A FACTORIAL EXPERIMENTAL DESIGN METHOD FOR ANALYSING CORROSION RATE OF AISI 316L STAINLESS STEEL IN SELECTED TROPICAL FRUIT JUICE MEDIA

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ABSTRACT: The utilisation of AISI 316L stainless steel in kitchenware is widespread due to its exceptional strength and remarkable corrosion resistance. Nevertheless, the susceptibility of stainless steel to corrosion from regularly utilised cooking substances, such as fruit juice, remains uncertain. Hence, it is crucial to assess the impact of frequently utilised fruit juice mediums on the corrosion resistance of 36L stainless steel kitchen equipment. The weight-loss method will be employed to assess the impact of the corrosion resistance quality of 316L stainless steel on specific tropical liquids (lime, tamarind, and pineapple). Measurements were conducted every 8 days over a period of 40 days. The experiment was designed and the data were analysed using experimental design (DOE) and variance analysis (ANOVA) methodologies. The results of this study indicate that tamarind juice had the highest corrosion rate of 0.4775mmyear^{-1}, followed by lime juice, while pineapple juice had the lowest corrosion rate of 0.0075mmyear^{-1}. The corrosion rates exhibited a maximum value during the initial week of the experiment, followed by a progressive decline over the course of time. This study also introduced a regression equation that includes the three distinct mediums studied.

KEYWORDS: *316L stainless steel; Corrosion rate; weight loss technique; Tropical fruit juice*

1.0 INTRODUCTION

Stainless steels are produced from elemental constituents often present in the earth's crust, including iron ore, chromium, silicon, nickel, carbon, nitrogen, and manganese [1,2]. Stainless steel is an iron-based alloy that contains a minimum chromium content of 10.5%. The element chromium generates a thin oxide coating on the steel's surface, referred to as the passive layer, which serves to prevent further corrosion and facilitates self-healing in the presence of oxygen. According to Yoo [3], an increase in chromium content leads to an enhancement in corrosion resistance. In addition to its primary constituent of iron, stainless steel is composed of varying quantities of silicon, carbon, and manganese. Additional elements, like molybdenum and nickel, can be included in the material to offer supplementary advantages, such as improved formability and resistance to corrosion [3-5]. As stated by Zaffora et al. [6], stainless steel has exceptional resistance to corrosion and outstanding mechanical properties, making it a suitable material for use in the food industry.

Stainless steel 316L (AISI 316L) variants are extensively employed in the manufacturing of utensils, including commercial cookers, cutlery, and process equipment for fruit juice processing. This preference is primarily attributed to their inherent properties, namely the ability to safeguard food taste and facilitate effortless cleaning with minimal upkeep requirements [1,7]. Although stainless steels are commonly utilised in the food business and as utensils, they can exhibit a high level of reactivity in acidic environments, hence giving rise to corrosion phenomena. Extended exposure of stainless steels to acidic environments might result in the occurrence of passive corrosion. Zaffora et al. [6] stated that corrosion in stainless steel can lead to the release of ions or metal particles, which could potentially pose health hazards to people. The corrosion of stainless steel is affected by various elements such as flow rate, temperature, pressure, ethanol concentration, and chloride ion content. Pitting corrosion is the predominant type of corrosion that occurs in stainless steel, resulting in material degradation. Pitting corrosion is then accompanied by uniform corrosion and stress corrosion cracking [8]. Furthermore, in the food industry, the production process can cause significant corrosion to the equipment materials, resulting in the release of metals in the form of ions, particles, or complexes [9]. These metal contaminants can have an adverse impact on the overall quality of the finished product [10]. Therefore, it is crucial to carefully choose equipment materials to prevent any contamination of the food or beverages.

Malaysia is acknowledged as a tropical country that produces millions of metric tonnes of various tropical fruits every year [11,12]. Malaysians demonstrate an extensive tendency towards using tropical fruits in their daily cooking activities. According to the studies conducted by Salleh et al. [13] and Shahida et al. [14], fruit juices is widely utilised as a main ingredient in everyday cooking, as a drink, and to enhance the flavour of other food products. Consequently, even the extremely resistant alloy can undergo substantial corrosion issues when exposed to conditions that include organic acids, such as tropical fruit juices.

Developing a comprehensive understanding of the corrosion characteristics of AISI 316L stainless steel in acidic environments is crucial for improving its efficiency in the food processing industry, where it often comes into contact with acidic substances. In order to systematically investigate the components that affect the rate of corrosion, one can utilise a factorial experimental design approach. This approach enables the examination of various factors and their simultaneous interactions, resulting in an extensive understanding of the corrosion mechanism in operation.

This work employs a factorial experimental design to evaluate the corrosion rate of AISI 316L stainless steel in several tropical fruit juice media, including pineapple, lime, and tamarind. The aim of the study is to determine the corrosion characteristics of 316L stainless steel by evaluating the impact of different types of commonly used fruit juices, taking into account parameters such as juice type and exposure period (duration, days). The results of this study will be beneficial for enhancing the durability and efficiency of stainless steel in food processing applications and other industries that frequently encounter organic acids.

2.0 MATERIALS AND METHODS

2.1 Raw Materials Preparation

The sample used in this study was an AISI 316L stainless steel plate with a thickness of 0.9 mm (Figure 1a). The samples went through surface roughness testing to measure the material's surface finish. Then, the plate was cut into a rectangular shape, as shown in Figure 1b. Each sample was rinsed with distilled water and ethanol before drying. The approach was based on the research conducted by Hamzat et al. [15]. The prepared samples were stored in desiccators to avoid atmospheric corrosion.


(a) (b)

Figure 1: (a) AISI 316L stainless steel plate used in this study (b) Samples after cutting process

The juice from three types of common juice producing tropical fruits were used as media in this study. The selected fruits were pineapple, line and tamarind, easily found as cooking ingredients and have also been consumed as juice for drinking in Malaysia [13,14]. Several steps were conducted to extract the pure fruit juice from the fresh fruit source. The fruits were crushed or blended using a food processor and filtered using a cloth filter to remove any fibres. Each of the produced juices was measured at 1500 ml and collected in the glass container to measure the pH value.

2.2 Corrosion Test

The corrosion test experiment was established in the laboratory and carried out for a duration of 40 days, with measurements taken on 5 occasions. The measured samples of AISI 316L stainless steel were hung using thread in separate beakers containing pineapple juice, lime juice, and tamarind juice. The beakers were kept still to prevent any movement or displacement. The duration of exposure was 40 days, and measurements were obtained every 8 days during this period. The pineapple, lime, and tamarind samples were extracted from the media and thoroughly rinsed in distilled water prior to being dried using a hand dryer. The desiccated specimens were then measured meticulously using a precision scale until a consistent weight was attained. Figure 2 presents a comprehensive overview of the procedure of sample preparation and the subsequent corrosion test.

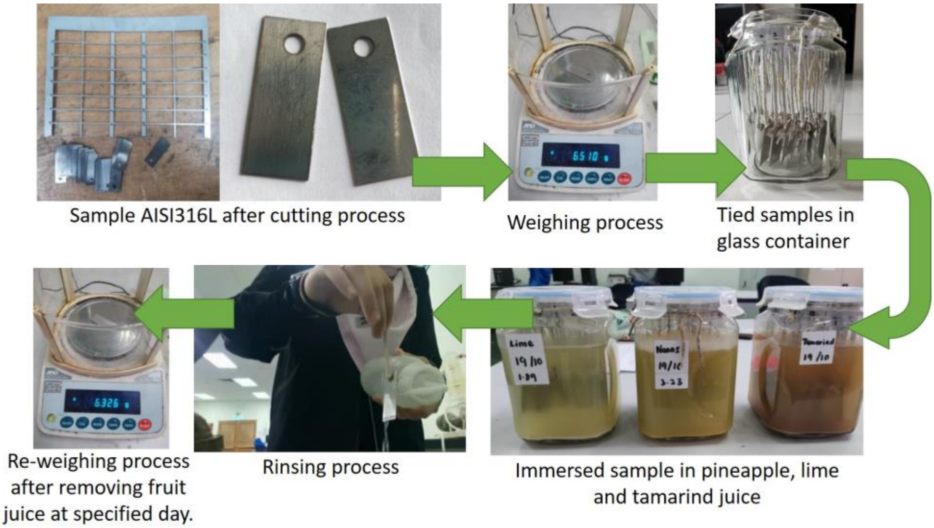


Figure 2 : Summary of process sample preparation and corrosion test done in this study

The average corrosion rates of 316L stainless steel in various types of tropical fruit juice environments were calculated using Equation (1) [16].

$$\text{Corrosion Rate} = \frac{WK}{\rho AT} \qquad (1)$$

The corrosion rate of the sample, denoted as CR, was measured in millimetres per year (mmyear^{-1}). It was calculated using the weight loss of the sample, denoted as W, in milligrams (mg), and the corrosion rate unit conversion factor, denoted as K, equal to 8.76×10^4 [17]. The density of the metal, denoted as ρ , was measured in milligrams per cubic meter (mg/m^3). The area of the specimen, denoted as A, is measured in square millimetres (mm^2). The exposure period, represented by the variable T, was quantified.

2.3 Generic Factorial Design

The corrosion rate of 316L stainless steel is influenced by several factors, as shown by existing literature and prior corrosion experiments. These factors include the time of exposure (measured in days), the thickness of the stainless steel specimen (measured in millimetres), and the type of media utilised (specifically pineapple, lime, and tamarind). These parameters are considered independent variables in the context of studying the corrosion rate of 316L stainless steel. The corrosion rate was determined using a generic factorial design, where various factor levels were applied. The design information for each parameter and its related levels may be found in Table 1.

In this study, the experiment consists of 15 runs, with two components, A and B, each having three and five levels, respectively, resulting in a total of 15 experimental runs. In order to mitigate bias and get a precise estimation of error, each trial of the experiment was randomised.

Table 1: Design information for the experiment conducted

Factor	Factor levels	Values
A : Medium	3	Pineapple (P) , Lime (L), Tamarind (T)
B : Duration (days)	5	1,2,3,4,5

3.0 RESULTS AND DISCUSSIONS

3.1 Corrosion Rate Analysis using ANOVA Method

The methodology relies on statistical analysis and seeks to evaluate the importance of different parameters in an experimental context. Factorial designs are beneficial in experimental design, especially when there are several components and their interactions that need to be taken into account. This approach has several benefits, such as the capability to examine various degrees of factor combinations and a certain number of factors utilising the minimum number of runs in a complete factorial experimental design. The results obtained from a comprehensive factorial design can be easily expressed with reference to the regression model.

The corrosion rate was determined by applying equation (1), and the resulting value was subsequently inputted into Minitab software, a commercially accessible program, for comprehensive analysis of the experimental data. Table 2 presents the experimental matrix for the single-replicate generic factorial design. The final column displays the recorded reaction, specifically the corrosion rate, for each iteration of the experiment. Since two components were examined at various levels in this experiment, using a single replicate factorial design for the investigation was appropriate. The absence of internal error estimation was a significant constraint in a single replicate design, notably in 2^k factorial experiments. It was noted that there was no internal estimation of error or the presence of genuine error.

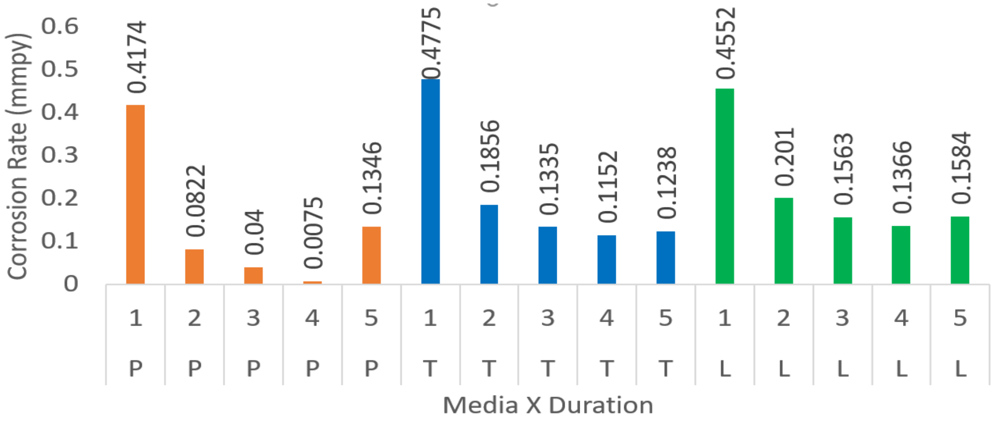
Table 2 : Generic Factorial Design with two process parameters and response on AISI 316L stainless steel

Experiment Number	Media	Interval time (Duration days)	Corrosion Rate (mmyear^{-1})
1	L	1	0.4552
2	P	5	0.1077
3	P	3	0.0400
4	L	3	0.1563
5	T	2	0.1856
6	P	1	0.4174
7	L	4	0.1366
8	T	4	0.1152
9	T	1	0.4775
10	L	5	0.1584
11	P	4	0.0075
12	P	2	0.0822
13	L	2	0.2010
14	T	5	0.1238
15	T	3	0.1335

Based on the data depicted in Figure 3, it was evident that the highest corrosion rate measured was 0.4775mmyear^{-1}. The aforementioned value was obtained by immersing 316L stainless steel in tamarind juice for a period of 8 days, specifically during interval 1. When submerged for 32 days, the pineapple juice demonstrated the least amount of corrosion, with a corrosion rate of 0.0075mmyear^{-1}. Moreover, the corrosion rate for an immersion duration of 8 days is as follows for the three substances: pineapple juice (0.4174mmyear^{-1}), tamarind juice (0.4775mmyear^{-1}), and lime juice (0.4552mmyear^{-1}). This discovery indicated that the rate of corrosion reached its maximum value for all types of liquids during the initial duration term.

The rate of corrosion often reached its maximum value for all types of fruit juice during the initial duration term due to the highly energetic interactions between the metal and the liquid when they first came into contact. The absence of a protective layer, such as an oxide film, on the fresh metal surface prevented any hindrance to the corrosion process. Additionally, at the beginning, the metal surface experienced the highest concentration of corrosive substances, such as oxygen, chloride ions, or other corrosive species. As shown by Zhang et al. [18], the concentration of these agents in close proximity to the metal surface may progressively diminish over time, leading to a reduction in the corrosion rate. In line with this study, all varieties of juices exhibited the greatest corrosion rate when immersed for a period of 8 days.

The higher rate of corrosion observed in tamarind juice as compared to lime and pineapple juices can be ascribed to its unique chemical composition, namely its elevated acid concentration. Tamarind includes a substantial quantity of tartaric acid, a potent organic acid designed to raise the acidity of the surrounding environment. Elevated acidity levels increase the concentration of hydrogen ions, therefore expediting electrochemical processes that are accountable for corrosion. By instance, lime juice, while acidic because of citric acid, has a lower total acidity than tamarind, perhaps accounting for its comparatively less severe corrosive behavior. Pineapple juice, which is abundant in ascorbic acid (vitamin C), also features a reduced level of acidity compared to tamarind. The results of this study align with previous research conducted by Bilcke et al [19], which examined the corrosive impacts of different organic acids on metals. A similar conclusion was reached that media containing more potent acids, such as tartaric acid, led to increased rates of corrosion.



P – Pineapple
T- Tamarind
L- Lime

1- Interval time 1
2- Interval time 2
3- Interval time 3

4- Interval time 4
5- Interval time 5

Figure 3 : Corrosion rate of 316L stainless steel in different media and immersion time

The mean squares are aggregated to calculate the error estimation. Table 3 presented the analysis of variance results, which enabled a statistical examination of the impact of the variables on the corrosion rate of 361L stainless steel, together with the related F- value and P – value statistics. The overall model had 6 degrees of freedom (DF) and an adjusted sum of squares (Adj SS) of 0.291981. the adjusted mean square (Adj MS) was 0.048664. The F- value was 77.37 with a P-value of 0.000, indicating that the overall model is highly significant. The model's adequacy was satisfactory due to the presence of a correlation between the dependent variable (corrosion rate) and the independent variable. The evidence for this may be found in Table 4, where the R-sq value and R-sq(Adj) value were 98.31% and 97.04% respectively. Thus, this provided a good explanation of the relationship between the independent factors and their responses (corrosion rate). This also supported the findings of Kingsley et al. [20], who investigated the corrosion behaviour of mild steel when exposed to tomato and pepper environment. The corrosion rate of mild steel in these environments was quantified, showing degradation over time influenced by the presence of corrosive substances.

This ANOVA result also indicated that both medium and duration (days) significantly affected the response variable, with duration having a more substantial impact. This is evident from their low P-values (0.0001 and 0.000, respectively), indicating that changes in these factors lead to significant changes in the response variable. The duration (days) factor has a much larger F-value compared to the Medium factor (106.64 versus 18.82), suggesting that duration (days) had a larger effect on the response variable compared to Medium.

The mathematical method known as regression analysis was utilised in order to produce a prediction about the value of a dependent variable (corrosion rate) by taking into consideration the values of independent variables. The aim was to establish a linear connection between them, where factor A was assigned as a categorical predictor and factor B was assigned as a continuous predictor. The factor specification varied due to the fact that factor A was not a numerical factor, unlike factor B. The corrosion rate of stainless steel in three distinct mediums was expressed by the regression in equations (2).

$$\begin{aligned}&\text{Corrosion Rate} = 0.18653 - 0.0557\,Medium\_P + 0.02059\,Medium\_T \\ &+ 0.03497\,Medium\_L + 0.2635\,Duration(days)\_1 - \\ &0.0303\,Duration(days)\_2 - 0.0766\,Duration(days)\_3 - \\ &0.1001\,Durations(days)\_4 - 0.0566\,Duration(days)\_5\end{aligned} \tag{2}$$

Table 3: Analysis of variance (ANOVA) of generic factorial design

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.291981	0.048664	77.37	0.000
Linear	6	0.291981	0.048664	77.37	0.000
Medium	2	0.023674	0.011837	18.82	0.001
Duration	4	0.268307	0.067077	106.64	0.000
Error	8	0.005032	0.000629		
Total	14	0.297013			

Table 4: Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0250798	98.31%	97.04%	94.04%

This study employed Minitab Software and a general factorial design to efficiently assess the results of corrosion tests. The results were consistent with other assessments of corrosion experimental data documented in the current literature. The chosen factors were media and duration, both of which were design components. The analysis of variance revealed that both main effects exhibited statistical significance, and there was a statistically significant interaction between them. It is essential to prioritise the severity of the environment and the longevity of the equipment when developing food production and processing equipment.

4.0 CONCLUSION

The study illustrated that the corrosion rate of AISI 316L stainless steel exhibited considerable variations in different fruit juice conditions and over time. Initially, the corrosion rate was highest during the first 8 days of exposure. Tamarind juice demonstrated the highest rate at 0.4775mmyear^{-1}, followed by lime juice at 0.4552mmyear^{-1} and pineapple juice at 0.4174mmyear^{-1}. During the 32-day period of the experiment, it was observed that pineapple juice had the lowest corrosion rate, measuring at 0.0075mmyear^{-1}. This finding suggested that the corrosion rate reached its peak for all liquid types during the first period. These findings also highlighted the significant influence of media type and exposure length on corrosion rate. The study indicated that additional research is necessary to improve the comprehension of corrosion in food processing environments, which is crucial for averting potential health risks associated with food contamination and guaranteeing the safety of present and future generations.

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AUTHOR CONTRIBUTIONS

Y. Yusuf: Idea and design of experimental setup, original draft manuscript writing; N.A. Yunadi: Performed the experiment; N. I. Omar: Involved in planning and supervising the work; N. Mustafa: Provided a significant role in designing and implementing the research, analysing the results, and producing the manuscript.; Z. C. Daud: Helped carry out analysis the result using Minitab Software, S.

D. Hadi: Conducting a review of the draft manuscript.

CONFLICTS OF INTEREST

The manuscript remains unpublished and not being reviewed by any other journals. All authors have given their approval for the review, are in agreement with its submission, and have declared no conflicts of interest with the paper.

REFERENCES

[1] M. Shamsuddin, "*Physical Chemistry of Metallurgical Processes*". The Minerals, Metals & Materials Society. Hoboken, New Jersey: John Wiley & Sons. 2016.

[2] J. Schlegel, "*Alloying Elements and Steel Properties*," in *The World of Steel*., J. Schlegel, Springer, Wiesbaden. 2023. pp. 63-103.

[3] J.S. Yoo, S.J. Ko, and J.G. Kim, "Effect of Chromium on Microstructure and Corrosion Behavior of High-Cr White Cast Irons Used in Coal-Fired Power Plant Desulfurization Facilities", *International Journal of Metal Casting*, vol.18, pp. 1664–1676, 2024.

[4] Y. Han, Z.H. Liu, C.B. Wu, Y. Zhao, G.Q Zu, W.W. Zhu, X. Ran, "A short review on the role of alloying elements in duplex stainless steels", *Tungsten,* vol. 5, pp. 419–439, 2023.

[5] S. Surjan, T. Atmaramudu, K.G. Arun, M. Raffi, "Effect of microstructural morphology on corrosion susceptibility of austenitic and super austenitic stainless steel", *Materials Today: Proceedings*, vol. 66, no. 2, pp. 514-518, 2022.

[6] A. Zaffora, F. Di Franco, M. Santamaria, "Corrosion of stainless steel in food and pharmaceutical industry", *Current Opinion in Electrochemistry,* vol. 29, 100760, 2021.

[7] X. Zhang, C. Yang, K. Yang, "Novel Antibacterial Metals as food contact materials; A review", *Materials*, vol. 16, no.8, pp. 1-19,2023.

[8] A. Abbas, A. Y. Adesina, R.K. Suleiman, "Influence of organics acids and related organic compound on corrosion behavior of stainless steel – A critical review", *Metals*, vol. 13, no.8, pp.1-25, 2023.

[9] G. K. Deshwal, N.R. Panjagari, "Review on metal packaging: materials, forms, food application, safety and recyclability", *Journal of food science and technology,* vol. 57, pp. 2377-2392, 2020.

[10] C. Andrea, B. Marco, D. Rogerta, B. Laura, E.D. Laura, "Procedure optimisation of type 304 and 420B stainless steels release in acetic acid", *Food Control*, vol. 120, 107509, 2021.

[11] F.K. Aimi, H. Asmaddy, A.S. Syadiyah, M.D. Siti Nurazira, A. Nursilah,

K. Zurina, M. Nurul Aini, M.A.Q. Abu Hassan, "An Overview Malaysia as a hub of planting prophetic fruits", *Malaysian Journal of Sustainable Agriculture (MJSA)*, vol. 3. no. 1, pp. 13-19, 2019.

[12] A. Roslina, H. Muhammad Hakimi, "The emerging export markets of Malaysian tropical fruits: a preliminary outlook", in 2021 ISTF International Symposium on Tropical Fruits , Kuala Lumpur, Malaysia 2021, pp. 136-147.

[13] M.M Salleh, R.M. Yusof, "Tropical fruits and vegetables in Malaysia : Production and impact on health," in 2006 Fruits and Vegetables for Health Workshop, Seoul, Korea, 2006. pp.1–5.

[14] M.N. Shahidah, D. Phebe, S. Siti Zaharah, I. Amin, Faridah, "A. Passion Fruit—A Potential Crop for Exploration in Malaysia: A Review", *Tropical Agricultural Science, Pertanika Journal*, vol. 45, no.3, pp. 761-780, 2022.

[15] A.K. Hamzat, I.A. Adediran, L.M. Alhems, M. Riaz, "Investigation of Corrosion Rate of Mild Steel in Fruit Juice Environment Using Factorial Experimental Design", *International Journal of Corrosion*, vol. 2020, no. 1, pp. 1-10, 2020.

[16] A. Rahman, M. Salleh, I. Othman, S. Subramonian, S. Yahaya, and N. Siswanto, "Investigation of Wear and Corrosion Characteristics of Short Heat Treated Thixoformed Aluminium Alloy", *Journal of Advanced Manufacturing Technology*, vol. 13, no.3. pp. 97-108, 2019

[17] M.M. Rahman, H.C. Raisha, A.R. Tahian, and S.R. Ahmed. "Corrosion Resistance of Scraped Copper in Velocity Varied Inland Water of Bangladesh." *Malaysian Journal on Composites Science and Manufacturing*, vol. 13, no. 1, pp. 25-35. 2024.

[18] W. Zhang, Y. Zhang, X. Miao, B. Sun, C. Li, C. Dong, X. Li, "Effect of Temperature and Concentration on the Corrosion Behavior of 42CrMoE Low Alloy Steel in Boric Acid Solution," *Journal of Material Engineering and Performance,* vol. 33, no.10, pp. 4640-4646, 2024.

[19] V.D. Bilcke, N. Alaerts, K. S Ghaffaripour,D.J. Simbo and R. Samson, "Physico-chemical properties of tamarind (Tamarindus indica L.) fruits from Mali: selection of elite trees for domestication," *Genetic Resource Crop Evolution,* vol. 61, no.2, pp. 537–553, 2014.

[20] C.C. Kingsley, R.A. Uche, J.O. Azubuike, E. Arinze, "Effect of Corrosion of Mild Steel in Tomato and Pepper Environment Using Factorial Experiment Design". *Journal of Applied Physical Science International*, vol. 15, no. 1, pp. 17-26, 2023.