dietetics

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Gluten Contamination in Household Kitchen Appliances: Risks and Cleaning Solutions

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Abstract

Strict adherence to a gluten-free diet (GFD) is the cornerstone of treatment in coeliac disease, yet gluten cross-contamination in household settings poses a persistent challenge. Guidance from dieticians and patient organizations is often not evidence-based. This study quantified gluten contamination risks associated with common kitchen appliances and evaluated the effectiveness of various cleaning methods in typical Dutch households. We performed a two-phase analysis of 417 samples of 275 chopping boards, 34 toasters/sandwich makers, and 108 deep-fat fryers/air fryers. Gluten levels were assessed on appliances and food items under different cleaning protocols, with Bayesian modeling used to estimate contamination probabilities. Plastic chopping boards showed the highest risks, with probabilities up to 0.868 when rinsed with cold water, compared with 0.147 after dishwasher cleaning. Glass and wooden boards cleaned in dishwashers had the lowest probabilities (0.0102 and 0.0194). Toasters and sandwich makers tested positive in 1 of 34 samples; at the 20 ppm threshold, contamination probability was 0.00001. In fryers, probabilities were 0.125 for deep-fat fryers and 0.070 for air fryers at the 5 ppm threshold, decreasing to 0.0405 and 0.0326 at 20 ppm. Across all appliances, gluten levels seldom exceeded the clinically relevant threshold of 20 ppm. This study highlights the importance of dedicated cleaning protocols and appliance-specific recommendations to mitigate gluten exposure. While complete elimination of gluten is challenging, adopting rigorous practices can substantially mitigate exposure for coeliac patients, enhancing safety and quality of life.

Keywords: coeliac disease; gluten-free diet; gluten contamination; household gluten safety; kitchen appliances

Academic Editors: Iain A. Brownlee and Dalia El Khoury

Received: 21 May 2025
Revised: 22 August 2025
Accepted: 27 August 2025
Published: 12 September 2025

Citation: Burger, J.P.W.; Pijls, C.; van Overveld, F.W.P.C.; Jacobs, M.; Wessels, M.M.S.; Wahab, P.J. Gluten Contamination in Household Kitchen Appliances: Risks and Cleaning Solutions. *Dietetics* **2025**, *4*, 41. https://doi.org/10.3390/dietetics4030041

1. Introduction

Coeliac disease is a T-cell-mediated autoimmune response to the ingestion of gluten that leads to inflammation and damage of the small intestinal mucosa in genetically susceptible individuals [1]. Gluten-sensitive enteropathy classically presents with a spectrum of symptoms such as abdominal pain, diarrhea, weight loss, anemia, and vitamin deficiencies. Patients may also suffer from fatigue, arthralgia, and neurological and dermatological manifestations [2].

The gluten-free diet is the cornerstone of the treatment for coeliac disease. Avoiding contact with gluten, i.e., withdrawal of gluten from the diet, stops the mucosal response to the immunogenic peptides followed by recovery of the mucosa and is supposed to mitigate symptoms and prevent long-term complications [2,3]. Although novel drug therapies focused on degradation of ingested immunogenic peptides show some potential, the gluten-free diet will probably remain the treatment of choice in the coming years [3,4].

A lifelong gluten-free diet, however, may be difficult to maintain, restrictive, and costly [5]. Patients refrain from social activities like dining out, going on holidays, or just eating with friends due to fear of gluten contamination [6]. This fear is not unfounded: a recent analysis of gluten-free bakery products by Catassi et al. found that 21.5% of samples labeled as gluten-free contained gluten levels exceeding the safety threshold, demonstrating that even certified products can be contaminated [7]. This highlights the complexity and difficulty in maintaining a truly safe gluten-free diet. While a gluten-free diet is intended to alleviate symptoms, up to 20 percent of patients continue to experience symptoms they attribute to gluten [8,9]. Conversely, some patients report no symptoms at all but still display serological markers of active coeliac disease. The risk of gluten cross-contamination is evident in everyday life, even in one's own household. Preparing gluten-free meals in a not 100 per cent gluten-free kitchen can be challenging. Where some patients consider it essential to have an almost full-time job cleaning their kitchen, others spend money on buying different sets of household kitchen appliances. Dieticians and patient organizations provide guidance on how to avoid cross-contamination with gluten in household situations, but few of the recommendations are evidence-based.

An American study on gluten cross-contamination in frying pans and toasters from gluten-consuming households found no gluten levels exceeding the 20 mg/kg threshold [10,11]. Additionally, thorough cleaning of utensils, such as spoons, knives, and pans, has been shown to reduce cross-contamination risk [11]. However, questions remain: what is the level of gluten contamination in a typical Dutch household, and, if present, could these levels pose a risk for individuals with coeliac disease?

To evaluate and possibly minimize the risk of clinically relevant gluten cross-contamination in an average Dutch kitchen, we conducted a pilot study to investigate the effect of different cleaning methods on the level of gluten on everyday household kitchen materials and appliances, such as a chopping board, toaster, sandwich iron, deep-fat fryer, and air fryers.

2. Materials and Methods

We divided our study into three sub-studies focused on evaluating: 1. chopping boards, 2. toasters and sandwich makers, and 3. deep-fat fryers and air fryers. For each sub-study, we selected three different types of gluten-contaminated items (previously used in a household setting) and gluten-free items (new). Gluten-free bread was used in the first and second sub-studies, while gluten-free croquettes were used in the third. We homogenized the gluten-free bread using a blender, and the croquettes were crushed in zip-lock bags.

For gluten extraction, we utilized Compact Dry Swabs (Nissui Pharmaceutical, Tokyo, Japan) and 12 mL polypropylene centrifuge tubes. Each swab was carefully but firmly swiped across a 10 × 10 cm surface, detached from its handle, and placed into a centrifuge tube, which was then sealed and stored at 5°C. We employed the Gliadin ELISA kit (RIDASCREEN®, R-Biopharm, Darmstadt, Germany), capable of detecting gluten concentrations between 5 and 80 ppm of product. Between rounds, we cleaned materials using 70% ethanol, scouring pads, dishwashing liquid, and dishwasher tablets. Deionized water was prepared in the laboratory using a Milli-Q® Advantage A10® purification system, EMD Millipore corporation (Billerica, MA, USA).

For the chopping boards, we used surface swaps to determine cross-contamination on the surface. For the toasters, sandwich makers, deep-fat fryers, and air fryers, we determined possible cross-contamination in the gluten-free food product that was used in them. The reasoning behind that was the impossibility of performing swabs on hot surfaces, inaccessibility of the surfaces and taking into account other mechanisms of cross-contamination than surface contact: i.e., through the oil or air.

2.1. Chopping Boards

We tested chopping boards used in a gluten-consuming household made of wood, plastic, or glass, and cleaned each board and bread knife before use. A baseline swab sample from the surface was obtained after cutting gluten-free bread on a gluten-free chopping board. A positive control swab sample was obtained after cutting gluten-containing bread on a gluten-containing chopping board. We tested a total of four different cleaning procedures on the gluten-containing chopping board surfaces: (1) rinsing with cold running water, (2) rinsing with warm running water, (3) cleaning with warm water and soap, and (4) cleaning with a dishwasher. A new scouring pad was used in each procedure, in which the rough side was applied first by swiping the pad in vertical and horizontal movements. For cleaning with warm water and soap, we poured 1.0 mL of soap onto the scouring pad. For the dishwasher procedure we used Bio Normal 50 degrees program for a duration of 165 min with a dishwasher tablet.

2.2. Toasters and Sandwich Makers

Upon arrival, we sampled each toaster and sandwich iron used in a gluten-consuming household at the mid-position without using any cleaning procedure. Following this test and the first cleaning procedure, we extracted a blank control sample (before toasting bread) and a positive control sample (after toasting bread). Each sandwich maker was pre-heated for five minutes, after which either a gluten-containing, or a gluten-free and gluten-containing sandwich was roasted simultaneously for four minutes (gluten-containing on the left and gluten-free on the right). After toasting, we removed the gluten-containing bread with or without shaking out the toaster or the sandwich maker. This was performed after both one-off and repeated (10x) toasting of gluten-containing bread. The amount of gluten contamination in the case of toasting gluten-free and gluten-containing bread simultaneously was also tested. In this case, the gluten-free bread was milled for 10 s in a blender and further investigated according to the protocol of the ELISA-kit (RIDASCREEN®, R-Biopharm, Darmstadt, Germany). Following each experiment the following cleaning procedure was followed: 1. remove the plug from the socket and cool the apparatus down for 15 min, 2. turn the apparatus upside down above a sink and shake it to remove all crumbs, 3. use a toothbrush to remove the sticky crumbs, 4. clean the inner side of the toaster with a sponge dipped in warm water and dried with a paper towel, and finally 5. clean the outer side of the toaster with an all-purpose cleaner sprayed on a wet cloth.

2.3. Deep-Fat Fryers and Air Fryers

All fryers used in a gluten-consuming household were tested for gluten upon arrival without any cleaning procedure. For the deep-fat fryers, we tested both the oil and sediment. For the air fryers, we tested the basket and the bottom. A negative control sample was taken from an unused deep-fat fryer by frying a gluten-free croquette in fresh oil. Also, a negative control sample was taken from an unused air fryer by frying a gluten-free croquette. Subsequently, a positive control sample was taken from each fryer by frying a gluten-containing croquette. To prepare the croquettes, we set the deep-fat fryers at 175 °C for five minutes using fresh oil. The air fryers we pre-heated to 200 °C and set at 200 °C for 11 min. Following the cool-down, both the gluten-containing and gluten-free croquettes

were placed in a (separate) ziplock bag and stored at 8 °C until further homogenization and analysis. Gluten-contamination was tested for three different situations: (1) gluten-free croquette directly after a gluten-containing croquette without cleaning, (2) gluten-free croquette after a gluten-containing croquette with cleaning, and (3) for deep-fat fryers, replacing the frying oil. The deep-fat fryers were cleaned with a paper towel, whereas the air fryers were first cleaned by washing the basket with dishwashing liquid and warm water and then with a paper towel.

Finally, we chose to test a kind of worst-case scenario, mimicking a household not used to welcoming guests adhering to a gluten-free diet. Therefore, we used three different types of deep-fat fryers and air fryers. The deep-fat fryers were pre-heated to 180 °C, after which as many croquettes as possible were placed in the basket until all sides were touched. Baking time was set at 180 °C for 5 min. After removal of the gluten-containing croquettes, we then immediately inserted the same number of gluten-free croquettes using the same oil. Baking time was again set at 180 °C for 5 min. Following baking, the croquettes were cooled in the basket above the oil and then placed in a plastic bag. The croquettes were finally ground together using a blender and then stored in a new plastic bag in the refrigerator. We used three different fryers, frying three batches of six croquettes in fryer one and two, and two batches of nine croquettes in fryer three, based on the capacity of the fryers.

The air fryers were pre-heated to 200 °C, after which as many croquettes as possible were placed in the basket until all sides were touched. Baking time was set at 200 °C for 10 min. After removal of the gluten-containing croquettes, we then inserted the same number of gluten-free croquettes using the same temperature and duration. The croquettes were cooled and immediately put in a plastic bag, and finally ground with a hand blender and stored in a new plastic bag in the refrigerator. We used three different air fryers, frying three batches of six croquettes in fryer one, and two batches of nine croquettes in fryer two, based on the capacity of the fryers. We performed several tests with air fryer number three: 2 batches of 4 croquettes and 2 batches of 5 croquettes. Air fryers number two and three did not have a basket, but a bottom with holes in it. We summarized all cleaning procedures in Table 1.

Table 1. Summary of different cleaning methods and tests for household kitchen appliances.

Appliance	Cleaning Methods Applied or Action	Sampling Location
Chopping boards (wood, plastic, glass)	(1) Cold water rinse (2) Warm water rinse (3) Warm water + soap (4) Dishwasher	Surface swab (10 × 10 cm) after cutting bread
Toasters/sandwich makers	Manual cleaning in between tests: remove plug, cool 15 min, shake upside down, use toothbrush to remove crumbs, sponge with warm water, outer cleaning with all-purpose cleaner. Test: simultaneous versus consecutive toasting.	Gluten-free bread (post-toasting)
Deep-fat fryers	(1) No cleaning (2) Paper towel cleaning (3) Oil replacement	Oil and sediment; gluten-free croquettes post-frying
Air fryers (basket and non-basket types)	(1) No cleaning (2) Warm water + dish soap for basket (3) Paper towel cleaning	Basket/bottom; gluten-free croquettes post-frying

2.4. Statistical Analysis

We applied Bayesian analysis to show the flow of statistical evidence on the probability of gluten across both phases. In any Bayesian analysis there are three key parts: (1) old

knowledge, (2) new information, and (3) new knowledge. Hence, we used the results of the first phase as prior knowledge to combine with the new information coming from the second phase (Appendix A). The results described here are thus the new knowledge we have obtained by conducting three studies across two phases. Unless stated otherwise, gluten detection was set at ELISA $\geq$ 5 ppm.

We used the R statistical software package and the brms library to estimate probabilities from a Bernoulli distribution using the logit link. Posterior probability estimates for each of the parameters included were obtained using four chains and 10,000 iterations, of which 1000 were warm-up iterations. By simulating the experiment 1000 times, using 1000 experiments, we can show the average number of times gluten can be expected when performing the experiment. From these simulations, we extracted the range to indicate the simulated minimum and maximum number of times gluten may be detected.

3. Results

We obtained a total of 417 samples: 275 for the chopping boards, 34 for the toasters, and 108 samples for the deep-fat fryers and air fryers.

3.1. Chopping Boards

We collected a total of 275 samples, comprising 85 from a glass chopping board, 85 from a wooden chopping board, and 115 from a plastic board. Of these, 15 samples were untreated, 80 were rinsed with cold water, 60 were cleaned in a dishwasher, 60 were rinsed with warm water, and 60 were washed with warm water and soap. Additionally, we collected 130 (47.2%) positive controls. Besides the positive controls another 51 samples tested positive for gluten. The probability for gluten detection is presented in Tables 1, A1, A2 and A5. The glass chopping board cleaned in a dishwasher showed the lowest probability of gluten presence (0.0102). The probability of detecting gluten on plastic chopping boards was high (0.4950–0.8680) except when cleaned in a dishwasher (0.1470). Tables 2 and A6 also illustrate the change in probability if we change the threshold for gluten from 5 to 20 ppm. Overall, plastic chopping boards had the highest probability of gluten contamination, while dishwasher cleaning resulted in the lowest probability. The wooden chopping board cleaned by a dishwasher exhibited the smallest probability of gluten presence.

Table 2. The probability of gluten presence for gluten-containing chopping boards based on the material and the treatment applied, and the ELISA threshold applied.

Cleaning Method	Material	Probability of Gluten Presence ELISA $\geq$5 ppm	Probability of Gluten Presence ELISA $\geq$20 ppm
Untreated	Glass	0.0604	0.0407
Untreated	Wood	0.1070	0.0266
Untreated	Plastic	0.5130	0.4370
Cold water	Glass	0.2870	0.2030
Cold water	Wood	0.4240	0.1370
Cold water	Plastic	0.8680	0.8200
Dishwasher	Glass	0.0102	0.0099
Dishwasher	Wood	0.0194	0.0062
Dishwasher	Plastic	0.1470	0.1540

Table 2. *Cont.*

Cleaning Method	Material	Probability of Gluten Presence ELISA ≥5 ppm	Probability of Gluten Presence ELISA ≥20 ppm
Warm water	Glass	0.1790	0.0859
Warm water	Wood	0.2850	0.0560
Warm water	Plastic	0.7780	0.6180
Warm water and soap	Glass	0.0580	0.0320
Warm water and soap	Wood	0.1020	0.0208
Warm water and soap	Plastic	0.4950	0.368

3.2. Toasters and Sandwich Makers

We collected 34 samples, 3 of which tested positive for gluten. Two positive tests were identified in the positive control and one sample showed gluten presence during simultaneous toasting (Tables 3, A3, A7 and A8). Due to similar results in toasters and sandwich irons, we chose to combine the results. In summary, all indicate a low probability of gluten. When we changed the threshold for gluten from 5 to 20 ppm, the probability of gluten detection became extremely low (i.e., both cases show a 0.00001 probability).

Table 3. Probability of gluten during consecutive or simultaneous toasting of gluten-containing toasters.

Action	Probability of Gluten Presence ELISA ≥ 5 ppm	Probability of Gluten Presence ELISA ≥ 20 ppm
Consecutive toasting	0.0213	0.00001
Simultaneous toasting	0.0545	0.00001

3.3. Deep-Fat Fryers and Air Fryers

For both deep-fat fryers and air fryers, we collected 54 samples, of which 1 and 7 sample(s) contained gluten, respectively (Tables 4, A4, A9 and A10). Increasing the threshold for gluten to 20 ppm resulted in a lower probability of gluten presence (Table 3). Fully loading the air fryers and deep-fat fryers, described as the worst-case scenario, did not result in a higher likelihood of detecting gluten.

Table 4. Probability of gluten for deep-fat fryers and air fryers based on threshold applied.

Equipment	Probability of Gluten Presence ELISA ≥5 ppm	Probability of Gluten Presence ELISA ≥20 ppm
Air fryer	0.0703	0.0326
Deep-fat fryer	0.1250	0.0405

4. Discussion

This study addresses a dilemma that challenges patients with coeliac disease in daily life. It was therefore sponsored by the Dutch coeliac patient society. We investigated the risk of gluten cross-contamination in various household kitchen appliances and the effectiveness of different cleaning methods. Our findings provide valuable insights for individuals with coeliac disease, who rely on a strict gluten-free diet to alleviate symptoms and prevent long-term complications.

We found that cross-contamination occurs, but the levels vary depending on the type of appliance and cleaning procedure. The results for chopping boards indicate that the

material and cleaning method play substantial roles in reducing gluten contamination. The likelihood of gluten contamination was highest when plastic chopping boards were rinsed with cold or warm water alone. However, with glass boards using more intensive cleaning methods, such as washing with warm water and soap or using a dishwasher, presence of gluten was substantially reduced. This aligns with previous findings that intensive cleaning methods can reduce contamination risk [11]. Similarly, Weisbrod et. Al. demonstrated that common kitchen practices, such as toasting gluten-free bread in shared toasters and reusing knives previously used on gluten-containing cupcakes, did not result in detectable gluten levels above 20 ppm. Their findings support the conclusion that effective cleaning procedures substantially mitigate cross-contamination risk, even when using shared utensils or appliances [12].

Both toasters and sandwich makers revealed relatively low contamination rates. Only three out of thirty-four samples showed gluten presence, with two positive controls and one sample from simultaneous toasting of gluten-free and gluten-containing bread. Statistical analysis further indicated a low probability of contamination. This result suggests that, under normal use conditions and with regular cleaning, toasters pose a low contamination risk.

Nevertheless, our study underscores a nuanced risk when gluten-free and gluten-containing items are toasted simultaneously. Although contamination was minimal, it may still be concerning for highly sensitive individuals. These results align with findings from prior research in the United States, where toasters used for both types of bread showed contamination levels generally below the 20 ppm threshold [11]. Yet there is a wide variety in the design and operation of household toasters, making it difficult to draw conclusions for use in daily life. The design could have an impact on the occurrence of cross-contamination. Therefore, our recommendation is to use separate toasters for gluten-free and gluten-containing products. When it comes to sandwich irons, those could be used for gluten-free items when thorough cleaning procedures are adopted, such as shaking out crumbs and wiping surfaces with a damp cloth or sponge.

Among the most interesting findings of the study are the results for deep-fat fryers and air fryers. The study collected 54 samples, of which 1 from a deep-fat fryer and 7 from air fryers contained gluten. However, statistical analysis indicated a low probability of exceeding clinically relevant contamination levels, particularly when the threshold was raised to 20 mg/kg [13]. This suggests that while gluten residues can transfer in these devices, they are unlikely to reach levels that would trigger a significant immune response in most individuals with coeliac disease.

The study's results imply that oil replacement in deep-fat fryers effectively reduces gluten contamination, while air fryers benefit from basket cleaning with soap and warm water. These findings are particularly important as air fryers have gained popularity as a healthier alternative to traditional deep-frying. However, as both devices involve circulating hot air or oil, gluten particles from gluten-containing foods could potentially adhere to surfaces or contaminate gluten-free foods if not adequately cleaned. The results here suggest that cross-contamination in these appliances can be managed, although patients with heightened sensitivity may prefer using dedicated devices or implementing stringent cleaning protocols.

Our study highlights the importance of rigorous cleaning practices in reducing gluten cross-contamination risks in households where gluten-free and gluten-containing foods are prepared. The results emphasize that, while certain kitchen items (like toasters and air fryers) pose lower risks, dedicated cleaning methods are critical to minimizing contamination. For patients with coeliac disease, these findings underscore that while cross-contamination

cannot always be entirely eliminated, specific cleaning methods significantly reduce the likelihood of clinically relevant contamination.

One limitation of the study is its focus on specific cleaning procedures, which may not account for all possible variations in real-world practices. Additionally, while the study employed Bayesian analysis to provide probabilistic estimates of contamination, real-life sensitivity to gluten varies widely among patients, so even low levels of contamination may affect some patients more than others.

Future studies could expand on these findings by exploring a broader range of kitchen appliances commonly used in households. Additionally, understanding the influence of different materials on gluten adhesion, particularly for porous surfaces like wood or certain plastics, could provide deeper insights into contamination risks. Moreover, investigating gluten cross-contamination in kitchen appliances used outside the household setting, particularly in professional kitchens such as those in restaurants or hotels, could be highly informative. In such environments, the simultaneous preparation of a wide variety of meals is common, potentially increasing the risk of cross-contamination. The risk is further compounded by the fact that many chefs and cooks have limited knowledge about coeliac disease and the strict requirements of a gluten-free diet [14]. Finally, longitudinal studies could help to assess the real cumulative impact of repeated exposure to low-level gluten contamination on patients with coeliac disease, as this remains an area of clinical concern.

5. Conclusions

In conclusion, our study contributes to more evidence on gluten cross-contamination and its implications for patients with coeliac disease in daily life. By systematically examining common kitchen appliances and cleaning methods, it offers practical recommendations that can help reduce contamination risks. We found that dishwashers effectively reduce gluten on chopping boards, especially glass and wooden ones, while plastic boards are harder to clean thoroughly. Toasters and sandwich makers pose a low risk but benefit from regular crumb removal and wiping with a damp cloth. Deep-fat and air fryers remain safe if oil is regularly replaced and baskets are cleaned properly. In shared kitchens, individuals with coeliac disease can benefit from employing more rigorous cleaning protocols, dedicating appliances for gluten-free use, or both. Although complete elimination of gluten traces may not be feasible, this study provides evidence that thoughtful practices can significantly mitigate the risk, improving safety and quality of life for those affected.

Author Contributions: Conceptualization, J.P.W.B., C.P., F.W.P.C.v.O., and P.J.W.; methodology, J.P.W.B., M.J., and P.J.W.; software, J.P.W.B. and M.J.; validation, J.P.W.B., F.W.P.C.v.O., M.J., and P.J.W.; formal analysis, J.P.W.B. and M.J.; investigation, C.P. and F.W.P.C.v.O.; writing—original draft preparation, J.P.W.B.; writing—review and editing, J.P.W.B., M.M.S.W., and P.J.W.; supervision, P.J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All research data are available upon request from the corresponding author.

Conflicts of Interest: Author Marc Jacobs was employed by the company Nederlandse Coeliakie Vereninging (NCV). The role of the company Modelling and Statistics for You (MSJ) was to advise on the design of the study, and conduct the statistical analysis of the data. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GFD Gluten-free diet

Appendix A. More Detailed Description of Data Gathering and Bayesian Analysis

Methods

We will describe each phase separately to show that the second phase was informed by the first phase, and that the first phase was informed by prior knowledge. The combination of prior knowledge (the prior) with new data (the likelihood) to form new knowledge (the posterior) is the backbone of Bayesian analysis. Hence, by basing the design of the second phase on the results of the first, we can mathematically combine data, and thus show a shift a potential shift in evidence for the probability of gluten when using kitchen equipment.

Design of phase one

We divided our study into three sub-studies: (1) chopping boards, (2) toasters and sandwich irons, (3) deep-fat fryers and air fryers. For each study, we selected three different types of gluten-containing (already used in a home situation) and gluten-free (new) specimens.

Statistical analysis of phase one

Analysis of the first phase served two objectives: (1) to estimate the likelihood and posterior probability for each intervention in each sub-study, and (2) to direct the design of phase two. We used the R statistical software package and the *brms* library to estimate probabilities from a Bernoulli distribution using the logit link. Posterior probability estimates for each of the parameters included were obtained using four chains and 10000 iterations, of which 1000 were warm-up iterations.

Design of phase two

The design of the second phase largely mimicked the design of the first phase. We will therefore only mention noteworthy differences, around the choice of solely focusing on a specific type of equipment (sandwich irons and not toasters) or a specific scenario (gluten-containing equipment instead of gluten-free). These choices are based on the prior knowledge coming from phase one, and a shift in aim (focusing on worst-case scenarios). For the specific Bayesian analysis, this made no difference if estimates could be combined.

Statistical analysis of phase two

The analysis of the second phase is equal to the analysis of the first phase, except that we added an additional analysis showing the number of times gluten can be expected when performing the experiment simultaneously 1000 times. From these simulations, we extracted the range to indicate the simulated minimum and maximum number of times gluten may be detected under the posterior distribution.

Results

To show the flow of evidence on the probability of gluten using kitchen equipment, we will focus on the results that allow the results of both phases to be performed in a Bayesian analysis. This means that the design of phase two dictates the use of the data from phase one, and thus also dictates the results described for phase one. Hence, for each phase, we will describe our prior knowledge, our findings (the likelihood), and our new knowledge (posterior) on the probability of gluten following a specific procedure on a specific piece of kitchen equipment. Unless stated otherwise, gluten detection was set at ELISA ≥ 5.

Phase one

Chopping breadboards

We had no prior knowledge, although one may assume that cold water is less effective than hot water, which is less effective than hot water and soap, which is less effective than a dishwasher. Hence, we started with a prior probability of 0.9 for cold water and decreased that probability by half until we reached the dishwasher. We had no idea regarding the influence of the material, so we set the probability at 0.5 (50%). This means that the prior probability for a wood chopping board rinsed with warm water is the combined probability of both (Table A1).

Table A1. Prior probabilities of gluten for gluten-containing chopping boards based on the material and the treatment applied.

Treatment/Material	**Prior Probability** *Mean (Variance)*
Cold water	0.9 (0.090)
Warm water	0.45 (0.248)
Warm water and soap	0.225 (0.175)
Dishwasher	0.1125 (0.099)
Untreated	0.5 (0.25)
Glass	0.5 (0.25)
Wood	0.5 (0.25)
Plastic	0.5 (0.25)
Base probability	0.5 (0.25)

We obtained three samples for each material by intervention combination and detected gluten twice on a plastic chopping board rinsed with cold water (Table A2). The lowest mean posterior probability was found for the wooden chopping board rinsed with warm water and soap.

Table A2. Likelihood and posterior probability estimates for gluten-containing chopping boards based on the material and the treatment applied.

Treatment	**Material**	**Likelihood**	**Posterior Probability**
Untreated	Glass	0/3	0.0684
Not applicable	Wood	0/3	0.0568
Not applicable	Plastic	0/3	0.1240
Cold water	Glass	0/3	0.2950
Cold water	Wood	0/3	0.2540
Cold water	Plastic	2/3	0.4300
Dishwasher	Glass	0/3	0.0602
Dishwasher	Wood	0/3	0.0524
Dishwasher	Plastic	0/3	0.1080
Warm water	Glas	0/3	0.0342
Warm water	Wood	0/3	0.0302
Warm water	Plastic	0/3	0.0586
Warm water and soap	Glass	0/3	0.0188
Warm water and soap	Wood	0/3	0.0152
Warm water and soap	Plastic	0/3	0.0362

Toasters and sandwich irons

After phase two, we focused on gluten-containing toasters, only involving simultaneous toasting or crumb removal. We assumed that simultaneous roasting is more likely to lead to gluten detection than crumb removal and so we set the odds at two, which means a two times increased probability of gluten versus no gluten when comparing simultaneous roasting to crumb removal (Table A3). We set the prior for crumb removal at 0.5 since we had no prior knowledge.

Table A3. Prior probability, likelihood, and posterior probability for gluten-containing toasters.

Treatment	Prior Probability	Likelihood	Posterior Probability
Crumb removal	0.5	0/3	0.0987
Simultaneous toasting	0.667	1/3	0.2060

Deep-fat fryers and air fryers

In the setting in which gluten-free products followed gluten-containing products, we detected gluten zero times using an air fryer and once using a deep-fat fryer.

Table A4. Prior probability, likelihood, and posterior probability for deep-fat fryers and air fryers after phase one.

Equipment	Prior probability	Likelihood	Posterior Probability
Air fryer	0.5	0/3	0.3120
Deep-fat fryer	0.5	1/4	0.2600

Phase two

In this phase, we obtained a total of 417 samples: 275 for the chopping boards, 34 for the toasters, and 108 samples for the deep-fat fryers and air fryers.

Chopping boards

We collected 275 samples across several treatments: blanc (15 samples), cold water (80 samples), dishwasher (60 samples), warm water (60 samples), and warm water and soap (60 samples). Of these 275 samples, 85 samples each are collected using a chopping board made of glass or wood, respectively, and another 105 samples are collected using a plastic board. A total of 130 (47.2%) positive control samples were collected. We detected gluten in 181 (65.8%) samples. Separating the 130 positive controls, which all contained gluten, we obtained likelihood estimates and posterior probability as described in Table A5.

Table A5. Prior probability, likelihood, and posterior probability of gluten for gluten-containing chopping boards based on the material and the treatment applied.

Treatment	Material	Prior Probability	Likelihood	Posterior Probability
Untreated	Glass	0.0684	0/5	0.0604
Untreated	Wood	0.0568	0/5	0.1070
Untreated	Plastic	0.1240	1/5	0.5130
Cold water	Glass	0.2950	1/10	0.2870
Cold water	Wood	0.2540	4/10	0.4240
Cold water	Plastic	0.4300	20/20	0.8680

Table A5. *Cont.*

Treatment	Material	Prior Probability	Likelihood	Posterior Probability
Dishwasher	Glass	0.0602	0/10	0.0102
Dishwasher	Wood	0.0524	0/10	0.0194
Dishwasher	Plastic	0.1080	0/10	0.1470
Warm water	Glass	0.0342	0/10	0.1790
Warm water	Wood	0.0302	7/10	0.2850
Warm water	Plastic	0.0586	9/10	0.7780
Warm water and soap	Glass	0.0188	0/10	0.0580
Warm water and soap	Wood	0.0152	0/10	0.1020
Warm water and soap	Plastic	0.0362	9/10	0.4950

The lowest probability can be found for the glass chopping board that is cleaned using a dishwasher. The prior lowest probability (wooden chopping board rinsed with warm water) contained gluten in 7 out of 10 samples taken. The plastic chopping boards almost always contained gluten, except when cleaned in a dishwasher. Table A6 shows what happens to our prior and posterior probabilities if we change the threshold for gluten from 5 to 20. Plastic chopping boards have the highest probability of gluten, whereas cleaning by dishwasher has the lowest. The combination with the lowest probability (smallest range) of gluten is a wooden chopping board cleaned by a dishwasher.

Table A6. Prior and posterior probability of gluten for gluten-containing chopping boards based on the material and the treatment applied, and the threshold applied.

Treatment	Material	Prior Probability ELISA ≥5 ppm	Prior Probability ELISA ≥20 ppm	Posterior Probability ELISA ≥5 ppm	Posterior Probability ELISA ≥20 ppm	Gluten Detected Using 1000 Repetitions ELISA ≥5 ppm	Gluten Detected Using 1000 Repetitions ELISA ≥20 ppm
Not applicable	Glass	0.0684	0.0644	0.0604	0.0407	33–91	23–65
Not applicable	Wood	0.0568	0.0693	0.1070	0.0266	74–129	10–50
Not applicable	Plastic	0.1240	0.0673	0.5130	0.4370	468–565	50–389
Cold water	Glass	0.2950	0.1790	0.2870	0.2030	240–342	159–242
Cold water	Wood	0.2540	0.1820	0.4240	0.1370	376–448	92–171
Cold water	Plastic	0.4300	0.1850	0.8680	0.8200	844–897	780–860
Dishwasher	Glass	0.0602	0.0646	0.0102	0.0099	2–16	0–14
Dishwasher	Wood	0.0524	0.0655	0.0194	0.0062	7–26	0–9
Dishwasher	Plastic	0.1080	0.0676	0.1470	0.1540	120–176	114–208
Warm water	Glass	0.0342	0.0342	0.1790	0.0859	137–199	50–137
Warm water	Wood	0.0302	0.0354	0.2850	0.0560	244–345	26–82
Warm water	Plastic	0.0586	0.0371	0.7780	0.6180	719–847	322–678
Warm water and soap	Glass	0.0188	0.0184	0.0580	0.0320	44–77	8–54
Warm water and soap	Wood	0.0152	0.0200	0.1020	0.0208	87–131	6–46
Warm water and soap	Plastic	0.0362	0.0210	0.4950	0.368	446–537	311–416

Toasters

We received 34 samples of which 3 contained gluten. Two were found in the positive control and one sample was found during simultaneous toasting (Table A7). Both show a low probability of gluten, which translates to a range of 0–1 when the threshold is increased to 20 (Table A8).

Table A7. Prior probability, likelihood, and posterior probability during consecutive or simultaneous toasting of gluten-containing toasters.

Treatment	Prior Probability	Likelihood	Posterior Probability
Consecutive toasting	0.0987	0/10	0.0213
Simultaneous toasting	0.2060	1/20	0.0545

Table A8. Prior and posterior probability during consecutive or simultaneous toasting of gluten-containing toasters based on the treatment and threshold applied.

Treatment	Prior Probability ELISA ≥5 ppm	Prior Probability ELISA ≥20 ppm	Posterior Probability ELISA ≥5 ppm	Posterior Probability ELISA ≥20 ppm	Gluten Detected Using 1000 Repetitions ELISA ≥5 ppm	Gluten Detected Using 1000 Repetitions ELISA ≥20 ppm
Consecutive toasting	0.0987	0.00833	0.0213	0.00001	8–41	0–1
Simultaneous toasting	0.206	0.0143	0.0545	0.00001	33–99	0–1

Deep-fat fryers and air fryers

For both deep-fat fryers and air fryers, we collected 54 samples, of which 1 and 7 sample(s) contained gluten, respectively (Table A9). Increasing the threshold for gluten to twenty resulted in a low probability (Table A10).

Table A9. Prior probability, likelihood, and posterior probability for deep-fat fryers and air fryers after phase two.

Equipment	Prior Probability	Likelihood	Posterior Probability
Air fryer	0.3120	1/54	0.0703
Frying pan	0.2600	7/54	0.1250

Table A10. Prior and posterior probability for deep-fat fryers and air fryers based threshold applied.

Equipment	Prior Probability ELISA ≥5 ppm	Prior Probability ELISA ≥20 ppm	Posterior Probability ELISA ≥5 ppm	Posterior Probability ELISA ≥20 ppm	Gluten Detected Using 1000 Repetitions ELISA ≥5 ppm	Gluten Detected Using 1000 Repetitions ELISA ≥20 ppm
Air fryer	0.3120	0.2060	0.0703	0.0326	37–81	6–55
Deep-fat fryer	0.2600	0.2160	0.1250	0.0405	95–162	23–53

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