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EXPLORING HAZELNUT SHELL-DERIVED CARBON AS AN ECO-FRIENDLY ADDITIVE IN BICYCLE TIRE MANUFACTURING

RAZISKOVANJE EKOLOŠKO PRIJAZNEGA OGLJIKA, PRIDOBLJENEGA IZ LUPIN LEŠNIKOV, KOT DODATKA V PROIZVODNJI KOLESARSKIH PLAŠČEV

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Recently, the tire industry has focused on eco-friendly practices, particularly on integrating waste materials into rubber formulations. Natural alternatives to carbon have offered a promising way to lower the carbon footprint by promoting recycling. This study explored the incorporation of carbon derived from hazelnut shells (HSC), an agricultural byproduct, as an additive in bicycle tire manufacturing. Bicycle tire formulations were prepared by maintaining a constant total carbon filler content of 28 parts per hundred rubber (phr). Initially, 28 phr of commercial carbon black and 0 phr of HSC were used. In subsequent formulations, the carbon black content was gradually reduced to (21, 14, 7, and finally 0) phr, while the HSC content was correspondingly increased to (7, 14, 21, and 28) phr to replace the reduced commercial carbon black. The produced tires were analyzed using density measurements, Mooney viscosity (MV), Mooney scorch (MS), rheological evaluations, mechanical testing, scanning electron microscopy (SEM), thermogravimetric analysis (TGA), plunger tests, and rolling resistance tests. The study demonstrates that, although increasing the amount of HSC in tire compositions reduces the mechanical performance, the required performance standards for bicycle tires are still met.

Keywords: hazelnut shell carbon (HSC), bicycle tire, carbon black alternatives, eco-friendly rubber additives

Gumarska industrija se vse bolj osredotoča na okolju prijazne tehnologije izdelave gume in še posebej na integracijo odpadnih materialov v maso za gume. Naravna alternativa ogljika ponuja obetajoč način za zmanjšanje ogljičnega odtisa in promocijo recikliranja. V tej študiji avtorja članka opisujeta raziskavo vključevanja dodatka ogljika iz lupin lešnikov (HSC; angl.: hazelnut shells) v proizvodnjo kolesarskih plaščev. HSC nastaja kot stranski bioprodukt izdelave lešnikovih jederc. Avtorji so maso za proizvodnjo gume za kolesarske plašče izdelali tako, da so ohranili konstantno vsebnost ogljikovega polnila (28 delov na 100 delov gume; phr). Na začetku so uporabili 28 phr komercialnega črnega ogljika in 0 phr HSC. Nadaljnje recepture so avtorji postopoma spreminjali. Vsebnost črnega ogljika so nadomeščali oziroma zmanjševali na (21, 14, 7) phr in nazadnje na 0 phr, medtem ko so vsebnost HSC v recepturi skladno povečevali z zmanjševanjem vsebnosti komercialnega črnega ogljika. Izdelane kolesarske plašče so nato analizirali; določili so njihovo gostoto, odpornost gume proti deformaciji oziroma Mooney-jevo viskoznost (MV) in Mooney-jev test odžiga (MS; Mooney Scorch), ovrednotili so reologijo izdelanih vzorcev gume, izvedli njihovo mehansko testiranje, izvedli preglede pod vrstičnim elektronskim mikroskopom (SEM), izvedli še termo-gravimetrične analize (TGA), teste potapljanja in teste odpornosti proti valjanju. V tej študiji sta avtorja dokazala, da se s povečevanjem vsebnost HSC v sestavi gume kolesarskih plaščev postopoma zmanjšujejo mehanske performance gume. Vendar so le te še vedno v okviru standarda oziroma predpisov za kolesarske gume.

Ključne besede: ogljik iz lupin lešnikov, kolesarski plašči, alternative črnemu ogljiku, ekološko prijazni dodatki gumi.

1 INTRODUCTION

In 2023, global bicycle production surged, particularly in Europe and Asia, with Europe producing 11.7 million bicycles. The global bicycle market, valued at $88.27 billion, is expected to grow, leading to an increased tire production and a corresponding rise in the consumption of natural resources and reliance on carbon-intensive materials like carbon black (CB).[1,2] This has raised environmental concerns, pushing industries to explore sustainable alternatives.[3,4] In response, the tire industry has begun developing eco-friendly materials. The increasing focus on waste management and resource efficiency is driving manufacturers toward lower carbon production processes.[5,6] Biomass, plastic, and agricultural waste, like food peels and plant stalks, offer potential as renewable resources.[7,8] Hazelnut shells, a commonly used type of agricultural waste, are especially valued in applications such as bioenergy production, biomass energy, and carbon material production due to their renewable properties.[9,10] Hazelnuts are one of Turkey's key agricultural crops. The north coastlines of Turkey are so suited for hazelnut cultivation that they supply almost 80 % of the world's total hazelnut crop.[11] Recent studies demonstrate that biomass waste, including hazelnut shells, can be converted into valuable products through various processes.[12,13] Alexander Bardha et al. examined the properties of hazelnut shell as a full or partial re-

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placement of CB in rubber composites. They demonstrated that the hazelnut shell biochars provide high reinforcement properties, meeting or exceeding those of CB and that a slurry-based activation of biochar improves the mechanical properties in the filled composite.[14] C.D. Midhun et al. explored rice husk ash (RHA) as a partial replacement for CB in a basic tire tread formulation. They found that substituting 5 phr RHA for CB produced composites with similar mechanical properties, improved rolling resistance, and thermal stability, though abrasion resistance was slightly decreased.[15] Öznur Bağ's study explored oak sawdust as a sustainable carbon source using hydrothermal carbonization and pyrolysis. The research demonstrated that activated carbons with high surface areas (up to 1661.97 m^2/g) could be produced, showing potential as an eco-friendly carbon alternative.[16]

John Boyd Dunlop's invention of the pneumatic tire for his son's tricycle in 1888 revolutionized transportation. Advances in tire technology, as well as chain drive and gear systems, have significantly shaped the bicycle industry since the late 1800s.[17] Today, with 100 million bicycles produced annually, estimates suggest that by 2050 there will be around 5 billion bicycles worldwide, further promoting the production of tires as an essential component of bicycles.[18]

Tires are made of synthetic and natural rubber, metal wire, carbon-sulfur compounds, and other components. Depending on the type of tires, they are made of rubber (60–65 % by weight), CB (25–35 % by weight), silica (0–5 % by weight), process oil, antioxidant, and accelerators.[19] CB has been used as a reinforcing filler in the rubber industry for several decades. It is primarily composed of elemental carbon, which is partly graphitic in structure.[20] CB improved the cure properties and mechanical strength of the natural rubber/styrene-butadiene rubber (NR/SBR) blends.[21] The properties of cured rubber largely depend on the additives and ingredients mixed with basic rubber blends.[22] However, the production and use of CB pose health and environmental risks. This has led to a search for sustainable alternatives in the rubber industry. Renewable fillers, such as natural plant fibers, are gaining interest due to their affordability, biodegradability, and favorable mechanical properties. Although HSC has been explored in recycling applications, its potential as a filler in bicycle tire formulations remains largely unexplored. This study addresses this gap by evaluating HSC in tire treads through density, MV, MS, SEM, TGA, rheological, mechanical, plunger, and rolling resistance tests. The tires were assessed according to the TSE 11187 standard, focusing on safety, durability, and performance requirements for bicycle tires and rims.

2 EXPERIMENTAL PART

2.1 Materials

The materials used in this study included natural rubber (NR) and carbon black (determined as N220), supplied by OMSK Carbon Group (Russia), as well as styrene butadiene rubber (SBR), provided by Kumho Petrochemical (Korea). Hazelnut shell carbon (HSC) and other rubber ingredients such as naphthenic oil, zinc oxide, stearic acid, sulfur, and accelerators (6PPD, TMQ, MBTS, NS) were supplied by local companies in Turkey. Regenerated rubber was obtained from Samsun Akin Rejenere Kauçuk, while all other ingredients were commercial grades used as received from ANLAS Tyre Company (Düzce, Turkey).

A comparison of the physical and chemical properties of HSC and N220, including parameters such as fines content, iodine value, oil absorption, and ash content, is shown in the **Table 1.**

Table 1: Comparison of physical and chemical properties of HSC and N220

ASTM designation	HSC	N220
Fines %	1.825	1.21
Iodine (mg/g)	30.7	121
325 mesh sieve	0.032	0.024
OAN (DBPA) (mL/100g)	62.4	114
Ash	2.15	0.4

The physical and chemical properties of commercially sourced HSC and N220 were compared to evaluate their suitability as fillers in rubber compounds. HSC shows a higher fines content (1.825 %) compared to N220 (1.21 %), while the iodine value, an indicator of surface area or porosity, is lower for HSC (30.7 mg/g vs. 121 mg/g for N220). Additionally, oil absorption is much lower for HSC (62.4 mL/100g) than N220 (114 mL/100g), which suggests a less structured filler network. Lastly, HSC has a higher ash content (2.15 %) than N220 (0.4 %), which may affect its thermal and mechanical properties. N220 meets and exceeds the me-

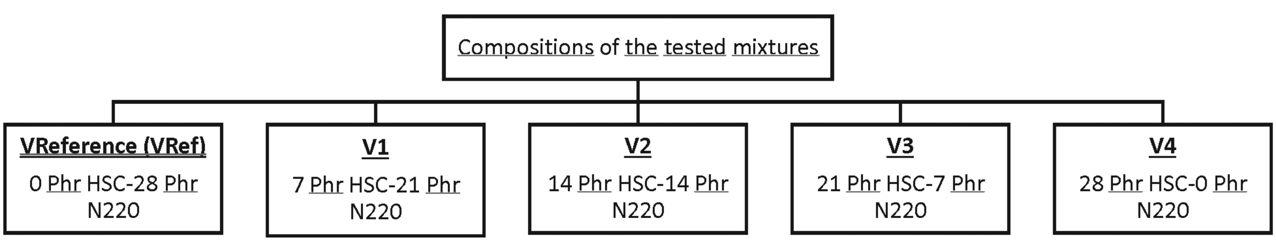

Figure 1: Codes and components of the mixtures

chanical requirements for bicycle tires, making it a reliable choice. However, the need for more sustainable alternatives has driven the interest in HSC. Although HSC demonstrates lower performance compared to N220, it has the potential to meet the minimum mechanical requirements for bicycle tires while offering an environmentally friendly option.

A typical tread formulation with N220 was used as the basic reference. Codes and components of the developed mixtures are shown in **Figure 1.**

The raw materials used in the formulations and their quantities in phr are listed in **Table 2**. The reference blend and the blends containing varying amounts of HSC are labeled as V1, V2, V3, and V4.

Table 2: Tread rubber formulations in phr

Raw materials	VRef (phr)	V1 (phr)	V2 (phr)	V3 (phr)	V4 (phr)
Natural rubber	20	20	20	20	20
SBR	35	35	35	35	35
Regenerated rubber	90	90	90	90	90
Carbon black	28	21	14	7	0
HSC	0	7	14	21	28
Process oil	3	3	3	3	3
White fill	10	10	10	10	10
Activator	6	6	6	6	6
Antioxidant	4	4	4	4	4
Resin	1.5	1.5	1.5	1.5	1.5
Accelerators	1.2	1.2	1.2	1.2	1.2
Sulfur	2	2	2	2	2

2.2 Methods

2.2.1 Preparation of rubber compounds

The rubber compound for the bicycle blend was mixed on a two-roll mill using the ingredients listed in **Table 2**. First, NR was added, followed by SBR, and they were mixed until a nearly uniform sheet formed. Next, organic and inorganic activators were added and thoroughly combined, then CB and process oil were mixed in. Finally, the remaining components, including antidegradants, were incorporated to ensure full blending.[23–25] After the compound was prepared, it was extruded to form a tire tread. The final bicycle tire, sized 29 × 2.1, was cured at 170 °C for 7 minutes.

2.2.2 Characterizations

Density, defined as the mass per unit volume of elastomeric material, was measured according to the TS 2827 EN ISO 2781 standard, which outlines two methods for determining the density of solid vulcanized rubbers. This test is crucial for calculating the meter weight of elastomers and cost estimates.[26] For this, crack-free and dust-free test specimens were weighed first in air and then in water. The measurements were performed using a Mettler Toledo density measurement kit.

The Mooney scorch test, conducted at 135 °C for 20 min, followed the ASTM D1646 standard to evaluate the heating behavior and vulcanization characteristics of rubber compounds. The Mooney viscosity (MV) test was also performed per ASTM D1646 at 120 °C for (1+4) min to assess the flow and viscosity properties of uncured rubber. This test helps control the compound's fluidity, as lower viscosity indicates softer compounds and higher viscosity indicates harder compounds, directly affecting processability.[27] Both tests were conducted using an EKTRON MV 2001M device.

Rheometer tests (MDR) were conducted using an EKTRON MDR 2000S, following the ASTM D5289/ ISO 6502 standards to assess the dynamic properties and vulcanization behavior of rubber. Mixtures were tested at 195 °C for 5 min to record variables like viscosity, scorch time (ts2), and cure time (t90). This test is commonly used in the rubber industry as it provides information about viscosity, scorch time (ts2), and cure time (t90).[28]

Mechanical tests were conducted on bow tie samples prepared by pressing at 170 °C for 10 min on plates. Tensile, elongation, and 300 % modulus tests were performed using an EKTRON-TS-2000 tensile testing machine according to ASTM D412, which specifies the procedure for determining the tensile properties of vulcanized rubber and thermoplastic elastomers, including tensile strength, elongation at break, and modulus at different elongations.

Scanning electron microscopy (SEM) helps us focus on surfaces to attain high-resolution imagery, thereby enabling a detailed analysis of surface features, including porosity, fissures, particle size, and surface morphology. The resulting HSC and commercial N220 were characterized using SEM.[29,30] The SEM analysis was conducted at Düzce University Scientific and Technological Research Application and Research Center (DÜBİT), while TGA was performed at Sampa A.Ş.

The thermal stability of the compounds was examined through TGA. The thermal degradation properties of the mixtures were determined using a TA Instruments Q500 thermogravimetric analyzer. The TGA was performed on the samples, heating them from 0 °C to 600 °C at a rate of 10 °C/min under a nitrogen (N_2) atmosphere, and from 600 °C to 800 °C under an air (O_2) atmosphere.

A plunger test (a tire strength test) is employed to assess the strength of reinforcement materials and the resistance of bias ply tires to road hazards. The test was conducted in accordance with the TSE 11187 Standard, Road Vehicles – Bicycles – Tires and Rims – Outer Tires, section 2.3.6, which provides guidelines for conducting a plunger test under specific conditions. In this procedure, the tire is mounted on an appropriate rim, inflated to a pressure of 0.343 N/mm^2, and left for 1 h under standard laboratory conditions. A piston with a head diameter of 8 ± 0.1 mm applies a vertical force on the

Figure 2: Plunger test machine

tread at a speed of 50 ± 2.5 mm/min until the tire ruptures. The penetration distance and applied force are used to determine the breaking energy. To pass the test, the tire's breaking energy must not be less than 6.9 J, as per section 1.2.3.6 – Breaking Energy of the standard. The required breaking energy W (in joules) was calculated using the following equation:[31]

$$W = \frac{F \times P}{2}$$

where,
W = breaking energy in J
F = force in N applied to the plunger
P = penetration of the plunger in m

The test was conducted at the Anlas R&D Center; images of the machine are shown in **Figure 2.**

A rolling resistance test was performed using a rolling resistance test machine in accordance with TSE 11187, Road Vehicles – Bicycles – Tires and Rims – Outer Tires, Section 2.3.8, which provides the guidelines for testing under specific conditions. The test sample was operated at 25 ± 10 °C, under a load of 128 kg (as per the project tire size), and at 40 ±4 km/h (11.11 m/s). For tires of 26 inches and above, the rolling distance is 5000 km. To pass the test, the rim must remain intact, with no ruptures or cracks in the tread.[32] The test was conducted at the Anlas R&D Center. Images of the test machine are shown in **Figure 3.**

3 RESULTS

3.1 Density test results

A density test was conducted to evaluate the specific gravity of each formulation. **Table 3** summarizes the density test results, presenting both the initial (a1) and final specific gravity values for all formulations.

Table 3: Density results of compounds.

(gr./cm^3)	Vref	V1	V2	V3	V4
a1	1.160	1.141	1.133	1.117	1.101
final	1.175	1.152	1.142	1.126	1.109

Figure 3: Rolling resistance test machine

When the densities of a1 and the final mixture are compared, low deviations indicate that the compounds were prepared with sufficient accuracy and homogeneity.

Comparing the reference carbon amount used in mass production with the maximum level of 28 phr hazelnut shell-based compound, a 6.6 % difference is observed. The impact of this difference on the process was evaluated in the next stage, focusing on the workability during tire production.

3.2 Mooney scorch (MS) and Mooney viscosity (MV) test results

Table 4 shows the Mooney scorch (MS) and Mooney viscosity (MV) test results for the reference formula and the formulations containing different percentages of HSC.

Table 4. MS and MV test results of compounds

Rubber compounds	VRef	V1	V2	V3	V4
Mooney scorch					
Temperature (°C)	135	135	135	135	135
ML (MU)	45.79	38.55	37.79	36.28	34.96
t5 (min:sec)	09:14	11:24	11:42	12:32	13:05
Mooney viscosity					
Temperature (°C)	120	120	120	120	120
ML (MU)	57.3	54.91	51.26	47.81	43.81
MF (MU)	57.3	54.91	51.26	47.81	43.81

The t5 value indicates the compound's pre-vulcanization tendency. The larger the t5, the lower is the pre-vulcanization tendency, so the rubber compound can be processed more reliably.[33] The t5 value was 09:14 min:sec for the VRef and 13:05 min:sec for V4. The MV value decreased with the increase in the amount of HSC in the formulation. The highest ML (MU) value of 57.3 ML (MU) was observed in the reference product, while its lowest value of 43.81 was measured in V4, which incorporated the highest percentage of HSC. This indicates a percentage difference of approximately 23.70 % between the highest and lowest MV values. This decrease led to an increase in the scorch values, consequently prolonging the onset of curing.[34]

3.3 Rheometer test results

The rheometer test is widely used in the rubber industry as it provides information on the Mooney viscosity (ML and MH), starting time (ts2), and curing time (t90). **Table 5** shows the rheometer test results for the base formulation and those containing different percentages of HSC.

Table 5: Rheometer test results for compounds

Rubber compounds	VRef	V1	V2	V3	V4
Time (min:sec)	05:00	05:00	05:00	05:00	05:00
Temperature (°C)	195	195	195	195	195
ML (dNm)	1.74	1.33	1.17	1.06	1
MH (dNm)	8.13	7.21	6.74	5.55	4.85
ts2 (min:sec)	00:34	00:36	00:36	00:40	00:47
t90 (min:sec)	00:57	01:00	01:01	01:02	01:05

The values of ts2 and t90 were observed to increase with the rise in the amount of HSC, indicating an extension in the curing time. This finding is supported by the MV value. Considering the intention to incorporate HSC, curing times should be increased in the production of bicycle tires.

3.4 Mechanical test results

Mechanical properties determined for the compounds are shown in **Table 6.**

Table 6: Mechanical properties of compounds

Rubber compounds	VRef	V1	V2	V3	V4
Testing time (min.)	10:00	10:00	10:00	10:00	10:00
Temperature (°C)	170	170	170	170	170
Tensile strength (kg./cm^2)	92.25	68.04	56.13	44.47	36.42
Elongation (%)	389	325.31	311.98	317.58	314.82
300% modulus (kg./cm^2)	71	45.67	40.35	41.9	24.26
Hardness (Shore A)	58.9	57.2	56.8	54.5	53.8
Percentage of abrasion (%)	14.00	18.47	21.47	27.27	30.10
Tear strength (kg/cm)	37.11	25.94	24.17	19.71	18.17

In this study, it was observed that as the HSC ratio in the compounds increased, viscosity, temperature, and hardness decreased. The hardness was measured in Shore A, with the highest value of 58.9 Shore A in the reference mixture and the lowest value of 53.8 in the V4 mixture, containing 28 phr HSC. As the amount of HSC increased, there was a decline in the tensile strength, 300 % modulus, and tear strength. The tensile strength of the reference product was 92.25 kg/cm^2, while it was 36.42 kg/cm^2 for the V4 mixture with the highest HSC content. Based on these results, rubber can still be produced as the V4 version, but a decrease in durability is expected. The tear strength showed an approximately 50 % decrease when comparing the reference mixture to the V4 mixture. These findings indicate that the use of HSC reduces mechanical performance. Additionally, the observed density differences between the reference sample and HSC-containing compounds may have contributed to these mechanical performance changes. Variations in density can influence the distribution and interaction of the materials within a compound, affecting its structural integrity and overall properties. The 6.6 % density difference observed for the V4 mixture likely reflects the changes in the material homogeneity, which could have

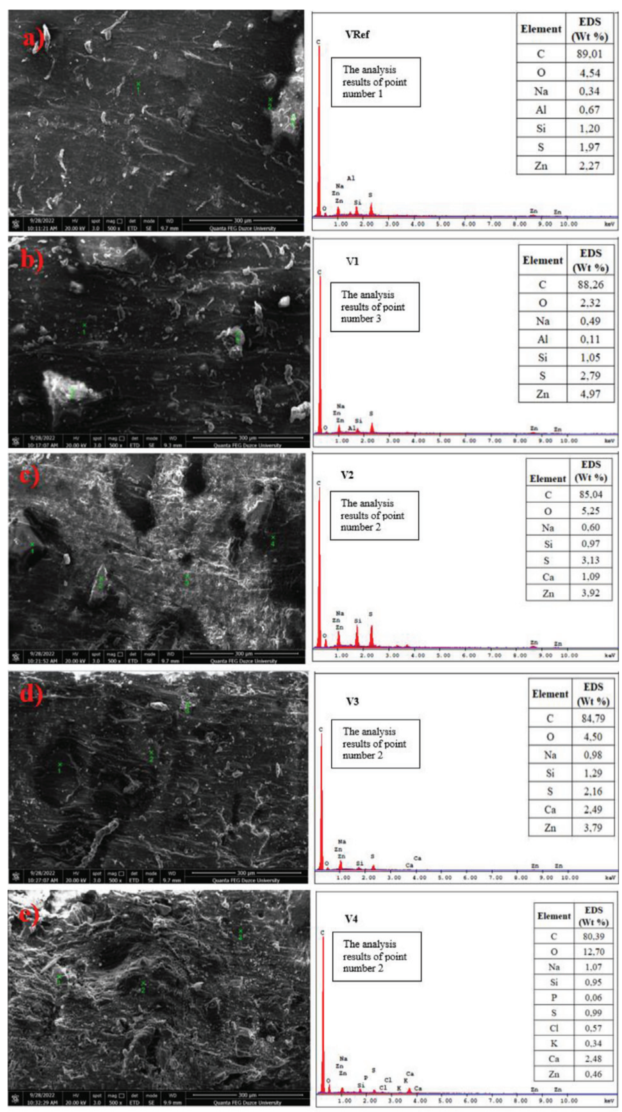

Figure 4: SEM and EDS results of: a) VRef, b) V1, c) V2, d) V3, e) V4

impacted the tensile strength, tear resistance, and hardness.

3.5 SEM test results

SEM and EDS results for the compounds are presented in **Figure 4.**

During the SEM analysis, multiple points were selected on a sample surface for the EDS analysis. EDS data were obtained for these points, and the results were consistent across the analyzed regions. Consequently, EDS results for a representative point are presented in each case. A comparative EDS analysis of the bicycle tire compounds indicates that carbon ratios vary approximately between 80 and 89 %. This suggests that the carbon content is not significantly affected by the added HSC amount. However, EDS results reveal an increase in impurities in the compound when the HSC content reaches 28 phr, its maximum level. Unlike other compounds, this compound contained Cl, P, and K, with their respective proportions being 0.57 % for Cl, 0.34 % for K, and 0.06 % for P.

3.6 TGA results

The results obtained with the TGA analysis of the compounds are presented in **Figure 5.**

Table 7 provides the TGA data for the compounds, expressed as weight percentage (%). 'Volatile matter' refers to the weight loss caused by the evaporation of low-molecular-weight components or moisture, while 'POL 1' and 'POL 2' represent the primary and secondary polymer fractions after thermal decomposition. 'CB 1' indicates the remaining carbon black content, and 'Inorganic' represents the residual inorganic matter left after the combustion in an oxygen atmosphere.

Table 7: TGA data of compounds (weight percentages, %)

	Volatile matter	POL 1	POL 2	CB 1	Inorganic	Total
VRef	4.166	33.787	22.141	36.426	3.480	100
V1	5.583	29.558	26.935	28.209	9.715	100
V2	7.435	30.190	26.063	26.295	10.017	100
V3	6.549	33.172	25.294	24.956	10.029	100
V4	7.078	33.331	25.269	23.662	10.660	100

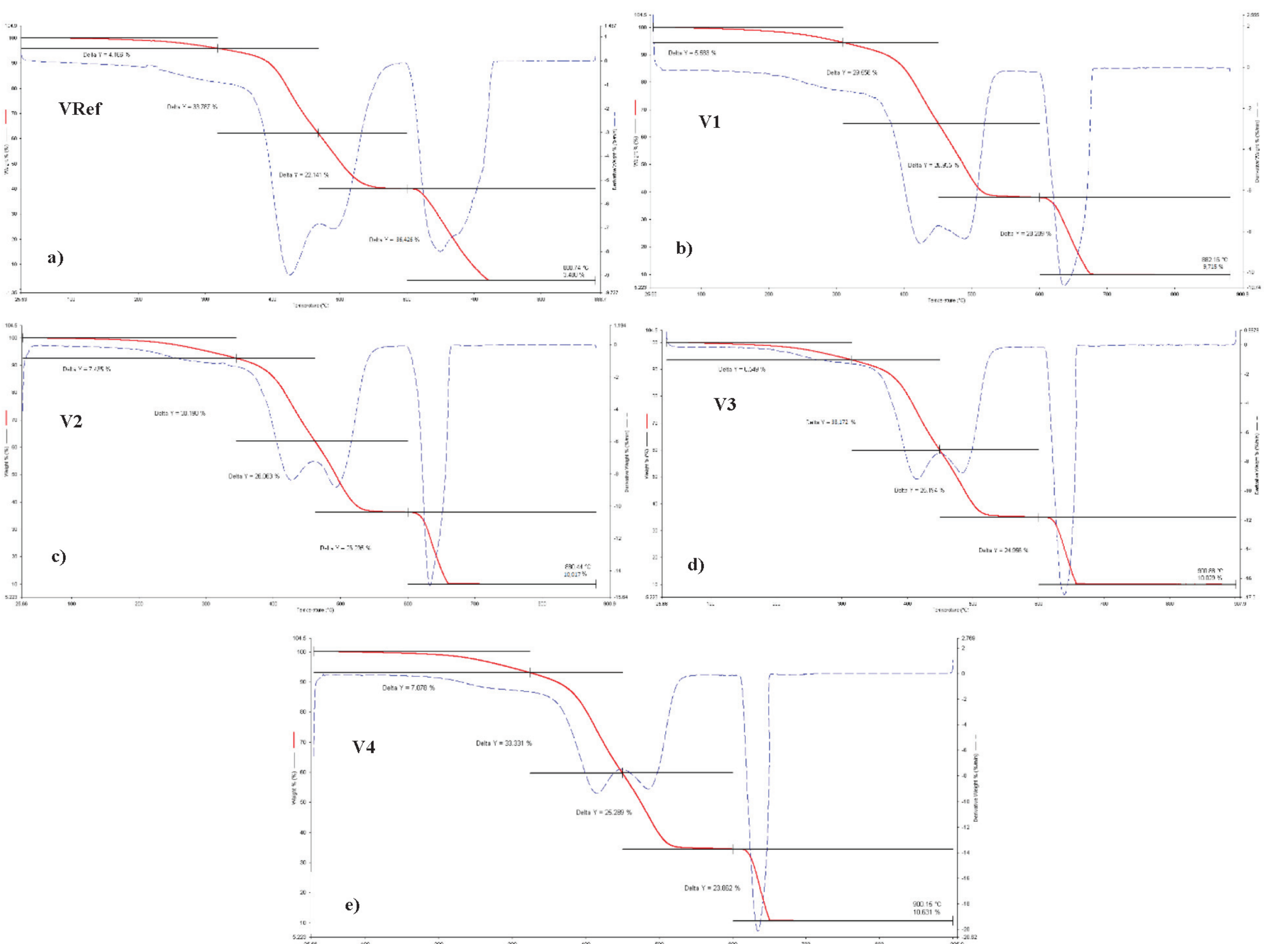

Figure 5: TGA analysis results of: a) VRef, b) V1, c) V2, d) V3, e) V4

The TGA results reveal significant differences in the residual weight percentages between the N220 (VRef) and HSC samples, indicating differences in the ash content and the presence of inorganic compounds. VRef has an ash content of about 3.48 %, typical for carbon black, whereas the HSC samples show increased ash contents, reaching up to 10.66 %. This increase in the inorganic residue aligns with the expected composition of HSC, an agricultural by-product containing a higher mineral content. The observed trend suggests that as the HSC content increases, the volatile matter and inorganic residue also increase, while the CB 1 fraction decreases.

3.7 Plunger test (tire strength test) results

The results of the plunger tests are shown in **Table 8**, indicating the effects of varying amounts of HSC mixture on the breaking energy.

Table 8: Plunger test results of compounds

	Load (N)	Displacement (m)	Breaking energy (J)
Vref	431.000	0.088	18.964
V1	407.000	0.086	17.501
V2	353.000	0.083	14.650
V3	304.000	0.082	12.464
V4	202.000	0.064	6.464

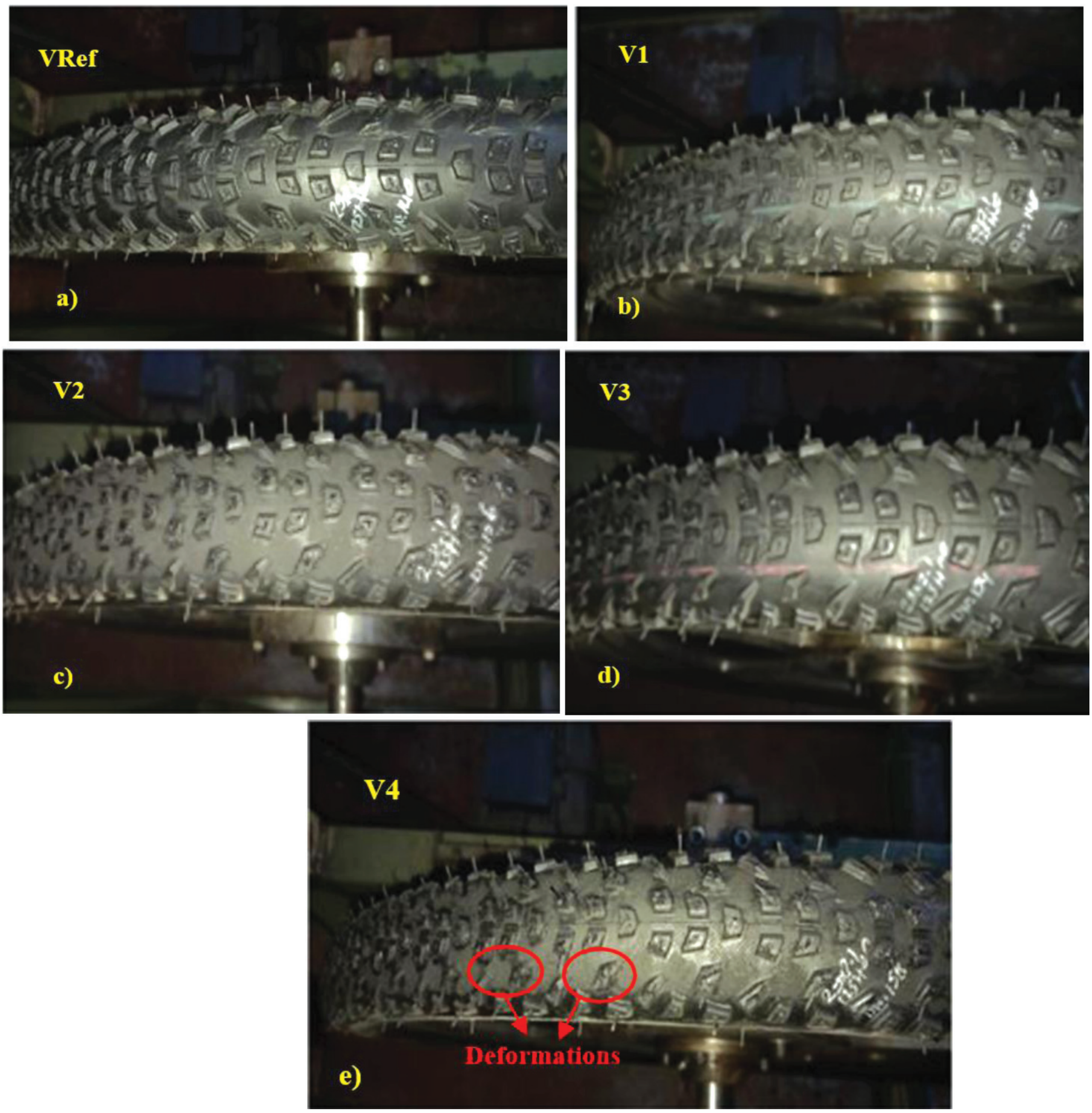

Figure 6: Post-test photos of: a) VRef, b) V1, c) V2, d) V3, e) V4

The results indicate that increasing the HSC ratio in the mixture reduces the breaking energy. All versions containing both N220 and HSC passed the test, meeting the minimum breaking energy requirement specified in Article 1.2.3.6 of the standard. However, the tires produced with only HSC (V4) failed to meet the minimum puncture energy requirement due to their puncture energy being below 6.9 J. These findings suggest that using HSC alone in a mixture is insufficient for achieving the necessary performance standards, and additional measures may be required to enhance the tire quality.

3.8 Rolling resistance test results

All tire types successfully completed 5000 km without any defects, meting the study's success targets. Post-test photos of the tires are shown in **Figure 6.**

After confirming that the samples met the requirements, it was observed that the 28 phr HSC/0 phr N220 sample exhibited greater surface deformation compared to the other samples. This tire, made of only the carbon mixture obtained from HSC, showed visible deformations. Although these deformations do not pose any safety risks to the user, they may be visually unappealing.

4 CONCLUSIONS

Tires were produced using five formulations and characterized through various tests, including density measurement, Mooney viscosity, rheological test, mechanical test, SEM, TGA, plunger, and rolling resistance tests. The sample with 7 phr HSC showed satisfactory physical properties, while (14 and 21) phr HSC samples also performed adequately. However, as HSC increased, there was a 65 % reduction in the tensile strength, modulus, hardness, and tear values. The plunger test results indicated a similar 65 % drop in the breaking energy with a higher HSC content. All tires, except V4 (28 phr HSC), met the rolling resistance standards. Although V4 exhibited surface deformations, these did not compromise safety. Overall, increasing HSC reduced the mechanical performance, but the values remained within acceptable limits for the bicycle tire use, positioning HSC as a sustainable alternative to N220.

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5 REFERENCES

[1] CONEBI (**2024**), Industry & Market Reports, available online: https://www.conebi.eu/industry-market-reports/

[2] Z. Wang, K. Burra, T. Lei, A. Gupta, Co-pyrolysis of waste plastic and solid biomass for synergistic production of biofuels and chemicals – a review, Progress in Energy and Combustion Science, 84 (**2021**), 100899, doi:10.1016/j.pecs.2020.100899

[3] S. Junga, D. Kwona, Y. Tsang, Y. Park, E. Kwon, CO2-cofeeding catalytic pyrolysis of macadamia nutshell, Journal of CO2 Utilization, 37 (**2020**), 97–105, doi:10.1016/j.jcou.2019.11.011

[4] S. Doja, L. Pillari, L. Bichler, Processing and activation of tire-derived char: A review, Renewable and Sustainable Energy Reviews, 155 (**2022**), 111860, doi:10.1016/j.rser.2021.111860

[5] I. Usman, M. Tijjani, Y. Ho, L. Baloo, M. Lam, W. Sujarwo, A comprehensive review on the advances of bioproducts from biomass towards meeting net zero carbon emissions, Bioresource Technology, 366 (**2022**), 128167, doi:10.1016/j.biortech.2022.128167

[6] J. Balart, V. Fombuena, O. Fenollar, T. Boronat, L. Sanchez-Nacher, Processing and characterization of high environmental efficiency composites based on PLA and hazelnut shell flour (HSF) with biobased plasticizers derived from epoxidized linseed oil (ELO), Composites Part B: Engineering, 86 (**2016**), 168–177, doi:10.1016/j.compositesb.2015.09.002

[7] B. Aydinli, A. Caglar, The investigation of the effects of two different polymers and three catalysts on pyrolysis of hazelnut shell, Fuel Processing Technology, 93 (**2012**), 1–7, doi:10.1016/j.fuproc.2011.09.011

[8] B. Aydinli, A. Caglar, The comparison of hazelnut shell co-pyrolysis with polyethylene oxide and previous ultra-high molecular weight polyethylene, Journal of Analytical and Applied Pyrolysis, 87 (**2010**), 263–268, doi:10.1016/j.jaap.2009.10.008

[9] G. G. Gozaydin, A. Yuksel, Valorization of hazelnut shell waste in hot compressed water, Fuel Processing Technology, 166 (**2017**), 96–106, doi:10.1016/j.fuproc.2017.06.020

[10] A. Di Michele, C. Pagano, A. Allegrini, et al., Hazelnut Shells as Source of Active Ingredients: Extracts Preparation and Characterization, Molecules, 26 (**2021**), 6607, doi:10.3390/molecules26216607

[11] H. Acma, The role of particle size in the non-isothermal pyrolysis of hazelnut shell, Journal of Analytical and Applied Pyrolysis, 75 (**2006**), 211–216, doi:10.1016/j.jaap.2005.05.002

[12] M. Livaniivani, M. Ghorbani, H. Mehdipour, Preparation of an activated carbon from HSC and its hybrids with magnetic NiFe2O4 nanoparticles, New Carbon Materials, 33 (**2018**), 578–586, doi:10.1016/S1872-5805(18)60366-9

[13] E. Amini, M. Safdari, J. DeYoung, D. Weise, Characterization of pyrolysis products from slow pyrolysis of live and dead vegetation native to the southern United States, Fuel, 235 (**2019**), 1475–1491, doi:10.1016/j.fuel.2018.08.024

[14] A. Bardha, S. Prasher, J. Villarta, et al., Nut shell and grain husk waste biochar as carbon black replacements in styrene-butadiene rubber composites and improvements through steam activation, Industrial Crops & Products, 203 (**2023**), 117180, doi:10.1016/j.indcrop.2023.117180

[15] C. Dominic, A. Balan, K. Neenu, et al., Sustainable Kerala rice husk ash for formulation of basic tyre tread: Taking first step, Sustainable Materials and Technologies, 32 (**2022**), e00427, doi:10.1016/j.susmat.2022.e00427

[16] Ö. Bağ, Production and Characterization of Carbon Materials from Biomass, Master's Thesis, Karabük University, Institute of Science, Department of Chemical Engineering, Karabük 2017, Turkey

[17] G. Altundal, H. Gerengi, E. Çetin, U. Kapcak, K. Kaymaz, Development and investigation of performance bicycle tire tread compounds, Duzce Univ. J. Sci. Technol., 8 (**2020**), 1661–1675, doi:10.29130/dubited.671526

[18] U. Kapcak, E. Çetin, L. Kahraman, H. Gerengi, The effect of tread pattern on performance in bicycle tires, Zeugma 2nd International Multidisciplinary Studies Congress, 2 (**2019**), 650–666

[19] A. Mavukwana, N. Stacey, J. Fox, B. Sempuga, Thermodynamic comparison of pyrolysis and gasification of waste tyres, Journal of Environmental Chemical Engineering, 9 (**2021**), 105163, doi:10.1016/j.jece.2021.105163

[20] A. Kaliyathan, A. Rane, M. Huskic, et al., Carbon black distribution in natural rubber/butadiene rubber blend composites: Distribution driven by morphology, Composites Science and Technology, 200 (**2020**), 108484, doi:10.1016/j.compscitech.2020.108484

[21] N. Seshaiah, N. Kumar, M. Afrid, et al., Investigation of cure behaviour and tensile properties of NR/SBR composite filled with carbon black and silica, Materials Today: Proceedings, 59 (**2022**), 387–391, doi:10.1016/j.matpr.2021.11.494

[22] C. Hayichelaeh, K. Boonkerd, Enhancement of the properties of carbon-black-filled natural rubber compounds containing soybean oil cured with peroxide through the addition of coagents, Industrial Crops & Products, 187 (**2022**), 115306, doi:10.1016/j.indcrop.2022.115306

[23] E. Çetin, H. Gerengi, G. Altundal, Development of Puncture Resistant High Performance Bicycle Tire, International Academic Research Congress, Bolu, (**2019**), 430–440

[24] G. Altundal, H. Gerengi, E. Çetin, U. Kapcak, K. Kaymaz, Development and investigation of performance bicycle tire tread compounds, Duzce Univ. J. Sci. Technol., 8 (**2020**) 1, 1661–1675, doi:10.29130/dubited.671526

[25] G. Altundal, İ. Uygur, T. Görmüşer, H. Gerengi, K. Metin, E. Çetin, Investigation of the effects of active ZnO instead of conventional ZnO on some physicomechanical properties in rubber compounds, Duzce Univ. J. Sci. Technol., 10 (**2022**), 107–113, doi:10.29130/dubited.731842

[26] V. Vahapoğlu, Rubber-type materials: Classification, Mehmet Akif Ersoy Univ. J. Inst. Sci. Technol., 4 (**2013**) 1, 25–34

[27] Rubber Water, Testing Instruments (**2023**), available online: https://www.tainstruments.com/products/rubber-testing/

[28] S. Erkek, The effect of carbon black/oil and carbon black/filler ratios on the physico-mechanical properties of EPDM, NBR, and SBR elastomers in different vulcanization systems, Master's Thesis, Çukurova Univ., Inst. Sci., Dept. Chem. Eng., Adana 2007, Turkey

[29] G. Akincioğlu, Investigation of the effects of walnut and hazelnut shell powder additives on the wear and friction behavior of commercial vehicle brake pads, PhD thesis, Department of Mechanical Engineering, Graduate School of Natural and Applied Sciences, Düzce University, Düzce 2018, Turkey

[30] SAMPA A. Ş. R&D Centre, CAMP, (**2023**), available online: https://www.sampa.com/tr/yetkinliklerimiz/camp-ar-ge

[31] S. P. Nalavade, B. J. Sagare, D. V. Moghe, N. V. Kulkarni, S. M. Bodhe, P. Purohit, R. Gurav, Ungraded tyre performance analysis for Indian road conditions, Materials Today: Proceedings, 90 (**2023**) 1, 61–66, doi:10.1016/j.matpr.2023.04.035

[32] Turkish Standards Institution (TSE), TS 11187:2006 – Road vehicles – Bicycles – Tires and rims – Outer tires, Ankara

[33] D. Klat, H. A. Karimi-Varzaneh, J. Lacayo-Pineda, Phase Morphology of NR/SBR Blends: Effect of Curing Temperature and Curing Time, Polymers, (**2018**), 510, doi:10.3390/polym10050510

[34] M. Dominic, R. Joseph, P. Begum, B. Parambath Kanoth, Green tyre technology: Effect of rice husk derived nanocellulose (RHNC) in replacing carbon black (N) in natural rubber (NR) compounding, Carbohydrate Polymers, 230 (**2020**), 115620, doi:10.1016/j.carbpol.2019.115620