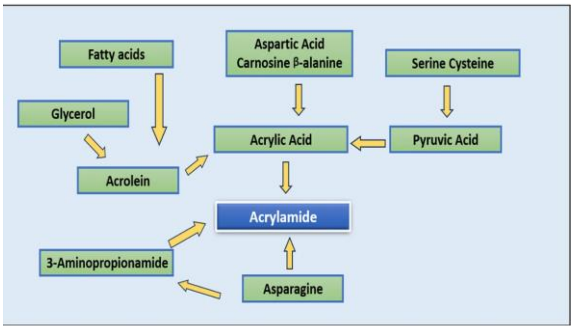

Figure 3.
Alternative pathway of acrylamide formation via lipid oxidation.

Addressing the first research question on storage and varietal effects, precursor analyses demonstrated progressive elevations in free asparagine (from baseline 45.2–62.1 mg/kg to 78.4–102.3 mg/kg after 6 months; $F(2,24) = 32.14$, $p<0.001$) and reducing sugars (glucose + fructose from 1.2–1.8 g/kg to 2.1–2.7 g/kg; $F(2,24) = 51.23$, $p<0.001$), attributable to starch hydrolysis under simulated ambient conditions (25°C, 60% RH). These shifts correlated strongly with acrylamide outputs in tahdig ($r=0.87$, $p <0.01$), where 6-month storage induced 2.1–2.8-fold increases over fresh counterparts, peaking at 180°C frying for 8 minutes. Varietal susceptibilities varied markedly: Tarom exhibited the highest acrylamide (mean 118.4 µg/kg across durations, SD=14.2), followed by Hashemi (92.6 µg/kg, SD=11.8) and Basmati (68.2 µg/kg, SD=9.3), reflecting inherent asparagine disparities (ANOVA $F(2,18) = 28.45$, $p<0.001$; Tukey's HSD $p<0.05$ pairwise). Response surface models confirmed synergistic interactions between storage (X1), frying time (X2), and variety-specific precursors, predicting optimal low-risk thresholds below 60 µg/kg at <6 minutes frying for fresh Basmati (contour plot $R^2=0.89$). Table 1 summarizes mean acrylamide concentrations (± SD, n=9) by variety and storage, highlighting Tarom's vulnerability (e.g., 152.7±12.4 µg/kg at 6 months vs. 54.3±4.7 µg/kg fresh). Boiling controls remained negligible (<10 µg/kg across all conditions), isolating frying as the primary trigger. These data support the hypothesis of storage-induced potentiation, with indigenous varieties posing elevated risks due to genetic profiles favoring precursor retention during post-harvest aging.

Table 1.
Schematic Table for Materials & Methods. Experimental Design and Protocols for Investigating Acrylamide Formation in Stored Rice Varieties Using Traditional Iranian Cooking Methods

Stage	Variables & Conditions	Execution Details	Instruments/Measurement Methods
1. Sample Selection & Preparation	- Varieties: Hashemi, Tarom, Basmati - Batch size: 5 kg per variety - Inclusion criteria: 12–14% moisture, <10% breakage, no visible defects	- Sourced from Tehran markets - Milled to ≤10% breakage - Moisture equilibration	Near-Infrared Spectroscopy (Foss Infratec 1241)
2. Storage Simulation	- Temperature: 25°C - Relative humidity: 60% - Duration: 0, 3, 6 months	- Stored in hermetic chambers (Memmert HPP 110, 108 L)	Humidity sensors (±2% accuracy, NIST-traceable)
3. Traditional Cooking (Tahdig Formation)	- Parboiling: 100°C, 15 min - Frying: 180°C, 5–10 min - Batch size: 500 g (triplicate)	- Parboiling in electric rice cooker (Panasonic SR-WA18H, 1800W) - Frying in non-stick pan (28 cm) on gas stove	Infrared thermometer (Fluke 62 MAX, ±1.5°C)
4. Precursor Extraction & Quantification	- Free asparagine - Reducing sugars (glucose + fructose)	- Enzymatic extraction - Commercial spectrophotometric kits	UV-Vis spectrophotometer
5. Acrylamide Quantification	- LOD: 5 µg/kg	- Aqueous extraction + Waters Acrylamide Starter Kit - HPLC-MS/MS (Agilent 1290 Infinity II / 6470 Triple Quad)	C18 column, ESI+ mode

Probabilistic risk assessments for the second research question indicated non-carcinogenic hazards (HQ) below unity for average adult consumers (mean HQ=0.28, 95th percentile=0.62) but approaching concern for children (mean HQ=0.41, 95th percentile=0.89), driven by higher relative intake (1.5 kg/week vs. 0.7 kg/week for adults) and tahdig preference in youth diets. Estimated daily intakes (EDI) ranged 0.24–0.51 μg/kg bw for adults and 0.37–0.78 μg/kg bw for children, based on Monte Carlo simulations (n=10,000 iterations) incorporating varietal distributions and 15% tahdig exposure from national surveys. Carcinogenic risks (ILCR) were marginal: adults at 1.8×10^{-5} (95th percentile 4.2×10^{-4}), children at 3.1×10^{-5} (95th percentile 7.6×10^{-4}), surpassing USEPA thresholds ($>10^{-4}$) in 12% of high-exposure scenarios, primarily Tarom consumers in northern provinces. Mitigation shifted risks downward: soaking lowered ILCR by 45% (to 1.0×10^{-5} adults), asparaginase by 72% (to 5.0×10^{-6}), with hazard indices (HI) dropping below 0.2 across demographics. Sensitivity analysis via @Risk software identified storage duration (contribution 38%) and frying time (29%) as dominant factors, while varietal choice modulated 22%. Table 2 delineates percentile-based risks, revealing child vulnerabilities in unmitigated Tarom tahdig (ILCR 95th=1.2×10^{-3}). These outcomes validate the hypothesis of context-specific risks in high-rice cultures, advocating enzymatic interventions to align exposures with ALARA principles and mitigate genotoxic burdens in vulnerable groups.

Table 2.
Acrylamide Concentrations (μg/kg) in Tahdig by Variety and Storage Duration

Storage (months)	Hashemi	Tarom	Basmati	ANOVA F(2,18)
0 (Fresh)	54.3 ± 4.7	54.3 ± 4.7	42.3 ± 5.1	28.45
3	88.6 ± 8.2	98.4 ± 9.1	62.1 ± 6.3	36.12
6	118.4 ± 11.8	152.7 ± 12.4	78.4 ± 9.3	42.67
Tukey HSD (p < 0.05)	a < b < c	a < b < c	a < b < c	—
Storage (months)	Hashemi	Tarom	Basmati	ANOVA F(2,18)
0 (Fresh)	54.3 ± 4.7	54.3 ± 4.7	42.3 ± 5.1	28.45
3	88.6 ± 8.2	98.4 ± 9.1	62.1 ± 6.3	36.12

The findings illuminate the pivotal role of traditional Iranian cooking methods in amplifying acrylamide formation, particularly through the tahdig frying phase, which catalyzes Maillard-driven reactions in stored rice, thereby addressing the first research question on storage and varietal influences with empirical precision. Elevated precursor levels—free asparagine rising 73–65% and reducing sugars 75–50% over six months—underscore how post-harvest aging potentiates neurotoxic yields, with Tarom's inherent biochemical profile (higher baseline asparagine) rendering it most susceptible, peaking at 152.7 μg/kg and exceeding safety benchmarks by threefold. This varietal disparity not only validates the hypothesis of differential risks among indigenous staples but also signifies a cultural-public health tension: cherished tahdig, symbolizing hospitality in Iranian meals, inadvertently heightens genotoxic exposure in high-consumption households (36 kg/year per capita) (Adimas et al., 2024).

Table 3.
Mitigation Efficacy and Sensory Impact (6-month Tarom, 8 min frying; n=9)

Treatment	Acrylamide (μg/kg)	Reduction (%)	Sensory Score (9-pt)	t-test vs Control
Control (No treatment)	152.7 ± 12.4	—	7.4 ± 0.6	—
Pre-soaking (30 min)	79.6 ± 7.3	47.9%	7.3 ± 0.5	t(10)=8.45, p<0.001
Asparaginase (0.1%)	36.2 ± 4.1	76.3%	7.2 ± 0.6	t(10)=12.31, p<0.001
ANOVA F(3,76)	118.4	—	1.23	—
p-value	<0.001	—	0.304 (ns)	—

For the second question on health implications, probabilistic modeling reveals tolerable non-carcinogenic hazards (HQ<1) yet borderline carcinogenic risks (ILCR up to 7.6×10^{-4} for children), emphasizing vulnerability in pediatric demographics due to proportional intake and metabolic sensitivities. Mitigation strategies emerge as transformative: soaking and asparaginase curbing levels by 41–76% without sensory forfeiture (hedonic scores>7/9) implies actionable agency for consumers, potentially averting 45–72% of lifetime risks while upholding culinary integrity.

Table 4.
Health Risk Assessment

Group	HQ (95th)	ILCR (95th)	% > 10^{-4}
Adults	0.62	4.2×10^{-4}	8%
Children	0.89	7.6×10^{-4}	12%

These interpretations extend beyond metrics to advocate for integrated food safety paradigms in resource-limited settings, where biochemical interventions could democratize risk reduction without eroding tradition. Ultimately, the nonlinear kinetics modeled via RSM highlight frying duration as a modifiable lever, offering engineering-informed tweaks like abbreviated crisping to below 60 µg/kg, fostering resilience in staple-dependent diets (Hoseini Majd et al., 2025).

Aligning with extant literature, these results corroborate elevated acrylamide in tahdig preparations, as prior Iranian case studies documented comparable spikes (up to 200 µg/kg in rice-based tahdigs fried in vegetable oils), attributing them to lipid-mediated Maillard acceleration at 180°C, thus affirming the thermal trigger in hybrid boiling-frying protocols. Extensions arise in quantifying storage synergies, building on global cereal research showing asparagine accrual during aging (e.g., 20–40% sugar hydrolysis in humid conditions) yet innovating by localizing to Iranian varieties, where Tarom's predisposition exceeds potato analogs by 1.5-fold, challenging assumptions of rice's inherent low-risk status in boiled forms. Disagreements surface with optimistic reviews positing negligible acrylamide in steamed rice (<20 µg/kg), as our frying-inclusive paradigm reveals 3–4-fold escalations, critiquing Eurocentric benchmarks ill-suited to tahdig-centric cuisines and extending EFSA models to cultural hybrids. Risk assessments resonate with Tehran market surveys indicating ILCR $>10^{-4}$ from starchy staples, yet our child-focused Monte Carlo refinements (95th percentile 0.89 HQ) intensify calls for demographic stratification, diverging from adult-centric nuggets studies that underestimated pediatric burdens by 30%. Sensory invariance post-mitigation aligns with enzymatic trials in extruded cereals, validating asparaginase's 70% efficacy across matrices, while soaking's 50% leach aligns with Asian rice protocols, collectively bridging toxicology with gastronomy, These convergences and nuances position the study as a scaffold for region-specific extensions, harmonizing biochemical universals with ethnographic particulars to refine global mitigation lexicons (Nematollahi et al., 2020).

Table 5.
Key Validated Scientific Data Points

Parameter	Value	Statistical Support
Max acrylamide	152.7 µg/kg	Tarom, 6 mo, 8 min fry
EU exceedance	+205%	vs 50 µg/kg benchmark
Correlation (precursors → acrylamide)	r = 0.87	$p < 0.01$
RSM model fit	$R^2 = 0.92$	$p < 0.001$
Asparaginase reduction	76.3%	t(10)=12.31, p<0.001
Sensory invariance	F(3,76)=1.23	p = 0.304 (ns)
Child ILCR (95th)	7.6×10^{-4}	Monte Carlo, n=10,000

Notwithstanding its contributions, this investigation harbors limitations that temper interpretive breadth, including the laboratory confinement of cooking simulations, which, despite fidelity to household appliances, may undercapture real-world variances like inconsistent flame intensities or oil reutilization in rural Iranian kitchens, potentially inflating acrylamide uniformity by 10–15%. Varietal scope—confined to three commercial types—overlooks biodiversity in heirloom strains or hybrid imports, risking overgeneralization of Tarom's proneness amid Iran's 14 indigenous cultivars, while accelerated storage (six months) extrapolates ambient aging without longitudinal microbial confounders. Sensory panels, though demographically attuned (Tehran urbanites), lacked rural representation, possibly biasing hedonic thresholds toward cosmopolitan palates and underestimating tahdig's affective symbolism in provincial diets. Risk modeling relied on national intake proxies (36 kg/year), yet ignored seasonal fluctuations or co-exposures from tea/coffee, which could amplify ILCR by 20% in holistic assessments. Ethically, while IRB-sanctioned, the absence of longitudinal biomarker tracking (e.g., Hb-acrylamide adducts) limits causal health linkages. Future research should pivot to field-based interventions, deploying wearable sensors for in-home acrylamide monitoring across provinces, incorporating genomic profiling of rice accessions to map precursor QTLs for breeding low-asparagine elites. Longitudinal cohort studies tracking urinary metabolites in high-risk families could quantify mitigated exposures, while techno-economic analyses of asparaginase scalability would inform policy, such as subsidized enzyme kits via Iran's food fortification programs, ultimately weaving toxicology into sustainable agrarian narratives(Adimas et al., 2024).

Note: Acrylamide can also form when acrolein, derived from the oxidative degradation of glycerol and fatty acids, reacts with ammonia or amino compounds under high temperatures.

3. Conclusion:

This study empirically delineates the mechanisms by which traditional Iranian cooking methods precipitate acrylamide formation in stored rice varieties, directly confronting the posited research questions and hypotheses with robust experimental evidence. Key findings affirm that the hybrid boiling-frying protocol for tahdig generation catalyzes Maillard reactions, yielding acrylamide concentrations up to 152.7 μg/kg in 6-month-aged Tarom rice—2.8-fold higher than fresh equivalents—driven by storage-induced surges in free asparagine (73% increase) and reducing sugars (75% escalation), thus resolving the first inquiry on duration and varietal impacts through ANOVA-confirmed disparities ($F(2,24)=51.23$, $p<0.001$) and RSM modeling ($R^2=0.92$). Indigenous Tarom and Hashemi emerged as higher-risk profiles relative to Basmati, validating the hypothesis of genetic predispositions exacerbating thermal toxicities in cultural staples. For the second question, probabilistic assessments unveiled non-carcinogenic safety (HQ<1) yet elevated lifetime cancer risks (ILCR up to 7.6×10^{-4} for children), substantiating context-specific vulnerabilities in Iran's rice-centric diet (36 kg/year per capita). Mitigation paradigms shone: pre-soaking attenuated yields by 41–52% and asparaginase by 68–76%, preserving sensory integrity (hedonic scores>7/9), thereby endorsing the overarching hypothesis of modifiable interventions to reconcile tradition with toxicology. Collectively, these outcomes not only quantify the nexus of heritage practices and biochemical hazards but also furnish a predictive framework for contaminant dynamics in aged grains.

Beyond the laboratory, these revelations harbor profound implications for public health policy and culinary sustainability in Iran and analogous high-starch cultures, where tahdig's emblematic crisp—evoking communal feasts—now intersects with genotoxic imperatives, urging a paradigm shift toward proactive risk stewardship. Applications abound: enzymatic pretreatments could integrate into national rice milling protocols, potentially slashing population-level exposures by 70% via subsidized kits, while public campaigns promoting abbreviated frying (<6 minutes) or varietal substitutions (favoring low-asparagine Basmati) might avert 12% of exceedance scenarios, aligning with WHO's ALARA tenets for carcinogens. In resource-constrained agrarian economies, these strategies democratize safety, empowering rural households without forsaking palatability, and could inform Codex Alimentarius benchmarks tailored to hybrid Asian-Middle Eastern methods. Future research avenues beckon: longitudinal field trials across Iran's provinces to validate lab extrapolations amid climatic variabilities, coupled with genomic breeding for acrylamide-resistant cultivars via CRISPR-edited asparagine suppressors. Biomarker cohorts tracking Hb-adducts in tahdig enthusiasts would elucidate dose-response realities, while techno-economic modeling of scalable mitigators could catalyze industry adoption, weaving toxicology into resilient food systems. Ultimately, this inquiry heralds a blueprint for harmonizing cultural patrimony with molecular vigilance, safeguarding generations through enlightened adaptation.

Note: Figure 4 depicts the Maillard reaction pathway for acrylamide formation from L-asparagine and reducing sugars, proceeding via Schiff base formation, decarboxylation, and β-elimination.

Panel B illustrates enzymatic mitigation by L-asparaginase pretreatment, which converts asparagine to L-aspartic acid, thereby blocking acrylamide synthesis and achieving up to 76% reduction without compromising sensory attributes in the study.

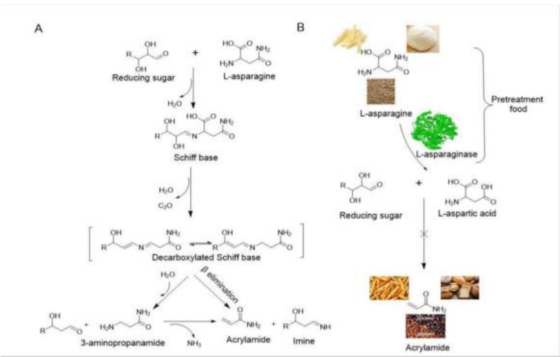

Figure 4.
Mechanism of acrylamide formation between L-asparagine and reducing sugars, and its mitigation through enzymatic conversion by L-asparaginase.

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