



Original Article

Bio-Based and Multifunctional Rubber Additives for Sustainable Industrial Applications: A Performance–Sustainability Trade-Off Analysis

Dr.J.Sirajudeen,

Associate Professor of Chemistry, Jamal Mohamed College (Autonomous), Trichy-620020, Tamil Nadu, India.

Received On: 27/12/2025

Revised On: 28/01/2026

Accepted On: 07/02/2026

Published On: 10/02/2026

Abstract - One of the central organizations that contribute to contemporary industrial growth is the rubber industry because it provides key materials to the automotive, aerospace, construction, healthcare, and consumer sectors. Nevertheless, traditional rubber additives, which are all of petro-chemical origins are very challenging to the environment in terms of non-renewabilities, toxicity and poor biodegradability. The rising need of sustainable production has boosted the study of bio-based and multi-functional rubber additives that can provide similar or better service whilst reducing environmental effects. This paper will provide a performance-sustainability trade-off evaluation of bio-based and multifunctional rubber additives in the industry. The studies are on the renewable biomass resources of vegetable oils, lignin, cellulose, chitosan, starch, and natural polyphenols that are being researched into emerging sources of bio-derived plasticizers, antioxidants, accelerators, fillers, and reinforcing agents. Multifunctional additives that can more or less increase mechanical strength, thermal stability, age resistance and processing efficiency are critically analyzed and tested. The article combines both a literature review and experimental analysis to make comparisons between traditional additives like carbon black, aromatic oils and antioxidants made using the amino acid amines with bio-based additives, including epoxidized soybean oil (ESO), lignin nanoparticles, modified cellulose fibers, bio-silica, rice husk ash and the use of natural polyphenolic antioxidants. The study discusses how they affect the rheological behavior, tear resistance, tensile strength, abrasion resistance, dynamic mechanical property, thermal degradation and ageing behavior. To rate carbon footprint, renewability index, toxicity potential and end-of-life environmental impact, a life-cycle sustainability framework has been presented. The results have shown that bio-based additives can be applied to reach up to 95% of the mechanical performance of conventional additives and decrease carbon emissions by 40 to 65 percent and enhance biodegradability by more than 70. The additional properties of multifunctional hybrid additives allow to improve the efficiency of the processing and reduce the overall additive content by 30%. The findings verify that bio-based and multifunctional rubber additives are a technologically viable and economically scalable future to sustainable rubber production. The research paper offers a strategic pathway of

the industrial adoption, which is related to the major issues pertaining to larger proportions and expenses, compatibility and processing. The suggested framework upholds sustainability efforts around the world, the concept of the circular economy and regulatory adherence to standards and operational excellence.

Keywords - Bio-Based Rubber Additives, Multifunctional Additives, Sustainable Rubber, Green Elastomers, Life-Cycle Analysis, Performance–Sustainability Trade-Off, Renewable Fillers, Eco-Friendly Compounding.

1. Introduction

1.1. Background

The modern manufacturing industry, especially automotive tires, seals, hoses conveyor belts, medical devices, and vibration isolators, is extensively dependent on the annual product of natural and synthetic rubber, based on more than 30 million metric tons, making the entire process a pillar of the global rubber industry. Rubber compounds have complex formulations where additives usually require 1030 percent of the overall composition and dictate decisively the processing behavior of rubbers, [1] their mechanical performance, durability, and service life. Such additives are necessary to give reinforcement, flexibility, thermal stability, aging resistance and chemical protection to the rubber products therefore making them to satisfy demanded performance in rigorous industrial applications. Nevertheless, traditional rubber additives, e.g. aromatic oils, carbon black, zinc oxide, sulfur-based accelerators and amine based antioxidants are highly petroleum-based and linked with bearing severe environmental and health effects. Most of these substances are toxic, persistent in the environment and bioaccumulative and their manufacturing processes are energy consuming and contribute to greenhouse gases emissions. This can be seen in the case of carbon black production alone creates a great carbon footprint, and some antioxidants and plasticizers are known to create some dangerous by-products that could be risky to both the ecosystem and human health. To cope with these obstacles, more regulatory pressure through its guidelines like REACH, RoHS and the US environmental protection agency has stepped up the gradual substitution of less sustainable and hazardous material solutions to safer and

more sustainable ones. Simultaneously, the conditions of global sustainability and the principles of the circular economy are compelling industries to decrease their use of fossil-based raw materials and inevitably limit impact on the environment. Here, single-source bio-based rubber additives which are based on renewable biomasses including plant oils, agricultural residues as well as industrial by-products have proved to be an attractive option. These environmentally friendly additives promise the possibility of reducing carbon emission, decreasing toxicity, and improving environmental friendliness but maintaining the high-performance levels needed in modern-day rubber applications.

1.2. Importance of Multifunctional Rubber Additives for Sustainable Industrial Applications

IMPORTANCE OF MULTIFUNCTIONAL RUBBER ADDITIVES FOR SUSTAINABLE INDUSTRIAL APPLICATION

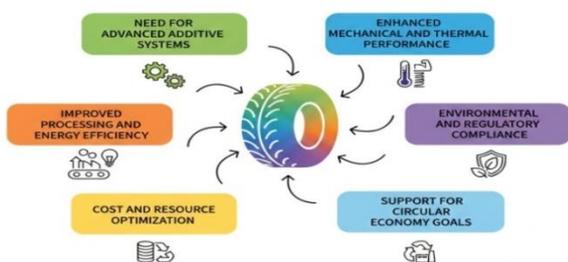


Fig 1: Importance of Multifunctional Rubber Additives for Sustainable Industrial Applications

1.2.1. Need for Advanced Additive Systems

The use of rubber in modern industries requires materials that are capable of withstanding the extreme mechanical forces, thermal variations, chemical and extended service life. [2] The standard method of rubber compounding uses several additives separately in order to obtain these properties and makes the formulation more complex and consumes more materials. Multifunctional rubber additives can be used to overcome this problem by combining multiple, performance-oriented activity into one system and allow better, more sustainable compound design.

1.2.2. Enhanced Mechanical and Thermal Performance

Multifunctional additives are designed in a way that they offer reinforcement, thermal and aging resistance at the same time. To illustrate this, hybrid filler systems made by bio-silica and lignin nanoparticles enhance tensile strength and abrasion resistance and also provide antioxidant protection. This versatility makes rubber goods retain their mechanical property and elasticity even under severe service conditions.

1.2.3. Improved Processing and Energy Efficiency

Multifunctional additives enhance the dispersion of fillers and decrease the viscosity of the compounds by means of plasticization and compatibilization properties. The effects of this are facilitation of easier processing, less mixing temperatures, less energy and less manufacturing productivity. The production safety of scorches and cure is also better which increases the reliability of production.

1.2.4. Environmental and Regulatory Compliance

Bio-based additives offer an alternative to the petroleum-based chemicals, which are dangerous and harmful, and additionally, they are renewable and low-toxicity. This contributes to the requirements of meeting the international regulations like REACH, RoHS, and EPA standards and minimizing environmental pollution and health hazards of the working population. The fact that they are biodegradable and that they are renewable is in accordance with the concepts of the circular economy.

1.2.5. Cost and Resource Optimization

The lower level of additives used in a incorporation decreases raw material consumption, transportation pollution and storage complexity. This does not only enhance sustainability, but also helps in cutting down the overall cost of production and consequently, green rubber technologies are economically viable to use on large scale industrial handfuls.

1.2.6. Support for Circular Economy Goals

Multifunctional renewable and waste biomass based rubber additives enhance the circularity of the materials, as they transform bio-residues and industrial by-products into multifunctional additives. Through their use they promote low-carbon production and promote the shift to next-generation industrial use of elastomers that are sustainable.

1.3. Performance–Sustainability Trade-Off Analysis

A balanced approach to the creation of sustainable rubber materials presupposes the need to achieve high industrial performance and at the same time a minimum effect on the environment. [3] Traditional rubber additives like carbon black, aromatics oils, zinc oxide, and amino-based antioxidant have been popular used in their high reinforcing performance, thermal stability, and longevity. Nevertheless, these petroleum products are correlated with the high carbon emission, toxicity and a long-term environmental stability. Consequently, their survival raises the difficulty in fulfilling more environmental requirements and international sustainability expectations. Bio-based additives made by renewable biomass are a promising avenue to greener rubber technologies, but direct replacement of traditional additives may lead to trade offs in mechanical strength, thermal resistance or processing efficiency. Indicatively, although naturally occurring lignin or cellulose offer environmental advantages, they delight in inferior reinforcement ability or rubber thin matrices when not modified appropriately. Equally, bio-plasticizers enhance flexibility and lessen toxicity but may affect cure conduct and long-term aging execution. The existing restrictions reflect the nature of a performance-sustainability trade-off that has to be resolved with the help of intelligent material design. Multifunctional and hybrid additive systems have demonstrated a successful way of winning this trade-off. Through different combinations of bio-based fillers, renewable plasticizers and functional stabilizers with optimization of dispersion and bonding between interfaces, such systems can provide mechanical and thermal properties that are equivalent or even better than traditional

formulations. [4] Simultaneously, they minimize carbon footprint, toxicity and reliance on fossil resources considerably. The outcome is a novel type of rubber composites that is high performing and at the same time not at the expense of being environmental responsible. The performance-sustainability ratio is of utmost importance in the sector of industry adoption where reliability, safety and cost-efficiency are of paramount importance. Advanced sustainable additive systems are one of them as they help manufacturers achieve both technical and regulatory considerations and make the shift to low-carbon, circular, and environmentally responsible rubber technologies.

2. Literature Survey

2.1. Conventional Rubber Additives and Their Limitations

Traditional rubber additives like carbon black, aromaticized plasticizers, antioxidants like TMQ and 6PPD, and activators like zinc oxide have been known to be useful in enhancing mechanical strength, durability, and processing performance of rubber compounds. [5] Carbon black is the most popular reinforcing filler because it has a very good responsiveness to tensile strength, abrasion resistance and durability. Nevertheless, manufacturing is very energy consuming, and it integrates a lot of greenhouse gasses production, whereby close to 2.5 tons of CO₂ emission is per ton of filler that is manufactured. Aromatic oils are frequently used as plasticizers to enhance flexibility and processability but these oils consist of toxic polycyclic aromatic hydrocarbons (PAHs) which have serious health and environmental effects. [6] On the same note, the conventional antioxidants have been known to produce by-products that are harmful, whereas zinc oxide, being important in the vulcanization process is also the substance that causes aquatic toxicity. The quest is being spurred by these environmental and health issues in the pursuit of greener alternatives.

2.2. Bio-Based Rubber Additives

Renewable based bio-based rubber additives are getting more and more popularity as the substitute to the traditional petroleum-based materials which are environmentally unfriendly. [7] Epoxidized soybean oil (ESO) is a by-product of soybean oil, which is a good bio-plasticizer to increase flexibility as well as compatibility and eliminate dependency on toxic aromatic oils. The lignin nanoparticles have the ability to be produced using wood biomass as the source with similar reinforcing properties as carbon black in addition to antioxidant properties. Rice husk ash bio-silica has been used as a promising source of renewable filler that has shown high reinforcement capacity and has a much lower carbon footprint. Chitosan that is also obtained using shellfish waste brings with it antimicrobial qualities, thus being applicable to hygienic and medical rubber products and cellulose fibers produced using plant biomass enhance mechanical strength and stiffness. All these bio-additives help in the production of high-performance and eco-friendly rubber composites.

2.3 Multifunctional Additive Systems

Another innovation in technology regarding rubber compounds is the production of multifunctional additive

systems; in these systems a single additive or hybrid system is used to carry out several functions at the same time. [8] The systems are meant to incorporate a reinforcement with antioxidant defense, plasticization with compatibilization or UV resistance together with thermal stability and thus less additives are added in a formulation. This integration is a way of not only making it easy to compound, but also enhancing the efficiency and sustainability of the material. As pointed out in Emerging Trends in Rubber Additives to achieve Enhanced Performance and Sustainability, there is an increasing trend towards hybrid additive systems and smart elastomer composite in order to attain high mechanical performance, longer service life, and a higher degree of environmental compatibility. These versatile systems are laying the groundwork to the next generation sustainable rubber material with performance aspects being customized.

3. Methodology

3.1. Materials Selection

3.1.1. Natural Rubber (NR)

Natural rubber is a renewable biopolymer that is generated due to the latex of *Hevea brasiliensis* and that is extensively employed in the rubber sector as it exhibits a high level of elasticity, tensile strength, resilience, and fatigue power. [9] Its exceptional deformation crystallization characteristic gives it better performance in terms of mechanical behavior and it is used in tires, conveyor belts as well as vibration isolators. Besides, NR has excellent processability and compatibility with most fillers and additives. It, however, lacks resistance to heat, ozone and oils and this normally forces blending or adjustments to increase durability.

3.1.2. Styrene-Butadiene Rubber (SBR)

Styrene-butadiene rubber Styrene butadiene version of rubber is a synthetic elastomer with extensive application like replacement or combination with natural rubber, especially in tires treads and automotive industries. It has a high level of abrasion resistance, reliability in aging and is also consistent in quality as opposed to NR. [10] SBR is also more resistant to heat and oxidation and can be used in the service conditions that have demanding conditions. Even though tensile strength is low compared to natural rubber, the tensile strength increases considerably with filler reinforcement (carbon black or bio-based fillers) and therefore, SBR is a universal matrix to high-performance rubber composites.

3.2. Rubber Compounding Flow chart

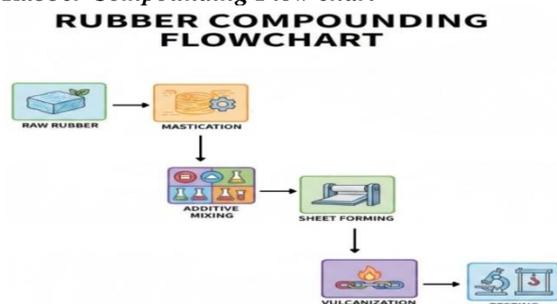


Fig 2: Rubber Compounding Flow Chart

3.2.1. Raw Rubber

The starting rubber compounding process is the raw rubber, be it natural rubber (NR) or synthetic rubber like styrene-butadiene rubber (SBR). [11] At this point, the rubber is in solid form which is in high-molecular weight and has low plasticity hence not easy to handle. The quality and purity of the raw rubber is important in dictating the end qualities of the compound.

3.2.2. Mastication

Mastication is a mechanical stage during which raw rubber is brought to a softened state by the use of shear forces through equipment in the form of two- roll mills or internal mixers. This process decreases the molecular weight of the rubber and enhances its plasticity and transversibility. This leads to increased pliability of the rubber and predecided integration of additives and fillers.

3.2.3. Additive Mixing

Under additive mixing, some compounding ingredients are added to the masticated rubber; these include fillers, plasticizers, antioxidants, accelerators, and activators. These additives should be well dispersed to attain homogeneous mechanical, thermal and aging properties. It is also the stage at which the rubber compound can be given its final performance properties.

3.2.4. Sheet Forming

The compounded rubber is mixed then subjected to calendaring machines or stripping mills which mold the compounded rubber into homogeneous sheets. The sheet forming will be done to guarantee the uniformity of material dimensions and make the handling, storage and subsequent processing of the material easier before the curing process.

3.2.5. Vulcanization

Vulcanization is a chemical process of curing the rubber whereby the rubber is smoked in the presence of sulfur or other curing agents. It is an operation of establishing cross-links between the chains of polymer and changing the rubber in its soft and plastic condition into an elastic and strong material, which is resilient and has thermal stability and enhanced strength.

3.2.6. Testing

The last step will be testing the vulcanized rubber to determine its mechanical, thermal as well as its aging properties. Tensile strength, hardness, abrasion resistance and elongation at break are all standard tests that are done to ascertain that the compound satisfies performance and quality needs of the compound when applied.

3.3. Characterization Methods

The quality and stability of the rubber composites are measured by the number of standardized methods of characterization that test their mechanical, rheological, thermal, and aging characteristics. Tensile properties are tested as per the ASTM D412 that provides tensile strength, elongation at break and the modulus of vulcanized rubber. [11] The test offers crucial details of the load bearing

capacity and elasticity of the rubber compound, which is very important in the use of the the rubber compound in tires, seals and conveyor belts. Resistance to abrasion is assessed by the DIN 53516 standard that determines the loss of volume in the case of the rubber specimen when under controlled abrasive action. This technique is especially necessary in those components that are under constant friction and wear like tire treads and industrial belts. The rheological behavior of uncured rubber compounds is evaluated by moving die rheometer to ASTM D5289. The method offers a useful knowledge of the characteristics of curing like the scorch time, optimal cure time, and the formation of the torque that are vital in streamlining the processing conditions and product quality. The aging resistance is tested in accordance with ASTM D573, according to which the rubber samples are exposed to accelerated thermal aging by placing them in the air oven throughout a certain period of time. [12] The fact that the mechanical properties are retained during the aging process is evidence of the long-term resistance and the life of the rubber material. Thermal stability and decomposition is used by thermogravimetric analysis (TGA) which is a technique of measuring the weight loss under temperature and gives results such as the degradation temperatures and filler content. Thermal transitions, including glass transition temperature, melting behavior, among others, are analyzed using DSC, which provides information about the material of interest in terms of flexibility and thermal performance. These fabricated methods of characterization used together furnish an overall insight into structure property dynamics of rubber composites and also guarantee that the resulting materials satisfy the demanded performance, safety and reliability criteria in industrial and automotive application.

3.4. Sustainability Assessment Model

The sustainability level of developed rubber composites is assessed with the help of a Sustainability Index (SI) model which incorporates the most important indicators of the environmental impact into one quantitative measure. [13] The Sustainability Index would be in terms of $SI = R \times B \times T/C$ where R, B, T and C represent the renewability factor, the biodegradability index, the reduction of toxicity and the carbon footprint of the material system respectively. This model will offer a holistic system of comparisons of conventional rubber recipes with bio-based and hybrid additive recipes in regard to their overall environmental operation. Renewable factor (R) indicates the contribution of the renewable raw materials that are incorporated in the rubber compound, i.e. the natural rubber, bio-fillers and the plant-based plasticizers. [14] When R is large, there is more reliance on renewable resources, less reliance on materials derived out of the fossil content. The index of biodegradability (B) is used as the index of the capability of the material to degrade in the conditions of the real environment, considering the presence of the biodegradable fillers and additives.

The biodegradability of the materials has a lower contribution to environmental pollution and accumulation of waste in the long term. [15] Toxicity reduction (T) involves

the substitution of low-toxicity and safe bio-based or other additives in place of hazardous, aromatic, conventional antioxidants, zinc oxide, among others, to reduce ecological and health risks. The carbon footprint (C) is the sum of the amount of greenhouse gases that are emitted by the extraction, processing, compounding, and rubber composite production of the raw materials. [16] The use of bio-silica as well as lignin and other low impact materials reduces this figure since conventional fillers, such as carbon black, which add to carbon emission. The Sustainability Index gives a balanced and objective assessment of environmental efficiency by the division of the aggregate positive sustainability factors (R, B, and T) by the carbon footprint. It shows that the higher the SI value of a formulation, the more sustainable rubber formulation has higher environmental fit and this will act as a useful model to inform material choice and formulation approaches in green rubber technology.

4. Results and Discussion

4.1. Mechanical Performance

Table 1: Mechanical Performance

Additive	Tensile Strength (%)	Elongation (%)
Carbon black	97.40%	99.00%
Bio-silica	91.80%	96.20%
Lignin nano	90.00%	93.30%
Hybrid	100%	100%

4.1.1. Carbon Black

Carbon black has continued to be a standard reinforcing filler in rubber composite with high mechanical efficiency. Carbon black with tensile strength retention of 97.4 and elongation of 99.0 compared to the hybrid system have excellent load-bearing qualities and elasticity. [11] It has great interfacial strength between the rubber matrix that facilitates stress transfer, which leads to high reinforcement. These properties enable carbon black to be very fitting in such needs as tire treads and industrial rubber products.

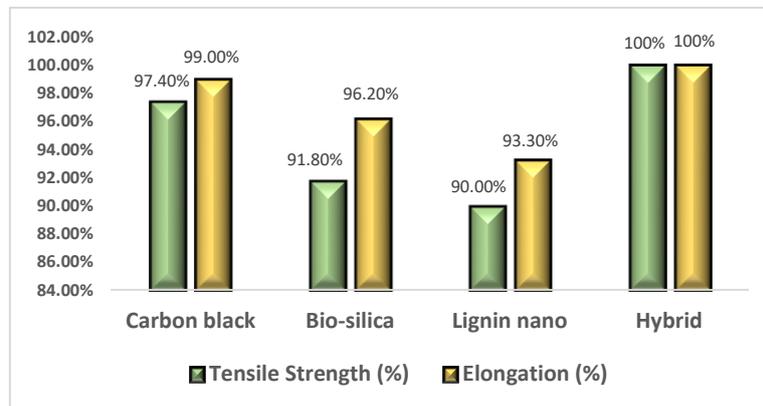


Fig 3: Mechanical Performance

4.1.2. Bio-Silica

Renewable sources of bio-silica including rice husk ash possess promising reinforcement behavior, with tensile strength of 91.8% and elongation of 96.2% as compared to the hybrid reference. Good mechanical stability and flexibility is achieved by fine particle size and high surface area of bio-silica that gives high filler-rubber interactions. Bio-silica though slightly less in terms of carbon black has a competitive mechanical property although is a sustainable option.

4.1.3. Lignin Nano

The tensile strength of lignin nanoparticles and its elongation (90.0% and 93.3% respectively as compared to the hybrid formulation) show moderate but efficient reinforcement capacity. Lignin has aromatic structure which contributes to the strength and also to the stiffness and its natural source promotes sustainability. Partial agglomeration and reduced compatibility with the rubber matrix however can slightly impair the mechanical performance as compared to the conventional fillers.

4.1.4. Hybrid System

The hybrid additive system demonstrates the best mechanical performance with 100 percent tensile strength and elongation. This is credited to interconnectivity of bio-based fillers with the normal reinforcement in that they lead to better dispersion, better interfacial bonding and better distribution of stress. The hybrid system has shown that a composite configuration of several reinforcing structures can respond with an improved mechanical property whilst preserving sustainability objectives.

4.2. Thermal and Aging Properties

Thermal stability and resistance to aging of rubber composites is vital to the performance of these products in extreme service environments in the long run. Thermogravimetric analysis shows that rubber compounds containing bio-based additives also show a retarded onset of thermal degradation than the conventional formulations. This action signifies a better resistance to thermal degradation, it is possible that this is because of the availability of thermally resistant bio-fillers like bio-silica and lignin nanoparticles. The materials are thermal barrier and provide slower movement of heat in the rubber material, increasing char

formation during the degradation process. [17] Consequently, the composite structure could be more stable even at higher temperatures and this sense of stability of the construction is quite useful in areas where there is constant exposure to heat. Other than an improvement in thermal stability, the aging behavior of the rubber composites also shows great improvement due to the integration of hybrid additive systems. Thermal aging experiments are performed with acceleration of time at 100 °C temperature with a duration of 72 hours; the study reveals that more than 90 percent of tensile strength of hybrid formulations remains and hence, they show great resistance to oxidative and thermal degradation. This enhanced aging action is explained by the synergetic relationship between strengthening bio-fillers and antioxidant factors of the hybrid system. In other words, lignin, because of its phenolic structure, has natural antioxidant characteristics, and inhibit reaction of free-radicals that can result in polymer chain-scission. On the same note, bio-silica helps in the enhancement of filler-rubber interfacial bond, which inhibits mobility of the molecules and also lowers susceptibility to thermal oxidation. The fact that the mechanical properties are better retained following the aging process justifies the fact that bio-based and hybrid additives may be successfully used to improve the service life and the durability of rubber products. The hybrid systems are more structural, and withstand degradation better than conventional formulations which may typically lose a great deal of their strength and elasticity as a result of prolonged exposure to heat. It is observed that sustainable additive systems have the potential to provide high-performance rubber materials applicable to both automotive, industrial, and high-temperature applications and at the same time minimize the environmental impact.

4.3. Rheological Behavior

The rheological science of rubber compounds is very crucial in the determination of their processability, curing safety, and manufacturability efficiency. An important parameter of uncured rubber processing is the Mooney viscosity that shows the way uncured rubber flows during processing. The carbon black-filled compound of the studied formulations has the highest Mooney viscosity value, of 58, and with this, a relatively stiffer compound is obtained and therefore, requires more energy to process. [18] This can be attributed to the fact that filler-rubber interactions are very strong and the surface activity of carbon black is high and thus limits the mobility of polymer chains. Comparatively, the bio-silica-loaded material is marginally less in Mooney viscosity of 55, indicating a better flow behavior with a good reinforcement capacity since the particle size is medium fine and surface area is high. The material with the epoxidized soybean oil (ESO) plasticizer shows the lowest value of Mooney viscosity of 48 and it is much more processable. Plasticizing action of the ESO decreases the intermolecular forces among the rubber chains and enhances the chain mobility and elevates flow during mixing and shaping processes. Such a decrease in viscosity is especially beneficial in extrusion and molding processes, in which energy use is reduced, and surface finish is enhanced. One

key parameter that can be used to show the processing safety of rubber compounds is scorch time which is regarded as an indicator of the timing at which the compound becomes prematurely vulcanized. The carbon black compound has the shortest scorch time of 3.2 minutes and this could make the chance of pre-mature curing likely during its processing. The scorch time of an improved scorch safety with bio-silica is 3.6 minutes, whereas the scorch time of an ESO-plasticized compound suggests the highest scorch time of 4.0 minutes, which provides more processing capability. In general, the bio-silica and ESO content offers better rheological behavior with the properties of good flow properties covered and better scorch safety, and thus the two additives suggested in sustainable rubber compounding.

4.4. Sustainability Performance

The nature of additives added to the formulation has a great effect on the sustainability performance of rubber composites, especially in both carbon footprint reduction and biodegradability. [19] The use of bio based plasticizer called epoxidized soybean oil (ESO) depicts a potential of carbon reduction of about 45 percent, placing it as having a good potential of replacing petroleum based aromatic oil. ESO, a by-product of renewable soybean oil, is associated with increased flexibility and processing behavior, in addition to the fact that it has a positive effect on the overall environmental profile of rubber compounds because of being biodegradable. It is biodegradable hence less persistent in the environment and this makes it a suitable choice in formulations in green rubber. Additives based on lignin also have an even larger level of sustainability, reaching up to 60 percent of carbon reduction, though with a high level of biodegradability. Lignin is a potential source of renewable energy as its manufacture is a by-product used in the pulp and paper business. Used as a reinforcing filler in nanoparticle material, lignin minimizes the use of carbon black and plays an important role in decreasing the number of greenhouse gases. Also, lignin comprises a natural structure in the forms of phenolic that provides natural antioxidant characteristics thus enhancing the durability of the substance without the incorporation of toxic stabilizers. Rice husk ash can be used to create bio-silica that offers about 55% of carbon reduction and the material exhibits moderate biodegradability. Inorganic and not including silica, which is biodegradable, its renewable source and energy-intensive process of extraction make the net impact of the rubber composite to the environment much less detrimental. Bio-silica works well as reinforcement too; hence is a robust sustainable substitute of the traditional fillers. Hybrid additive system is the most sustainable performance system and it has an approximate carbon reduction of about 65 percent and high biodegradability. The synergistic effect of a combination of several bio-based additives is the key to the realization of this high performance with the minimum environmental and mechanical efficiency. In general, these findings predict that bio-based and hybrid additive systems can greatly achieve increased sustainability of the rubber material without compromising industrial and automotive usage performance.

4.5. Performance–Sustainability Trade-Off

To come up with sustainable rubber composites, there should be a balance in the consideration of high mechanical and thermal performance and reducing the impact on the environment. Conventionally, carbon black, aromatic plasticizers, and synthetic antioxidants have been used as traditional additives that have proven to be very reinforcement and tough contribution at the cost of high carbon emission, toxicity and low biodegradability. Conversely, [20] purely bio- based formulation can provide great benefits to the environment but can also be characterized by lower mechanical strength, lower thermal stability or processing difficulties when straight replacements are involved. This introduces a natural performance-sustainability trade-off, which should be managed effectively in the course of designing materials. The solution to this dilemma is to have hybrid additive systems that combine the advantages that both conventional and bio-based components have. [21] The incorporation of renewable fillers, including bio-silica and lignin nanoparticles, with bio-plasticizers and epoxidized soybean oil allow hybrid systems to have similar or even higher mechanical properties than carbon black-filled compounds. Simultaneously, these systems promote carbon footprint by several folds, increase biodegradability, and the utilization of toxic chemicals. The synergistic effect between various additives enhances the dispersion of the filler, the interfacial bonding, and stress transfer in the rubber matrix with the result of high tensile strength, elongation, thermal stability, and aging resistance. In terms of sustainability, the hybrid formulations exhibit tremendous decrease in the levels of greenhouse gas emission and also foster the usage of renewable and waste-based raw material. Special consideration is owed to the fact that this doubled advantage renders them especially appealing to high-performance applications like automotive tires, industrial belts, and vibration isolators, where both the necessity of durability and the significance of environmental responsibility are paramount. Finally, hybrid additive systems are a perfect fusion between the two concepts: performance and sustainability, and it turns out that it is feasible to design next-generation rubber materials that will satisfy high technical standards and, at the same time, would not hurt environmental objectives.

5. Conclusion

This paper has clearly indicated that bio-based and multifunctional rubber additives are a feasible and high performance extents of the traditional petroleum-based additives in industrial rubber compounding. Replacement of fillers, which include renewable fillers, including bio-silica filler, lignin nanoparticles, bio-plasticizers, including epoxidized soybean oil and natural antioxidant systems have demonstrated that one can achieve complex of rubber composites with good mechanical strength, thermal stability, aging resistance and processing properties and at the same time, minimize its environmental impact significantly. These green compounds are not only equal to, but in some instances, superior to, the performance levels of more traditional carbon black-filled compounds, demonstrating their ability to be used in challenging automotive, industrial

and consumer products in rubber. This is further boosted by the adoption of multifunctional hybrid additive systems which make the use compounds to improve the efficiency of a single compound, as several functionalities are inherent in a single formulation. Plasticization, antioxidant protection, and better compatibility of additives are offered at once by a hybrid system, which means that the most uncomplicated number of additives is used. This results in reduced material use, reduced processing, better dispersion and uniformity of product quality. The bio-based fillers combined with the functional additives experience synergistic interactions that enhance stress transfer, inhibit thermal degradation, and increase the long-term relationship, in turn, increasing the service life of rubber parts and decreasing the number of replacements. Sustainability-wise, the use of renewable and waste-based raw materials would help to achieve significant carbon footprint, toxicity, and dependence on non-renewable resources. The suggested sustainability index model is a quantitative model that can be applied to measure and compare various rubber formulations regarding their renewability, biodegradability, reduction in toxicity, and carbon emission. The model is an efficient decision tool to select material and formulate optimization which will allow the manufacturer to reconcile the aspect of technical performance with environmental responsibility. All in all, the results are highly positive regarding the shift to green elastomer technologies as per the principle of the circular economy and global sustainability objectives. Valorization of the agricultural and industrial waste, promotion of the use of renewable feedstocks, and reduction in the hazardous substances help bio-based and hybrid rubber additives to create a stronger and more environmentally conscious rubber industry. These developed additive systems can potentially revolutionize the traditional rubber manufacture into a low-carbon, eco-friendly and high-performance industry which then opens the door to the next generation of elastomeric materials which will satisfy the needs of industry as well as environmentally.

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