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ORIGINAL RESEARCH ARTICLE

CORROSION OF ALUMINIUM METAL IN FOOD ENVIRONMENTS AND ITS ASSOCIATED HEALTH RISK ISSUES: A REVIEW

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ABSTRACT

A material for use in contact with food must have adequate strength and integrity to avoid its accidental fracture and leaching of pernicious substances into the food due to corrosion or abrasion of the material. This review covers the basics of aluminium metal and its corrosion in food-handling usage and the associated health-risk issues of its particle intake by human food consumers, as well as current research on the topic. The review findings show that aluminium metal has outstanding advantages in food handling in terms of low cost, wide availability, light weight, ability to heat and cool fast, high temperature tolerance, good corrosion resistance, and perennial shiny appearance in unpolluted natural environments. Its other advantage is excellent formability into designed kitchenware shapes. On the other hand, the findings show that aluminium metal has lower strength and hardness integrity. It is also leachable with lower health-safety level for food-handling usage compared to many other food-grade metals such as stainless steel. Furthermore, daily intake of aluminium substances above 10 mg per kilogram by an individual is risky to their health. The other findings are that food environments with high chloride, acidity, and alkalinity contents can cause greater corrosion of aluminium metal to leach its particles into food, with a higher chance of intaking the particles into the human body system than other food environments. Finally, the findings show that only appropriately alloyed and adequately coated aluminium of sufficient strength should be used in contact with food. The information from the review is meant to serve as a consolidated current literature position on corrosion in the use of aluminium metal for food handling and associated health-risk issues for safe-guarding or a way forward by researchers and stakeholders that need background information for making the metal safer for food handling

1.0 Introduction

Corrosion is an inevitable natural process that attacks an engineering-serviceable material, especially metal, by its interaction with the environment, resulting in deterioration of its cherished properties and service attributes (Guma *et al*, 2017., Inan-Eroglu et al, 2019). Material corrosion occurs to various degrees wherever an environment other than a vacuum exists. Corrosive environments include all natural and synthetic gases and liquids and chemicals, soils, all living and dead animal bodies and waste products from them, bacteria and viruses and other microorganisms, plants and extracts from them, all kinds of food, etc. All environments are corrosive to different metals in various ways or levels. Material corrosion directly or indirectly affects us in all spheres of our human activities. Metallic corrosion has a massive technological and economic cost, as well as implications for environmental and personal safety (Guma *et al*, 2017., Inan-Eroglu et al, 2019).

Food processing is one of the largest industries in the world since everyone out of the over seven billion humans on earth eats daily (Salas *et al*., 2012). Corrosion in food environments is therefore a significant problem because it can lead to many equipment failures with costly downtime and the potential to impact food safety and quality. According to reports from the National Association of Corrosion Engineers over the last few decades, the total direct cost of corrosion to the food industry has been estimated to be more than $2.1 billion per year (Guma and Sukuntuni, 2019., Montanari, 2015). The cost includes costs of food machinery, cutlery and utensils, commercial and restaurant equipment and appliances, cans, use of corrosion inhibitors and other preventive methods, and improvement research (Bryan, 2021). Metals and alloys can be used in contact with food in processing equipment and containers, household utensils, and foils for wrapping food. Metals and alloys used in food environments are usually covered with protective surface coatings but can inevitably be de-coated by corrosion or abrasion with the release or leaching of metallic substances into food. Leached substances can endanger human health if their total content in food exceeds the health-safe guideline value, or if they cause an unacceptable change in the composition of the food or deterioration of its organoleptic properties (Guma and Sukuntuni, 2019., Montanari and Montanari, 2015). According to the Food and Drug Administration (FDA) authorities, a material for use in contact with food must meet several conditions for food safety, such as by (Guma and Sukuntuni, 2019., Noemie et al, 2022):

i. Not allowing deleterious substances to migrate into food or impart odours, colours, and tastes to it.
ii. Being durable, corrosion-resistant, and non-absorbing.
iii. Having sufficient weight and thickness and strength to withstand repeated washing and forces.
iv. Being well finished with smooth and easily cleanable surface.
v. Being resistant to pitting, crazing, scratching, chipping, scoring, distortion, and decomposition.

All the above conditions can be anticipated and fulfilled except material corrosion, because the level of environmental corrosivity and material degradation rates vary randomly at different locations and can in many cases be unpredictable and not adequately counteracted. There are therefore established guidelines defined by food and feedstuff laws on the use of metals and alloys in contact with food and feedstuffs with regards to corrosion and toxicology (Council of Europe's Policy, 2002., Alabi and Adeoluwa, 2020., Sambathkumar et al, 2023). Of the food-grade metals, there has been notable concern about the use of aluminium due to the toxicological effects of its ions in the human body system. Because of toxicity issues associated with aluminium metal, not all its types are used for food processing or handling. Aluminium substances that are naturally found in food or water are known to be strongly and stably bound to benign substances or elements and less absorbable into the human body, so they present much lower health risks to humans when taken into their bodies with food compared to corroded or abraded aluminium ions, which are free and highly unstable radicals (Al-Zubaidy *et al*., 2011., Alabi and Adeoluwa, 2020., Sambathkumar et al, 2023). The problem with even food-grade aluminium metal is that it can undergo erosion, crevice, pitting, filiform, cavitation, exfoliation, inter-granular, galvanic, and micro-biologically influenced corrosion, etc., and leach health-risky substances into food due to a lack of awareness of the need for its corrosion prevention or proper control in many food environments (Guma and Sukuntuni, 2019., Stahl *et al*., 2017., Alabi and Adeoluwa, 2020., Sambathkumar et al, 2023).

The aim of this paper is to present a consolidated basic current literature position on the corrosion of aluminium metal with regard to the use of the metal for food handling and its associated health-risk issues. The objective is to provide readily available basic facts for safe-guarding or a way forward for researchers and stakeholders that need the background information for making the metal safer for food handling.

Information presented in this review paper was sourced from various relevant books, scholarly journals, and organizational activities. The sourced information was integrated and fined-tuned using our experiences as professionals and academics in the field for easy reading and understanding by people for safety awareness or research purposes.

2. The Corrosion Issues with the Use of Aluminium Metal for Food Handling

2.1 Aluminium as a Food-Handling Material

The common metals for food handling include cast iron, grade 304 and 316 stainless steels, aluminium, and copper (Nordic Council, 2015., Zunko and Turk, 2022). However, the bulk of food-grade materials are stainless steel at the top of the scale and aluminium, but any material can be used if it is covered with a protective coating that can withstand corrosion aggressiveness in food handling applications. Compared to aluminium, stainless steel is significantly stronger, harder, and less likely to affect the flavour or texture of food due to its neutral chemical makeup (Zunko and Turk, 2022). On the other hand, aluminium can affect the way food tastes if it comes in contact with the metal's surface for an extended period of time. Not only this, aluminium can change the appearance of food, and this does not bode well for restaurants and chefs. Although stainless steel is used more than aluminium for equipment, utensils, and cutleries for food matters, aluminium has advantages as a food contact material because it is light in weight, low cost, rust resistant, and is prized in cookware for the speed with which it heats and cools compared to stainless steel. Like steel, the aluminium used to make cookware and utensils or build food equipment is alloyed with other elements to the requisite level to meet strength, hardness, durability, and health-safety requirements for food-handling. This is because pure aluminium per se exhibits good corrosion resistance but has poor mechanical properties and a low food safety level, so it must be alloyed with other suitable elements to meet food handling requirements. The main alloy elements used to impart these properties are manganese, silicon, iron, and copper (Council of Europe's Policy, 2002., Nordic Council, 2015., Stahl et al, 2017., Rahimzadeh et al, 2022., Weidenhamer et al, 2022). The percentages present in each of those elements determine the aluminium grade's physical properties. Aluminium pots, plates, pans, and spoons are commonly used in our kitchens in homes, restaurants, and hotels for food preparation or service. Aluminium foil and soda cans are also used in the cooking industry.

Formal inquiries with the use of aluminium metal for food handling are its greater softness, ability to tolerate less abuse, inability to be much stressed before fracture, and intake of its ions in the human body system above acceptable levels causes liver toxicity and leads to Alzheimer's disease and other degenerative symptoms compared to the other commonly known metals used for food handling such as stainless steel (Bryan, 2021). It is prohibited to use objects in contact with foodstuffs that do not meet the requirements of regulation (EC) No. 1935/2004 in accordance with section 31 of the German Food and Feedstuffs Law, 2005 (Guma & Sukuntuni, 2019). Pure aluminium and some aluminium alloys contain elements in quantities and/or numbers that negate health safety levels, so use of aluminium in the food industry is guided by rules as to what the content of each aluminium alloy should be for applications. There are maximum tolerances laid down according to regulation EN 602:2007 of European standards in connection with the use of aluminium in the food industry. Stipulated maximum contents of various allowable elements in aluminium alloys for food industry applications are shown in Table 1 (Guma & Sukuntuni, 2019).

Table 1: The maximum content of various allowable elements in aluminium alloys for food industry applications

Element	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Zi	Ti	Others
Max. content by mass [%]	13.5	2	0.6	4	11	0.35	3	0.25	0.3	0.3	0.15

*Source: Guma and Sukuntuni, 2019

For example, Al 6061 alloy with percentage elemental weight composition of: 96.85 Aluminium, 0.9 Magnesium, 0.7 Silicon, 0.6 Iron, 0.3 Copper, 0.25 Chromium, 0.20 Zinc, 0.10 Titanium, 0.05

Manganese, and 0.05 others within the specified ranges given in Table 1, is a commonly used food aluminium alloy (Guma and Sukuntuni, 2019).

2.2 Corrosion and Status of Aluminium as a Food-Grade Material

It is important that abrasion and corrosion problems be taken into consideration when using any material in contact with food so as to prevent deterioration of the material and leaching of its particles into food. Among the food-grade metals, aluminium and stainless steel are notable for their generally high corrosion resistance (Nordic Council, 2015., Inan-Eroglu et al, 2019).

Pure aluminium has very good corrosion resistance in most unpolluted environments, such as the atmospheric environment. This is primarily attributed to the ability of aluminium metal to spontaneously form a thin oxide layer on its surface, which effectively prevents further oxidation of the metal. The oxide layer is impermeable and strongly adheres to the aluminium body, in contrast to oxide layers on many other metals. If the formed oxide layer is damaged by mechanical action, it repairs itself immediately (ASM, 1999., Inan-Eroglu et al, 2019). The formed oxide layer is the fundamental reason for aluminium's good corrosion resistance. The oxide layer is stable in environments with pH in the range of 4–9. Aluminium can, however, corrode greatly in highly alkaline and acidic environments with pH values outside the 4–9 range (ASM, 1999., Al-Rudaini and Al-Saadie, 2021).

In food preparation environments, many cleaning and sanitation agents, including alkaline, acidic, oxidizing, and reducing chemicals, are employed to remove bacteria, scale, fouling, and corrosive biological and mineral deposits on equipment and utensils and cutleries, to ensure a high hygiene level (Ellis, 2021., Salas *et al*, 2012). These cleaning and sanitation agents can, however, cause various levels of material corrosion, including aluminium equipment and kitchenware. Water is also a great agent of aluminium corrosion and is widely used for food processing. Extensive use of high-pressure water and steam is the leading cause of aluminium corrosion in food processing facilities. This is due to the ability of high-pressure water and steam to cause erosion corrosion of aluminium, often in combination with the other different corrosive agents comprising alkaline, acidic, oxidizing, and reducing chemicals for cleaning purposes (Ellis, 2021., Salas *et al*, 2012). Some food products with highly acidic contents, such as citric fruit juices, tomatoes, cabbage, jams, soft fruits, pickled vegetables, and dressings, as well as alkaline foods or ingredients, and foodstuffs with much added salts, are also inherently corrosive to aluminium metal (Ellis, 2021., Salas *et al*, 2012). The pH ranges of different food categories in the food industry as a measure of their corrosivity extent to metals, including aluminium, are shown in Table 2.

Table 2: pH ranges of different food categories as measures of their corrosivity levels

Food category	pH range
Vegetables	3.0-6.0
Fruits	2.0-5.0
Bakery	5.0-6,5
Meat	6.0-7.0
Fish	5.5-6.0
Dairy	5.0-6.5
Beverages	2.0-5.5

*Source: Salas *et al*, 2012

The food processing environment is indeed a complex composition consisting of various levels of alkaline such as caustic soda (NaOH), alkali phosphates (Na_3PO_4), sodium carbonate (Na_2CO_3) and bicarbonate ($NaHCO_3$); acids such as phosphoric, citric, and sulfamic acids; and oxidizers such as chlorine, nitric acid, ozone, hypochlorite, hydrogen peroxide (H_2O_2), which can be very corrosive to aluminium and other metals. If aluminium utensils are coated with protective coatings such as Teflon, there is no leaching of aluminium during cooking as long as the coating is intact. Aluminium can accumulate much more in foods stored or cooked in uncoated aluminium pans than in coated cookware (Ellis, 2021; Salas *et al*., 2012). The amounts of aluminium that accumulate in foods during preparation depend on the pH of the foods, the length of cooking periods, and the types of utensils. Ingested aluminium can accumulate in the brain, bones, and liver and cause some diseases like, encephalopathy, as well as bone and other disorders (Ellis, 2021).

2.3 Some Current Researches on the Food Environment corrosion of Aluminium Metal and the Associated Health Risks

A review of some recent researches pertaining to food corrosion of aluminium has been made as follows:

Jimenez and Kane (1994) described aluminium as one of the most common materials with alloy elements added to improve its physical and chemical properties for food packaging. They discovered that applying coating materials or plastic laminates to aluminium containers and flexible foil packages improves their end-of-life performance. They demanded thorough compatibility testing with the specific product to be used as a requirement for the final selection of packaging and extensively discussed test results on the interactions of various foods and beverages with aluminium containers. They reviewed the electrochemical action of foods wrapped with aluminium foil and placed in contact with other metallic objects. Their conclusion was that aluminium and its salts have a harmless effect when ingested with foods that have been exposed to the metal (Jimenez and Kane, 1994).

The possibility of foods interacting with non-coated aluminium was modelled by Piergiovanni *et al.* (1990), using corrosion behaviour results from an aluminium household foil under different conditions of acidity, temperature of the contacting phase, and dissolved oxygen. They kept the aluminium foil in contact with acetic acid solutions whose pH values ranged from 2.5 to 3.5 and dissolved oxygen concentrations ranged from 0 to 8 ppm, under various temperature conditions of 0.3 to 50°C and contact durations of 24 to 120 hrs. They detected corrosion and found that all the three variable factors had an influence on its rate and, consequently, the extent of the interaction; but pH and temperature had greater effects on the rate since their relationships with the rate were exponential in nature. They also found a linear relationship with a minor accelerating effect between corrosion rate and dissolved oxygen. By applying the Arrhenius equation, they evaluated the thermal sensitivity of the phenomenon with respect to the different variable factors. They showed that the activation energies varied within 31-635 and 88-471J/mol, giving an indication of higher thermal sensitivity at the lower pH values and higher dissolved oxygen amounts (Piergiovanni *et al.,*1990).

A method of estimating aluminium leaching from aluminium cookware in some meat extracts and liquid milk was investigated by Al-Juhaimam (2010), using four kinds of aluminium cookware from four countries chosen from the local market. He used extracts of boiled lamb, chicken, and fish to make 10–50% (w/v) concentrations. In addition, he diluted fresh liquid milk and long-life milk to make 10–50% (v/v) concentrations. He applied weight loss, atomic absorption, and polarization methods, and surface study to the methods. His estimated aluminium intake per person from weight loss in 30% meat extract and milk ranged from 8.16 to 12.75 mg/h, with fish extract having the highest leaching and chicken extract having the lowest leaching. Atomic absorption gave comparable results to those of weight loss. Comparing the results of his study with the provisional weekly intake of aluminium approved by the FDA/WHO showed that aluminium leaching from aluminium cookware might add high doses of aluminium into the diet (Al Juhaimam, 2010).

Al-Zubaidy *et al.* (2011), studied the effects of pH, salinity, and temperature on aluminium cookware leaching during food preparation. They noted that intake of aluminium by humans portends hazards, and the subject had been under study for some years and had attracted significant attention from the media as it is believed that the intake enhances or causes diseases like the well-known Alzheimer's disease. In the study, the effects of pH, salinity, and temperature of Egyptian and Indian aluminium cookware were measured during food preparation using tap water and drinking water. They used the weight loss method to study aluminium leaching into different food solutions. They also used environmental scanning electron microscopy to study the morphology of the cookware samples before and after exposing them to the different food solutions and applied the Arrhenius equation to find activation energies. They found that cookware aluminium was very sensitive to low and high pH as the corrosion rate increased in an alkaline environment. They also observed that corrosion rates decreased with drinking water compared to tap water, and increasing salt concentration increased the corrosion rate up to a certain value, after which a decrease was observed to reach a plateau of constant corrosion rate. They attributed this behaviour to the combination of high conductivity and oxygen solubility of the solutions (Al Zubaidy *et al., 2011*).

Mohammad *et al.* (2011), studied the effect of aluminium leaching from cookware on food. They observed that the intake of aluminium from utensils had been of growing concern for the health of the community. In their study, they investigated the leaching of aluminium from aluminium utensils in different food solutions. They chose two available aluminium utensils of different origins from the local market. They used minced meat with drinking water and tap water for the study. They also used two other techniques of analysis: weight loss measurement and inductively coupled plasma-mass spectrometry, for the study. They found that their results showed little variation between the whole meat and meat extract solution. They chose the meat extract solution for all experimental work and examined different solutions starting from water, different concentrations of meat extract, and a 40% meat extract solution with tomato juice, citric acid, and table salt. They found that the results of the two measurements were almost consistent. They found that the amount of aluminium leaching was high in the cooking solutions using all the above additives. They observed that, according to the World Health Organization (WHO), their obtained values could be considered unacceptable in relation to their limitations, indicating a high risk to the consuming community (Mohammad *et al*., 2011).

A study on the corrosion behaviour of wrought aluminium alloy under domestic food cooking conditions was conducted by Adeosun *et al.* (2012), using the gravimetric method. They subjected flat, cold-rolled and annealed sheets of wrought aluminium alloy to solutions of *capsicum annuum*, *L. esculentum, allium cepa*, and their blends under heating and cooling conditions in still air, a refrigerator, and left some in the open still atmosphere. The results of their study showed that corrosion occurred within the 288-hour test period in the test environments. They also found that there was severe degradation within the first 70-hour period of the tests when coupons were heated and cooled, and unheated coupons showed low corrosion propensity. Their micro-structural analysis showed the presence of corrosion pits on coupon surfaces with second phase particles sandwiched in α-aluminium matrix. Immersed coupons in the blended media showed a higher number of pits on the surface. They attributed rapid corrosion of wrought aluminium alloy in *capsicum annuum, L. esculentum, and allium cepa* media to the presence of corrosion-aggressive elements such as allicin, diallyl-disulphide, and allyl-propyl disulphide present in the corrosion media (Adeosun *et al*., 2012).

Odularu *et al.* (2013), carried out a comparative study on leaching from aluminium, clay, stainless steel, and steel cooking pots through the absorption of aluminium by rice boiled in distilled water in a variety of containers, such as old and new aluminium pots, clay receptacles, stainless steel pots, and steel pots. They took 10 g of rice as a representative sample and used colorimetric analysis of classical methods to determine the concentration of aluminium. They used a control for aluminium of 350 ±130 μg/g. They found that new aluminium pots had a concentration of 126 ± 64 *μg/g*, old steel utensils had 186.83 ± 75.18 *μg/g*, new steel pots had 241.00 ± 200 *μg*/g, old aluminium pots had 314 ± 128 *μg*/g, new clay pots had 132 ± 68 *μg/g, ol*d clay pots ± 137 *μg*/g, new stainless-steel utensils had 289.00 ± 75.155 μg/g. They detected aluminium leaching in all forms of new and old cooking utensils, but the leaching was below and within the control concentration range. They also found that old aluminium pots had the highest concentration of leaching while new steel pots had the least leaching of aluminium. They concluded from their study that the aluminium contamination of the tested foods was insufficient to constitute a health risk (Odularu *et al*., 2013).

Rahem (2014), studied the effects of citric acid in tomato paste and sodium chloride (NaCl) as cooking salt on the corrosion behaviour of kitchenware aluminium by electrochemical technique under different cooking temperatures of 30, 50, and 70^{o}C and different paste solutions of 1, 3, and 5% with and without the addition of 1%-NaCl. He found that an increase in paste concentration increased current density, the addition of NaCl increased current density more rapidly than without addition, and an increase in temperature had a strong effect on the corrosion behaviour of the aluminium (Rahem, 2014).

Jabeen *et al*. (2016), conducted a study to identify the correlation between food and aluminium intoxication through leaching. They opined that ingestion is the main route of aluminium exposure to the human body. They therefore deem it necessary to identify the aluminium levels in the human body leached out from aluminium wares and aluminium foil. They baked pieces of chicken and red meat with different types of solutions containing tomato juice, fresh yogurt, salt, and vinegar in different combinations. From there, they wrapped them in aluminium foil in different combinations, marinated them in aluminium pans, and tested them for the pH and weight of the pieces and foil. They found that citric acid, in combination with lactic acid, was the source of elevated levels of aluminium in food items, especially raw beef. They also found that citric acid with tomato juice had the highest aluminium accumulation rate of 292.25 mg/kg in beef than other solutions, while the chicken leaching rate was 209.52 mg/kg with the combination of yogurt and lemon juice. They concluded that once aluminium exceeds the acceptable limit from the daily ingestion of food cooked in these pots, coupled with other sources from the environment, this environmental factor may contribute to an increase in neurodegenerative diseases. The aim of their research study was to detect the leaching of aluminium levels from aluminium foil in different food solutions, as it is becoming a common practice (Jabeen *et al*., 2016).

Juhaiman (2016), studied curcumin extract as a green inhibitor of leaching from aluminium cookware at quasi-cooking conditions. He successfully used curcumin aqueous extract as a green corrosion inhibitor at quasi-cooking conditions at 90°C to inhibit leaching from aluminium cookware in solutions containing vegetables or meat. He bought the cookware from the market from four countries and cut them to make the aluminium samples. He chose six types of vegetables and three kinds of meat and used each type of vegetable and meat to prepare 30% w/v aqueous solutions. He used three methods: the gravimetric method, atomic absorption, and Fourier transform infrared spectroscopy. He applied the gravimetric method to determine the leaching rate and the corrosion inhibition efficiency with and without NaCl; and also investigated the effect of curcumin concentration, tab water, immersion time, and alloying elements. He found good consistency between gravimetric and atomic absorption methods. He also found that adsorption of curcumin on the aluminium surface was in accordance with Langmuir isotherm and calculated and discussed the values of the adsorption constant (K_{ads}) and the free energy of adsorption (G_{ads}). His Fourier integral transform spectrum indicated that curcumin coordinated with Al^{3+}, resulting in the formation of an Al^{3+}-curcumin complex on the metal surface; and using a small amount of curcumin decreased leaching from aluminium cookware into food by 60%-80% depending on the food type (Juhaiman, 2016).

Aluminium leaching from aluminium-only foil and baking paper-aluminium foil into baked meat was determined by Inan-Eroglu *et al.* (2018). They cooked mutton, beef, and chicken breast and drumstick in the oven using the two foil types at 150, 200, and 250°C temperatures for 60, 40, and 20 minutes, respectively, and determined the aluminium content in the meat by ICPS-MS. They discovered that increasing the fat content of the meat, increasing the cooking temperature and time, and decreasing the pH increased leaching from aluminium-only foil rather than baking paper-aluminium foil. They concluded their studies by recommending further studies on the effects of foil types on aluminium leaching into food under different conditions (Inan-Eroglu *et al.*, 2018).

Guma and Durami (2019), reaffirmed that the outstanding demerits of aluminium as a food-grade metal are its low tensile strength and impact tolerance, with greater liability to break compared to other common food-grade metals. They pointed out that aluminium can corrode appreciably in alkaline environments of pH higher than 9 with aggravation in its strength and that frequent intake of its substances along with food into the human body due to corrosion or abrasion can be health-risky. They observed that aluminium containers were in use for preparing and serving various menus from the general Nigerian diet to about 1000 cadets on a daily basis at the Nigerian Defence Academy (NDA) cadets' mess (canteen). They also noted that the menus and various ingredients used to make them amidst the general mess environment were inevitable in corroding the containers. They used accelerated corrosion tests to find out whether some of the commonly prepared and served menu items at the mess, such as Eba, fried rice, Egusi soup, tomato stew, Alayafu vegetable dressings, and their possible different combination admixtures in any alkaline environment of pH greater than 9, had severe corrosion effects on the tensile strength of the containers. They procedurally produced and prepared 64 ASTM standard tensile samples of aluminium 6063, as a commonly used food-grade alloy for such containers. They then subjected 62 samples in pairs to alkaline treatments that mimicked the alkaline environment and corrosivity extremity of each menu sample to the containers. Then, they tested the samples for their ultimate tensile strengths (UTS) and collated and reported the results as the respective average pair values. Their analysis of the reported results relative to those of the control sample pair showed negligibly small tensile strength reductions of 0.00027% to 0.00135%. Their further analysis of the results using literature facts understandably indicted that the menu samples amidst the mess environment have negligible effects on corrosion and tensile strength of the containers and the health of the cadets (Guma and Durami, 2019).

Guma and Sukuntuni (2019), discussed the health risks that can be associated with daily intake of aluminium substances above prescribed amounts into the human body system, as well as its low strength and impact resistance as a food-contact material, which makes it unable to take much force without breaking. They described corrosion as a severe, typical degrading process that worsens the effects of using aluminium metal as a food contact material. They reaffirmed that aluminium can corrode appreciably in acidic media with a pH of less than 4. The purpose of their research was to experimentally understand the corrosivity extents of some Nigerian menu items, such as Akamu, lemon juice, okro soup, pounded yam, and beans, amidst any unusual acidic environments to aluminium cookware and utensils used to prepare or serve food on a daily basis to more than 900 cadets at the cadets' mess of the Nigerian Defence Academy. They also assessed the effects of the menu items on the impact strengths of the cookware and utensils. They procured and ascertained the Al 6061 aluminium alloy as a commonly used metal for cookware and utensils and used it to produce 60 ASTM impact specimens. After procedurally cleaning the specimens to a similar surface finish, they used 5 specimen pairs for control and 25 other pairs each soaked for 28 days in the prepared menu samples separately sequentially homogenized with 0, 2, 4, 8, and 10% by weight of concentrated phosphoric acid (H_3P0_4) under ambient laboratory conditions. After the soaking, they removed and tested the specimens for their impact strengths. Their analysis of their collated test data revealed that the strength of the specimens in the menu media decreased as the H_3P0_4 treatment of the media increased. They found that the lemon fruit juice medium treated with 10% by weight of H_3PO_4 caused the comparatively highest but negligible impact strength reduction of 0.031% only relative to the control (un-soaked) specimen's impact strength value. They came to the conclusion that the menu samples amidst any acidic environmental conditions of the mess have negligible effects on corrosion and impact strength of aluminium cookware and utensils as used there (Guma and Sukuntuni, 2019).

Guma and Aliyu (2021), noted that sufficient hardness is a necessary quality of every cookware material to prevent its leaching of harmful particles into food due to corrosion and/or abrasion, but aluminium metal is less hard with health concerns compared to the majority of other cookware metals. They reaffirmed that chloride media play an important role in the corrosion and hardness reduction of the metal. They experimentally investigated the corrosion, hardness integrity, and food safety level of aluminium cookware under the food chloride environmental exposures at a canteen. Their investigation stemmed from a desire to understand the extent to which some commonly prepared and served Nigerian foods, named Amala, Moimoin, Ogbono (*Irvingia gabonensis*) soup, sweet potatoes (*Ipomoea batatas*), and boiled beef, can cause corrosion and affect the hardness integrity and food safety level of aluminium cookware as used at the mess under various chloride environmental exposure conditions. They procedurally produced hardness coupons from unused aluminium cookware and soaked them for 30 days in the separate menu media, which were each prepared, characterized by pH and chloride content, and progressively homogenized with 0–1200ppm of NaCl to accelerate the chloride corrosivity of the menus and their exposure environments to different degrees. After the soaking, they removed and measured the Vickers micro-hardness values of the coupons. Their analysis of the hardness measurements showed that the NaCl additions to the test media minutely decreased the coupons' hardness values by only 0.000667 to 0.023 percent, which presupposed a negligible deterioration in the hardness of the utensils themselves. Their X-ray fluorescence analysis of Ogbono soup test medium, which caused the comparatively highest hardness reduction of 0.023%, revealed undetected aluminium content that could be negligibly much less than 0.03% by weight in the medium and less than the Food and Drug Administration (FDA) Authority of the USA's 10 mg maximum aluminium substances per kilogramme of daily food intake stipulation, with a negligible chance of any health risk to the soup consumers (Guma and Aliyu, 2021).

Fatunsin et al. 2022, investigated the effect of pH on the leaching of potentially toxic metals from different types of used cooking pots. They noted that humans are exposed to potentially toxic metals through many routes. They also noted that cooking foods in cookware that is prone to material leaching can be an exposure route to the potentially toxic metals. In their study, they assessed the effect of pH on the leaching of some potentially toxic metals from used cooking pots into deionized water. They prepared a series of deionized waters with a pH of 3 to 7. They brought each pot of water to a boil in clay, non-stick, stainless steel, cast aluminium, pressed aluminium, and glass pots, respectively. They determined the potentially toxic metals leached from each sample pot by inductively coupling a plasma-optical emission spectrophotometer of the Agilent Nu7M Technologies 700 Series. They found that the deionized water from the aluminium cast pot and non-stick pot had the highest concentrations of aluminium at 2273 μg/L and zinc at 24.39 μg/L. They also found that the clay pot had the highest concentrations of chromium and nickel, at 7.27 and 22.63 μg/L respectively. From the stainless steel pot, they found the highest concentration of iron to be 237 μg/L and lead to be 24.39 μg/L. However, they found no potentially toxic metals in the deionized water from the glass pot. The results from their study showed that more leaching of potentially dangerous metals into deionized water occurred at lower pH values of 3 to 5 than at neutral pH for almost all the pots. They therefore concluded that cooking acidic foods in pots except when glass pots are used, should be avoided. The results of their study therefore revealed the health implications associated with using metal pots for cooking slightly acidic foods, as metals can be easily leached from the pots into the foods (Fatunsin et al., 2022).

3. Remedies So Far Used to Mitigate Effects of Aluminium Metal Corrosion in Food Environments

The deterioration of the mechanical properties of aluminium metal as an excellent material coupled with its toxicological effects of corrosion leaching in food has created a need for remediating its use for food handling. The common feasible remedies for the problem include:

i. Use of only the correct aluminium grade, such as AA 6061, and AA 6063 aluminium, for the manufacture of cookware, food utensils, and food processing machinery in accordance with reputable authorities on the subject such as the German Food and Feedstuffs Law, 2005 (Montanari, 2015., Guma and Sukuntuni, 2019)
ii. Production of all aluminium equipment, cookware, utensils, and other facilities that are used for food handling with highly smooth and cleanable surface finishing and regular geometrical patterns to minimize corrosion (Ellis, 2021., Montanari, 2015., Gupta et al, 2019).
iii. Protecting the surfaces of aluminium facilities that must be used for food handling by coating the surfaces to a thickness of 50-100 µm with a suitable material that should be hard-anodized (Ellis, 2021., Montanari, 2015., Gupta et al, 2019).
iv. Avoiding contact of food-handling aluminium facilities with acids or using the facilities for cooking acidic foods such as simmering tomato sauce (Ellis, 2021., Montanari, 2015., Gupta et al, 2019).
v. Using only suitable soft materials to clean food-handling aluminium facilities such as cookware, utensils, equipment, etc, and taking precautions to preserve the protective anodized coating layer on them. Avoiding prevalent cleaning practices involving the use of corrosive fluids and hard or metallic scrub which leads to erosion of the protective coating. That is, only materials that are not harmful or corrosive should be used for cleaning aluminium cookware, utensils, packages, and other food-handling facilities (Eliss, 2021; Montanari, 2015., Gupta et al, 2019).
vi. Complying to the manufacturers' instructions that aluminium cookware, utensils, packages, and other food-handling facilities should never be rubbed with hard or metallic scrub (Montanari, 2015., Gupta et al, 2019).

4. Conclusion

A literature review on the food-handling usage of aluminium metal, as well as issues of its corrosion leaching into food and associated health-risk to food consumers, has been presented as a consolidated basic current literature position on the subject for the renewal of public awareness, and for researchers and stakeholders who need the information to better the metal for the usage. The review critically shows that aluminium is the foremost food-grade metal due to its many outstanding advantages and extensive use in the food industry in various forms such as utensils, food processing equipment, food containers, foils for wrapping food, and bottles. However, a critical concern from the bulk of the reviewed literature is that daily intake of aluminium metal by humans above a permissible level can be detrimental to their health, and the quantity of its intake can be enhanced by the extent to which the metal dissolves and leaches into food; as determined by the extent of its corrosion in contact with particular food environments. The review has also shown that only certified and standardly coated aluminium alloys must be used in contact with food. However, increased acidity, alkalinity, or chloride content of foods or food environments can even corrode the certified and standardly coated food-grade aluminium alloys and cause leaching into food. Much conducted research for a better understanding of the corrosion leaching of aluminium into food and ways of counteracting its leaching in different food environments has been found in the literature, but the utopian solution to the problem is still to be found. Further research on alloy modifications of aluminium to utopian or better strength and corrosion resistance levels in all environments appears to be the foreseen way out of the problem.

References

Alabi, OA. and Adeoluwa, YM. 2020. Production, Usage and Potential Public Health Effects of Aluminium Cookware: A Review. Annals of Science and Technology, 5(1): 20-30.

Adeosun, SO., Akpan, EI. and Balogun, SA. 2012. Wrought Aluminium Alloy Corrosion Propensity in Domestic Food Cooking Environment. International Scholarly Research Network, Hindawi Publishing Corporation, Corrosion, London, pp. 1-6.

Al-Juhaimam, LA. 2010. Estimating Aluminium Leaching from Aluminium Cookware in Different Meat Extracts and Milk. Journal of Saudi Chemical Society, 14(1): 131-137.

Al-Rudaini, KAK. and Al-Saadie, KAS. 2021. Study the Corrosion behaviour of AA7051 Aluminium alloy at different temperatures and inhibitor concentration in Acidic medium**.** Research Journal of Pharmacy and Technology, 14(9): 4977-4982. Doi: 10.52711/0974-360X.2021.00866

Al-Zubaidy, EAH., Mohammad, FS. and Bassioni, G. 2011. Effect of pH, Salinity and Temperature on Aluminium Cookware Leaching During Food Preparation. International Journal of Electrochemical Science, 6: 6424-6441.

ASM 1999. Corrosion of Aluminium and Aluminium Alloys (#06787G), Chapter 1, Introduction, JR. Davis (Ed). American Society of Metals International, Russell Township, Ohio. pp 1-10.

Byran, JM. 2021. Aluminium and Aluminium Alloys in the Food Industry with Special Reference to Corrosion and its Prevention. Centre for Agriculture and Bioscience International, Wallingford, Oxfordshire, England. pp. 1-50. Available Online at: https://www.cabdirect.org/cabdirect/abstract/19482702129. Accessed September, 16, 2021

Council of Europe's Policy 2002. Part II Technical Document Guidelines on Metals and Alloys used as Food Contact Materials. Council of Europe's Policy Statements Concerning Materials and Articles intended to Come into Contact with Foodstuffs Policy Statement Concerning Metals and Alloys, 13 02 2002, pp. 13-18. Published by the Council of Europe Policy, Strasbourg, France

Ellis, S. 2021. Knowledge about Corrosion Prevention Crucial for Success in Food Manufacturing Industry, pp. 1-5. Mon, 05/18/2015. Published by Food Manufacturing Net, Madison, United States. Available online at:

https://www.manufacturing.net/operations/article/13184126/knowledge-about-corrosion Accessed, October, 23, 2021.

Fatunsin, OT., Adeyeye, OF., Olayinka, KO., and Oluseyi, TO. 2022. Effect of pH on the Leaching of Potentially Toxic Metals from Different Types of Used Cooking Pots. Journal of the Nigerian Society of Physical Sciences, 4: 1-8.

Guma, TN. and Durami, JA. 2019. Assessment of Alkaline Food Environment Corrosion with some Menus at a Cadet Mess on the Tensile Strength of Aluminium 6063 Alloy. International Journal for Research in Applied Science & Engineering Technology (IJRASET), 7(1): 621-630.

Guma, TN. and Sukuntuni, SA. 2019. Effects of Acidic Food Environment Corrosion on Impact Strength of Aluminium 6061 Alloy: A Case Study with some Menus at a Cadets' Mess. International Journal of Engineering Trends and Technology (IJETT), 67(7): 70-78.

Guma, TN., Atiku, SA. and Abdullahi, AA. 2017. Corrosion Management and Control: Entrepreneurial Opportunities and Challenges in Nigeria, International Journal of Engineering Research and Application, 7(10): 14-23.

Guma, TN. and Aliyu, J. 2021. Effects of Food Chloride Environment at a Canteen on Corrosion, Hardness Integrity and Food-Safety Level of Aluminium Cookware. Nigerian Journal of Engineering, 28(3): 50-55.

Gupta, YK., Meenu, M. and Peshin, SS. 2019. Aluminium utensils: Is it a concern? The National Medical Journal of India, 32(1):38-40. Doi: 10.4103/0970-258X.272116

Inan-Eroglu, E., Gulec, A. and Ayaz, A. 2018. Determination of aluminium leaching into various baked meats with different types of foils by ICP-MS. Journal of Food Processing and Preservation, 42(12): 1-10. https://doi.org/10.1111/jfpp.13771

Inan-Eroglu, E., Gulec, A. and Ayaz, A. 2019. Effects of different pH, temperature and foils on aluminium leaching from baked fish by Inductively coupled plasma mass spectrometer (ICP-MS). Czech Journal of Food Science., 37: 165–172. https://doi.org/10.17221/85/2018-CJFS

Jabeen, J., Ali, B., Khan, MA., Khan, MB. and Hasan, SA. 2016. Aluminum Intoxication Through Leaching in Food Preparation. Alexandria Science Exchange Journal, 37(4): 618-626.

Jimenez, MA. and Kane, EH. 1994. Chemistry of Food Packaging, Chapter 4, Advances in Chemistry, American Chemical Society, 135, pp. 35-48. DOI:10.1021/ba-1974-0135.ch004.

Juhaiman, L. 2016. Curcumin Extract as a Green Inhibitor of Leaching from Aluminium Cookware at Quasi-Cooking Conditions. Green and Sustainable Chemistry, 6(2): 57-70. Doi: 10.4236/gsc.2016.62005.

Mohammad, FS., Al Zubaidy, EAH. and Bassioni, G. 2011. Effect of Aluminium Leaching Process of Cooking Wares on Food. _International Journal of Electrochemical Science, 6: 222 – 230.

Montanari, A. 2015. Basic Principles of Corrosion of Food Metal Packaging, Chapter 6: In Food Packaging Hygiene, Springer Briefs in Molecular Science Book series. Edited by Savatore Parisi. Springer International Publishing, New York City, pp.105-132. DOI: 10.1007/978-3-319-14827-4-6

Noemie, T., Ifo, G., Mafouba, J., Samba, V., Diamouangana, M., Mboho, N., Nsimba, C. and Moutou, J. 2022. Effect of Cooking Condiments on the Mass Loss of Artisanal Aluminum Cooking Utensils: The Case of Congo-Brazzaville. Journal of Minerals and Materials Characterization and Engineering, 10: 139-152. Doi: 10.4236/jmmce.2022.102011.

Nordic Council 2015. Food contact materials – metals and alloys Nordic Guidance for Authorities, Industry and Trade. Nordic Council of Ministers 2015, Hanne Lebech, Denmark.

Odularu, AT., Ajibade, PA. and Onianwa, PC. 2013. Comparative Study on Leaching of Aluminium from Aluminium, Clay, Stainless Steel, and Steel Cooking Pots, International Scholarly Research Notices, 2013: 1-4. https://doi.org/10.1155/2013/517601

Piergiovanni, L., Fava, P., Ciappellano, S. and Testolin, G. 1990. Modelling Acidic Corrosion of Aluminium Foil in Contact with Foods. Packaging Technology and Science, 3(4): 195–201, Doi: 10.1002/pts.2770030404.

Rahem, SK. 2014. Studying of Aluminium Corrosion in Citric Acid and NaCl. Chemical and Processes Engineering Research, 27: 23-36.Rahimzadeh, MR., Rahimzadeh, MR., Kazemi, S., Amiri, RJ., Pirzadeh, M. and Moghadamnia, AA. 2022. Aluminum Poisoning with Emphasis on Its Mechanism and Treatment of Intoxication. Hindawi Emergency Medicine International, 2022, 1-13. Doi: 10.1155/2022

Salas, BV., Wiener, MS., Stoytcheva, M., Zlatev, R. and Beltran, MC. 2012. Corrosion in the Food Industry and its Control, In: Food Industrial Processes-Methods and Equipment, Edited by: Benjamin Valdez, Intech Publication, February 2012 pp. 262-371.

Sambathkumar, M., Gukendran, R., Mohanraj, T., Karupannasamy, DK., Natarajan, N. and Christopher, DS. 2023. A Systematic Review on the Mechanical, Tribological, and Corrosion Properties of Al 7075 Metal Matrix Composites Fabricated through Stir Casting Process, Advances in Materials Science and Engineering, 2023: 1-17. https://doi.org/10.1155/2023/5442809

Stahl, T., Falk, S., Rohrbeck, A., Georgii, S., Herzog, C., Wiegand, A., Hotz, S., Boschek, B., Zorn, H. and Brunn, H. 2017. Migration of aluminium from food contact materials to food—a health risk for consumers? Part I of III: exposure to aluminium, release of aluminium, tolerable weekly intake (TWI), toxicological effects of aluminium, study design, and methods. Environmental Sciences Europe, 29**(**19): 1-25. https://doi.org/10.1186/s12302-017-0116-y

Weidenhamer, JD., Chasant, M. and Gottesfeld, P. 2022. Metal exposures from source materials for artisanal aluminium cookware. International Journal of Environmental and Health Research, 31: 1-12. Doi: 10.1080/09603123.2022.2030677.

Zunko, H. and Turk, C. 2022. Martensitic Stainless Steel for Food Contact Applications. Berg Huettenmaenn Monatsh, 167(9): 408–415. https://doi.org/10.1007/s00501-022-01267