**When combined with household aluminum foil, do common cooking additives pose health risks to the general public?**

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**Abstract**

This study aims to investigate the impact of aluminum foil when exposed to solutions of varying pH (pH = 0 to 14), especially since aluminum leaching can pose serious health concerns. We hypothesized that as the pH of the solution decreases (i.e. solution is more acidic), the average decomposition of aluminum foil into the solution increases after being submerged for 4 days. To test the hypothesis, pieces of aluminum foil were submerged in different common household cooking additives of varying pH: lemon juice (acidic; average pH of 2.45), white vinegar (acidic; average pH of 2.80), water (neutral; average pH of 7.58), and baking soda (alkaline/basic; average pH of 8.78). The selected solutions reflected typical culinary conditions and did not undergo dilution. Results of single-factor ANOVA and Kruskal-Wallis were statistically significant (i.e. $p < .05$); Tukey-Kramer Honestly Significant Difference (HSD) showed that the acids facilitated the statistical significance. To attain those results, we incorporated procedural changes to our original methodology. Our study ultimately revealed that acidic solutions increased the amount of aluminum foil degradation, thus increasing the risk of aluminum leaching.

**Introduction**

Aluminum is a ubiquitous element in the environment that enters our bodies via several routes: food additives, processing, and packaging (Fekete et al., 2013). Aluminum foil is widely used for packaging. The estimated annual production in Europe alone is approximately 860,000 tons. Aluminum intake is a grave concern since only the human can only efficiently excrete very small amounts. The wider population is exposed to unhealthy amounts of aluminum (Dordevic et al., 2019). High concentrations of aluminum in humans have been strongly linked to health problems. Compromised brain cell growth rate, neurological disorders, musculoskeletal disorders, hematopoietic diseases, immune disorders, chronic renal failure, respiratory problems, and metabolic process dysfunction. Aluminum leaching is higher in acidic and/or heated foods (Deshwal et al., 2019; Duru & Duru, 2020; Mol & Ulusoy, 2020; Sheth & Shah, 2022).

If a household cooking additive is very acidic (pH < 7), the amount of aluminum leaching is concerningly high (Bassioni et al., 2012). The strong negative correlation between pH and aluminum leaching is another reason to avoid aluminum foil during food preparation (Duru & Duru, 2020; Inan-Eroglu et al., 2018; Inan-Eroglu, et al., 2019; Müller et al., 1993).

Everyone has to be extremely careful to avoid exceeding the tolerable weekly aluminum intake (Fermo et al., 2020). Aluminum contamination and toxicity levels are ongoing societal concerns due to the adverse impacts on human health regardless of cooking method, e.g frying, boiling, roasting/sautéing, (Ertl & Goessler, 2018). The longer a person consumes aluminum foil-wrapped food, the more that person's health is at risk (Osman & Elsayed, 2007).

Safe levels of aluminum consumption depend on factors such as age, weight, health status, and duration of exposure. The World Health Organization (WHO) set a provisional tolerable weekly intake (PTWI) of 2 mg of aluminum per kg body weight. Therefore, the safe weekly intake of aluminum for an average adult weighing 70 kg would be 140 mg (WHO, 2003). Alarmingly, the estimated average intake of aluminum was approximately 1-2 mg per week (Exley, 2013). In order to address health concerns associated with increased aluminum uptake, a study on red cabbage samples paired with a specific acidic additive (lemon juice, wine vinegar, or cider apple vinegar) was done. Results showed that higher pH was associated with less aluminum leaching (Veríssimo et al., 2006). A variety of foods tested for aluminum leaching showed a statistically significant relationship with pH; however, treatment conditions caused excessive variation (Dordevic et al., 2019).

Our focus was to answer the question, "Do common cooking additives with varying pH levels cause aluminum foil to leach into food?". We hypothesized that pH impacted aluminum leaching and predicted that acidic pH values caused more leaching than solutions with non-acidic pH values.

## Methods

To test for a correlation between decreased pH and increased mass loss of aluminum foil, different solutions were used: distilled water, ReaLemon lemon juice, matcha powder, Heinz white vinegar, and dissolved baking soda. The baking soda solution was made using 1.42 g of baking soda to 250 mL of distilled water. The matcha powder solution was made using 1.42 g of powder to 250 mL of distilled water. The pH of each solution was measured with a pH probe. To enhance accuracy and avoid potential errors, there were 3 replicates per solution. A pipette transferred 50 mL of each solution into its respective glass, each labelled to ensure accurate data collection (eg: Water 1). Alcan aluminum foil was hole-punched 20 times for each replicate. Each set of hole-punched foil pieces was measured with a jewellers scale (unit A3); the mass readings were recorded to the third decimal place (eg: 0.145 g). The pieces of aluminum foil were submerged in each solution and left to sit for 7 days. Afterwards, the pH of each solution was recorded using the same pH probe. After data collection, the average mass differences were calculated. The average pH values per solution were also calculated so that solutions were categorized as acidic, neutral, or alkaline/basic based on the pH scale of 0 to 14.

Our initial methodology generated inconclusive results due to various errors, so we redid our study with procedural modifications. The foil was cut into 12 pieces since the hole-punching resulted in pieces that were too small to record accurate mass differences. Due to time constraints, the foil pieces were submerged in their respective solutions for 4 days. After the treatment period, the foil pieces were separately rinsed in a soap solution followed by 3 distilled water rinses. These washes removed potential precipitate that risked altering the nass measurements. After the foil was left for 24 hours to dry on paper towels, each piece of aluminum foil was re-reweighed using the same jewellers scale (which prevented variance in devices). The hole-punching and presence of precipitate caused positive mass differences regardless of the solution, which contradicted the literature. We also omitted the matcha solution since it was acidic (which contradicted our expectation that it would be basic) and the thick precipitate was difficult to completely rinse. Therefore, these procedural modifications reduced the risk of confounding variables.

A single-factor ANOVA tested the significance of our results to see if varying pH levels (categorical explanatory variable) changed the mean mass difference (numerical continuous response variable) after the aluminum foil was submerged in a given solution for the given time period. We assessed the normality of our data by crafting preliminary grouped histograms, enabling us to see if the nonparametric version of single-factor ANOVA (i.e. Kruskal-Wallis) needed to be conducted. Kruskal-Wallis does not assume normality and is more reliable than single-factor ANOVA, especially for smaller sample sizes. Due to a small sample size and a non-normal distribution, Kruskal-Wallis was performed in addition to single-factor ANOVA. The null hypothesis for both tests was that all pH treatment groups (i.e. acid, neutral, and base) have equal variance. If the p-value (i.e. $p$) was below $\alpha(1) = 0.05$, then the null hypothesis was rejected, indicating no variance among groups. We expected statistical significance for both tests. Tukey Kramer Honestly Significant Difference (HSD) was performed afterwards to see if a specific pH categorization resulted in the rejection of the null hypothesis; this test has the same assumptions as single-factor ANOVA in addition to the rejection for the null hypothesis after the ANOVA. In addition, we expected statistical significance for both pairs involving ‘acid’ to demonstrate that lower pH values had a noteworthy effect on aluminum foil mass difference (final mass - initial mass); $p$ being below $\alpha(1) = 0.05$ for a given pair indicated a significant difference between treatment groups. All statistical tests were conducted on R-Studio.

**Results**

Original Methodology: Water had an average mass difference of 0.008 g; lemon juice had an average mass difference of 0.011 g; white vinegar had an average mass difference of 0.006 g; baking soda had an average mass difference of 0.015 g; matcha had an average mass difference of 0.017 g. The effect of pH was statistically insignificant based on the single-factor ANOVA, $F(2, 12) = 0.838$, $p = .456$. The effect of pH was statistically insignificant based on Kruskal-Wallis, $H(2) = 2.559$, $p = .278$. Tukey-Kramer HSD revealed that no solution was able to facilitate the rejection of the null hypothesis, $p_{acid\text{-}neutral} = .686$, $p_{acid\text{-}base} = .743$, $p_{neutral\text{-}base} = .425$. **Figure 1** displays the relationship between pH and the average difference in aluminum foil mass based on the original methodology, and the results informed our procedural changes.

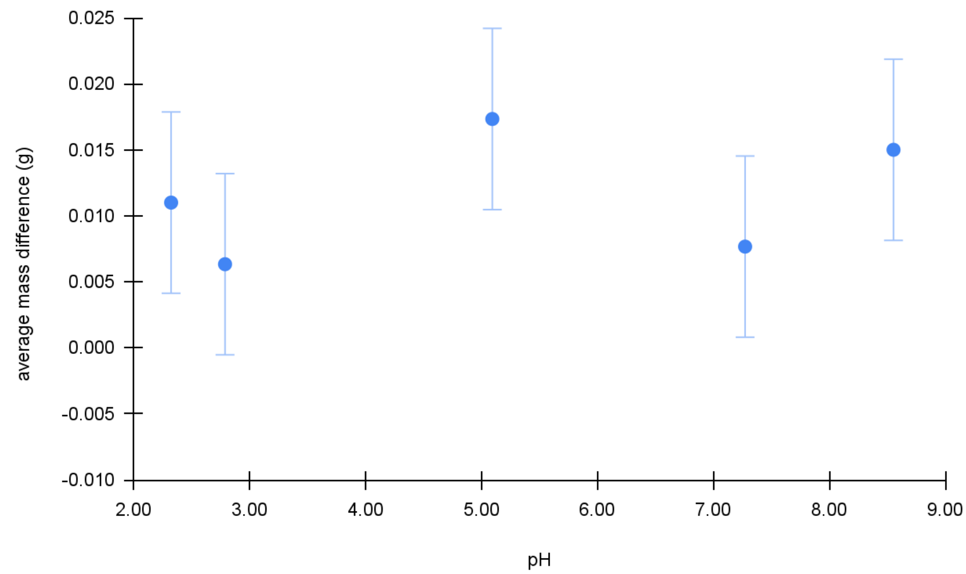


**Figure 1**. Average difference in aluminum foil mass (g) had no relation to pH. Points indicate the average mass difference (g) for 5 different solutions, each with a specific average pH based on 3 replicates ($M_{water}$ = 7.28; $M_{lemon\ juice}$ = 2.33; $M_{white\ vinegar}$ = 2.79; $M_{baking\ soda}$ 8.56; $M_{matcha}$ = 5.10). The average mass difference was obtained after submersion for 7 days. Error bars ($SD_{group}$ = 0.007; obtained from the single-factor ANOVA) were included. This graph was generated by Google Sheets. Data was collected from a lab at UBC's Biological Science Building in February-March 2023.

Modified Methodology: Water had an average mass difference of -0.001 g; lemon juice had an average mass difference of -0.004 g; white vinegar had an average mass difference of -0.005 g; baking soda had an average mass difference of 0.001 g. The effect of pH was statistically significant based on the single-factor ANOVA, $F(2, 9) = 11.37$, $p = .003$. The effect of pH was statistically insignificant based on Kruskal-Wallis, $H(2) = 8.498$, $p = .014$. Tukey-Kramer HSD revealed that the acidic solutions facilitated the rejection of the null hypothesis, $p_{acid\text{-}neutral} = .003$, $p_{acid\text{-}base} = .046$, $p_{neutral\text{-}base} = .345$. **Figure 2** displays the relationship between pH and the average difference in aluminum foil mass.

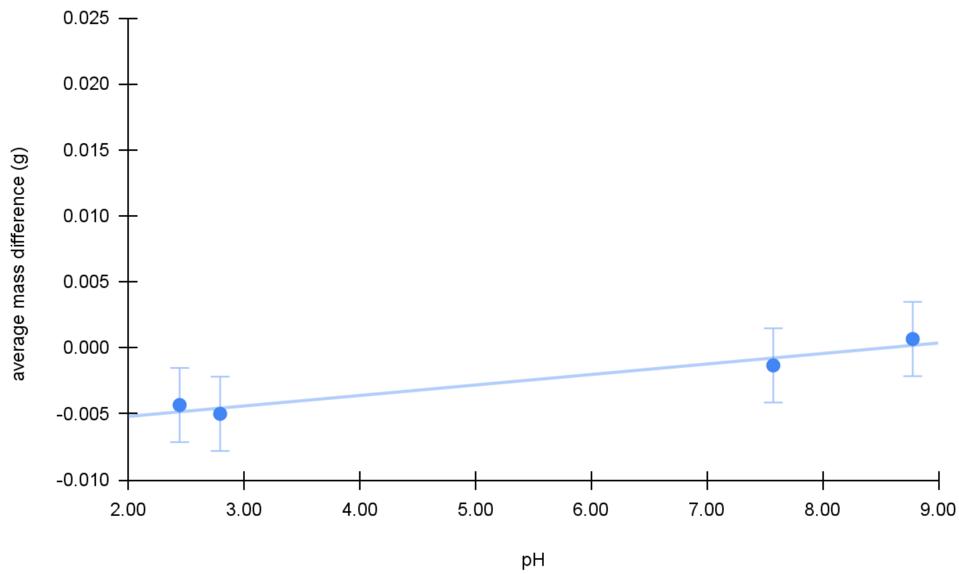


**Figure 2**. Average difference in aluminum foil mass (g) was positively related to pH ($r^2 = 0.953$). Points indicate the average mass difference (g) for 4 different solutions, each with a specific average pH ($M_{water} = 7.58$; $M_{lemon\ juice} = 2.45$; $M_{white\ vinegar} = 2.80$; $M_{baking\ soda} = 8.78$). The average mass difference was obtained after submersion for 4 days. Error bars ($SD_{group} = 0.003$; obtained from the single-factor ANOVA) were included. This graph was generated by Google Sheets. Data was collected from the home of one of the co-authors in February-March 2023.

**Discussion**

The cooking additives for our study were chosen to represent a different range of pH values from acidic to alkaline/basic. The experimental setup involved immersing a strip of aluminum foil in each solution for 4-7 days then measuring the corrosion rate using weight loss analysis on a jewellers scale. Initially, using 20 smaller pieces of aluminum foil cut by using a hole puncher yielded precipitate from the solutions that could not be removed, even after three washes with distilled water. Consequently, all of the final masses were higher. It was also incorrect to assume uniformity of those twenty circles because their masses likely had slight variances affecting the associated initial masses. These smaller pieces could have stuck together during the cutting process, causing higher masses than originally recorded. Due to the large amount of very small foil pieces, it is possible that some pieces were either misplaced or lost. It was found that the matcha powder sample in the original methodology was acidic instead of basic; this sample also resulted in large amounts of precipitate. As such, it was not used in the modified methodology.

Upon revising the procedural methods and using larger pieces of aluminum foil (0.142 to 0.151 g), challenges associated with size were averted. The results showed that the corrosion rate of aluminum foil was lowest in the baking soda solution and that there was an average mass increase. Previous studies revealed that aluminum corrosion gets inhibited when sodium bicarbonate is used relative to deionized water. An oxide layer is produced and stabilized in alkaline solutions, providing a barrier to protect the underlying metal from further corrosion (Zheng et al., 2019). Contrastingly, the corrosion rate of aluminum foil was significantly higher in the lemon juice and vinegar solutions. The findings aligned with the literature; higher acidity increased aluminum leaching (Inan-Eroglu et al., 2019). The water resulted in an intermediate corrosion rate compared to the other solutions.

Future studies can be done on using more solutions with different pH levels from 0 to 14 while observing the surface using scanning electron microscopy as done in literature; observing surface-level changes to aluminum foil and subsequent testing can reveal if a solution's concentration also affects aluminum leaching. Testing on the absorbance of food when exposed to aluminum and various pH levels can further reveal if the amount of leaching poses any significant health risks. There can also be testing the effect that a longer period of time (such as a month or a year) may have on aluminum foil. Limitations of this study included that four solutions were used, concentration was not measured, and the submersion period was 4-7 days.

Our findings have important implications for industries that use aluminum in acidic and alkaline environments, providing insight into the effects of pH. For instance, the food industry uses aluminum foil extensively. As learned, pH caused mass changes in aluminum foil. Degradation would be expected to occur when aluminum foil is used when cooking with an acid. Furthermore, aluminum foil was often used in cooking at high temperatures alongside marinating methods that are acidic or basic.

**Conclusion**

There is a statistically significant relationship between pH levels of cooking additives and degradation of aluminum foil; decreasing the pH of cooking additives (i.e. using more acidic cooking additives) will increase mass loss of the aluminum foil (i.e. degradation). Therefore, it becomes more probable that there would be a higher chance of aluminum leaching into food. Consequently, there is increased risk of adverse health effects occurring in humans. For future cooking, there ought to be a significant reconsideration in the use of aluminum foil so that adverse health risks can be proactively prevented.

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