Metallurgical and Materials Data 3, no. 2 (2025): 41-45

Publisher: Association of Metallurgical Engineers of Serbia

Metallurgical and Materials Data

www.metall-mater-data.com

Electrochemical Evaluation of 304 Stainless-Steel in Aqueous Curry-Leaf Extract: Effect of NaCl on Passivity and Food-Contact Safety

T. Umamathi [1], T. Uma Sankareswari[2], P. Vijayalakshmi[3], M. Devika[3], V. Kanmani[3], T. Lakshana[3], A. Mariya Agnes Deena[3], Susai Rajendran[3]*, Abdulhameed Al-Hashem[4], Caslav Lacnjevac[5]

[1] *Sri Meenakshi Government College, for Women (A), Department of Chemistry, Madurai, Tamil Nadu, India*
[2] *Rajapalayam Rajus' College, Rajapalayam, Department of Chemistry, Tamil Nadu, India*
[3] *St Antony's College of Arts and Sciences, Corrosion Research Centre, Dindigul, India (Affiliated to Mother Teresa Women's University, Kodaikanal, Ind(a)*
[4] *Kuwait Institute for Scientific Research, Petroleum Research Centre, Kuwait*
[5] *University of Belgrade, Faculty of Agriculture, Belgrade, Serbia*

A R T I C L E I N F O R M A T I O N :

https://doi.org/10.56801/MMD61

Received: 14 March 2025
Accepted: 21 June 2025

Type of paper: Research paper

A B S T R A C T

Stainless-steel drinkware and food containers must withstand complex, plant-based beverages that may include dissolved salts. This study quantifies the corrosion behaviour of 304 stainless steel (commercially "Ever Silver") in three media at 25 °C: de-ionised water, an aqueous extract of shade-dried curry leaves (CLE), and CLE containing 5 000 ppm NaCl. Potentiodynamic polarisation was carried out in a three-electrode cell (Ever Silver working electrode, SCE reference, Pt counter). Key parameters—including corrosion potential (E_corr), Tafel slopes, linear polarisation resistance (LPR), and corrosion current density (i_corr)—were extracted from the Tafel plots. Relative to water (LPR ≈ 6.2×10^4 Ω cm^2; i_corr ≈ 0.86 μA cm^{-2}), exposure to CLE alone reduced passivity markedly (LPR ≈ 4.0×10^4 Ω cm^2; i_corr ≈ 1.11 μA cm^{-2}), indicating enhanced anodic dissolution driven by phytochemicals that adsorb on the surface. Incorporating 5 000 ppm NaCl partially restored passivity (LPR ≈ 4.4×10^4 Ω cm^2; i_corr ≈ 1.05 μA cm^{-2}): chloride ions appear to promote a more compact, adsorbate-assisted film, offsetting some of the extract's aggressiveness, though the alloy remains less resistant than in pure water. The hierarchy of corrosion resistance derived from LPR and i_corr is: water > CLE + NaCl > CLE. Practically, 304 stainless vessels can safely accommodate curry-leaf infusions, and moderate chloride contents (typical of culinary use) mitigate rather than exacerbate deterioration compared with salt-free extracts. These findings support the suitability of "Ever Silver" containers for flavoured beverages while providing quantitative guidance for food-contact applications involving herbal ingredients.

Keywords: Stainless steel 304, Ever Silver, curry-leaf extract (CLE), potentiodynamic polarisation, linear polarisation resistance, corrosion current density, food-contact safety.

1. Introduction

Metal beverage cans have become an indispensable component of contemporary food-and-drink logistics. Their combination of low mass, stackability, and complete recyclability satisfies modern demands for mobility and environmental stewardship, while the inherent barrier properties of metals—effective exclusion of light, oxygen, and moisture—preserve carbonation, flavour, and micronutrient stability throughout distribution. Consequently, steel and aluminium alloys dominate container manufacture, and their corrosion performance in food and beverage environments has been the subject of sustained investigation (Friedrich 2019; Steiner Petrovič & Mandrino 2016; Hossain 2015; Baeghbali et al. 2022; Rossi et al. 2024; Mareci et al. 2017; Chang et al. 2023; Kiczek et al. 2024; Tranchida et al. 2020; Santamaria et al. 2020).

Within this context, austenitic stainless steels—particularly the 18 wt % Cr, 8 wt % Ni grade known as AISI 304—occupy a prominent niche in filling lines, vats, and household "Ever Silver" utensils because of their corrosion resistance, chemical inertness, ease of cleaning, and hygienic certification (Friedrich 2019; Hossain 2015). Nevertheless, real-world service exposes these alloys to synergistic combinations of chloride contamination, acidic food simulants, and aggressive detergents that can undermine passivity and initiate localised attack. Field observations

* Corresponding author.
E-mail address: susairajendran@gmail.com (Susai Rajendran).

of snack-bar equipment, for instance, revealed pitting on both AISI 304 and its ferritic counterpart AISI 430 after eighteen months of use; surface-sensitive Auger electron spectroscopy and X-ray photoelectron spectroscopy linked the damage to residual cleaning agents not removed during routine maintenance (Steiner Petrovič & Mandrino 2016). To mitigate such degradation without compromising food safety, engineers have explored low-temperature carburising or nitriding treatments that increase surface hardness and wear resistance while preserving corrosion behaviour (Friedrich 2019).

Stainless steel also figures prominently in bulk-handling equipment. Baeghbali et al. (2022) catalogue the variety of vats, vessels, and tanks employed across dairy, edible-oil, and beverage operations, whereas Rossi et al. (2024) emphasise that even the widely used 304 L grade remains susceptible to pitting and crevice corrosion once chloride activity, temperature, or residual tensile stress surpass critical thresholds. Mareci et al. (2017) further demonstrated that austenitic alloys immersed in acidified, carbonated soft drinks exhibit measurable metal dissolution, underscoring the need for alloy modification or protective coatings. Tinplate containers, valued for strength and formability, continue to evolve through easy-open technology, yet their tribological interfaces must be carefully optimised to avoid coating breakdown (Chang et al. 2023).

The interplay of wear and corrosion, or tribocorrosion, receives particular attention in cutting and filling components that experience simultaneous mechanical loading and chemical attack. Kiczek et al. (2024) showed that tempering 420 martensitic stainless steel at 200 °C yielded the lowest mechanical wear under onion-extract lubrication, whereas intermediate tempering at 400 °C maximised resistance under combined tribocorrosion conditions. From a micro-electrochemical perspective, Tranchida et al. (2020) and Santamaria et al. (2020) linked the electronic structure of passive films on 304 L, 316 L, and duplex 2507 stainless steels to their breakdown behaviour during prolonged immersion in hot purified water or acidic food simulants, illuminating the factors that lead to “rouging” and generalised dissolution.

Taken together, these studies emphasise that the corrosion performance of stainless-steel food containers is highly solution-specific—sensitive not only to chloride concentration and pH but also to organic species capable of adsorbing on and modifying the passive layer. The present contribution therefore addresses a heretofore unstudied scenario: the storage of curry-leaf infusions, with and without culinary levels of dissolved sodium chloride, in household “Ever Silver” (AISI 304) vessels. By employing potentiodynamic polarisation to quantify linear polarisation resistance, corrosion potential, and corrosion current density, we aim to clarify how phytochemicals and moderate chloride additions jointly influence passivity and to offer guidance for the safe domestic use of stainless-steel drinkware.

This work investigates the suitability of household “Ever Silver” (AISI 304) vessels for storing aqueous curry-leaf (Murraya koenigii) infusions. Potentiodynamic polarisation was used to characterise the alloy’s corrosion behaviour in three media—de-ionised water, curry-leaf extract, and curry-leaf extract containing 5 000 ppm NaCl—thereby isolating the effects of phytochemicals and moderate chloride levels on stainless-steel passivity.

2. Methods and materials

This section outlines the experimental methods and materials employed in the study.

2.1. Curry leaves

Curry leaves (Figure 1) are abundant in beneficial phytochemicals, including alkaloids, glycosides, and phenolic compounds, which contribute to the herb’s significant health advantages. Research indicates that curry leaves possess various compounds such as linalool, alpha-terpinene, myrcene, mahanimbine, caryophyllene, murrayanol, and alpha-pinene. Many of these compounds act as antioxidants within the body, which are crucial for maintaining health and preventing disease. They neutralize potentially harmful substances known as free radicals and mitigate oxidative stress, a condition linked to the onset of chronic diseases. Numerous studies have demonstrated that curry leaf extract exhibits strong antioxidant properties. Curry leaves contain compounds that have significant anticancer effects. Curry leaves may provide antibacterial, antidiabetic, analgesic, and anti-inflammatory benefits (Nigam 2023).

Fig. 1. Morphology of shade-dried Murraya koenigii (curry) leaves used for extract preparation

Curry leaves, referred to as kadi patta in India, serve as more than a mere culinary ingredient. These aromatic green leaves are rich in essential nutrients, including vitamins A, B, C, and E, as well as minerals like calcium, iron, and antioxidants. Historically utilized in Ayurvedic practices and natural beauty treatments, curry leaves are celebrated for their remarkable capacity to nourish, heal, and revitalize both skin and hair.

2.2. Curry leaves extract

50 g of shade dried curry leaves were boiled with water. The suspended impurities were removed by filtration. The resulting solution was made up to 100 ml in a standard flask. This solution was used in the present study.

2.3. Ever Silver Composition

Ever Silver was sourced from the vessel markets. Ever Silver is also known as SS 304 (World Material, n.d.; Umamathi et al., 2024; Horak et al., 1985; Choudhary and Singh, 2020). The constituents of SS 304 (Stainless Steel 304) are as follows: Chromium (Cr): 18-20%; Nickel (Ni): 8-10.5%; Carbon (C): Maximum 0.08%; Manganese (Mn): Maximum 2%; Silicon (Si): 0.75%; Phosphorus (P): Maximum 0.045%; Sulfur (S): Maximum 0.03%.

2.4. Electrochemical study

2.4.1. Polarization study

A three-electrode cell setup was utilized to acquire polarization curves. Different test solutions, such as water system, curry leaves extract (CLE) system, and curry leaves extract (CLE) + salt (sodium chloride- 5000 ppm) system were tested with the Ever Silver electrode. Polarization investigations were carried out using a CHI 660A electrochemical workstation. The corrosion resistance of the Ever Silver electrode was evaluated while submerged in the various test solutions. The configuration included a working electrode composed of Ever Silver, a saturated calomel electrode (SCE) functioning as the reference electrode, and a platinum counter electrode (refer to Figure 2).

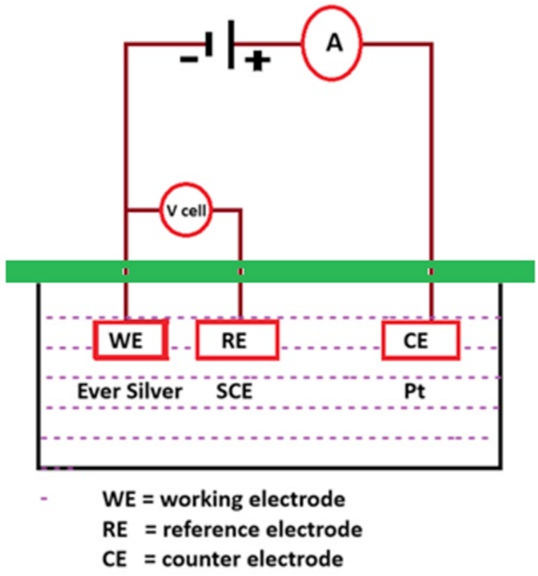

Fig. 2. Schematic of the three-electrode cell employed for potentiodynamic polarisation experiments

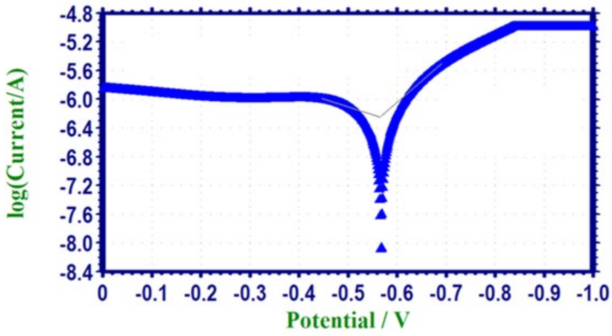

Fig. 3. Tafel polarisation curve of 304 stainless steel ("Ever Silver") in de-ionised water at 25 °C

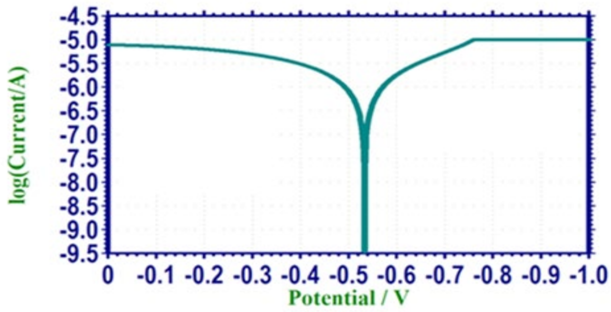

Fig. 4. Tafel polarisation curve of 304 stainless steel in curry-leaf extract (CLE, 50 g L^{-1}) at 25 °C

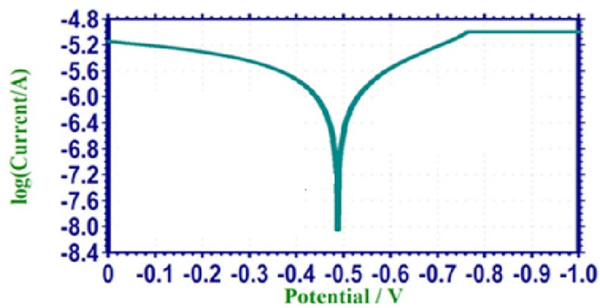

Fig. 5. Tafel polarisation curve of 304 stainless steel in CLE containing 5 000 ppm NaCl at 25 °C

3. Results

The corrosion resistance of Ever Silver (SS 304 alloy) has been assessed through polarization studies while immersed in various environments, including water system, curry leaves extract (CLE) system, and curry leaves extract (CLE) + salt (sodium chloride- 5000 ppm) system.

The resulting polarization curves are illustrated in Figures 2-4. Key corrosion parameters, including corrosion potential, Tafel slopes (βc for cathodic and βa for anodic), linear polarization resistance (LPR), and corrosion current values, are presented in Table 1. A comparative analysis of these values is depicted in Figures 5-7. It is widely recognized that in polarization studies, an increase in corrosion resistance corresponds to a rise in LPR values and a decrease in corrosion current, as shown in Figure 8 ((Parveen et al., 2025; Soedarsono et al., 2025; Bedair et al., 2025; Zgueni et al., 2025; Xu et al., 2025).

Table 1. The corrosion parameters of Ever Silver containing aqueous extract of curry leaves (ECL) with salt (sodium chloride) and without salt

System	E_{corr} mV vs SCE	β_c mV/decade	β_a mV/decade	LPR Ohmcm²	I_{corr} A/cm²
Water	-567	168	454	61698	0.8638 x10^{-6}
ECL without salt	-533	189	218	39663	1.111 x10^{-6}
ECL with salt	-487	199	226	43845	1.047x10^{-6}
Observation (Comparison of without salt and with salt)	The shift is almost within 50 mV			increases	decreases
Inference	Corrosion process at anode and cathode are controlled to an equal extent			Corrosion resistance increases	Corrosion resistance increases
Implication	*A solution derived from curry leaves, which includes sodium chloride, can be safely stored in Ever Silver containers.*				

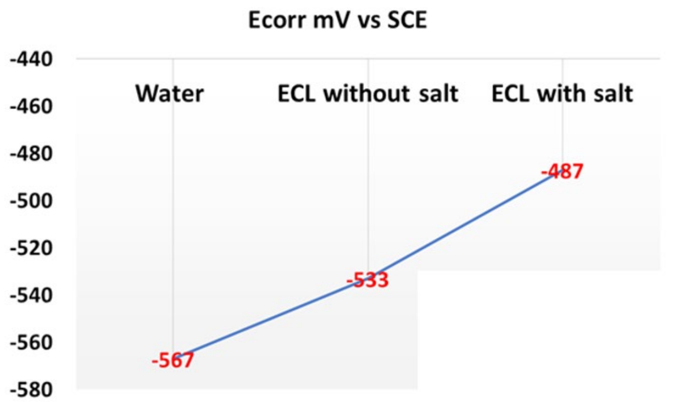

Fig. 6. Corrosion potential (Ecorr) of 304 stainless steel in water, CLE, and CLE + NaCl environments

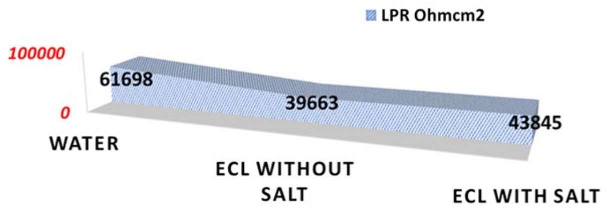

Fig. 7. Linear polarisation resistance (LPR) of 304 stainless steel in the three test media

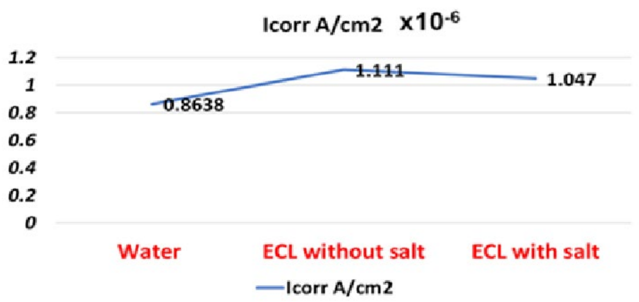

Fig. 8. Corrosion current density (icorr) of 304 stainless steel as a function of test solution

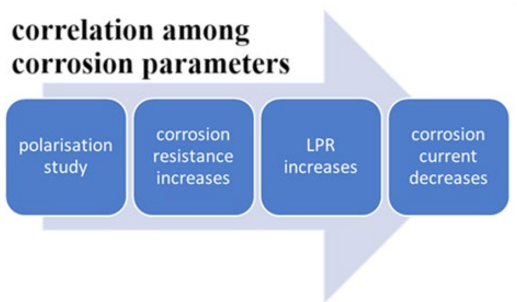

Fig. 9. Correlation among Ecorr, LPR, and icorr derived from Tafel analysis for the studied systems

4. Discussion

The electrochemical data obtained in this study confirm that passivity of AISI 304 stainless steel is highly sensitive to the chemical milieu typically encountered in culinary practice. In de-ionised water, the alloy displayed the most noble corrosion potential (-567 mV vs SCE), the highest polarisation resistance (6.17×10^4 Ω cm^2) and the lowest corrosion current density (0.86 µA cm^{-2}), reflecting the stability of its chromium-rich passive film under near-neutral, chloride-free conditions. These values align well with the baseline behaviour reported for 304 SS in non-aggressive media (Mareci et al., 2017; Santamaria et al., 2020) and serve as a reference for assessing the impact of plant extracts and dissolved salts.

Introducing an aqueous curry-leaf extract (CLE) altered the electrochemical response markedly. The linear polarisation resistance fell to 3.97×10^4 Ω cm^2 and i_corr rose to 1.11 µA cm^{-2}, indicating that phytochemical constituents compromise passivity. Curry leaves are rich in phenolics, terpenoids and alkaloids (Nigam, 2023); several of these species can chelate iron or chromium and adsorb competitively on the steel surface, thereby thinning or destabilising the native oxide film. A comparable acceleration of anodic dissolution has been observed for stainless steels exposed to polyphenol-bearing beverages such as tea and wine (Rossi et al., 2024). The net effect is an increase in the defect density of the passive layer, reflected in the steeper Tafel slopes and higher i_corr recorded in the present work.

The addition of 5 000 ppm NaCl to the extract produced a more nuanced response. Chloride ions are classically viewed as promoters of localised corrosion; however, in the CLE matrix they appear to interact synergistically with adsorbed organics, yielding a slightly more protective interphase. Both LPR (4.38×10^4 Ω cm^2) and i_corr (1.05 µA cm^{-2}) moved towards the values measured in pure water, though not fully recovering the original passivity. One plausible interpretation is that chloride accelerates the ionisation of certain phytochemicals, allowing them to polymerise or cross-link on the steel surface and form a denser, mixed organic-inorganic film. Similar chloride-assisted compaction of inhibitor layers has been reported for amino-acid–derived films on mild steel (Parveen et al., 2025) and could account for the modest improvement seen here. Nevertheless, the persistence of a higher corrosion current than in water indicates that the protective action is partial and that prolonged exposure or elevated chloride activities might still trigger pitting, as cautioned by field studies in food-processing equipment (Steiner Petrovič & Mandrino, 2016).

Taken together, the hierarchy of corrosion resistance established—water > CLE + NaCl > CLE—highlights two key points. First, plant extracts alone can be more aggressive than their salted counterparts, underscoring the need to evaluate so-called “natural” beverages case-by-case rather than assuming benignity. Second, moderate culinary concentrations of sodium chloride do not invariably exacerbate corrosion and, under specific chemical conditions, may even temper it. From a practical perspective, short-term storage of curry-leaf infusions in household 304 SS vessels is unlikely to pose a significant risk, particularly when the beverage contains typical seasoning levels of salt. However, the limited test temperature (25 °C) and immersion time mean that longer exposures, elevated temperatures, or cyclic cleaning procedures could still challenge the alloy, warranting further investigation through extended immersion, tribocorrosion trials, and surface-analytical characterisation (SEM/EDS, XPS, AFM).

5. Conclusions

Potentiodynamic polarisation at 25 °C confirmed that AISI 304 (“Ever Silver”) exhibits its highest passivity in de-ionised water, whereas an aqueous curry-leaf extract accelerates dissolution; adding 5 000 ppm NaCl moderates this effect, yielding an intermediate but acceptable corrosion rate and indicating that salted curry-leaf infusions can be stored in 304-steel vessels without undue risk during short contact times. These findings are constrained by a single temperature, brief immersion periods, and the absence of surface-analytical verification of the passive film; they also reflect only one extract concentration and chloride level. Future work should therefore couple longer, multi-temperature or tribocorrosion exposures with SEM/XPS characterisation and broaden the test matrix to include varied chloride activities and other culinary herb extracts.

References

Baeghbali, Vahid, Somayeh Hedayati, and Seyed M. Jafari. "Storage vats, vessels, and tanks." In Transporting Operations of Food Materials within Food Factories: Unit Operations and Processing Equipment in the Food Industry, 15-30 (2022). https://doi.org/10.1016/B978-0-12-818585-8.00012-X

Bedair, Mohammed A., Q. A. Yousif, Z. Fadel, F. A. Al-Odail, and A. M. Abuelela. "Experimental and theoretical analyses of the corrosion-inhibition efficacy of new penicillanic acid derivatives for carbon steel in hydrochloric-acid environment." Journal of Molecular Structure 1328 (2025): 141282. https://doi.org/10.1016/j.molstruc.2024.141282

Chang, Y. H., Y. Iyama, S. Kawaguchi, J. Suehiro, and H. Kawarada. "Ion-sensitive stainless-steel vessel for all-solid-state pH sensing system incorporating pH-insensitive diamond solution-gate field-effect transistors." IEEE Sensors Journal 23, no. 9 (2023): 9110-9119. https://doi.org/10.1109/JSEN.2023.3257348

Choudhary, Gourav, and Gurpreet Singh. "Comparative analysis of corrosion behaviour of stainless-steel grades 304 and 316L for different applications." i-Manager's Journal on Material Science 7, no. 4 (2020): 8. https://doi.org/10.26634/jms.7.4.16094

Friedrich, A. "Migration testing of low-temperature surface-hardened stainless steels." Italian Journal of Food Science 31, no. 5 (2019): 109-115.

Horak, J. A., V. K. Sikka, and D. T. Raske. Review of Effects of Long-Term Aging on the Mechanical Properties and Microstructures of Types 304 and 316 Stainless Steel. Oak Ridge: Oak Ridge National Laboratory, 1985.

Hossain, Md R. "Metallurgical aspect of chemical pickling and recent developments." In Stainless Steel: Microstructure, Mechanical Properties and Methods of Application, 141-167 (2015).

Kiczek, Tomasz, Anna Stachowiak, Dawid Ulbrich, Agnieszka Bartkowska, and Agnieszka Bieńczak. "Tribocorrosion behavior of 420 martensitic stainless steel in extracts of Allium cepa." Wear 558-559 (2024): 205576. https://doi.org/10.1016/j.wear.2024.205576

Mareci, D., L. C. Trinca, V. V. Cotea, and R. M. Souto. "Electrochemical studies on the stability and corrosion resistance of two austenitic stainless steels for soft-drink containers." International Journal of Electrochemical Science 12, no. 6 (2017): 5438-5449. https://doi.org/10.20964/2017.06.35

Nigam, Lata. "A review on medicinal benefits of curry leaves." Journal of Advancement in Pharmacognosy 3, no. 1 (2023).

Parveen, Mosarrat, Mohammad Mobin, Saman Zehra, Manilal Murmu, and Priyabrata Banerjee. "L-tryptophanium picrate as novel anticorrosion agent for mild steel in 5% HCl: A detailed experimental and in silico investigation." Journal of Molecular Structure 1324 (2025): 140894. https://doi.org/10.1016/j.molstruc.2024.140894

Rossi, Silvia, Sonia M. Leso, and Marta Calovi. "Study of the corrosion behavior of stainless steel in food industry." Materials 17, no. 7 (2024): 1617. https://doi.org/10.3390/ma17071617

Santamaria, Mariano, Giuseppe Tranchida, and Fabio Di Franco. "Corrosion resistance of passive films on different stainless-steel grades in food and beverage industry." Corrosion Science 173 (2020): 108778. https://doi.org/10.1016/j.corsci.2020.108778

Soedarsono, J. W., A. Andoko, K. Diharjo, S. M. Rangappa, and S. Siengchin. "Biodegradable PLA/HEC-ZnO nanocomposite for corrosion protection of ASTM A36 steel: A combined quantum and electrochemical analysis." Case Studies in Chemical and Environmental Engineering 11 (2025): 101039. https://doi.org/10.1016/j.cscee.2024.101039

Steiner Petrovič, Darko, and Darko Mandrino. "AES and XPS investigations of the cleaning-agent-induced pitting corrosion of stainless steels used in the food-processing environment." Food and Bioproducts Processing 100 (2016): 230-237. https://doi.org/10.1016/j.fbp.2016.07.006

Tranchida, Giuseppe, Fabio Di Franco, Benedetta Megna, and Mariano Santamaria. "Study of corrosion resistance of stainless steels for food and beverage industry." Metallurgia Italiana 112, no. 4 (2020): 16-21.

Umamathi, Thangarajan, Venkatachalam Prathipa, Arockiam Roslin, Arockiaraj Little Jewelcy, Micheal Velankanni Jeevithe Clara, Nilavan Anitha, Mohamed Ibrahim Nasrin Sahana, Rajendran Susai, and Arjunan Krishnaveni. "Influence of sodium chloride on corrosion resistance of ever-silver vessels in the presence of curd rice." Zastita Materijala 65, no. 4 (2024): 765-777. https://doi.org/10.62638/ZasMat1173

World Material. "304 Stainless Steel Properties: SS304 Composition, Density, Yield Strength, Thermal Conductivity, Hardness, Modulus of Elasticity." Accessed 30 June 2025. https://www.theworldmaterial.com/304-stainless-steel/

Xu, D., X. Wang, M. Li, X. Zhang, and Y. Huang. "Enhancing titanium-osteointegration: Antimicrobial, anti-inflammatory and osteogenic properties of multifunctional coatings through layer-by-layer self-assembly." Applied Surface Science 686 (2025): 162149. https://doi.org/10.1016/j.apsusc.2024.162149

Zgueni, H., M. E. Mesky, A. Moussaif, S. Echihi, and D. Chebabe. "Theoretical and experimental study of the corrosion inhibition of carbon steel in 1 M HCl solution by a new synthesized organic compound derived from carbendazim." Journal of Molecular Structure 1327 (2025): 141230. https://doi.org/10.1016/j.molstruc.2024.141230