DOI: https://doi.org/10.61841/m9bw1j38 Publication URL: https://jarmhs.com/index.php/mhs/article/view/623

COMPARATIVE STUDY ON ALUMINUM MIGRATION FROM FOOD-CONTACT MATERIALS DURING THE PREPARATION OF MOI-MOI AND FISH DELICACIES.

[1]Stephen Monday Suru*, [2]Ifeanyi Chinaza Anene, [3]Ifeoma Priscilia Ezeugwunne, [4]Ikedichukwu Chibueze Ejiogu, [5]Chidiebere Emmanuel Ugwu

[12345]*Department of Human Biochemistry, Faculty of Basic Medical Sciences, Nnamdi Azikiwe University, Nnewi Campus, Nnewi, Anambra State, Nigeria.*

Corresponding Author:
sm.suru@unizik.edu.ng

To Cite This Article: Suru, S., Anene, I. C. ., Ezeugwunne, I. P. ., Ejiogu, I. C. ., & Ugwu, C. E. . (2026). COMPARATIVE STUDY ON ALUMINUM MIGRATION FROM FOOD-CONTACT MATERIALS DURING THE PREPARATION OF MOI-MOI AND FISH DELICACIES. *Journal of Advanced Research in Medical and Health Science (ISSN 2208-2425)*, 12(5),20-28. https://doi.org/10.61841/m9bw1j38

ABSTRACT

Aluminum-containing food-contact materials may contribute to dietary aluminum intake via migration during food preparation. This study quantified and compared the aluminum concentration in moi-moi and fish prepared using conventional and alternative food-contact materials, focusing on aluminum cookware, aluminum foil, repurposed aluminum roofing sheets, stainless steel, and plant-leaf wrapping. Moi-moi was prepared using plant leaves, stainless steel, an uncoated aluminum pot/pan, aluminum foil, or a repurposed aluminum roofing-sheet container, and fish was oven-baked or roasted with or without double-layer aluminum foil. Three independent replicates were made for each condition, and aluminum contents were measured by atomic absorption spectrophotometry after nitric acid digestion. Calibration, blanks, replicate measurements, certified reference material, and spike-recovery evaluation were all used to ensure analytical quality. Aluminum levels were lowest in non-aluminum-contact preparations. The moi-moi concentrations were 0.00 ± 0.00, 0.03 ± 0.05, 1.07 ± 2.10, 0.70 ± 0.17, and $1.57 \pm 0.23 \times 10^{-2}$ mg/kg for plant leaf, stainless steel, aluminum pot/pan, aluminum foil, and repurposed roofing sheet. Concentrations were 0.00 ± 0.00 and $1.53 \pm 0.47 \times 10^{-2}$ mg/kg for baked fish without and with foil, respectively, and 0.03 ± 0.06 and $1.90 \pm 0.78 \times 10^{-2}$ mg/kg for roasted fish. Aluminum-contact preparations contained considerably more aluminum than non-aluminum-contact preparations ($p < 0.001$). These findings show quantifiable aluminum transfer during food preparation, highlighting repurposed aluminum roofing sheets and aluminum foil as key food-contact materials that warrant precautionary use and require further food-safety testing.

KEYWORDS: *Aluminum migration; Food-contact materials; Aluminum cookware; Aluminum foil; Repurposed aluminum roofing sheet; Moi-moi; Fish preparation; Food safety.*

INTRODUCTION

Aluminum, abundant in the environment, is commonly used in food preparation, processing, packaging, and storage due to its low density, thermal conductivity, malleability, and cost-effectiveness. Dietary intake occurs from natural aluminum in foods and aluminum-containing materials like cookware and packaging [1-5]. Although high toxicity is linked to prolonged exposure, recent evidence suggests that food and food-contact materials significantly contribute to human exposure, making aluminum transfer during food preparation a critical food safety issue. Prepared and processed foods notably increase total aluminum intake [2,5].

Aluminum exposure poses toxicological risks affecting various biological systems, as outlined in experimental and toxicological studies highlighting neurological, cellular, and oxidative impacts [3,4,6]. The link between typical dietary aluminum and chronic disease is complex and not definitively established, yet concerns about cumulative exposure linger. The transfer of aluminum from food-contact materials is significant due to its potential to increase dietary intake and is potentially preventable through appropriate selection and use of food-contact materials [1,5,7].

Aluminum cookware can leach dietary aluminum into food or food-simulating solutions, with release influenced by cookware characteristics, food matrix, and cooking conditions [8-12]. Al Zubaidy *et al.* [8] emphasized the roles of pH, salinity, and temperature in aluminum release during food preparation, while Al Juhaiman [9] noted varying aluminum leaching in vegetable extracts. Mohammad *et al.* [10] found measurable increases in aluminum concentrations in prepared foods due to leaching from cookware. Recent studies using inductively coupled plasma mass spectrometry (ICP-MS) have confirmed elemental migration from aluminum vessels during food preparation [11,12]. Thus, aluminum cookware should not be viewed as an inert barrier, but rather as a potential source of dietary aluminum.

The composition and condition of cookware can impact metal transfer, varying with material, temperature, heating duration, and medium [13,14]. Of particular concern is the production and use of artisanal or recycled form of aluminum cookware in low- and middle-income regions. Weidenhamer *et al.* [15] identified significant metal exposure risks from aluminum cookware materials, linking it to broader metal exposure issues in developing countries [16]. Research in South Africa revealed artisanal cookware made from recycled scrap metal as a potential multi-metal exposure source [17]. Similar risks have emerged in Nigeria, where locally made aluminum cookware is associated with measurable leaching potential and toxic-metal exposure [18]. The public health implications are critical, especially with uncontrolled recycled materials and limited access to safer options.

Aluminum foil represents a significant food-contact material used for wrapping, baking, grilling, and storing food due to its large contact surface. Studies indicate aluminum can migrate from aluminum foil into foods during cooking and is influenced by food type and cooking conditions [19,20]. Fermo *et al.* [19] quantified aluminum release during baking, while Mol and Ulusoy [20] found increased aluminum concentrations in seafood cooked in foil. Ewangulu *et al.* [21] conducted a systematic review supporting these findings, highlighting the evidence of aluminum transfer into fish processed with aluminum foil, despite variability in experimental methods and results. These reports are especially disturbing since fish and other foods are widely prepared by baking or roasting in aluminum foil.

Beyond the presence of aluminum, metal migration is influenced by various factors, including food composition, acidity, salinity, temperature, contact duration, and the characteristics of food-contact materials. Experimental evidence underscores the significance of these variables in aluminum release [8-10,19,20]. Cookware studies reveal that prolonged use and surface condition impact metal leachability, with potential toxicological consequences. Research indicates that extended exposure to aluminum cookware may have systemic, genetic, and reproductive effects in mice [22,23]. These findings highlight the need for understanding aluminum transfer during realistic food preparation.

The use of non-food-grade or repurposed metallic materials in food preparation, particularly repurposed aluminum roofing sheets, raises public health concerns. These materials, intended for construction, can differ significantly in composition, surface treatment, and exposure history compared to those manufactured for food contact [15-18]. Their potential to leach aluminum or other elements into food needs further investigation, especially in resource-constrained settings where such adaptive reuse practices are common. While research on metal migration from cookware is growing [12,24], there is still a lack of empirical evidence comparing conventional aluminum cookware, aluminum foil, stainless steel, plant-based materials, and repurposed roofing sheets in comparable food-preparation conditions.

The selection of plant leaves and stainless steel as food-contact materials is crucial for food safety. Traditionally, plant-leaf wrapping is used for foods like moi-moi, offering a non-metallic alternative to aluminum. Conversely, stainless steel is durable and chemically resistant, leading to its widespread use. However, most studies have focused on isolated materials or limited food types [13,14], lacking comprehensive evaluations of various food-preparation materials in diverse cooking and processing methods within a unified experimental context.

The present study was therefore designed to evaluate aluminum transfer into foods from various food-contact materials, focusing on aluminum cookware, foil, repurposed aluminum roofing sheet, stainless steel, and plant-leaf wrapping. Findings aim to enhance understanding of dietary aluminum exposure and inform food-safety recommendations for material selection in food preparation.

MATERIALS AND METHODS

STUDY DESIGN

This study used a controlled laboratory experiment design to assess aluminum transfer to food during preparation using various food-contact surfaces. Two regularly consumed Nigerian dishes, moi-moi and fish, were chosen to demonstrate various food matrices and preparation methods. The experiment was carried out in two stages: (i) standardized food preparation using specified food-contact materials under controlled laboratory-simulated conditions, and (ii) determination of aluminum concentrations in the prepared food samples using atomic absorption spectrophotometry (AAS). All food preparation experiments were carried out at the Department of Human Biochemistry Laboratory, Nnamdi Azikiwe University, Nnewi Campus, Nnewi. The aluminum analysis was done at Docchy Analytical Laboratory in Awka, an ISO/IEC 17025-accredited laboratory for heavy-metal analysis.

FOOD-CONTACT MATERIALS AND EXPERIMENTAL GROUPS

Nine experimental preparation conditions were studied: five moi-moi food-contact conditions (plant-leaf wrapping, stainless-steel cookware, aluminum cookware, aluminum foil, repurposed aluminum roofing container) and four fish preparation conditions (oven-baking and roasting, each with and without aluminum foil). The experimental groups were designated as shown in Table 2.2.

Table 1: Experimental groups

Food	Preparation condition	Food-contact material	Code
Moi-moi	Plant-leaf wrapped	Plant leaf	MMPL
Moi-moi	Stainless-steel preparation	Stainless steel	MMSS
Moi-moi	Aluminum cookware	Uncoated aluminum pot	MMAC
Moi-moi	Aluminum foil wrapped	Aluminum foil	MMAF
Moi-moi	Repurposed aluminum roofing sheet	Locally fabricated repurposed aluminum roofing sheet	MMRA
Fish	Oven-baked without foil	None	BFN
Fish	Oven-baked with foil	Aluminum foil	BFAF
Fish	Roasted without foil	None	RFN
Fish	Roasted with foil	Aluminum foil	

PROCUREMENT OF FOOD-CONTACT MATERIALS AND FOOD INGREDIENTS

Food-contact materials were sourced from major market places in Onitsha and Asaba. These included five new uncoated aluminum pots/pans (3-mm thick), five locally fabricated aluminum containers made from repurposed aluminum roofing sheets, one roll of commercial aluminum foil (0.016-mm thick), five 18/10-grade stainless-steel pots (3-mm thick), and 30 fresh “Miracle” leaves *(Thaumatococcus danielli;* Herbarium number: NAUH 256A). The plant leaves were cleaned and heat-treated by swiftly passing them over a flame before use to increase the malleability of the leaves. Fresh food ingredients for preparation were sourced from the same market each day, including brown beans *(Vigna unguiculata*), tomatoes, onions, groundnut oil, seasoning cubes, and salt. Fresh catfish, *Clarias gariepinus,* were sourced from Cable Point Market, Asaba, placed in an ice pack, transported to the laboratory, and stored in a deep freezer.

EXPERIMENTAL REPLICATION AND SAMPLE SIZE

Each experimental condition included three independent experimental replicates (n = 3), which were examined in duplicate by AAS, producing six measurements. Statistical analyzes focused on replicates rather than using duplicate readings as separate observations.

CONTROL SAMPLES

For moi-moi, MMPL (plant-leaf wrapping) and MMSS (stainless steel) were negative controls. For fish, BFN (oven-baking) and RFN (roasting) served as controls, both without aluminum foil. These controls established baseline aluminum concentrations from ingredients and environment, excluding aluminum material contact. Reagent blanks of distilled water subjected to the same digestion procedure were analyzed in batches of 20 samples to monitor potential laboratory contamination; For analytical validation, selected food samples were fortified with aluminum standard to determine percentage recovery.

PREPARATION OF MOI-MOI SAMPLES

Each replicate batch involved soaking 1 kg of dried black-eyed beans (*Vigna unguiculata*) in 2 L of tap water for 15 minutes. After manually removing seed coats and rinsing, the beans were blended with onions (400 g), fresh “Shombo” pepper (*Capsicum annuum*) (100 g), and water into a slurry paste. Subsequently, groundnut oil (200 mL), salt (10 g), seasoning cubes (10 g), and ground crayfish (15 g) were added and thoroughly mixed. The 200 g portions of bean paste were distributed among five groups: MMPL in plant leaves, MMSS in stainless-steel cookware, MMAC in uncoated aluminum cookware, MMAF in double-layer aluminum foil bowls, and MMRA in containers made from repurposed aluminum roofing sheets. All moi-moi samples were steamed in a stainless-steel pot with 2 L water at 98–100 °C for 1 h, then cooled to 40 °C. Approximately 50 g from the food-contact surface was collected in acid-washed containers using a stainless steel spatula.

PREPARATION OF FISH SAMPLES

Fresh fish, *Clarias gariepinus*, weighing 450–550 g, were gutted, washed, and patted dry. Each fish was seasoned with 5 g salt, 2 g pepper, and two crushed seasoning cubes for 30 min marination at room temperature. The unwrapped group (BFN) was baked directly on a tray, while the foil-treated group (BFAF) was tightly wrapped in aluminum foil before baking at 180 ± 5 °C for 30 minutes. The RFN specimens were roasted directly on a wire rack over a charcoal fire, while RFAF specimens were wrapped in aluminum foil. Both were roasted for 30 minutes at an average surface temperature of 220 ± 15 °C, with the fish flipped once. After cooking, fish samples were cooled to 40 °C; about 50 g of the edible portion in direct contact with cookware or wrapping surface was collected in acid-washed containers using a stainless steel spatula.

SAMPLE HANDLING AND PREPARATION FOR ELEMENTAL ANALYSIS

Samples were treated to reduce exogenous metal contamination, placed in acid-washed polyethylene containers post-collection, homogenized for 2 minutes in a stainless-steel blender, and a 5.00 ± 0.01 g aliquot was sent for digestion in an acid-washed borosilicate beaker.

ACID DIGESTION PROCEDURE

Aluminum was analyzed using an acid-digestion method adapted from APHA Method 3111B (1993). Ten (10) mL of concentrated nitric acid was added to 5.00 g of homogenized sample, followed by 2 hours of pre-digestion. Samples were heated at 120 °C for 30 min and then at 180 °C until the volume reached about 10 mL. Additional nitric acid was added to achieve a clear solution. After cooling, the digest was filtered through Whatman No. 42 paper into a 100-mL flask, rinsed with deionized water, and diluted to volume.

DETERMINATION OF ALUMINUM BY ATOMIC ABSORPTION SPECTROPHOTOMETRY

Aluminum concentrations were measured with a Varian AA240 Atomic Absorption Spectrophotometer at 309.3 nm, using a 0.5-nm slit and air–acetylene flame, calibrated daily with certified standards (Merck, Germany). Digested sample solutions were aspirated into AAS flame; absorbance converted to aluminum concentrations via calibration curve.

QUANTIFICATION AND EXPRESSION OF ALUMINUM CONCENTRATION

Aluminum concentration in food samples was calculated using

$$C_{Al}\ (\text{mg/kg}) = (C \times V) / M$$

where C is the aluminum concentration measured in the digest by AAS (mg/L), V is the final digest volume (0.100 L), and M is the mass of sample digested (0.005 kg). Results were expressed as mg/kg of prepared food.

STATISTICAL ANALYSIS

Results data are presented as mean ± SD. The primary outcome was aluminum concentration in prepared food, analyzed using one-way ANOVA to compare nine conditions (MMPL, MMSS, MMAC, MMAF, MMRA, BFN, BFAF, RFN, and RFAF), testing the null hypothesis of equal means. Fisher's LSD post hoc test examined specific pairwise comparisons, with $p < 0.05$ as significant. Due to differences in food types and processing methods, separate analyses were conducted within each food category. For moi-moi, aluminum concentrations were compared across five preparation methods. For fish, aluminum concentration analysis considered aluminum foil exposure and cooking methods across four combinations.

RESULTS

ALUMINUM CONCENTRATIONS VARIED SUBSTANTIALLY AMONG THE NINE FOOD-PREPARATION CONDITIONS.

In moi-moi, the lowest concentration was observed in the plant-leaf preparation (MMPL; $0.00 \pm 0.00 \times 10^{-2}$ mg/kg), followed by stainless-steel preparation (MMSS; $0.03 \pm 0.05 \times 10^{-2}$ mg/kg). Higher concentrations were recorded in samples prepared using an aluminum pot/pan (MMAC; $1.07 \pm 2.10 \times 10^{-2}$ mg/kg), aluminum foil (MMAF; $0.70 \pm 0.17 \times 10^{-2}$ mg/kg), and repurposed aluminum roofing sheet (MMRA; $1.57 \pm 0.23 \times 10^{-2}$ mg/kg). Among the fish preparations, aluminum concentrations were $0.00 \pm 0.00 \times 10^{-2}$ mg/kg in oven-baked fish without aluminum foil (BFN), $1.53 \pm 0.47 \times 10^{-2}$ mg/kg in foil-wrapped baked fish (BFAF), $0.03 \pm 0.06 \times 10^{-2}$ mg/kg in roasted fish without foil (RFN), and $1.90 \pm 0.78 \times 10^{-2}$ mg/kg in foil-wrapped roasted fish (RFAF). The reported pairwise comparisons showed significant differences between the non-aluminum control conditions and several aluminum-contact conditions, as indicated by the corresponding significance levels in Table 3.1.

Table 2: An overall nine-condition comparison of aluminum concentrations for moimoi and fish

Food	Cookware	LABEL	Aluminum concentration (mg/kg) x 10^{-2}
Moimoi	Plant Leaf	MMPL	0.00 ± 0.00
Moimoi	Stainless Steel	MMSS	0.03 ± 0.05
Moimoi	Aluminum Pot/Pan	MMAC	1.07 ± 2.10 †^{ab},
Moimoi	Aluminum Foil	MMAF	0.70 ± 0.17 *^{ab},
Moimoi	Repurposed Aluminum Roofing Sheet	MMRA	1.57 ± 0.23 †^{ab},#^{d}
Baked Fish	None	BFN	0.00 ± 0.00
Baked Fish	Aluminum Foil	BFAF	1.53 ± 0.47 †^{abfg},#^{d}
Roasted Fish	None	RFN	0.03 ± 0.06
Roasted Fish	Aluminum Foil	RFAF	1.90 ± 0.78 †^{abdfg},#^{c}

Data are expressed as means ± SD. * = $p<0.05$; # = $p<0.01$; † = $p<0.001$, a=MMPL vs MMAC, MMAF, MMRA, BFAF, RFAF; b=MMSS vs MMAC, MMAF, MMRA, BFAF, RFAF; c=MMAC vs MMAF, MMRA, BFAF, RFAF; d=MMAF vs MMRA, BFAF, RFAF; e=MMRA vs BFAF, RFAF; f=BFN vs BFAF, RFAF; g=RFN vs BFAF, RFAF; h=BFAF vs RFAF

ALUMINUM CONCENTRATION IN MOI-MOI PREPARED WITH DIFFERENT FOOD-CONTACT MATERIALS

Comparison of the five moi-moi preparation conditions showed marked differences in aluminum concentration (Table 3.2). MMPL and MMSS had concentrations of 0.00 ± 0.00 and 0.03 ± 0.05 × 10^{-2} mg/kg, respectively. In contrast, aluminum concentration increased to 1.07 ± 2.10 × 10^{-2} mg/kg in MMAC, 0.70 ± 0.17 × 10^{-2} mg/kg in MMAF, and 1.57 ± 0.23 × 10^{-2} mg/kg in MMRA. One-way ANOVA followed by Fisher's LSD post hoc testing identified significant pairwise differences among the preparation conditions, including differences between the non-aluminum-contact groups and the aluminum-contact groups, as well as between selected aluminum-contact conditions.

Table 3: Aluminum concentration in moi-moi prepared with different food-contact materials

Food	Cookware	LABEL	Aluminum concentration (mg/kg) x 10^{-2}
Moimoi	Plant Leaf	MMPL	0.00 ± 0.00
Moimoi	Stainless Steel	MMSS	0.03 ± 0.05
Moimoi	Aluminum Pot/Pan	MMAC	1.07 ± 2.10 †^{ab}
Moimoi	Aluminum Foil	MMAF	0.70 ± 0.17 †^{ab},*^{c}
Moimoi	Repurposed Aluminum Roofing Sheet	MMRA	1.57 ± 0.23 †^{abd},#^{c}

Data are expressed as means ± SD. Data were analyzed by one-way ANOVA followed by Fisher's LSD post hoc test. * = $p<0.05$; # = $p<0.01$; † = $p<0.001$; a=MMPL vs MMAC, MMAF, MMRA; b=MMSS vs MMAC, MMAF, MMRA; c=MMAC vs MMAF, MMRA; d=MMAF vs MMRA

ALUMINUM CONCENTRATION IN BAKED AND ROASTED FISH PREPARED WITH AND WITHOUT ALUMINUM FOIL

The fish experiment showed consistently higher aluminum concentrations in foil-wrapped samples than in corresponding non-foil preparations (Table 3.3). Oven-baked fish without foil (BFN) contained 0.00 ± 0.00 × 10^{-2} mg/kg aluminum, compared with 1.53 ± 0.47 × 10^{-2} mg/kg in foil-wrapped baked fish (BFAF). Similarly, roasted fish without foil (RFN) contained 0.03 ± 0.06 × 10^{-2} mg/kg, whereas foil-wrapped roasted fish (RFAF) contained 1.90 ± 0.78 × 10^{-2} mg/kg. Fisher's LSD analysis indicated significant differences between the non-foil and foil-wrapped fish groups, with the BFAF and RFAF conditions differing from both BFN and RFN at the reported significance levels.

Table 4: Aluminum concentration in baked and roasted fish prepared with and without aluminum foil

Food	Cookware	LABEL	Aluminum concentration (mg/kg) x 10^{-2}
BAKED FISH	NONE	BFN	0.00 ± 0.00
BAKED FISH	ALUMINUM FOIL	BFAF	1.53 ± 0.47 #^{ab}
ROASTED FISH	NONE	RFN	0.03 ± 0.06
ROASTED FISH	ALUMINUM FOIL	RFAF	1.90 ± 0.78 †^{ab}

All None-Al-Container vs All-Al-Container

Data are expressed as means ± SD. Data were analyzed by one-way ANOVA followed by Fisher's LSD post hoc test. * = $p<0.05$; # = $p<0.01$; † = $p<0.001$; a=BFN vs BFAF, RFAF; b=RFN vs BFAF, RFAF; c=BFAF vs RFAF

COMPARISON OF FOODS PREPARED USING NON-ALUMINUM AND ALUMINUM FOOD-CONTACT MATERIALS

When moi-moi and fish preparations were combined according to contact with aluminum-containing materials, samples prepared without aluminum cookware had a mean aluminum concentration of 0.02 ± 0.03 × 10^{-2} mg/kg (n = 12), whereas samples prepared using aluminum cookware/materials had a substantially higher mean concentration of 1.35 ± 0.57 × 10^{-2} mg/kg (n = 15) (Table 3.4). The difference between the two groups was statistically significant (independent-samples t-test, $p < 0.001$).

Table 5: Comparison of foods prepared using non-aluminum and aluminum food-contact materials

Food	Cookware	Aluminum concentration (mg/kg) x 10^{-2}
ALL FOODS	NO ALUMINUM COOKWARE (n=12)	0.02 ± 0.03
ALL FOODS	ALUMINUM COOKWARE (n=15)	1.35 ± 0.57†

Data are expressed as means ± SD. Data were analyzed by Independent Samples T test. * = $p<0.05$; # = $p<0.01$; † = $p<0.001$

All None-Al-Container vs All-Al-Container irrespective of food type

COMPARISON OF ALUMINUM CONCENTRATION BETWEEN MOI-MOI AND FISH

When all cookware/contact conditions were considered within each food category, the mean aluminum concentration was 0.67 ± 0.64 × 10^{-2} mg/kg for moi-moi (n = 15) and 0.87 ± 0.09 × 10^{-2} mg/kg for fish (n = 12) (Table 3.5). The difference between the two food groups was statistically significant according to the independent-samples t-test ($p < 0.05$).

Table 6: Comparison of aluminum concentration between moi-moi and fish

Food	Cookware	Aluminum concentration (mg/kg) x 10^{-2}
MOIMOI (n=15)	ALL COOKWARE	0.67 ± 0.64
FISH (n=12)	ALL COOKWARE	0.87 ± 0.09*

Data were analyzed by Independent Samples T test. * = $p<0.05$; # = $p<0.01$; † = $p<0.001$

Moimoi All Cookware vs Fish All Cookware irrespective of type cookware

DISCUSSION

The present research shows that food-contact materials and preparation procedures have a significant impact on aluminum content in prepared foods. Aluminum concentrations were consistently low in the non-aluminum-contact controls across all nine testing conditions, while significantly higher quantities were found in meals prepared or wrapped in aluminum-containing materials. The overall study revealed a significant difference between foods prepared without and with aluminum cookware/materials (0.02 ± 0.03 vs 1.35 ± 0.57 × 10^{-2} mg/kg, respectively; $p < 0.001$). This finding is consistent with experimental evidence that aluminum is not completely inert during food preparation and can migrate from cookware and other food-contact materials into food [1,2,7,13]. Previous research has shown that aluminum is released from cooking vessels under certain thermal conditions, and the level of migration is determined by the type of the contacting material and the food environment [9-10].

The plant-leaf and stainless-steel preparations for moi-moi showed the lowest aluminum concentrations, but interaction with traditional aluminum cookware, aluminum foil, and, in particular, repurposed aluminum roofing sheet resulted in much greater concentrations. Among the moi-moi preparations, the MMRA group's concentration was numerically the highest. This trend is generally in line with other studies demonstrating that cookware made of aluminum may transfer quantifiable amounts of aluminum to cooked foods [8-10,22]. While Mohammad *et al.* [10] validated the transfer of aluminum from cookwares into food, Al Juhaiman [9] and Al Zubaidy *et al.* [8] showed that aluminum release from cookware varies according to the parameters of the food-contact environment. These observations are further supported by the current findings, which show that under a standardized moi-moi preparation method, the choice of food-contact material continues to be a significant driver of aluminum content.

Notable is the very high proportion of aluminium found in moi-moi made from repurposed aluminum roofing sheets. The results align with concerns about artisanal and recycled aluminum materials used in food preparation, even if there are few direct comparisons with this particular approach. Cookware that is recycled or produced informally may have unpredictable surface properties that may affect elemental release, as well as varied metal compositions [15–17]. While Street *et al.* [17] identified recycled scrap-metal cookware as a potential source of multi-metal exposure, Weidenhamer *et al.* [15,16] reported possible metal exposure from artisanal aluminum cookware and its raw materials. The leaching potential of cookware and related industrial materials has also been demonstrated by a recent study from Nigeria [18]. The current finding raises concerns that repurposing aluminum roofing sheets for food preparation may be an avoidable source of aluminum exposure. However, the current study only evaluated aluminum and cannot determine if the aluminum roofing-sheet material discharged any other potentially dangerous elements.

The fish study gave more evidence of aluminum migration through direct foil contact. Aluminum concentrations in baked fish rose from $0.00 \pm 0.00 \times 10^{-2}$ mg/kg to $1.53 \pm 0.47 \times 10^{-2}$ mg/kg in foil-wrapped baked fish, and from $0.03 \pm 0.06 \times 10^{-2}$ mg/kg in unwrapped roasted fish to $1.90 \pm 0.78 \times 10^{-2}$ mg/kg in foil-wrapped roasted fish. The considerably higher concentrations in aluminum foil-contact groups are consistent with recent studies that showed aluminum migration from foil into food during heat processing [19,20]. Fermo *et al.* [19] measured aluminum leaching in foods cooked in aluminum foil, while Mol and Ulusoy [20] found that cooking conditions affected aluminum concentrations in fish prepared in aluminum foil. The observed findings support the idea that aluminum foil should be viewed as an active food-contact medium with the potential for detectable aluminum transfer during heating, rather than a passive wrapping material.

The slightly higher aluminum content observed in roasted foil-wrapped fish compared to baked foil-wrapped fish should be viewed with caution. The two preparation protocols differed not only in the presence of foil, but also in the thermal environment: baking was done at roughly 180 °C in an electric oven, whereas roasting was done over an open charcoal fire with an estimated surface temperature of around 220 °C. Thus, while the present setup shows variations in overall preparation conditions, it does not allow temperature to be identified as an independent predictor of aluminum migration. This distinction is essential since prior research has shown that temperature and other food-environment factors can alter aluminum release [8,20].

When all cookware/contact conditions were evaluated for each food group, fish had a little higher mean aluminum content than moi-moi. This difference may be due to changes in food matrices and preparation conditions, though the present study was not designed to evaluate the individual impact of matrix composition. Previous studies have shown that aluminum migration is influenced by the features of both the contacting food and the preparation environment [8,9,20]. As a result, the observed food-specific difference should be interpreted as evidence of a putative matrix- or process-dependent impact, rather than confirmation that fish promotes increased aluminum migration.

The findings have practical food-safety implications since the materials with the highest aluminum concentrations in this study (conventional aluminum cookware, aluminum foil, and repurposed aluminum roofing sheet) are used in everyday food preparation. The significant difference between aluminum-contact and non-aluminum-contact preparations suggests that material selection may be a modifiable factor in aluminum exposure. This is crucial in environments where aluminum cookware is widely used and recycled or repurposed materials may be preferred due to cost or availability [16-18]. Nonetheless, the current investigation was carried out under controlled preparation settings and evaluated a small variety of meals and preparation situations. As a result, it cannot determine the level of aluminum exposure during long-term household usage, or its contribution to overall dietary aluminum consumption.

In conclusion, the study provides experimental evidence that aluminum-containing food-contact materials can increase aluminum concentrations in moi-moi and fish, with the highest concentrations found in moi-moi prepared with repurposed aluminum roofing sheet and fish wrapped in aluminum foil. These findings highlight the importance of further evaluation of aluminum migration from atypical food-contact materials, notably repurposed aluminum roofing sheets, and determining the potential contribution of such practices to dietary aluminum intake.

REFERENCES

1. Schäfer, U., & Seifert, M. (2006). Oral intake of aluminum from foodstuffs, food additives, food packaging, cookware and pharmaceutical preparations with respect to dietary regulations. Trace Elements & Electrolytes, 23(3), 150.
2. Stahl, T., Falk, S., Rohrbeck, A., Georgii, S., Herzog, C., Wiegand, A., *et al.* (2017). Migration of aluminum from food contact materials to food—a health risk for consumers? Part I of III: exposure to aluminum, release of aluminum, tolerable weekly intake (TWI), toxicological effects of aluminum, study design, and methods. Environmental Sciences Europe, 29(1), 19.
3. Soni, M. G., White, S. M., Flamm, W. G., & Burdock, G. A. (2001). Safety evaluation of dietary aluminum. Regulatory Toxicology and Pharmacology, 33(1), 66–79.
4. Niu, Q. (2023). Overview of the relationship between aluminum exposure and human health. In Neurotoxicity of Aluminum (pp. 1–32).
5. Yokel, R. A. (2025). Aluminum in beverages and foods: A comprehensive compilation of regulations; concentrations in raw, prepared, and stored beverages and foods; and intake. Comprehensive Reviews in Food Science and Food Safety, 24(3), e70175.
6. Behra, P., Bhadauria, M., & Nirala, S. K. (2025). Aluminum toxicity: a comprehensive narrative review. Toxicology Research, 14(6), tfaf167.
7. Stahl, T., Falk, S., Taschan, H., Boschek, B., & Brunn, H. (2018). Evaluation of human exposure to aluminum from food and food contact materials. European Food Research and Technology, 244(12), 2077–2084.
8. Al Zubaidy, E. A., Mohammad, F. S., & Bassioni, G. (2011). Effect of pH, salinity and temperature on aluminum cookware leaching during food preparation. International Journal of Electrochemical Science, 6(12), 6424–6441.
9. Al Juhaiman, L. A. (2012). Estimating aluminum leaching from aluminum cookware in different vegetable extracts. International Journal of Electrochemical Science, 7(8), 7283–7294.
10. Mohammad, F. S., Al Zubaidy, E. A. H., & Bassioni, G. (2011). Effect of aluminum leaching process of cooking wares on food. International Journal of Electrochemical Science, 6(1), 222–230.
11. Ammar, H. R., Saleh, S. M., Sivasankaran, S., Albadri, A. E., & Al-Mufadi, F. A. (2023). Investigation of element migration from aluminum cooking pots using ICP-MS. Applied Sciences, 13(24), 13119.
12. Ali Sultan, S. A., Ahmed Khan, F., Wahab, A., Fatima, B., Khalid, H., Bahader, A., *et al.* (2023). Assessing leaching of potentially hazardous elements from cookware during cooking: a serious public health concern. Toxics, 11(7), 640.
13. Sianturi, M., Gultom, F. L., Faradiba, F., Heumasse, P. V., & Febriza, F. (2020). Study of elements released from various cooking utensil after heating on cooking utensil of aluminum, stainless steel, titanium-coated stainless steel and Teflon and their potential health hazards. International Journal of Progressive Sciences and Technologies, 23(1), 459–467.
14. Uymaz, H. G., İnce, N., & Akanyeti, İ. (2025). Heavy metal transitions from cooking utensils to different solutions. International Journal of Environmental Health Research, 35(8), 2216–2226.
15. Weidenhamer, J. D., Chasant, M., & Gottesfeld, P. (2023). Metal exposures from source materials for artisanal aluminum cookware. International Journal of Environmental Health Research, 33(4), 374–385.
16. Weidenhamer, J. D., Fitzpatrick, M. P., Biro, A. M., Kobunski, P. A., Hudson, M. R., Corbin, R. W., & Gottesfeld, P. (2017). Metal exposures from aluminum cookware: an unrecognized public health risk in developing countries. Science of the Total Environment, 579, 805–813.
17. Street, R. A., Mathee, A., Tanda, S., Hauzenberger, C., Naidoo, S., & Goessler, W. (2020). Recycling of scrap metal into artisanal cookware in the informal sector: A public health threat from multi metal exposure in South Africa. Science of the Total Environment, 699, 134324.
18. Abdulrasheed, Z. A., Adie, G. U., & Iniaghe, P. O. (2026). Preliminary assessment of toxic metals in cookware, moulding materials and soils from manufacturing sites in southwest Nigeria, with evaluation of cookware leaching potential. BMC Chemistry, 20(1), 23.
19. Fermo, P., Soddu, G., Miani, A., & Comite, V. (2020). Quantification of the aluminum content leached into foods baked using aluminum foil. International Journal of Environmental Research and Public Health, 17(22), 8357.
20. Mol, S., & Ulusoy, S. (2020). The effect of cooking conditions on aluminum concentrations of seafood, cooked in aluminum foil. Journal of Aquatic Food Product Technology, 29(2), 186–193.
21. Ewangulu, O. E., Zaruwa, M. Z., Bamidele, T. O., Chibuzor, C. N., & Ogunnodi, O. C. (2026). Systematic Review of Quantification of the Aluminum Content Leached into Fish Processed Using Aluminum Foil. African Journal of Advances in Science and Technology Research, 22(1), 11–21.
22. Alabi, O. A., Apata, S. A., Adeoluwa, Y. M., & Sorungbe, A. A. (2020). Effect of the duration of use of aluminum cookware on its metal leachability and cytogenotoxicity in Allium cepa assay. Protoplasma, 257(6), 1607–1613.
23. Alabi, O. A., Unuigboje, M. A., Olagoke, D. O., & Adeoluwa, Y. M. (2021). Toxicity associated with long term use of aluminum cookware in mice: a systemic, genetic and reproductive perspective. Mutation Research/Genetic Toxicology and Environmental Mutagenesis, 861, 503296.

24. Binkadem, M. S., Akhdhar, A., Abd El-Hady, D., Alowaifeer, A. M., Almutairi, M. A., Alnabati, K. K., *et al.* (2025). Release of elements from disposable aluminum cookware during conventional cooking with water. Current Analytical Chemistry, 21(4), 288–297.