

Evaluating Vegetable Oils as Eco-Friendly Alternatives in Metal Heat Treatment : Review

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Abstract--Mineral oils are still widely used as quenching media in steel heat treatment; however, their use raises environmental, health, and fire-safety concerns, motivating interest in vegetable oils as biodegradable and renewable alternatives. Recent studies indicate that vegetable oils can provide cooling performance comparable to or better than petroleum-based oils. However, a comprehensive framework linking their molecular structure to cooling behavior and steel properties remains limited. This review aims to develop a quantitative, mechanistic understanding of how vegetable-oil chemistry controls thermophysical behavior, quenching severity, microstructural evolution, and mechanical performance in low- and medium-carbon steels. A systematic synthesis of experimental and modeling studies published between 2010 and 2024 was performed, focusing on thermophysical properties, cooling curves, phase transformations, and mechanical test results of steels quenched in various vegetable oils. The analysis shows that vegetable oils exhibit higher quenching severity than mineral oils, with Grossmann H values of 0.17–0.21, mainly due to suppressed film boiling and dominant nucleate boiling heat transfer. Their relatively high thermal conductivity ($0.13\text{--}0.18\text{ W m}^{-1}\text{ K}^{-1}$) and high viscosity index enable more uniform heat extraction during the martensitic transformation, resulting in finer martensitic–bainitic microstructures. As a result, vegetable-oil-quenched steels commonly achieve hardness above 40 HRC, tensile strengths above 800 MPa, and improved impact toughness compared with mineral-oil-quenched steels. Oleic-rich oils, such as palm and canola, also show better oxidative stability and cooling performance than highly polyunsaturated oils, such as soybean. Properly stabilized vegetable oils are environmentally benign and scientifically engineerable quenching media capable of delivering high and tunable thermal–mechanical performance for industrial steel heat treatment.

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1. INTRODUCTION

Vegetable oils as environmentally friendly alternative quenching media have gained increasing attention in steel heat-treatment processes in response to the growing demand for high-performance materials and sustainable manufacturing [1]. Steel remains one of the most widely used engineering materials due to its low cost and the versatility of its mechanical properties, which can be tailored through control of chemical composition, microstructure, and heat-treatment conditions [2, 3, 4]. Among the various strengthening techniques, quenching is the most widely used because it effectively modifies the steel microstructure by rapidly cooling from the austenitic region [5, 6]. However, the success of this process strongly depends on the selection of the quenching medium, as different cooling rates result in varying degrees of martensitic transformation, hardness, and microstructural stability [7, 8]. Therefore, choosing an appropriate quenching medium, including the use of vegetable oils as alternatives to mineral oils, is a critical factor in achieving optimal mechanical performance, particularly for components subjected to severe service conditions [9, 10, 11].

Water and mineral oils are widely used as conventional quenching media in steel heat treatment; however, both exhibit significant limitations [12, 13]. Water provides a high cooling rate but often generates large temperature gradients between the steel surface and the cooling medium. This condition induces excessive thermal stresses, thereby increasing the risk of distortion and cracking, particularly during low-water-temperature quenching [14]. Attempts to mitigate this risk by increasing the water temperature instead reduce the cooling rate, which may lead to incomplete phase transformation and deterioration of the steel's mechanical properties [15]. Therefore, although water is adequate for rapid cooling, its practical application is limited by concerns related to dimensional stability and structural integrity after heat treatment [16, 17, 18, 19, 20, 21]. In contrast, mineral oils provide slower and more controlled cooling, thereby reducing the risk of cracking [22]; however, they are relatively expensive, toxic, and flammable, and pose significant environmental concerns due to their poor biodegradability [23, 24].

To address the limitations of conventional quenching media, such as water and mineral oils, biodegradable vegetable oils have emerged as promising, environmentally friendly alternatives. Vegetable oils are non-toxic, renewable, and readily biodegradable, making them safer and more environmentally benign than petroleum-based oils. In steel quenching, vegetable oils can provide adequate cooling, although their cooling rates are generally lower than those of water. Their viscosity and thermal conductivity characteristics allow more uniform and controlled heat extraction, thereby reducing thermal gradients, residual stresses, and the risk of distortion and cracking in quenched steels. Numerous studies have demonstrated that vegetable oils such as canola, soybean, and palm oil can produce martensitic and Bainitic microstructures with hardness and tensile strength comparable to or superior to those obtained using mineral oils. Furthermore, by selecting appropriate oils and incorporating antioxidant additives, the oxidative stability and cooling performance of vegetable oils can be engineered to meet industrial requirements, making them not only environmentally friendly alternatives but also high-performance quenching media [25, 26].

This review aims to provide a comprehensive, mechanistic, and performance-oriented overview of recent Research on vegetable oils as alternative quenching media, elucidating how their thermophysical properties and heat-transfer behavior govern cooling kinetics, microstructural evolution, residual stresses, and the mechanical performance of quenched steels, while also identifying key challenges and opportunities for future Research and industrial implementation.

2. LITERATURE SEARCH STRATEGY

This review examined scientific articles from various platforms and databases, including ScienceDirect, SpringerLink, Taylor & Francis, ResearchGate, and Google Scholar, on the use of vegetable oils as quenching media for steel. The selected articles were peer-reviewed publications from 2010 to 2024 that reported mechanical properties or microstructural data. From this selection, five key studies were analyzed to compare the performance of pure vegetable oils and bio–mineral oil blends. The analysis was conducted narratively to evaluate the effectiveness, limitations, and development potential of vegetable oils as more sustainable quenching media.

3. SYNTHESIS OF THE LITERATURE

Steel remains the dominant engineering material due to its superior mechanical properties, wide availability, ease of fabrication, and low cost. To meet the demands of heavy-load applications, improvements in hardness and tensile strength are commonly achieved through heat-treatment processes such as quenching. The use of vegetable and animal oils as quenching media dates back thousands of years. Although cold water has historically been the most frequently used cooling medium, its extremely high cooling rate often causes thermal cracking and embrittlement in steel, thereby encouraging the use of natural oils to achieve more controlled cooling. Although the industrial use of natural oils declined after the Second World War, Research interest has resurged over the past decade due to their renewable nature, biodegradability, and strong potential as environmentally friendly quenching media.

Vegetable oils offer several advantages, including high biodegradability, low toxicity, and stable viscosity across temperature variations, enabling more uniform cooling and reducing the film-boiling phenomena commonly observed in mineral oils. These advantages make vegetable oils strong candidates for environmentally friendly quenching media. However, their primary limitation lies in their low thermo-oxidative stability, particularly in oils with a high degree of unsaturation, such as soybean oil, which leads to rapid degradation when used or exposed to elevated temperatures [26]. The following presents a comparison between vegetable oils and mineral oils:

Table 1. Comparison between vegetable oils and mineral oils [26, 27].

ASPECT	VEGETABLE OILS	MINERAL OILS
Sustainability & Environmental Impact	Renewable, biodegradable, environmentally friendly	Non-renewable, potential environmental pollutant
Film-Boiling Behavior & Cooling Performance	Thin and short-lived film-boiling; more uniform cooling	Thick and persistent film-boiling; less stable initial cooling
Resulting Microstructure	Produces finer and more homogeneous martensite/bainite; lower distortion	Less uniform microstructure; higher dimensional distortion
Hardness & Mechanical Properties	Generally yields higher hardness; improved mechanical performance	Lower hardness under comparable quenching conditions
Thermal & Oxidative Stability	Low without additives; prone to oxidation	High thermal and oxidative stability; suitable for long-term use
Operational Safety (Flash Point)	Higher flash point; lower fire risk	Lower flash point; higher fire hazard

Vegetable oils demonstrate strong potential as next-generation, sustainable quenching media, although improving their oxidative stability, particularly through the incorporation of appropriate additives, remains essential for ensuring long-term performance [27].

To understand the cooling behavior of quenching media at various stages of the process, it is necessary to measure viscosity at 40 °C and 100 °C. At 40 °C, higher viscosity indicates the fluid's ability to effectively wet the metal surface, while at 100 °C, the decrease in viscosity enhances fluid flow and accelerates heat transfer through convection. The comparison of these two values produces the Viscosity Index (VI), which reflects the stability of viscosity with respect to temperature changes. Quenching media with a high VI exhibit more consistent cooling performance and can minimize the risk of distortion and defects in steel during the quenching process [28, 29, 30, 31, 32].

Table 2. Viscosity Characteristics of Vegetable Oils at 40 °C and 100 °C

QUENCHED SAMPLE	Viscosity at 40°C (cSt)	Viscosity at 100°C (cSt)	Reference
Palm kernel oil	41.69	8.94	[33]
Cottonseed oil	34.8	6.9	[33]
Palm oil	39.7	8.2	[33, 34, 35]
Neem seed oil	32.41	7.89	[33]
Neem oil	20.78		[36]
Watermelon Seed oil	35.355	7.90	[36]
Marula oil	68.92	23.40	[37]
Shea butter oil	70.40	28.90	[37]
Peanut oil	90.53	33.65	[37]
Cottonseed oil	110.35	33.50	[37]
Cottonseed oil	33.86	7.75	[38]
Soybean oil	31.49	7.51	[34, 35, 38]
Canola oil	34.92	7.91	[38]
Sunflower oil	33.21	7.78	[38]
Corn oil	33.51	7.70	[38]

Vegetable-oil-based quenching media exhibit distinctive heat-transfer behavior compared to conventional mineral oils, primarily due to the absence of a stable film-boiling phase. As a result, the cooling process is governed predominantly by nucleate boiling and convective heat transfer, enabling relatively rapid cooling within the critical transformation temperature range. The cooling characteristics of these bio-based quenchants are evaluated using the ASTM D6200 cooling curve methodology, which provides key parameters, including cooling rates at critical temperatures and the vapor-to-boiling transition time (t_{A-B}). To obtain a more comprehensive thermophysical assessment, the cooling analysis is strengthened through regular-condition heat-transfer modeling, allowing quantitative

estimation of the effective heat flux at the probe surface [38].

The transient heat-conduction phenomenon inside the probe is described by the one-dimensional heat equation,

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (1)$$

T = Temperature inside the probe (K or °C), t = time (s)

$\frac{\partial T}{\partial t}$ = Rate of change of temperature with respect to time

α = Thermal diffusivity of the probe material (m²/s), representing the ability of the material to conduct heat relative to its heat storage

$\nabla^2 T$ = Spatial variation of temperature inside the probe

Subject to a convective boundary condition

$$\lambda \frac{\partial T}{\partial t} = -\alpha(T - T_m) \quad (2)$$

T_m = Temperature of the quenching medium (K or °C)

λ = Thermal conductivity of the probe material (W m⁻¹ K⁻¹)

α = Heat transfer coefficient between the probe and the quenching medium (W m⁻² K⁻¹)

$(T - T_m)$ = Temperature difference driving heat transfer

The corresponding solution under regular conditions is expressed using the cooling constant m

$$\frac{T - T_m}{T_0 - T_m} = A_0 e^{-mt} \quad (3)$$

T_0 = Initial temperature of the probe, A_0 = Constant depending on initial conditions, t = Time

m = Cooling constant

The value of m is experimentally obtained from two points on the cooling curve.

$$m = \frac{\ln(T_1 - T_m) - \ln(T_2 - T_m)}{t_2 - t_1} \quad (4)$$

T_1, T_2 = Probe temperatures at times t_1 and t_2 , t_1, t_2 = Two selected times on the cooling curve

m = Experimentally determined cooling constant

Alternatively, through the instantaneous cooling rate

$$m = \frac{\omega}{T - T_m} \quad (5)$$

ω = Instantaneous cooling rate $\frac{\partial T}{\partial t}$, T = probe temperature, T_m = medium temperature

The resulting cooling constant is then used to calculate the Kondratiev number.

$$Kn = \frac{m}{m_\infty} \text{ where: } m_\infty = \frac{\alpha}{k} \quad (6)$$

Kn = Kondratjev number, m = cooling constant, m_∞ = limiting cooling constant

α = heat-transfer coefficient, k = thermal conductivity of the probe

The relationship between Kn and the generalized Biot number is given by

$$Bi_V = \frac{Kn}{1 + 1.437Kn + 0.52Kn} \quad (7)$$

Bi_V = generalized Biot number, Kn = Kondratjev number

From this, the effective heat-transfer coefficient can be calculated.

$$\alpha = \frac{Bi_V \lambda S}{V} \quad (8)$$

α = heat-transfer coefficient, Bi_V = generalized Biot number, λ = thermal conductivity of the probe
 S = surface area of the probe, V = volume of the probe

This parameter represents a critical indicator of the quenchant's cooling capacity. The evaluated vegetable oils consistently exhibit higher α and Grossmann H-severity values (0.17–0.21) than conventional mineral oils (0.11–0.14). These findings suggest that vegetable oils deliver stronger quenching severity while maintaining high viscosity stability across temperatures. Collectively, the thermal performance, environmental compatibility, and stable viscosity behavior strongly position vegetable oils as promising sustainable quenchants suitable for the heat treatment of low- and medium-carbon steels.

To evaluate the effectiveness of quenching media in transferring heat from the steel surface during cooling, precise information regarding their thermal conductivity is essential. The rate of heat extraction directly governs microstructural evolution, achieving target hardness levels, and minimizing distortion or thermal cracking. Accurate thermal conductivity data are also fundamental for maintaining process stability and controllability, selecting appropriate oils, designing additive formulations, and developing simulation-based thermal models. Consequently, thermal conductivity represents a critical parameter in determining the suitability of vegetable oils as quenching media for industrial applications [41].

Table 3. Thermal Conductivity of Various Quenching Media from Previous Studies

QUENCHED SAMPLE	Stabilitas Termal	Thermal Conductivity (W/m °C)	Reference
water	Very unstable	0.6	[42]
SAE40 Engine Oil	Stable	0.145	[43]
Palm kernel oil	Very stable	0.131-0.182	[33, 44]
Cottonseed oil	Stable	0.139	[33]
Palm oil	Less stable	0.169	[33]
Neem seed oil	Less stable	0.152	[33]
Sunflower Oil	Less stable	0.17–0.19	[45]

Matijevic et al. compared the quenching intensity of palm oil, canola oil, and petroleum oil using the industrial Liscic/Petrofer probe. Palm oil showed the best performance, bypassing film boiling and entering nucleate boiling directly, with higher ΔT_{10} and ΔT_{max} values, a maximum HTC of ~3000 W/m²K, and the shortest cooling time. Canola oil exhibited intermediate performance, slower than palm oil but better than petroleum oil. Petroleum oil displayed the weakest quenching behavior due to prolonged film boiling, slow initial cooling, and a lower maximum HTC of ~1940 W/m²K. Water served as a reference, providing extremely rapid but overly aggressive cooling. Overall, the study highlighted palm oil as a strong, environmentally friendly candidate to replace petroleum oils, particularly for low-hardenability steels. [46].

To ensure long-term stability, operational safety, and the effectiveness of vegetable oils as environmentally friendly alternatives to industrial quenching media, the evaluation of Acid Value and Iodine Value is critical. These parameters provide comprehensive insight into the degree of degradation and oxidative stability of the oils during repeated thermal exposure. A high Acid Value indicates an increasing concentration of free fatty acids resulting from hydrolysis or oxidation, which can alter viscosity, reduce cooling quality, and ultimately lead to inconsistent quenching performance. Meanwhile, a high Iodine Value reflects a greater proportion of unsaturated fatty acids, making the oil more susceptible to thermal oxidation, sludge formation, and reduced heat-transfer efficiency.

Table 4. Acid Value and Iodine Value of Vegetable Oils

QUENCHED SAMPLE	Acid Value	Iodine Value	reference
Palm kernel oil	Low	Low	[33]
Cottonseed oil	Medium	Medium	[33]
Palm oil	Low	Low	[33]
Palm oil (murni)	45.18	57.36	[34, 35]
Soybean Oil	15.90	124.74	[34, 35]
Neem seed oil	High	Medium	[33]
Neem Oil	13.945	74.9	[36]
Watermelon Seed Oil	3.08	121.8	[36]

A comparative study by Agboola et al. (2015) examined the feasibility of several Nigerian vegetable oils as alternative quenching media for the industrial heat treatment of medium-carbon steel. The study involved characterizing the physicochemical properties and fatty acid profiles of cottonseed oil, palm kernel oil, neem seed oil, and palm oil. The quenching performance of these vegetable oils was tested at bath temperatures of 34°C, 50°C, 70°C, and 100°C, with SAE40 engine oil (as the standard medium) and tap water used as controls. Similarly, Sani and Aminu performed a comparative analysis of other Nigerian vegetable oils as alternative quenchants to replace salt baths for the heat treatment of ductile and grey cast irons. Their study involved characterizing the physicochemical properties and fatty acid profiles of marula seed oil, cottonseed oil, groundnut oil, and shea butter. The samples were austenitized at 900°C, soaked for 1 hour, and subsequently austempered by quenching separately at 250°C, 260°C, and 270°C for 1, 2, 3, and 4 hours [33, 37].

Salihu, S. A. et al. investigated and compared the performance of neem seed oil and watermelon seed oil as alternative quenching media to SAE40 mineral oil for the heat treatment of medium-carbon steel. The steel samples were austenitized at 800–900°C, quenched in each oil, and then tempered at 250–400°C. Meanwhile, Kolawole, M. Y. et al. examined the effect of bio-mineral oil blends, groundnut oil and SAE40 on the mechanical properties of low-carbon steel carburized using a mixture of eggshell and date seed. The samples were carburized at 950°C for 3 hours and then quenched using six media: water, 100% SAE40, 100% groundnut oil, and three blends (70/30, 60/40, 50/50). All samples were subsequently tempered at 200°C. Additionally, E. A. Pérez R. et al. assessed the performance of vegetable blend oil, soybean, canola, and sunflower oils, as well as 10W30 mineral oil, as quenching media for AISI 1045 steel. Quenching was performed after heating the steel to 870°C, holding for 50 minutes, and cooling in each medium. [36, 48, 49].

Rahardja and Prumanto examined the Influence of heating temperature variation on the hardness improvement of ST37 steel through quenching using Crude Palm Oil (CPO). Specimens were heated to 200, 400, 600, 800, and 965°C, then immediately quenched in CPO. Belinato et al. expanded the investigation into oxidative stability. They found that soybean oil is highly prone to degradation due to its high degree of unsaturation, whereas palm oil is naturally more stable. The addition of antioxidants (Irganox L109, propyl gallate, TBHQ) significantly increased the oxidation onset temperature without reducing cooling performance. Civera et al. confirmed that olive and sunflower oils provide sufficient cooling for martensite formation while minimizing residual stresses and dimensional distortion, reinforcing the environmental and industrial viability of vegetable-based quenchants [34, 50, 51].

O. T. Johnson et al. studied marula oil, a local Namibian vegetable oil, as a potential alternative to SAE 40 engine oil for the heat treatment of medium-carbon steel. Samples were heated to 850°C, 900°C, 950°C, and 1000°C with holding times of 45 and 90 minutes, then quenched using marula oil and SAE40 oil. Ajiboye and Abdulsalam evaluated the use of mixed vegetable oils as quenching media for medium-carbon steel. Four vegetable oils were blended into two mixtures: Blend A (cottonseed oil + neem oil) and Blend B (cottonseed, neem, palm kernel, and shea butter oils). Samples were heated to 850°C and quenched in the various oil blends to determine their effects on mechanical properties and microstructure. Consistently, K. J. Franklin et al. analyzed the Influence of biodegradable oil-based quenching media on the microstructure and hardness of EN 31 steel. The steel was heated to 1000°C, held for 30 minutes, and quenched in four different media: 100% groundnut oil, 100% neem oil, a 60% groundnut + 40% neem blend, and a 40% groundnut + 60% neem blend. In parallel, I. Y. Suleiman et al. evaluated the effectiveness of coconut oil and ghee oil as quenching media for hardening and tempering of plain carbon steel containing 0.35% C. The steel samples were austenitized at 850°C, soaked, and then quenched accordingly [12, 52, 53, 54, and 56].

Overall, these studies indicate that the quenching medium plays a critical role in controlling the microstructural evolution and mechanical properties of heat-treated samples. Variations in cooling rate,

viscosity, thermal conductivity, and wetting behavior across different quenching media strongly influence phase transformations, grain refinement, and precipitate formation, ultimately governing the strength, hardness, and toughness of the material. In this respect, vegetable oils have attracted increasing attention because their cooling behavior can be tailored by composition and temperature, enabling more uniform and controlled heat extraction compared to conventional mineral oils. As a result, hardness measurements consistently show that vegetable oils can outperform mineral oils under certain processing conditions, thereby reducing thermal stresses and the risk of cracking. However, despite these advantages, water quenching still yields the highest hardness values due to its exceptionally rapid cooling rate, which promotes the formation of more challenging phases such as martensite. Nevertheless, this aggressive cooling often leads to severe thermal gradients, making water quenching more prone to distortion, residual stresses, and microcrack formation, thereby highlighting the need to balance hardness with overall structural integrity in practical heat-treatment applications.

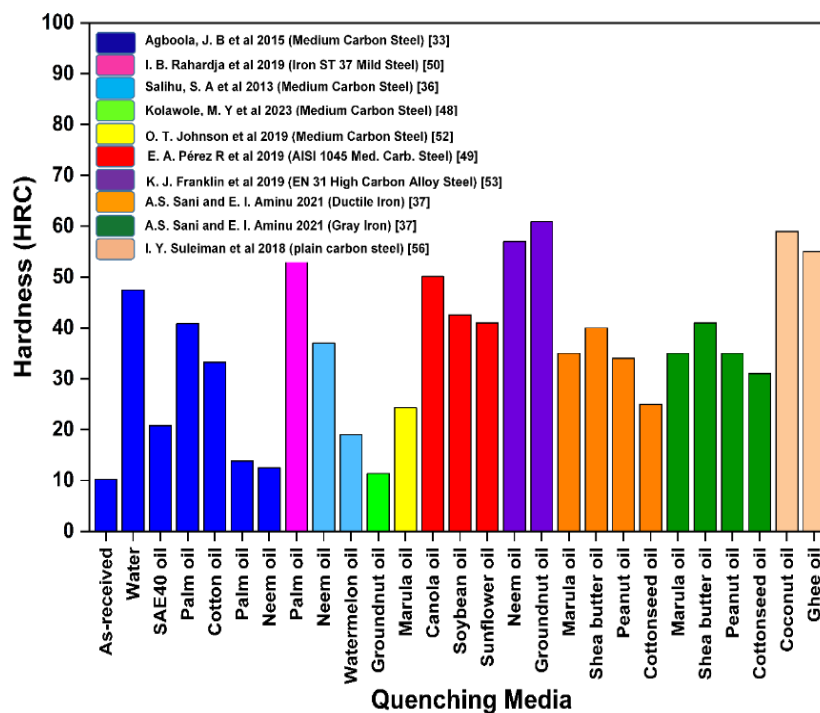


Figure 1. Influence of Vegetable-Oil Quenching Media on Hardness Development: A Comparative Analysis from Multiple Studies [33, 36, 37, 48, 49, 50, 52, 53, 56]

Impact testing is essential in analyzing vegetable-oil quenching media because it reveals the material's toughness and ensures an optimal balance between hardness and ductility, which is influenced by the vegetable oils' cooling rates.

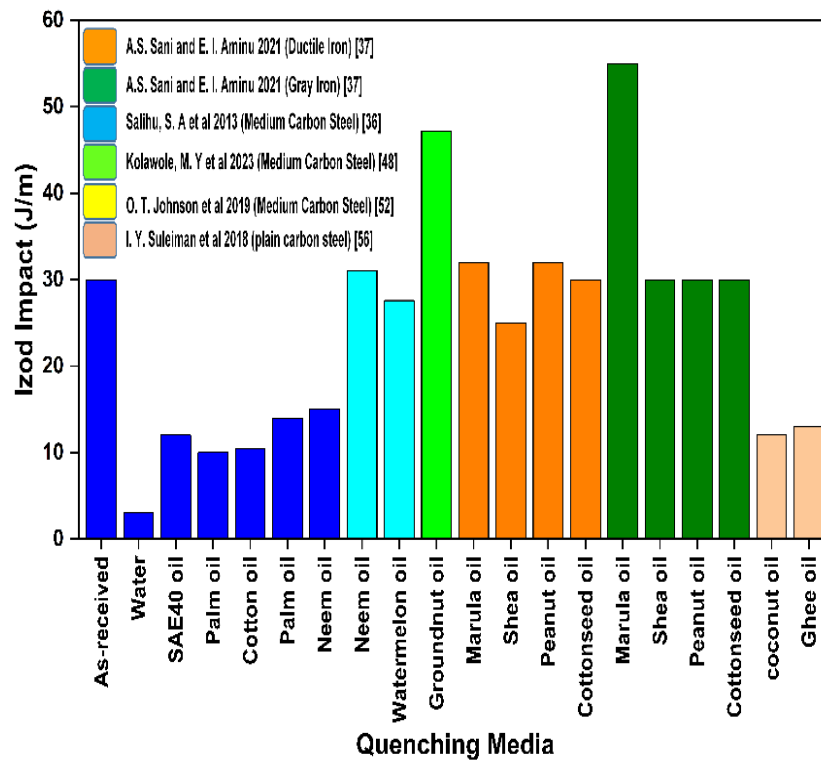


Figure 2. Influence of Vegetable-Oil Quenching Media on Izod Impact Performance: A Comparative Analysis Across Multiple Studies [36, 37, 48, 52, 56]

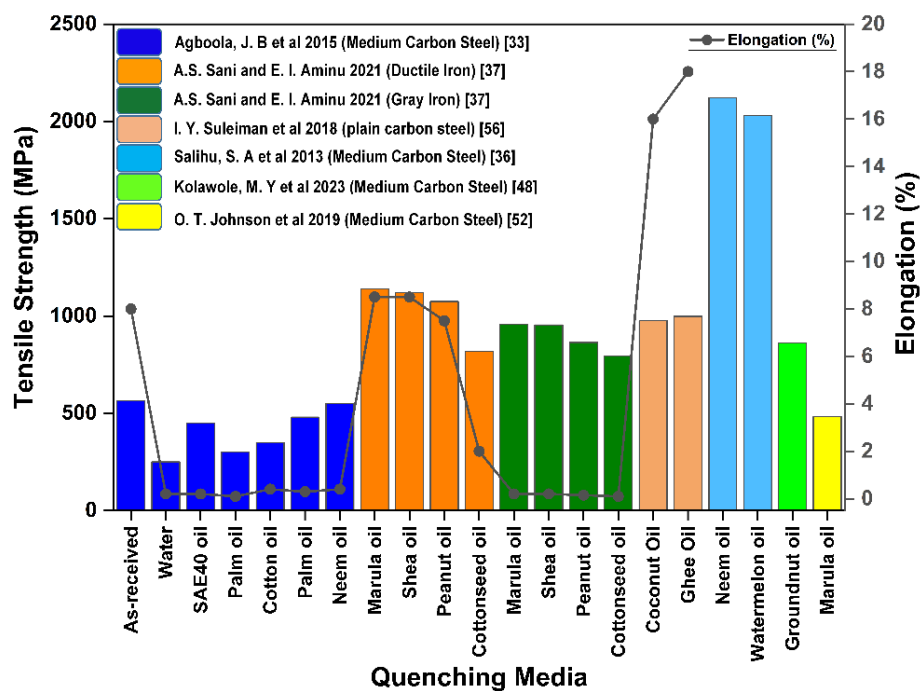


Figure 3. Influence of Vegetable-Oil Quenching Media on Tensile Strength and Elongation: A Comparative Multi-Study Evaluation [33, 36, 37, 48, 52, 56]

In addition, the tensile strength and yield strength of several specimens quenched in vegetable oil media also increased, indicating that vegetable oils can enhance hardness while maintaining ductility through their more controlled cooling rates.

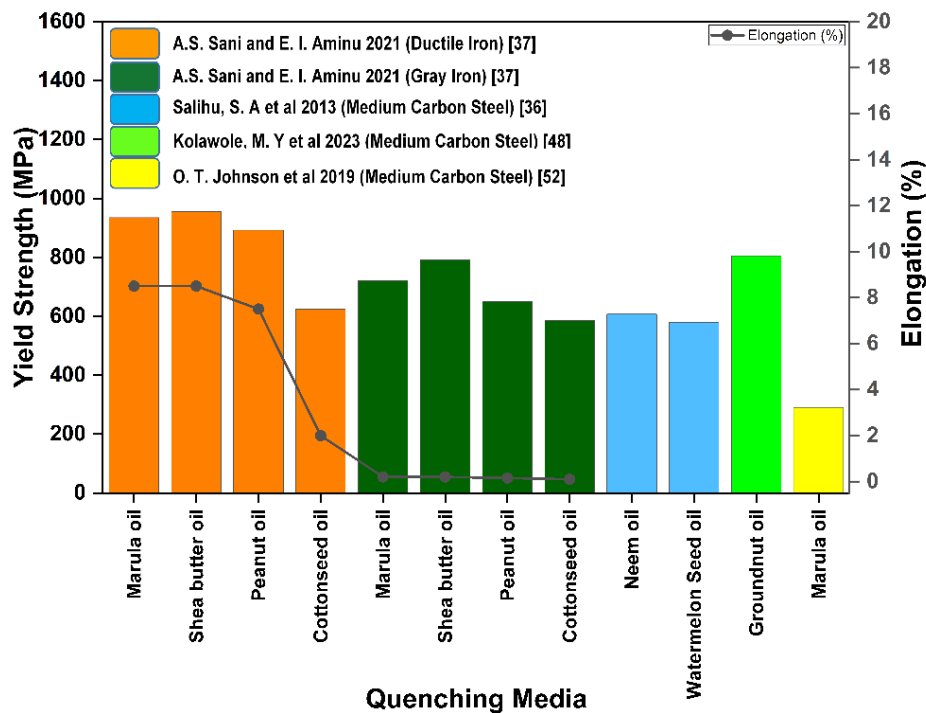


Figure 4. Influence of Vegetable-Oil Quenching Media on Yield Strength and Elongation: A Comparative Multi-Study Evaluation [36, 37, 48, 52]

Further studies have highlighted the physicochemical factors influencing the quenching process. Kobasko et al. compared five vegetable oils with mineral oils and found that vegetable oils exhibit higher viscosity indices and faster cooling rates, thereby suppressing pearlite formation and providing greater quench severity. Passanha et al. evaluated coconut, karanja, and pinnay oil emulsions mixed with brine and egg yolk, showing that a 25% coconut oil emulsion produced the highest hardness, while lower oil fractions enhanced cooling performance due to reduced viscosity. Overall, these findings consistently indicate that vegetable oils, particularly when formulated as blends or emulsions or supplemented with antioxidants, can serve as effective, environmentally friendly, and mechanically advantageous quenching media for various steels [38, 55].

The physicochemical properties of oils—including oxidative stability, viscosity, and their tendency to degrade under repeated thermal exposure—are strongly influenced by their degree of unsaturation and fatty acid composition. In the context of quenching, these molecular variations play a critical role: oils with high bis-allylic carbon content and polyunsaturation are more susceptible to oxidation and viscosity increases, ultimately reducing cooling rates and leading to less consistent quenching performance. Conversely, oils with a higher proportion of oleic acid exhibit superior thermal stability and more favorable viscosity behavior, thereby maintaining a more stable cooling rate that supports martensite formation. These chemical characteristics explain differences in cooling rate and quench severity among vegetable oils and underscore their potential as effective, environmentally benign quenching media. This phenomenon is clearly illustrated in Figure 5, which presents the ^{13}C NMR spectra of five vegetable oils—cottonseed, canola, sunflower, corn, and soybean—revealing variations in triglyceride structures through differences in the intensity of olefinic, allylic, bis-allylic, saturated, and carbonyl carbon peaks, all of which directly correlate with the physicochemical behavior of the oils during quenching [57].

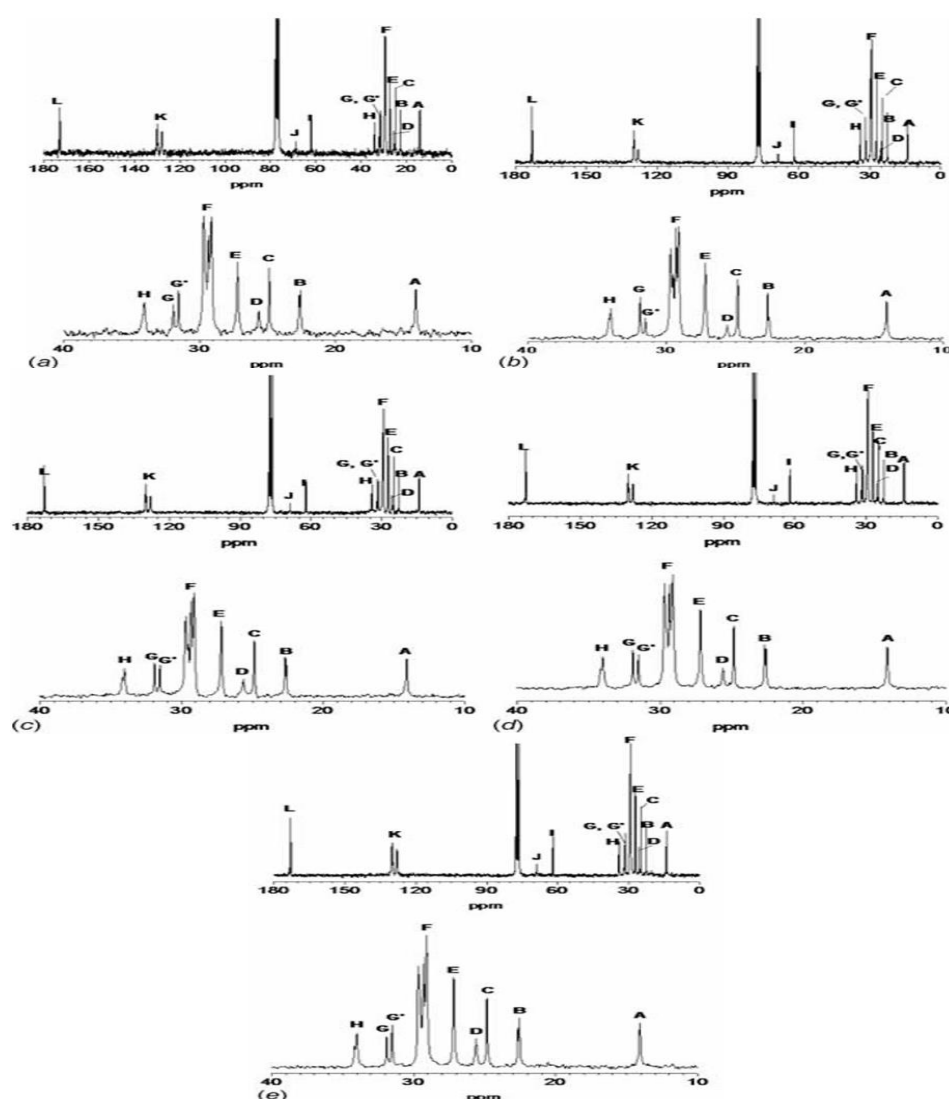


Figure 5 (a) Cottonseed oil ^{13}C NMR spectra. (b) Canola oil ^{13}C NMR spectra. (c) Sunflower oil ^{13}C NMR spectra. (d) Corn oil ^{13}C NMR spectra. (e) Soybean oil ^{13}C NMR spectra. [Excerpted from Journal 57]

4. CONCLUSIONS

This review demonstrates that vegetable oils possess favorable thermophysical properties, high biodegradability, and effective cooling performance, collectively supporting their use as sustainable alternatives to conventional mineral-oil quenchants. The analysis confirms that vegetable oils can achieve competitive hardness, improved microstructural refinement, and reduced distortion, thereby addressing the Research objective of identifying environmentally friendly quenching media with adequate thermal performance. These findings highlight the practical potential of vegetable oils to minimize environmental impact while maintaining quenching efficiency, and they also contribute theoretically by strengthening the understanding of how viscosity, thermal conductivity, and oxidative stability influence quenching behavior. To maximize their applicability, antioxidants, optimized blends, or tailored formulations are recommended to address the challenge of low thermo-oxidative stability in highly unsaturated oils. The primary limitations of current Research include the lack of standardized cooling-curve evaluation and limited industrial-scale validation; thus, future studies should focus on enhancing high-temperature stability, real-time heat-transfer modeling, and large-scale implementation across different steel grades. Overall, vegetable oils represent a promising pathway toward greener, safer, and high-performance quenching technologies.

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