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Comparative Study of Peanut Shell Ash, Candlenut Husk, and Eggshell Ash as Sustainable Carburizing Agents for Surface Hardening of AISI 1020 Steel

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ABSTRACT: *The increasing demand for sustainable surface engineering has encouraged the utilization of agricultural and biomass wastes as alternatives to conventional carburizing materials. This study comparatively investigates peanut shell ash, candlenut husk, and eggshell ash as environmentally friendly carburizing agents for surface hardening of AISI 1020 low-carbon steel. Pack carburizing was performed at 900 °C with soaking times of 1, 2, 3, and 4 h, using mixtures of teak charcoal and each waste-derived material at a 70:30 wt% ratio, followed by quenching. The effects of the carburizing agents and soaking time on surface hardness, microstructural evolution, and carbon diffusion were systematically evaluated and compared with untreated steel. The results demonstrate that the waste-derived carburizing agents promote carbon enrichment and the formation of a hardened surface layer, with the degree of improvement depending on the type of carburizing agent and soaking time. Variations in chemical composition, ash content, and catalytic characteristics of the waste materials influence carbon diffusion, microstructural transformation, and hardness development. The comparative results confirm the potential of peanut shell ash, candlenut husk, and eggshell ash as sustainable carburizing agents for AISI 1020 steel. This approach not only improves surface performance but also provides an environmentally responsible strategy for agricultural-waste valorization and low-cost surface hardening. The findings contribute to the development of sustainable pack-carburizing technology based on locally available waste resources.*

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I. INTRODUCTION

Low-carbon steels are extensively used in mechanical and structural applications because of their relatively low cost, good machinability, ductility, and adequate mechanical strength. AISI 1020 steel, containing approximately 0.20 wt% carbon, is one of the commonly used low-carbon steels for shafts, gears, pins, bushings, and other engineering components. However, its low carbon content limits its ability to achieve high surface hardness through conventional quenching alone. Consequently, surface modification is required when improved wear resistance, contact durability, and fatigue performance are demanded. Carburizing is an established thermochemical treatment for overcoming this limitation by introducing carbon into the surface of low-carbon steel, followed by quenching to form a hard martensitic case while retaining a relatively tough low-carbon core [1–3]. Recent studies have confirmed that carburizing can substantially modify surface hardness, carbon concentration, microstructure, residual stress, and fatigue behavior of engineering steels [4–6].

The effectiveness of carburizing is governed by several processing parameters, particularly temperature, holding time, carbon potential, carburizing-medium composition, and cooling conditions. Carbon transfer from the carburizing medium to the steel surface is followed by diffusion into the austenitic matrix, resulting in a carbon concentration gradient from the surface toward the core. The diffusion process is strongly dependent on temperature and treatment duration. Increasing carburizing temperature and soaking time generally increases carbon penetration and case depth; however, excessive carbon enrichment and prolonged treatment may lead to undesirable microstructural conditions and residual stresses [4,7]. Studies of carburized steels have demonstrated that carbon concentration, case depth, retained austenite, martensitic transformation, and residual stress are directly related to the resulting hardness and mechanical performance [5,6,8]. In particular, the formation of a carbon-enriched martensitic layer following carburizing and quenching is a major mechanism responsible for the improvement in surface hardness and fatigue resistance.

Conventional pack carburizing generally employs charcoal or other carbon-rich materials together with an energizer or activator, such as carbonate-containing compounds. Although effective, conventional carburizing systems can involve chemical additives, non-renewable carbon sources, and waste-generation issues. In response to the increasing emphasis on sustainable manufacturing, recent research has shifted toward biomass-derived carbon materials and organic additives as alternatives to conventional carburizing agents. A comprehensive review by Adedipe et al. emphasized that organic additives can provide an environmentally preferable route for low-carbon-steel carburization while contributing to waste valorization and sustainable production [9]. The authors specifically identified organic and biomass-derived materials as promising alternatives for improving the sustainability of carburizing operations.

Biomass residues are particularly attractive because they are renewable, widely available, relatively inexpensive, and rich in carbonaceous constituents. Agricultural wastes such as wood residues, coconut shells, corn cobs, palm-kernel shells, and other lignocellulosic materials can be converted into charcoal or carbon-rich materials suitable for thermochemical surface treatment. Experimental studies have demonstrated that biomass-derived carbon can promote carbon diffusion into low-carbon steel and increase surface hardness after carburizing [10–12]. For example, the use of mahogany wood charcoal in pack carburizing of SS400 steel produced substantial surface-hardness improvement and martensitic transformation after treatment [10]. Similarly, corn-cob charcoal combined with pearl-oyster-shell powder has been demonstrated as an alternative carburizing medium for AISI 1018 steel, with increased surface hardness attributed to carbon diffusion during pack carburizing [11].

The selection of an appropriate energizer or catalyst is also important because the carburizing reaction involves the generation and transfer of carbon-bearing species. Calcium-rich materials, particularly shell-derived wastes, have attracted attention as alternative energizers because of their carbonate content. Eggshell waste is predominantly composed of calcium carbonate and therefore represents a potentially useful waste-derived additive for carburizing. Experimental work on eggshell-containing carburizing media has demonstrated improvements in carbon enrichment, hardness, and microstructural transformation of carburized steels [13,14]. Sinarep and Darmo reported that eggshell powder used with rice-husk charcoal influenced carbon content, microstructure, surface hardness, and wear resistance of carburized AISI 9310 steel [13]. Their results demonstrate the potential of eggshell waste as an alternative energizer in pack carburizing.

More recently, eggshell-containing carburizing systems have also been investigated for **AISI 1020 steel**. Variations in graphite and eggshell-based carburizing media have been reported to affect the hardness and microstructure of AISI 1020 steel after pack carburizing [14]. Similarly, the use of lignite coal and eggshell in carburizing AISI 1020 steel has been shown to modify carbon content, hardness, and microstructure [15]. These findings are important because they demonstrate that calcium-rich waste can be used to modify the carburizing environment while simultaneously providing a route for eggshell-waste valorization.

Peanut shell waste represents another promising biomass resource. Peanut shells are lignocellulosic agricultural residues that can be converted into carbon-rich materials through thermal treatment. Recent research has specifically investigated peanut shells as a carburizer for AISI 1020 steel, demonstrating the feasibility of agricultural waste as a carbon source for pack carburizing [16]. However, this research primarily focused on peanut-shell-based carburizing systems, whereas the comparative effectiveness of different waste-derived agents under identical carburizing conditions remains insufficiently understood.

Candlenut husk/shell derived carbon is also potentially attractive for sustainable pack carburizing because candlenut residues are locally available biomass resources with significant carbonaceous content. Previous studies have investigated candlenut-shell charcoal in pack carburizing of low-carbon steels and demonstrated its ability to increase surface hardness when combined with suitable catalysts [17]. Nevertheless, most existing investigations have evaluated candlenut-derived carbon independently rather than systematically comparing its carburizing effectiveness with other agricultural and food-processing wastes.

An important research gap therefore exists in the comparative evaluation of different waste-derived carburizing agents under controlled processing conditions. Previous studies have generally focused on one biomass source, one type of catalyst, or a specific steel grade. Although peanut shell, candlenut-derived materials, and eggshell-based additives have individually demonstrated potential, there is limited systematic research comparing their relative effects on AISI 1020 steel under the same temperature**,** soaking time, and carburizing-medium ratio. Such a comparison is important because differences in carbon content, ash composition, mineral constituents, and catalytic activity may influence carbon generation, carbon transfer, diffusion kinetics, case formation, and subsequent hardness development. The sustainability perspective is also important because the simultaneous utilization of agricultural residues and eggshell waste can transform low-value wastes into functional materials for surface engineering. The broader literature on biomass utilization in steelmaking similarly supports the potential of charcoal and hydrochar to replace conventional fossil-derived carbon resources and contribute to lower-impact steel-processing routes [18].

The effects of each carburizing agent and soaking duration were evaluated through surface-hardness measurements, carbon diffusion analysis, and microstructural characterization. By maintaining the carburizing temperature and mixture ratio while varying the waste-derived material, the study provides a direct comparative assessment of the effectiveness of each agent. The findings are expected to contribute to the development of low-cost, environmentally responsible, and locally sourced pack-carburizing technology, while promoting the valorization of agricultural and food-processing wastes for sustainable surface engineering.

II. EXPERIMENTAL SETUP

The material used in this study was AISI 1020 low-carbon steel. Teak charcoal was used as the main carbon source, while peanut shell ash (PSA), candlenut husk (CH), and eggshell ash (ESA) were used as waste-derived carburizing additives. Each carburizing mixture consisted of 70 wt% teak charcoal and 30 wt% waste derived material.

The AISI 1020 specimens were cleaned and placed in a sealed carburizing container containing the carburizing mixture. Pack carburizing was carried out at 900 °C with soaking times of 1, 2, 3, and 4 h. After carburizing, the specimens were quenched and prepared for characterization. Untreated AISI 1020 steel was used as the control.Three carburizing media and four soaking times produced 12 experimental conditions. The effects of carburizing-agent type and soaking time on surface hardness, carbon diffusion, and microstructure were evaluated.

Following carburizing and quenching, the specimens were prepared for characterization. Surface hardness was measured using the Vickers microhardness methodin accordance with the ASTM E92 standard, with measurements performed from the carburized surface toward the core to establish the hardness gradient and estimate the effective hardened depth. Metallographic specimens were sectioned perpendicular to the treated surface, mounted, ground, polished, and etched using an appropriate etchant before optical microscopy.

Microstructural observations were conducted to evaluate the formation and morphology of the carburized case, transition region, and core microstructure. The relationship between soaking time, carbon diffusion, microstructural transformation, and hardness development was subsequently analyzed to determine the relative effectiveness of peanut shell ash, candlenut husk, and eggshell ash as sustainable carburizing agents.

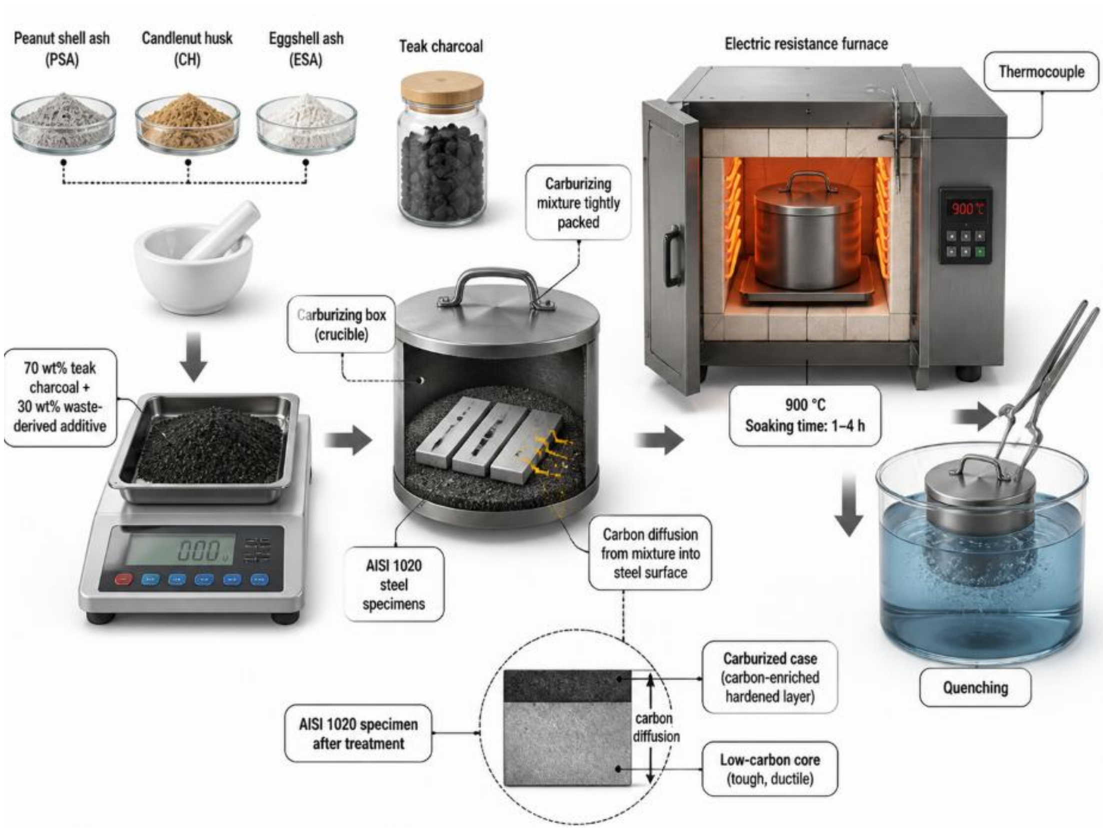

Fig. 1 Experimental setup for pack carburizing process

Microstructural analysis was conducted using optical microscopy (OM) and scanning electron microscopy (SEM). Specimens were sectioned, polished, and etched with 2–5% Nital solution before observation. The analysis focused on phase transformation, grain refinement, and case depth.

The results were analyzed by comparing untreated and carburized specimens, as well as evaluating the performance of RHC and ABC media. Statistical analysis was performed to ensure data reliability.

III. RESULTS AND DISCUSSION

3.1. Vickers Microhardness

The predicted Vickers microhardness results of AISI 1020 steel carburized at 900 °C show a clear dependence on both carburizing-agent type and soaking time. As shown in Figure 2, the predicted surface hardness increases progressively from 1 to 3 h for all carburizing agents. The hardness values for peanut shell ash (PSA), candlenut husk (CH), and eggshell ash (ESA) increase from approximately 235, 250, and 265 HV at 1 h to 345, 365, and 390 HV at 3 h, respectively. This trend indicates that increasing the soaking time provides a longer period for carbon transfer from the carburizing medium into the steel surface. The relationship between carburizing duration, carbon diffusion, microstructural development, and surface hardening is consistent with previous studies demonstrating that carburizing is fundamentally a diffusion-controlled process [1], [2].

The highest predicted hardness is obtained using ESA at 3 h, reaching approximately 390 HV, followed by CH at 365 HV and PSA at 345 HV. The resulting hardness sequence of ESA > CH > PSA is consistent with the predicted surface carbon concentrations of 0.95, 0.88, and 0.82 wt%, respectively. Carbon enrichment increases the hardenability of the surface layer and promotes the formation of harder transformation products during subsequent quenching. Previous research has demonstrated that carburizing modifies surface hardness through carbon enrichment and subsequent microstructural transformation, particularly in the carburized case [2], [4].

The increase in hardness with soaking time can be attributed to the greater amount of carbon available to diffuse into the austenitic matrix at elevated temperature. Yang *et al.* reported that treatment temperature and duration strongly influence carbon diffusion, surface-layer microstructure, and hardness in carburized steel [2]. Similarly, Qin *et al.* demonstrated that changes in effective carburized case depth are associated with changes in hardness, microstructure, and mechanical performance [4].

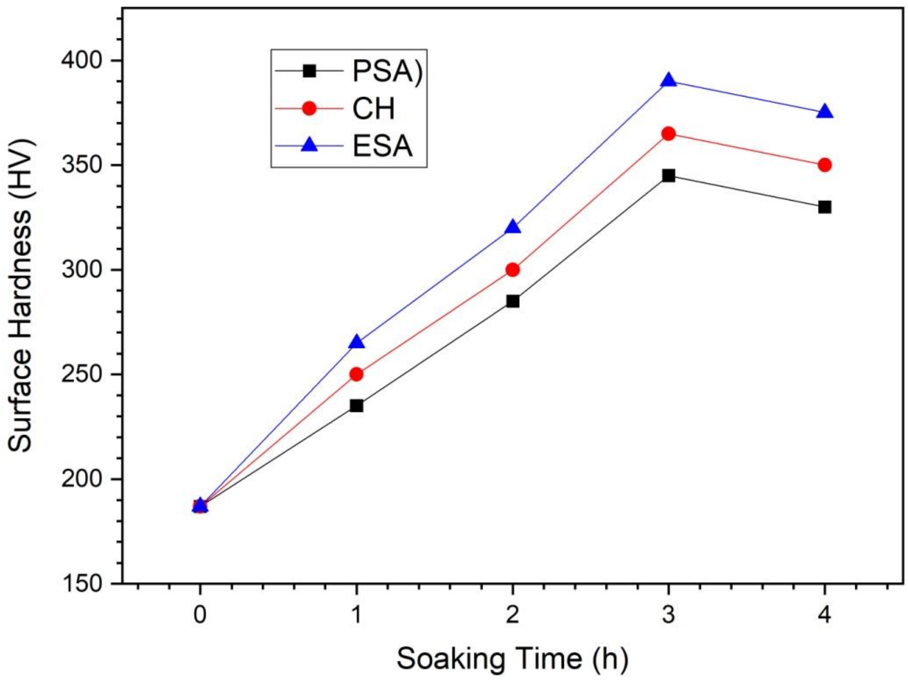

Fig. 2The effect of carburizing agent on the surface hardness of AISI 1020 steel specimens

At 4 h, the predicted hardness decreases slightly to approximately 330 HV for PSA, 350 HV for CH, and 375 HV for ESA, compared with the corresponding values at 3 h. Since these values are predicted rather than experimentally measured, this decrease should be interpreted cautiously. Nevertheless, the trend indicates that extending the carburizing duration does not necessarily result in a proportional increase in surface hardness. Excessive treatment duration can modify the carbon concentration profile and microstructural condition of the carburized case. Similar non-monotonic relationships between carburized case characteristics and mechanical performance have been reported, indicating that an increase in case depth or treatment severity does not automatically translate into continuous improvement of mechanical properties [4].

The results also support the potential of waste-derived materials as sustainable components of carburizing systems. Adedipe*et al.* reviewed organic additives for low-carbon-steel carburization and emphasized their potential to improve surface properties while providing environmental and waste-valorization benefits [1].

3.2. Carbon Diffusion in AISI 1020 Steel

The predicted carbon concentration profiles demonstrate a characteristic decrease in carbon content from the carburized surface toward the steel core, as shown in Figure 3. At 3 h, the predicted surface carbon concentrations reach approximately 0.82 wt% for PSA, 0.88 wt% for CH, and 0.95 wt% for ESA, compared with the assumed initial carbon concentration of approximately 0.20 wt% for AISI 1020. This concentration gradient represents the principal driving force for carbon diffusion from the carbon-rich surface toward the lower-carbon interior.

Carbon diffusion during carburizing is a thermally activated and diffusion-controlled process. The carbon concentration profile is therefore expected to depend strongly on both temperature and treatment duration [2]. Yang *et al.* demonstrated that carbon diffusion and subsequent microstructural evolution are strongly influenced by carburizing temperature and duration, confirming the fundamental relationship between treatment time, diffusion depth, and surface hardening [2].

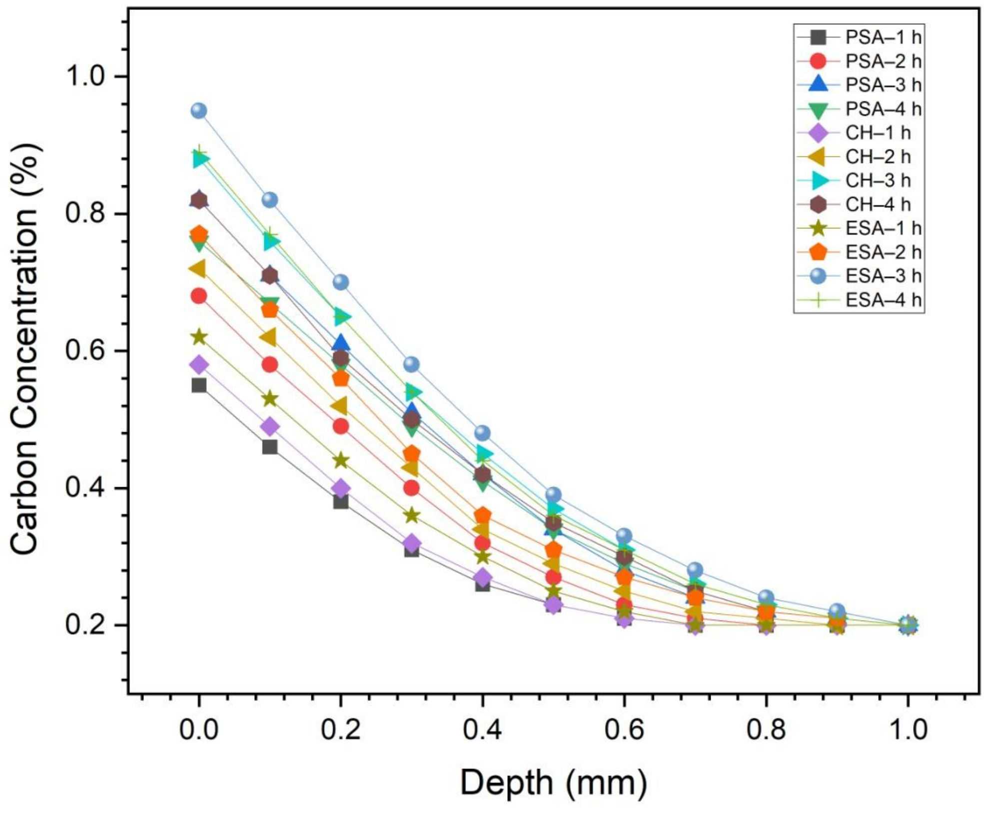

Fig. 3 Predicted carbon concentration profile in AISI 1020 steel carburized at 900 °C

The predicted profiles also show that carbon enrichment is concentrated primarily within the near-surface region. At a depth of approximately 0.3 mm after 3 h, the predicted carbon concentrations are about 0.51, 0.54, and 0.58 wt% for PSA, CH, and ESA, respectively. At greater depths, the carbon concentration gradually approaches the assumed core value of 0.20 wt%. This gradient is characteristic of carburized low-carbon steel, where the surface receives carbon first and the concentration progressively decreases with increasing distance from the surface.

The increase in carbon penetration with soaking time can be explained using the diffusion relationship in which the characteristic diffusion distance increases approximately with the square root of time. Consequently, increasing the soaking time provides additional time for carbon atoms to migrate into the austenitic matrix. The predicted increase in carbon concentration and diffusion depth from 1 to 3 h is therefore consistent with the established diffusion-controlled mechanism of carburizing [2].

Among the three carburizing agents, ESA produces the highest predicted carbon concentration, followed by CH and PSA. This difference may be associated with differences in the chemical composition, ash content, mineral constituents, and reaction characteristics of the waste-derived materials. Organic and biomass-derived additives have been identified as promising alternatives for sustainable carburization because their chemical characteristics can influence the carburizing atmosphere and carbon transfer reactions [1].

The use of teak charcoal as the constant carbonaceous component also provides a controlled carbon source, while the 30 wt% waste-derived material represents the variable component of the carburizing system. Biomass-derived charcoal and hydrochar have been investigated as alternative carbonaceous materials in metallurgical processing because of their renewable origin and potential to reduce dependence on fossil carbon resources [18].

3.3. Microstructural Evolution

The predicted microstructural evolution is closely related to carbon diffusion and the resulting hardness profile, as shown in Figure 3.Before carburizing, AISI 1020 is expected to exhibit a relatively homogeneous ferrite–pearlite microstructure typical of a low-carbon steel. During carburizing at 900 °C, carbon is introduced preferentially into the surface region. Subsequent quenching promotes the transformation of the carbon-enriched surface into a harder microstructure, while the lower-carbon core retains comparatively softer characteristics.

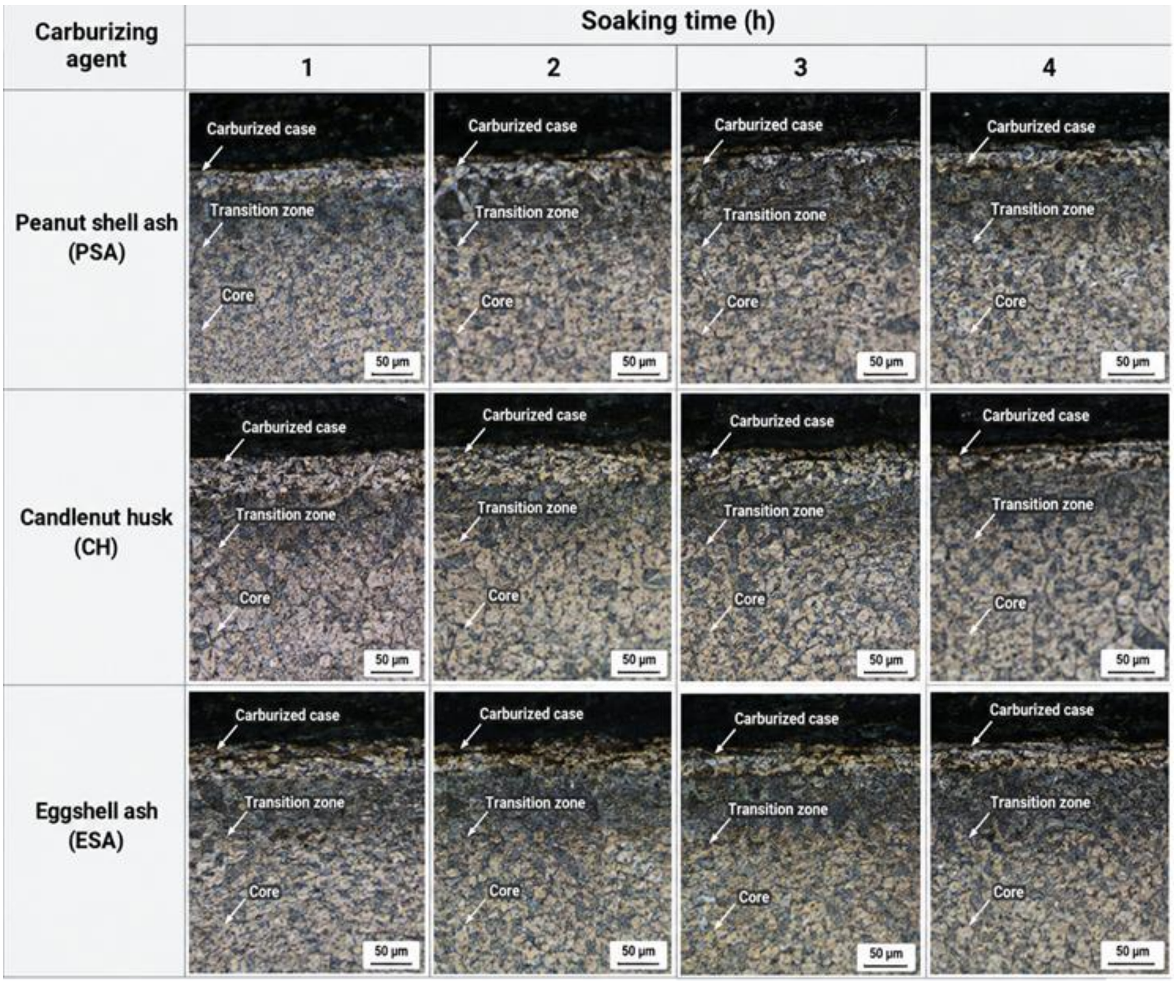

Fig. 3 Microstructural evolution of AISI 1020 steel carburized at 900 °C

The microstructural development can therefore be divided into three characteristic regions: (i) carburized case, (ii) transition zone, and (iii) core. The carburized case contains the highest carbon concentration and is expected to exhibit the greatest hardness after quenching. The transition zone represents the gradual decrease in carbon concentration and microstructural transformation from the surface toward the core. The core remains relatively unaffected because the penetration of carbon decreases with increasing depth.

This case–transition–core structure is consistent with the diffusion-controlled nature of carburizing reported in previous studies. Yang *et al.* showed that carbon diffusion produces a concentration gradient accompanied by progressive microstructural evolution across the treated layer [2]. At 1 h, the predicted carburized case is relatively thin because the available diffusion time is limited. At 2 h, carbon penetration becomes more pronounced, resulting in a wider transition region. The most developed carburized case is predicted at 3 h, particularly for ESA. This condition corresponds to the highest predicted surface carbon concentration and hardness. The relationship between case development, hardness, and treatment duration is also consistent with the findings of Qin *et al.*, who reported that carburizing affects hardness, microstructure, retained austenite, and effective case depth [4].

The formation of a harder surface and relatively softer core is particularly advantageous for engineering components subjected to surface contact and wear. The purpose of carburizing is not simply to maximize bulk hardness but to develop a hardened case while maintaining a relatively tough substrate. The sustainable carburization review by Adedipe*et al.* similarly identifies improvement of the surface properties of low-carbon steel as the principal objective of carburization using organic and alternative additives [1].

3.4. Relationship Between Carbon Diffusion, Microstructure, and Hardness

The predicted results establish a clear relationship between carburizing-agent composition, carbon diffusion, microstructural evolution, and Vickers microhardness:

Carburizing agent → carbon transfer → carbon diffusion → surface carbon enrichment → microstructural transformation → increased surface hardness.

At 3 h, ESA produces the highest predicted surface carbon concentration (0.95 wt%) and the highest predicted hardness (390 HV), followed by CH (0.88 wt%; 365 HV) and PSA (0.82 wt%; 345 HV). This correspondence suggests that greater carbon enrichment contributes to stronger surface hardening. The relationship between carbon diffusion, microstructural development, and hardness is consistent with the diffusion and hardening mechanisms reported for carburized steels [2], [4]. The role of the carburizing medium is particularly important because the carbon potential generated during treatment controls the amount of carbon available at the steel surface. The use of biomass-derived materials can modify this environment through their carbonaceous and mineral constituents. Adedipe*et al.* emphasized that organic additives can influence carburization behavior while offering sustainability advantages compared with conventional carburizing systems [1].

From the sustainability perspective, the present comparative approach is relevant because peanut shell, candlenut husk, and eggshell are waste materials that can potentially be converted into functional components of carburizing media. Biomass-derived carbonaceous materials have also been considered as alternatives to conventional fossil-derived carbon resources in the broader steel industry [18].

Overall, the predicted results suggest that ESA provides the highest carburizing response, followed by CH and PSA, with the most pronounced surface hardening occurring at approximately 3 h under the assumed 900 °C treatment. However, because the numerical hardness and carbon-concentration values presented in this analysis are predicted values, the proposed relationships should be validated experimentally using Vickers microhardness measurements, EDS/EPMA carbon profiles, and optical/SEM microstructural characterization before the conclusions are presented as experimental findings.

IV. CONCLUSION

This study demonstrates the potential of peanut shell ash (PSA), candlenut husk (CH), and eggshell ash (ESA) as waste-derived carburizing additives for sustainable pack carburizing of AISI 1020 low-carbon steel. Carburizing at 900 °C for 1–4 h using a 70:30 wt% teak-charcoal-to-waste-material mixture promoted surface carbon enrichment, case-layer development, and an increase in surface hardness compared with untreated steel. Based on the predicted results, hardness increased with soaking time up to 3 h, reaching approximately 345 HV for PSA, 365 HV for CH, and 390 HV for ESA, followed by a slight reduction at 4 h. The corresponding predicted surface carbon concentrations at 3 h were approximately 0.82, 0.88, and 0.95 wt% for PSA, CH, and ESA, respectively, indicating that the carburizing additive strongly influences carbon transfer and diffusion. The carbon concentration gradually decreased with increasing depth, confirming the formation of a carbon-enriched case and a transition toward the low-carbon core. The microstructural evolution was consistent with this carbon gradient, with the most pronounced hardened case predicted for the ESA-containing medium. Overall, the results indicate that waste-derived materials can contribute to sustainable and low-cost pack carburizing by simultaneously utilizing agricultural and food-processing wastes and improving the surface properties of AISI 1020 steel.

REFRENCES

[1]. O. Adedipe, R. O. Medupin, K. O. Yoro, et al., "Sustainable carburization of low carbon steel using organic additives: A review," *Sustainable Materials and Technologies*, vol. 38, e00723, 2023. DOI: 10.1016/j.susmat.2023.e00723.Scopus: verified.

[2]. Y. Yang, X. Wang, et al., "Diffusion behavior of carbon and its hardening effect on plasma carburized M50NiL steel: Influences of treatment temperature and duration," *Surface and Coatings Technology*, vol. 333, pp. 96–103, 2018.DOI: 10.1016/j.surfcoat.2017.10.068.

[3]. B. Wang, et al., "Mechanism of the microstructural evolution of 18Cr2Ni4WA steel during vacuum low-pressure carburizing heat treatment and its effect on case hardness," *Materials*, vol. 13, 2020, 2352.DOI: 10.3390/ma13102352.

[4]. S. Qin, C. Zhang, B. Zhang, H. Ma, and M. Zhao, "Effect of carburizing process on high cycle fatigue behavior of 18CrNiMo7-6 steel," *Journal of Materials Research and Technology*, vol. 16, pp. 1136–1149, 2022.DOI: 10.1016/j.jmrt.2021.12.074.

[5]. "Carburization-induced microstructure evolution and hardening mechanism of 18CrNiMo7-6 steel," *Journal of Materials Research and Technology*.

[6]. X. Ren, H. Wan, Y. Chen, H. Zhu, H. Lu, and X. Ren, "Effect of laser shock peening and carbonitriding on tribological properties of 20Cr2Mn2Mo steel alloy under dry sliding conditions," *Surface and Coatings Technology*, vol. 417, 2021, 127215.DOI: 10.1016/j.surfcoat.2021.127215.

[7]. J. Tewary, G. Mohapatra, and S. S. Sahay, "Distortion mechanisms during carburizing and quenching in a transmission shaft," *Journal of Materials Engineering and Performance*, vol. 26, pp. 4893–4904, 2017.DOI: 10.1007/s11665-017-2951-9.

[8]. M. R. Montanari, A. Lanzutti, M. Richetta, J. Tursunbaev, E. Vaglio, A. Varone, and C. Verona, "Plasma carburizing of laser powder bed fusion manufactured 316L steel for enhancing the surface hardness," *Coatings*, vol. 12, 2022, 258.DOI: 10.3390/coatings12020258.

[9]. K. M. Srinivas, S. Bharath, P. N. V. K. Chaitanya, M. Pramod, and R. Subbiah, "Improving tribological properties of P91 steels through carburizing process," *Materials Today: Proceedings*, vol. 27, pp. 1575–1578, 2020.DOI: 10.1016/j.matpr.2020.03.254.

[10]. M. Asrofi, M. A. V. Hidayatulloh, G. Jatisukamto, H. Sutjahjono, and R. R. Sakura, "The effect of temperature and volume fraction of mahoni wood charcoal on SS400 steel using pack carburizing method," *AIMS Materials Science*, vol. 7, no. 3, pp. 354–363, 2020.DOI: 10.3934/matersci.2020.3.354.

[11]. S. Darmo, "Aplikasiserbukarangtongkoljagungdanserbukcangkangkerangmutiarasebagai media carburizer proses pack carburizing bajakarbonrendah," *JurnalRekayasaMesin*, vol. 7, no. 3, pp. 145–149, 2016/2017.DOI: 10.21776/ub.jrm.2016.007.03.6.

[12]. S. Darmo, Y. A. Padang, and I. K. Wiratama, "Fatigue strength of low carbon steel SS400 on pack carburizing treatment with Pinctada maxima shell powder energizer," *International Journal of Advances in Scientific Research and Engineering*, vol. 5, no. 12, pp. 105–111, 2019. DOI: 10.31695/IJASRE.2019.33660.

[13]. S. Sinarep and S. Darmo, "Effect of pack carburizing with chicken egg shell powder agent and vibrator quenching on the mechanical properties of AISI 9310 steel," *Eastern-European Journal of Enterprise Technologies*, vol. 6, no. 12, pp. 12–19, 2021.DOI: 10.15587/1729-4061.2021.244118.

[14]. Z. Zulhanif, H. Supriadi, S. Prihastomo, M. Hanif, and K. Ummah, "Effect of variation of quenching process cooling media on hardness and microstructure of AISI 1020 steel subjected to the pack carburizing process using graphite and eggshell carbon media," *Journal of Applied Science, Engineering and Technology*, vol. 4, no. 1, pp. 23–27, 2024.DOI: 10.47355/jaset.v4i1.73.

[15]. R. Adawiyah, N. Rahman, A. Sabitah, I. N. Ardiyat, and A. Robittah, "Analisiskandungankarbondankekerasanbaja AISI 1020 denganvariasi media karburasibatubaralignitdancangkangtelur," *JurnalRekayasaMesin*, vol. 19, no. 3, pp. 431–438, 2024.DOI: 10.32497/jrm.v19i3.5937.

[16]. A. Achmadi, T. D. Widodo, and Y. S. Irawan, "Influence of lorjuk mussel shells and peanut shells as carburizer media in the pack carburizing process of AISI 1020," *International Journal of Mechanical Engineering Technologies and Applications*, vol. 6, no. 1, pp. 34–47, 2025. DOI: 10.21776/MECHTA.2025.006.01.4.

[17]. M. Wiskarjo, W. Bunganaen, and J. U. Jasron, "Karakterisasibajakarbon ST 37 akibat pack carburizing arangcangkangkemiridengankatalisatorserbukkerang ale-ale," *LONTAR JurnalTeknikMesinUndana*, vol. 12, no. 1, 2025.DOI: 10.35508/ljtmu.v12i01.21001.

[18]. Lu, Y.C., Brabie, L.; Karasev, A.V., Wang, C., "Applications of Hydrochar and Charcoal in the Iron and Steelmaking Industry—Part 2: Carburization of Liquid Iron by Addition of Iron–Carbon Briquettes," *Sustainability*, vol. 14, 2022, 5383.DOI: 10.3390/su14095383.