engineering proceedings

Proceeding Paper

Investigation of the Corrosion of Steel S235JR in Common Beverages †

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† Presented at the 15th International Scientific Conference TechSys 2026—Engineering, Technologies and Systems, Plovdiv, Bulgaria, 14–16 May 2026.

Abstract

The widespread application of plain S235JR steel across various industries often involves its exposure to degradative conditions, such as the organic acid concentrations typically found in various foodstuffs. This study investigates the corrosion behavior of S235JR steel immersed in several common beverages. The corrosion of steel S235JR was evaluated by gravimetric and electrochemical study. Statistical modeling via multiple linear regression and ANOVA was utilized to verify the experimental dataset. Based on the results, the highest early-stage corrosion occurs in coffee and tomato juice, though apple cider vinegar stands out for its steadily intensifying corrosive effect over the immersion period. Conversely, the presence of citric acid in lemon and orange juices appears to act as an inhibitor, leading to the lowest observed corrosion rates. The strong correlation between electrochemical parameters (I_{corr} and E_{ocp}) and physical mass loss confirms that the chemical nature of each beverage significantly governs the corrosion kinetics of S235JR.

Keywords: S235JR steel; corrosion rate; food environments; statistical analysis

1. Introduction

S235JR steel is widely employed in mechanical engineering for manufacturing metal structures for industrial and residential construction, technical equipment components, marine facilities, gas and oil platforms, and other structures. Due to its widespread use in industry, it is often in contact with aggressive environments that cause its corrosion. Such environments can include a number of organic acids contained in fruit and vegetable juices, as well as in coffee [1–4]. Previous research has demonstrated that while certain organic compounds accelerate metal dissolution, many natural extracts from fruits and plants can exhibit inhibitory properties, forming a protective layer on the steel surface [5–7]. This makes the study of common beverages particularly relevant for understanding the long-term durability of structural alloys like S235JR. This article investigates the corrosion behavior of S235JR steel in several common beverages such as lemon juice, orange juice, coffee, and tomato juice using gravimetric analysis over a period of 7 to 27 days, alongside potentiodynamic polarization measurements after 7 days of immersion.

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Academic Editors: Nikola G. Shakev, Valyo N. Nikolov, Nikolay R. Kakanakov and Sevil A. Ahmed-Shieva

Published: 12 August 2026

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2. Materials and Methods

2.1. Gravimetric Analysis

Following surface cleaning to remove contaminants, the S235JR alloy samples were weighed using an analytical balance. They were then immersed in freshly prepared lemon and orange juices, coffee (espresso), apple cider vinegar, and tomato juice (canned) and left in a refrigerator at 0 °C for the specified test periods. After 7 days of immersion, the samples were re-weighed to determine the mass loss. The measurements were repeated after 14, 20, and 27 days.

2.2. Electrochemical Analysis

The electrochemical characteristics of the S235JR alloy were evaluated in various media—specifically espresso, canned tomato juice, and fresh citrus juices (lemon and orange)—utilizing a potentiostat/galvanostat (Model 263A, Princeton Applied Research, Oak Ridge, TN, USA). The experimental setup consisted of a standard three-electrode configuration, featuring a platinum auxiliary electrode, an $Ag/AgCl$ (saturated KCl) reference, and the steel sample as the working electrode. To ensure precise measurements, only 1 cm^2 of the working electrode was exposed to the solution, with the remaining surface area insulated by protective varnish.The testing protocol began by monitoring the open circuit potential (E_{OCP}) for a duration of 200 s within each beverage. This was followed by potentiodynamic polarization, conducted at a steady scan rate of 0.16 mV/s. The potential was swept automatically from -0.250 V to $+0.250$ V relative to the E_{OCP}, and all resulting data were analyzed using the Power Suite v. 2.56 software package (Princeton Applied Research, Oak Ridge, TN, USA).

3. Results

3.1. Gravimetric Analysis

After 7 days of immersion, the highest corrosion rate was observed in tomato juice, followed by coffee, apple cider vinegar, and orange juice, while the lowest rate was recorded in lemon juice. The probable reason for this behavior is the inhibitory effect of citric acid, which is present in these citrus juices. At the end of the study period (27 days), the corrosion rates in lemon and orange juices remained low compared to those in apple cider vinegar, coffee, and tomato juice, where the values remained high. These findings are supported by the electrochemical measurements, with the notable exception of apple cider vinegar.

Figure 1 illustrates the corrosion rate in various food environments over periods ranging from 7 to 27 days. Both charts present the same experimental data using different visualization methods (line and bar charts) for a more comprehensive analysis. The results clearly indicate that the initial corrosion is highest in tomato juice and coffee; furthermore, while the corrosion rate generally decreases over time for most media, it exhibits a distinct increasing trend in the case of apple vinegar.

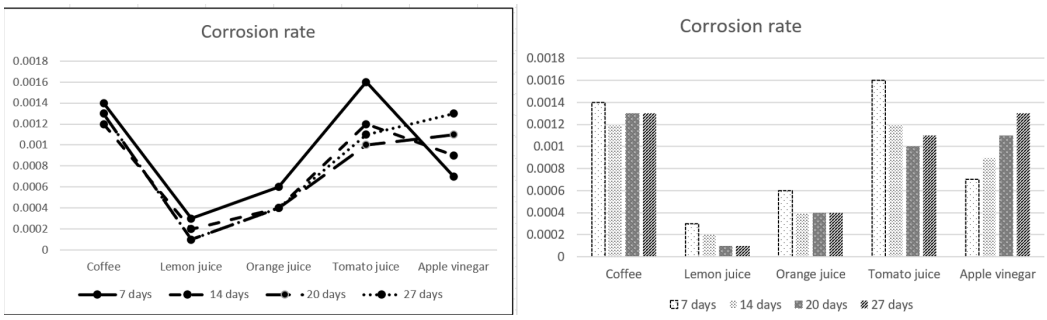

Figure 1. Corrosion rate of alloy S235JR.

To statistically validate the experimental observations and evaluate the overall reliability of the mathematical model, a multiple linear regression analysis was performed.

The summary statistics in Figure 2 demonstrate a strong correlation between the variables, with a multiple correlation coefficient (R) of 0.945. The coefficient of determination (R^2) is 0.893, indicating that 89.3% of the variance in the corrosion rate of the S235JR alloy is directly explained by the independent variables used in the study (type of environment and exposure time). Furthermore, the significance level ($p < 0.001$) confirms that the overall regression model is highly statistically significant and reliable for predicting the corrosion behavior.

Model Summary									
					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	0.945[a]	0.893	0.855	0.00018329	0.893	23.407	5	14	0.000

a. Predictors: (Constant), Supp.= Tomato juice, time, day, Supp.= Coffee, Supp.= Lemon juice

Figure 2. Model summary for the multiple linear regression analysis.

To further assess the overall significance of the regression model, an Analysis of Variance (ANOVA) was conducted.

The ANOVA results (Figure 3) indicate that the multiple linear regression model is highly significant ($F(5, 14) = 23.407, p < 0.001$). This confirms that the combination of the selected predictors (exposure time and type of environment) significantly predicts the corrosion rate of the S235JR alloy. Therefore, the proposed mathematical model is statistically robust and not a result of random chance.

ANOVA[a]						
Model		Sum of Squares	dF	Mean Square	F	Sig.
1	Regression	0.000	5	0.000	23.407	0.000[b]
	Residual	0.000	14	0.000		
	Total	0.000	19			

a. Dependent Variable: CR S235JR

b. Predictors: (Constant), Supp.= Tomato juice, time, day, Supp.= Coffee, Supp.= Lemon juice

Figure 3. Analysis of Variance (ANOVA) for the multiple linear regression model.

After confirming the overall significance of the regression model, the individual contribution of each independent variable was evaluated.

The analysis of the regression coefficients (Figure 4) reveals the specific impact of each tested environment on the corrosion behavior. The results demonstrate that lemon juice ($p < 0.001$), orange juice ($p = 0.001$), and coffee ($p = 0.036$) have a statistically significant effect on the corrosion rate. Conversely, within the investigated timeframe, the duration of exposure (time, days; $p = 0.519$) and the tomato juice medium ($p = 0.104$) do not show a statistically significant linear correlation with the dependent variable in this specific model. The inhibitory effect of citrus juices observed in the gravimetric study is consistent with broader research on plant-derived green inhibitors, which often form a protective adsorption layer on the steel surface in acidic media [8–10]. This protective mechanism explains why lemon and orange juices exhibit significantly lower corrosion rates compared to the more aggressive apple cider vinegar environment.

https://doi.org/10.3390/engproc2026150130

Coefficients[a]						
Model		Unstandardized B	Coefficients Std, Error	Standardized Coefficients Beta	t	Sig.
1	Constant	0.001	0.000		8.076	0.000
	Time, days	−0.00000367	0.000	−0.058	−0.661	0.590
	Supp.= Coffee	0.000	0.000	0.256	2.315	0.036
	Supp.= Lemon juice	−0.001	0.000	−0.703	−6.366	0.000
	Supp.= Orange juice	−0.001	0.000	−0.469	−4.244	0.001
	Supp.= Tomato juice	0.000	0.000	0.192	1.736	0.104

a. Dependent Variable: CR S236JR

Figure 4. Multiple linear regression coefficients for the corrosion rate of S235JR alloy.

The multiple linear regression equation for predicting the corrosion rate (CR) of the S235JR alloy is expressed as follows:

$$CR = 0.001 - (3.67 \times 10^{-6}T) + (0.000C) - (0.001L) - (0.001O) + (0.000T_{om}),$$

where T represents the exposure time in days, and C, L, O, and T_{om} are indicator variables (0 or 1) assigned to coffee, lemon juice, orange juice, and tomato juice, respectively. Apple cider vinegar serves as the reference category for the model.

3.2. Electrochemical Analysis

The electrochemical parameters measured for alloy S235JR after 7 days of immersion indicate a high corrosion rate in apple cider vinegar, tomato juice, and coffee. Conversely, the lowest corrosion rate was exhibited by the alloy in lemon juice, followed by orange juice. The corrosion behavior of alloy S235JR in various media is summarized in Table 1.

Table 1. Electrochemical parameters of alloy S235JR after 7 days.

Solution 7 Days	E_{OCP} (V)	I_{corr} (μA)	CR (mpy)
Lemon juice	−0.447	6.7×10^{-7}	6.2×10^{-7}
Orange juice	−0.504	7.13×10^{-6}	6.54×10^{-6}
Coffee	−0.489	1.871×10^{-5}	1.716×10^{-5}
Tomato juice	−0.559	2.975×10^{-5}	2.732×10^{-5}
Apple vinegar	−0.480	4.214×10^{-5}	3.869×10^{-5}

A deeper analysis of these parameters provides insight into both the thermodynamics and kinetics of the corrosion process. The corrosion current (I_{corr}), which is directly proportional to the corrosion rate according to Faraday's law, indicates the highest kinetic activity in apple cider vinegar (0.00004214 µA) and tomato juice (0.00002975 µA). Conversely, the lowest Icorr was exhibited by the alloy in lemon juice (0.00000067 µA), followed by orange juice. Furthermore, the open-circuit potential (E_{ocp}) values characterize the thermodynamic tendency of the steel to corrode in these specific environments. The most noble (least negative) E_{ocp} value was recorded in lemon juice (−0.447 V), suggesting a higher thermodynamic stability of the surface, potentially due to the rapid formation of a passive film facilitated by the citric acid. In contrast, tomato juice exhibited the most active (most negative) potential (−0.559 V), indicating a strong thermodynamic driving force for anodic dissolution. Similar electrochemical behavior has been documented for various natural organic extracts, where theire presence leads to a shift in the corrosion potential and a reduction in the corrosion current density [11,12]. Crucially, these instantaneous electrochemical parameters measurements are in agreement with the previously discussed 7-day gravimetric mass loss data, confirming the aggressive nature of the acetic acid in the vinegar compared to the inhibitory behavior observed in the citrus juices.

4. Conclusions

Based on the comprehensive gravimetric, electrochemical, and statistical analyses of S235JR steel exposed to various food environments, the following main conclusions can be drawn:

- Varying Aggressiveness of Media: The corrosion rate of S235JR steel is highly dependent on the type of food environment. Apple cider vinegar and tomato juice are the most aggressive media, exhibiting the highest corrosion currents (I_{corr}), leading to significant material degradation.
- Inhibitory Effects: Citrus juices demonstrate a notable inhibitory effect on the corrosion process. Lemon juice, in particular, exhibited the lowest corrosion rate, highest thermodynamic stability, and lowest kinetic activity, likely facilitated by the protective nature of citric acid.
- Time-Dependent Behavior: While the corrosion rate generally decreases or stabilizes over time for environments like tomato juice and coffee, exposure to apple cider vinegar results in a continuously increasing corrosion trend over the 27-day test period.
- Statistical and Methodological Validity: There is a strong correlation between the 7-day gravimetric findings and the electrochemical measurements, which validates the overall experimental approach. Furthermore, the statistical robustness of the proposed model was confirmed through regression and ANOVA ($p < 0.001$), demonstrating that the specific food environment exerts a significant and predictable influence on S235JR corrosion.

Author Contributions: Conceptualization, K.K. and I.N.; methodology, K.K., I.N., R.T., I.P. and R.K.; software, I.N. and R.T.; validation, K.K., I.N., I.P. and R.T.; formal analysis, K.K. and I.N.; investigation, K.K. and I.P.; resources, K.K., I.P. and R.K.; data curation, K.K. and I.N.; writing-original draft preparation K.K., I.P., I.N. and R.T.; writing-review and editing, K.K. and I.N.; visualization, R.T. and R.K.; supervision, I.N. and R.T.; project administration, R.T.; funding acquisition, K.K., I.N., R.T., I.P. and R.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors would like to thank the Research and Development Sector at the Technical University of Sofia for providing financial support.

Conflicts of Interest: The authors declare no conflicts of interest.

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