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# Suitability of white potash, red potash and zobo (Hibiscus tea) solutions as quenchant for medium carbon steel

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## Abstract

This study investigates the effectiveness of using red potash, white potash, and Habiscus Tea as alternative quenching media for hardening medium carbon steel, compared with conventional water and brine. Samples were normalized at 850°C and then austenitized at 870 °C for 1 hour before being quenched. Key mechanical properties hardness, tensile strength, impact strength and microstructural changes were evaluated. Results showed significant improvements in hardness (up to 50.40 HRC) and tensile strength (up to 1850.22 MPa), with Habiscus Tea and brine yielding the highest values. However, brine resulted in the lowest impact strength (0.38 J/mm²), indicating brittleness. Habiscus Tea produced a full martensitic structure with a good balance of high hardness (50.40 HRC), high tensile strength (1748.50 MPa), and moderate impact toughness (0.50 J/mm²). Compared to the normalized state, Habiscus Tea-quenching improved hardness and tensile strength by 230 % and 200 %, respectively. The study concludes that Habiscus Tea is a promising, cost-effective, and safer alternative to conventional quenchants for enhancing the mechanical properties of medium carbon steel.

**Keywords:** Quenching media; Medium carbon steel; Mechanical properties; Microstructure; *Hibiscus sabdariffa* (Zobo); Potash-based quenchants; Sustainable/eco-friendly heat treatment; Martensitic transformation

## 1. Introduction

Heat treatment remains an essential manufacturing process employed to enhance specific properties of metallic components, particularly steels, prior to their deployment in engineering applications. Among the critical processes under heat treatment is quench hardening, which is widely applied to improve hardness, wear resistance, and strength by inducing martensitic transformation from austenite through rapid cooling (Masoumi et al., 2019). Medium carbon steels, due to their balanced composition of carbon and alloying elements, are particularly favored for structural components, gears, axles, and shafts that require high strength and toughness [1] (Adeyemi and Adebayo, 2009).

Conventionally, quenchants such as water, brine, and petroleum-based oils have been employed for quench hardening. These media exhibit distinct cooling characteristics that influence the final microstructure and mechanical properties of steel components. While water and brine provide high quenching severity necessary for martensite formation, they also introduce high thermal gradients that may lead to distortion and quenching cracks [8] [9] (Mohammad et al., 2019;

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Ogedengbe et al., 2021). Oil quenching, on the other hand, offers lower quenching severity, thereby reducing the risk of cracking but sometimes failing to produce sufficient hardness in medium-carbon steels (Agboola et al., 2015).[2]

Environmental concerns and operational limitations associated with conventional quenchants—such as oil degradation, flammability, and disposal issues—have intensified the search for renewable, biodegradable, and cost-effective alternatives. In this context, natural aqueous extracts such as plant-based solutions and soil-derived salts are gaining attention due to their environmental compatibility, local availability, and promising thermal properties (Kobasko et al., 2010; Hassan and Aigbodion, 2013).[7] [5]

Despite a growing body of research into bio-based and eco-friendly quenchants, the suitability of white potash (sodium carbonate), red potash (native lake salt), and Zobo (Hibiscus sabdariffa) solutions has not been explored. These materials, widely available and traditionally used for culinary and medicinal purposes in parts of Africa and Asia, possess ionic content and organic compounds that may influence quenching behavior and heat transfer characteristics. This study therefore seeks to investigate the performance of these solutions as alternative quenching media for medium carbon steel.

The work aims to evaluate their effectiveness in promoting martensitic transformation, improving mechanical performance, and minimizing distortion. This study represents a novel contribution to the growing field of sustainable quenchants and offers potential industrial applications, particularly in resource-constrained or environmentally sensitive settings.

## 2. Materials and Methods

### 2.1. Sample preparation

Uniaxial tension and Charpy impact samples with geometry as shown in Figure 1 and Figure 2, were prepared from medium carbon steel rods purchased from the Samaru Iron and Steel Market in Zaria, Nigeria. Quenching media included Hibiscus sabdariffa, red potash, and white potash. Table 1 shows the steel composition.

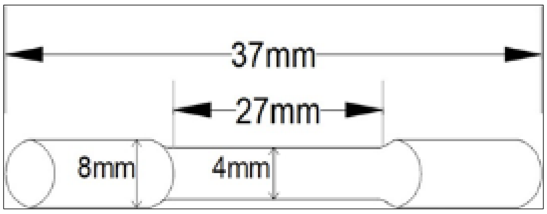


**Figure 1** Tensile test geometry

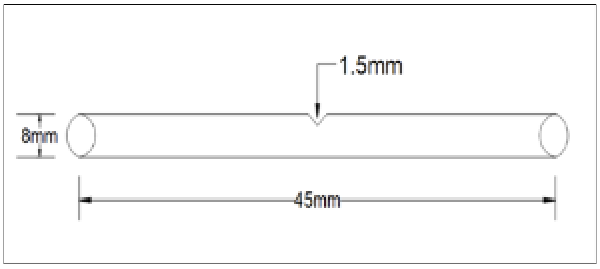


**Figure 2** Charpy impact test geomery

*2.1.1. Two sample conditions were characterized*

As-received and normalized. 30 samples were heated to 850°C and soaked for 1 hour to obtain the necessary transformation and achieve homogenization, after which the samples were air cooled. This normalizing heat treatment was carried out to remove the effect of undesirable structure due to machining and also to restore the original condition of the structure and induce homogeneity in the samples (Dodo et al., 2016). Thus, the normalized microstructure was used as the starting structure for this work.

**Table 1** Chemical Composition of Medium Carbon Steel (wt%)

| C | Fe | Si | Mn | Cu | Cr | P | S | Ni | Balance |
|---|---|---|---|---|---|---|---|---|---|
| 0.349 | 98.4 | 0.154 | 0.499 | 0.298 | 0.138 | 0.014 | 0.025 | 0.059 | 0.067 |

### 2.2. Preparation of quenching media and heat treatment

Five quenching media were prepared for this study. For each, 100 g of red potash, white potash, or zobo flower was mixed with 2 liters of boiled water to ensure adequate dissolution and extraction. Similarly, a brine solution was formulated by dissolving 100 g of sodium chloride in 2 liters of water to match the concentration of the other quenchants. Additionally, 2 liters of distilled water was prepared to serve as the control medium.

A total of 25 samples were then subjected to quench hardening heat treatment. The specimens were loaded into the furnace and heated to the austenitizing temperature of 870°C, held at this temperature for 1 hour for complete homogenization, and then immediately quenched in each of the five media (white potash, red potash, brine, zobo, and water). After quenching, the samples were tested for tensile strength, impact, and hardness. Table 2 shows the distribution of the test sample.

### 2.3. Mechanical testing

Tensile testing was performed at room temperature as recommended for the Hounsfield tensometer, and the samples were mounted one after the other on the tensometer. A small load was initially applied to set the specimen in the grips, and then the load was increased until failure occurred. The load extension relationship was plotted simultaneously. The breaking and maximum tensile loads of the quenched samples were obtained. The ultimate tensile strength (UTS) was determined from the relationship UTS = Pmax/A0.

**Table 2** Distribution of Test Samples

| Condition | Tensile | Impact | Hardness/Metallography |
|---|---|---|---|
| As-received | 2 | 2 | 1 |
| Normalized | 2 | 2 | 1 |
| Water | 2 | 2 | 1 |
| Brine | 2 | 2 | 1 |
| Zobo | 2 | 2 | 1 |
| White Potash | 2 | 2 | 1 |
| Red Potash | 2 | 2 | 1 |

Sample used for the metallography were subjected to hardness test using the Rockwell hardness test (scale C) method on the indentec universal hardness testing machine 187.5 LKV. Each sample was mounted on the machine with the polished surface faced up. Three indentations were made on the surface, and the depth of indentation made was measured by the electronic scale which converts the depth measurement to the corresponding hardness value. The average of the three hardness values was determined and recorded (Dodo, 2015).[3]

The Charpy impact test of the as-quenched steel sample was performed using the Hounsfield balanced impact testing machine. The as-quenched notched impact specimens were subjected to the weighted pendulum load on the impact testing machine. Sample steel machined to the dimensions of 45 mm length x 8 mm diameter and 1.5 mm deep notch of angle of 45° were used. The trigger was released for the pendulum to strike the specimen from an initial potential energy of 10 J. The energy absorbed before fracture was then read directly on the gauge of the machine and recorded and the same was repeated for other test pieces.

### 2.4. Microstructural characterization

The as-quenched samples in the various quenching media were mounted on Bakelite powder before grinding. The grinding of the samples was carried out manually on a water-lubricated grinding machine using silicon carbide abrasive paper of grades 180, 240, 400, and 600 grit sizes. The ground samples were then polished to completely remove the fine scratches and smooth the surface. The polishing was carried out at a speed of 250 rpm, covered with a polishing cloth impregnated with 1-micron alumina solution. The samples were rotated slightly against the surface of the impregnated polishing disc so that it skids over the paste without touching the fibers of the polishing cloth. The final polishing was performed with 0.5-micron alumina polishing solution until the surface of the samples was scratch-free and mirror-like. The specimens were then etched with 2%Nital solution. After etching, the samples were washed in running water and alcohol and then dried in hot air. The etched samples were then placed on the sample stage of a metallurgical microscope, and the microstructures were observed and recorded with the aid of the built-in camera (Dodo et al., 2020). [4]

## 3. Results

This section presents the results from chemical composition analysis of the quenching media, mechanical tests, microstructural evaluation, and cooling curve measurements. Each dataset highlights the influence of different quenching media on the properties of medium carbon steel

### 3.1. Chemical Composition Analysis

Tables 3 and 4 show the elemental and oxide composition of red potash, white potash, and zobo flower as determined by elemental and XRF analysis respectively.

**Table 3** Elemental Composition of Red Potash, White Potash and Zobo Flower

| Element | Red Potash | White Potash | Zobo |
|---|---|---|---|
| O | 35.080 | 35.310 | 29.395 |
| Mg | 7.197 | 6.571 | 4.946 |
| Al | 2.082 | 2.232 | 6.858 |
| Si | 4.169 | 2.696 | 3.358 |
| P | 0.000 | 0.000 | 0.532 |
| S | 13.497 | 14.954 | 0.941 |
| Cl | 25.985 | 23.747 | 4.986 |
| K | 6.815 | 11.675 | 27.799 |
| Ca | 3.030 | 1.425 | 17.605 |
| Ti | 0.268 | 0.225 | 0.358 |

**Table 4** XRF Analysis of White Potash, Red Potash and Zobo Particle

| Compound | White Potash (%) | Red Potash (%) | Zobo (%) |
|---|---|---|---|
| SiO2 | 5.77 | 8.92 | 7.19 |
| SO3 | 37.35 | 33.70 | 2.35 |
| CaO | 1.99 | 4.24 | 24.63 |
| MgO | 10.89 | 11.93 | 8.20 |
| K2O | 14.06 | 8.21 | 33.49 |
| Al2O3 | 4.22 | 3.93 | 12.96 |
| Cl | 23.75 | 25.99 | 4.99 |

### 3.2. Mechanical Properties

The mechanical properties, including hardness, tensile strength, and impact energy of the as-received and quenched samples, are presented in Table 5.

**Table 5** Mechanical Properties of As-Received and Heat-Treated Medium Carbon Steel Samples

| **Condition** | **Hardness (HRC)** | **UTS (MPa)** | **Impact Strength (J/mm2)** |
|---|---|---|---|
| As-received | 11.50 | 825.94 | 1.94 |
| Normalized | 15.20 | 586.50 | 1.95 |
| Water | 41.40 | 1632.85 | 0.46 |
| Brine | 46.60 | 1850.22 | 0.38 |
| Zobo | 50.40 | 1748.50 | 0.50 |
| White Potash | 24.60 | 1309.00 | 0.85 |
| Red Potash | 28.20 | 1627.91 | 0.40 |

### 3.3. Microstructural Analysis

The microstructural characteristics of the specimens were observed using optical microscopy after etching in 2%Nital. Figures 7 to 12 show microstructures including ferrite, pearlite, martensite, and retained austenite, depending on the quenching medium used.

### 3.4. Cooling Curve Analysis

Figure 6 illustrates the cooling curves of all the quenching media. Zobo and brine showed higher severity due to reduced vapor blanket stage, indicating faster heat extraction and supporting their observed effects on mechanical properties.

## 4. Discussion

The experimental results shows a significant influence of the quenchants and thermal behavior on the mechanical performance of the quenched medium carbon steel.

Among the quenching media, the zobo extract exhibited the highest surface hardness (50.4 HRC Figure 3). This is attributed to the formation of a fine martensitic microstructure, a result of its high concentration of CaO and K2O, which likely enhanced the thermal conductivity and quenching severity. The presence of these oxides contributes to increased nucleate boiling efficiency, promoting a steeper cooling rate (Figure 6) and complete transformation of austenite to martensite. These observations are consistent with the findings of Rajan et al. (2012), who noted that the presence of ionic compounds in quenchants significantly affects the heat extraction capacity and phase stability.

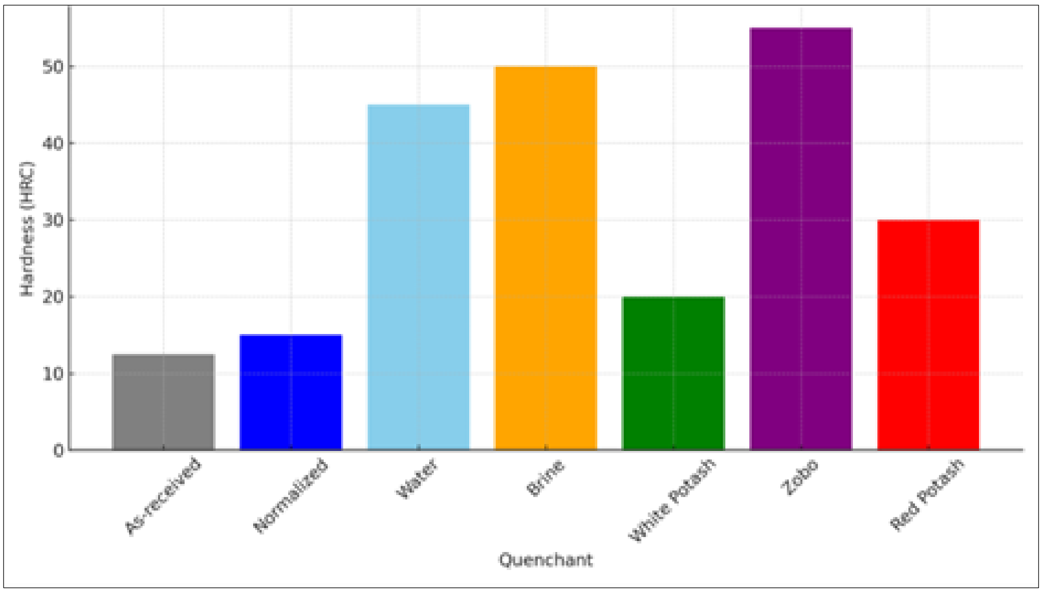


**Figure 3** Hardness of Medium Carbon Steel by Quenching

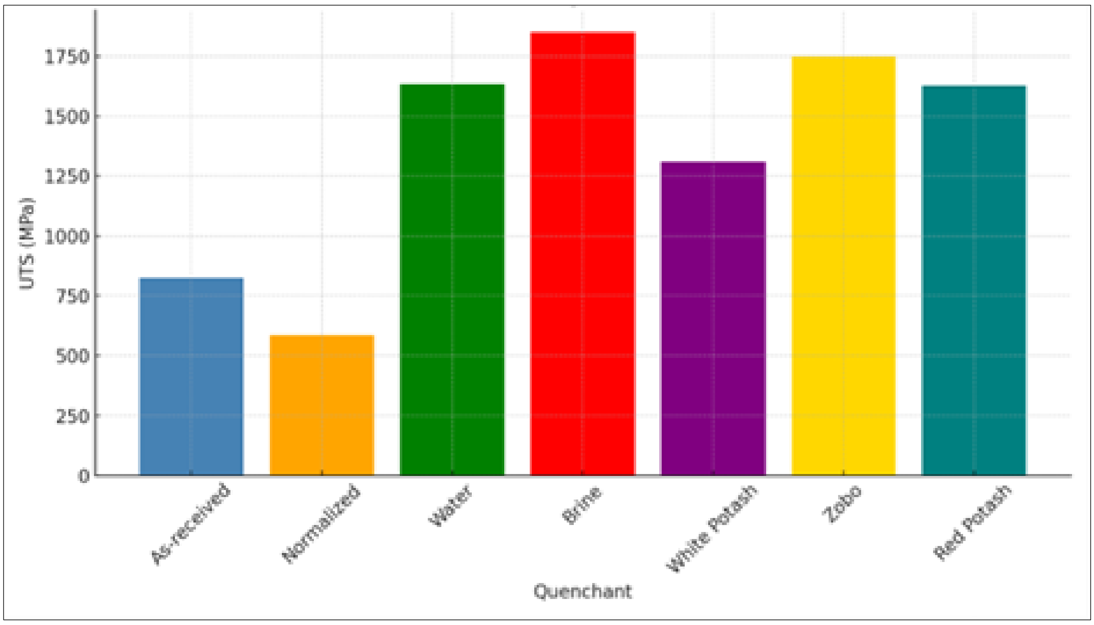


**Figure 4** Variation of UTS in different Quenching Media

Brine, a conventional high-severity quenchant, yielded the highest ultimate tensile strength (1850.22 MPa, Figure 4), a characteristic indicative of high martensite fraction. However, it showed the lowest impact strength (0.38 J/mm2, Figure 5), reflecting increased brittleness typical of fully martensitic structures without adequate tempering. In contrast, zobo provided a competitive tensile strength (1748.50 MPa) and moderate impact toughness (0.50 J/mm2, Figure 5), suggesting a refined martensitic matrix with minimal microstructural defects. This intermediate toughness is crucial in mitigating quench-induced cracking while maintaining high strength levels.

On the other hand, white potash resulted in the highest impact energy (0.85 J/mm2, Figure 5) but considerably lower hardness and tensile strength. This implies a lower cooling rate(Figure 6), causing incomplete austenite-to-martensite transformation and greater retention of ductile ferrite and retained austenite (Figure 11). This behavior was also observed in the optical micrographs, where the presence of retained austenite was more prominent. The soft phases present contribute to enhanced energy absorption but at the cost of reduced load-bearing capacity.

The cooling curves (Figure 6) further substantiate these observations. Zobo and brine exhibited minimal vapor blanket formation (Stage I) and rapid transition into nucleate boiling (Stage II), promoting fast heat dissipation. This behavior aligns with the classical cooling curve profiles described by Skidmore (1986)[]. Conversely, white and red potash showed prolonged vapor blanket stages, indicative of slower cooling and reduced severity. Red potash demonstrated intermediate behavior, offering mechanical properties between those of water and white potash.

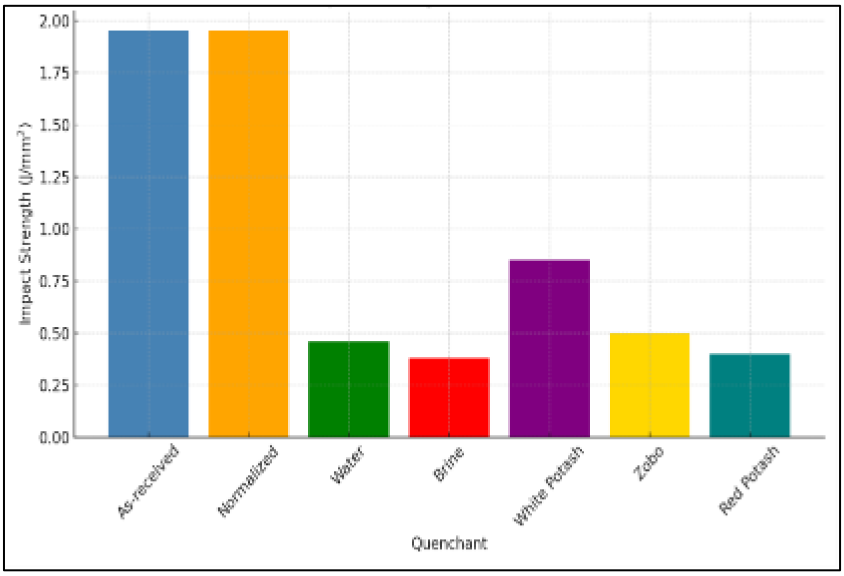


**Figure 5** Variation of Impact Strength in Quenching Media

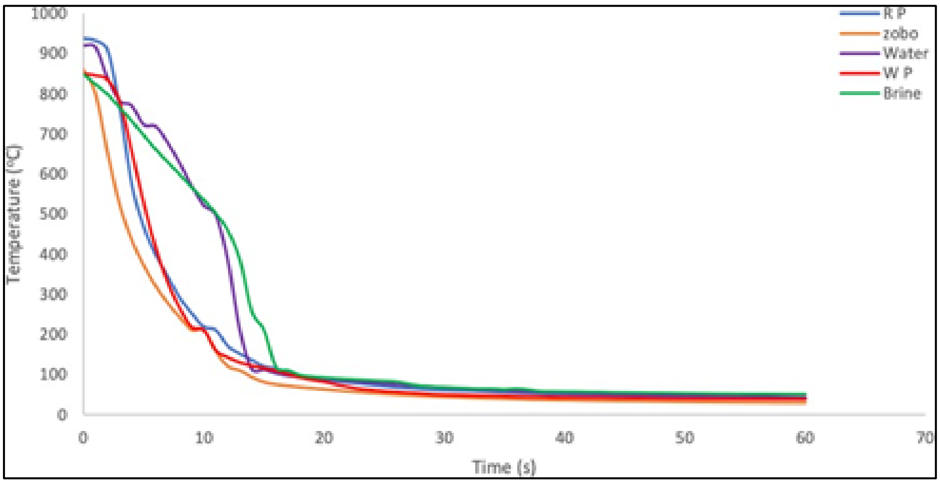


**Figure 6** Cooling curves of medium carbon steel in various quenchants

In summary, the zobo quenchant demonstrated high quenching efficiency, balancing hardness, and ductility, qualities often mutually exclusive in quenched steels. Its biodegradable nature and local availability make it a promising sustainable alternative to conventional quenchants such as brine. These conclusions corroborate the reports of Hassan et al. (2009) and Vivek et al. (2014)[6] [10], who emphasized the viability of plant-based quenching solutions in achieving desirable mechanical performance in ferrous alloys.

The microstructures of the as-received (Figure 7) and normalized medium carbon steel samples (Figure 8)consist predominantly of ferrite, a soft and ductile phase, and pearlite, which has a harder, lamellar structure. These phases contribute to the mechanical behavior observed: the as-received sample exhibits a hardness of 11.5 HRC (Figure 3) and an ultimate tensile strength (UTS) of 825.94 MPa, while the normalized sample shows slightly increased hardness at 15.2 HRC but reduced UTS at 586.5 MPa. Both conditions demonstrate high impact strength (1.94–1.95 J/mm²), attributable to the tough, energy-absorbing ferritic matrix. The normalization process leads to grain refinement and stress relief, but also eliminates any work hardening effects, thus reducing tensile strength.

Quenching in water and brine results in the formation of martensite along with retained austenite (Figure 9) and 10) . The rapid cooling during quenching suppresses diffusional transformations, promoting a martensitic phase that is extremely hard and strong but inherently brittle. This is reflected in the high hardness values of 41.4 HRC (water) and 46.6 HRC (brine), and elevated UTS values of 1632.85 MPa and 1850.22 MPa respectively. However, this increase in strength comes at the cost of ductility, with impact strengths dropping sharply to 0.46 J/mm$^2$ for water and 0.38 J/mm$^2$ for brine. The needle-like morphology of martensite and internal stresses from rapid transformation contribute to these poor toughness values. Brine, having a higher cooling rate than water, forms a greater volume fraction of martensite, thereby enhancing strength and hardness further but exacerbating brittleness.

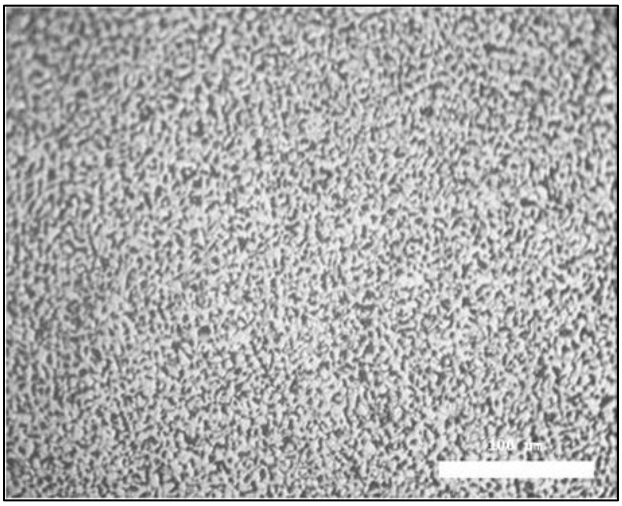

**Figure 7** Microstructure of as- received specimen of 0.349%C steel showing pearlite (dark) in ferrite (white) matrix, Mag. x100

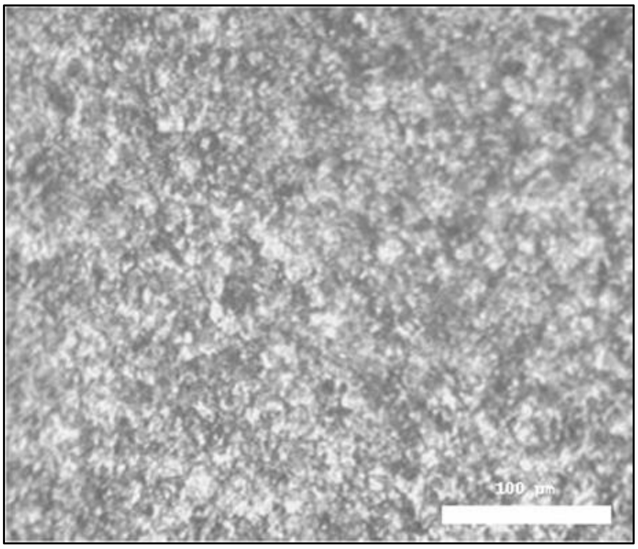

**Figure 8** Microstructure of normalized 0.349%C steel showing a ferrite (white) in pearlite(dark)matrix

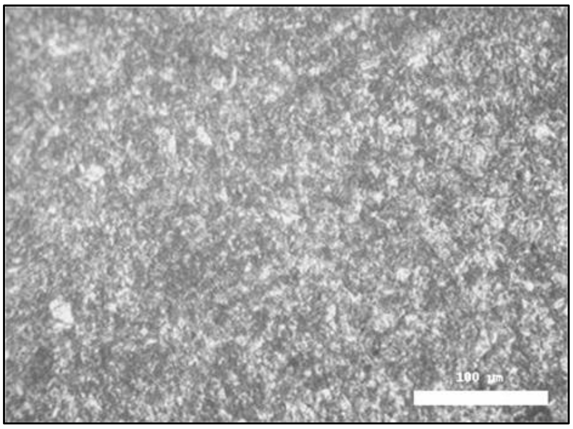


**Figure 9** Microstructure of 0.349%C steel quenched in water showing martensite (dark) structure with retained austenite (white) Mag.x100

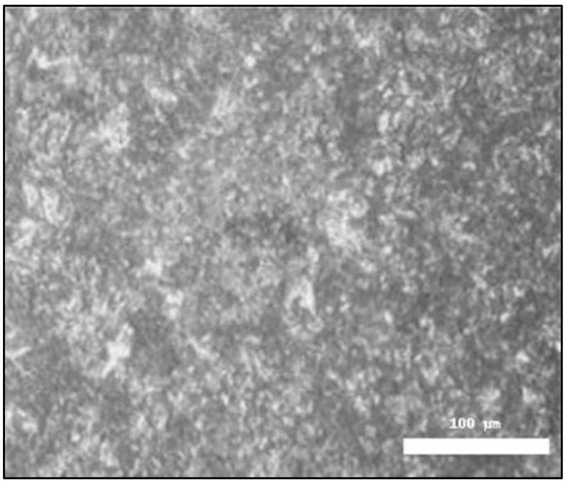


**Figure 10** Microstructure of 0.349%C steel quenched brine solution showing martensite (dark) structure with retained austenite (white) Mag. x100

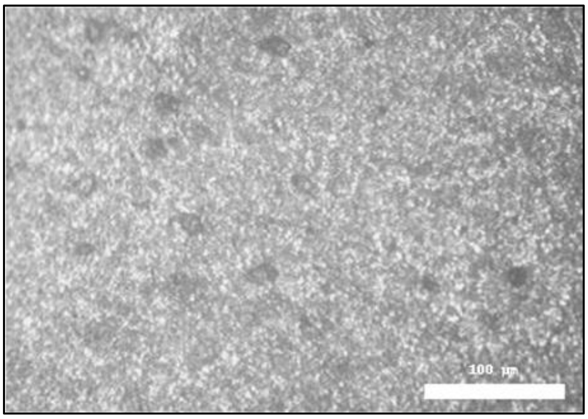


**Figure 11** Microstructure of 0.349%C steel quenched in white potash solution showing martensite (dark) with retained austenite (white) Mag. x100

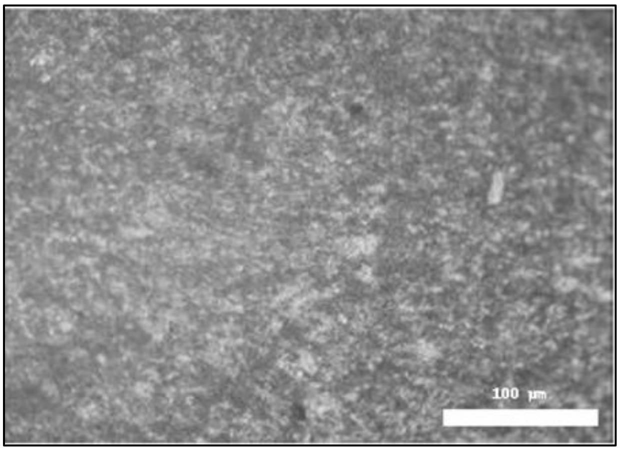


**Figure 12** Microstructure of 0.349%C steel quenched in zobo solution showing full martensite (dark) Mag. x100

In contrast, quenching in white and red potash solutions leads to coarser martensite and a higher amount of retained austenite (Figures 11 and 12) due to the less severe cooling rate. Consequently, the mechanical properties reflect a trade-off: moderate hardness (24.6 HRC for white potash and 28.2 HRC for red potash, Figure 3) and UTS values of 1309 MPa and 1627.91 MPa, respectively. Interestingly, white potash provides the highest impact strength among all quenched samples (0.85 J/mm$^2$), while red potash offers a relatively lower value (0.40 J/mm$^2$). The slower cooling rate allows some austenite to transform into softer phases like pearlite or bainite, which, combined with the presence of retained austenite, enhances toughness but at the expense of maximum achievable strength and hardness.

The sample quenched in the zobo solution exhibits a fine martensite microstructure with minimal retained austenite (Figure 12. The chemical composition of the zobo, rich in CaO and K2 O, probably improves its thermal conductivity and the severity of the quenching. This results in the formation of finer martensitic grains, which increase dislocation density and internal lattice strain, thus increasing the hardness to the highest observed value (50.4 HRC, Figure 3). The UTS is also notably high at 1748.5 MPa, second only to brine. Despite the high strength, the zobo-quenched sample retains a moderate impact strength (0.50 J/mm$^2$), suggesting that the refined microstructure helps mitigate brittleness to some extent. The balance of high strength and reasonable toughness makes zobo a promising quenchant for applications that require enhanced performance without excessive brittleness.

**Table 6** Summary of Microstructure–Property Relationship

| **Condition** | **Dominant Microstructure** | | **Hardness (HRC)** | **UTS (MPa)** | **Impact Strength (J/mm2)** |
|---|---|---|---|---|---|
| As- | Ferrite + Pearlite | | 11.5 | 825.94 | 1.94 |
| Received | (coarse grains) | | | | |
| Normalized | Refined ferrite + | | 15.2 | 586.5 | 1.95 |
| | pearlite | | | | |
| Water | Martensite | | 41.4 | 1632.85 | 0.46 |
| Quenched | + Retained | | | | |
| | Austenite (low | | | | |
| | proportion) | | | | |
| Brine | Martensite | | 46.6 | 1850.22 | 0.38 |
| Quenched | + Retained | | | | |
| | Austenite | | | | |
| | (moderate) | | | | |
| Zobo | Fine | Martensite | 50.4 | 1748.5 | 0.50 |

| | | | | |
|---|---|---|---|---|
| Quenched | (minimal retained | | | |
| | austenite) | | | |
| White | Coarse Martensite | 24.6 | 1309.00 | 0.85 |
| Potash | + Retained | | | |
| Quenched | Austenite | | | |
| Red | Coarse Martensite | 28.2 | 1627.91 | 0.40 |
| Potash | + Retained | | | |
| Quenched | Austenite | | | |

## 5. Conclusion

This study investigated the quenching performance of locally sourced white potash, red potash, and zobo (Hibiscus sabdariffa) solutions on the mechanical and microstructural characteristics of medium carbon steel. The results demonstrated that quenching in zobo, white potash, and red potash media produced varying degrees of hardness and microstructural transformation, reflecting distinct differences in heat extraction severity.

Optical micrographs revealed that samples quenched in zobo solution developed predominantly martensitic structures, whereas those quenched in red and white potash exhibited a mixture of martensite and retained austenite. The zobo solution produced the highest hardness value of 50.4 HRC, exceeding that of brine (46.6 HRC), water (41.4 HRC), red potash (28.2 HRC), and white potash (24.6 HRC), highlighting its effectiveness as a fast and severe quenchant suitable for hardening processes.

Although impact strength generally decreased after quenching compared to as-received and normalized conditions, the zobo-quenched steel retained better toughness (0.50 J/mm2) than the brine-quenched counterpart (0.38 J/mm2) at similar hardness levels. Cooling curve analysis further supported this behavior, with zobo exhibiting minimal vapor blanket phase and rapid heat extraction during the nucleate boiling stage, facilitating full martensitic transformation as earlier discussed by Skidmore (1986) and Vivek et al. (2014).

The findings confirm the potential of zobo solution as a biodegradable, cost-effective, and efficient alternative to conventional quenchants for medium carbon steel hardening, particularly where a balance of hardness and impact strength is required.

### *Recommendations*

Based on the mechanical and microstructural outcomes, zobo solution is recommended for use as a natural quenchant in industrial heat treatment of medium carbon steels. Its ability to deliver superior hardness and tensile strength, while maintaining moderate toughness, makes it an attractive alternative to water and brine.

In view of its performance, researchers and industries should be encouraged to adopt locally available plant-based quenchants as substitutes for imported or synthetic media. This approach not only conserves foreign exchange but also promotes sustainable and environmentally friendly practices in metallurgical processing.

Moreover, further investigation into the applicability of zobo solution in the quenching of high carbon steels and low-alloy steels is recommended, including studies on fatigue behavior, corrosion resistance, and scalability for industrial operations.

### *Future Direction*

While this study has demonstrated the promising potential of zobo and potash-based quenching media for medium carbon steel, further investigations are warranted to expand the scope and understanding of these alternative quenchants. Future research should focus on:

- Exploring the long-term performance of quenched samples under cyclic loading and fatigue conditions.
- Evaluating the corrosion resistance behavior of steels quenched in natural solutions compared to conventional quenchants.

- Conducting thermophysical and chemical characterizations of the quenching media to correlate constituent properties with quenching severity and phase transformation kinetics.
- Investigating the performance of zobo and potash quenchants on different grades of steels, including high carbon and low alloy steels.
- Developing standardized procedures for preparation, reuse, and disposal of plant- based quenchants to promote their safe and scalable industrial application.

## Compliance with ethical standards

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### *Disclosure of conflict of interest*

Authors 1 and Author 2 contributed equally and share first authorship.
Authors 3 and 4 provided supporting contributions.

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