BioLastane: A Novel Plant-Derived Elastane Alternative from *Hevea brasiliensis* Natural Rubber and Plant-Derived Additives

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INTRODUCTION

For the last century, the textile industry has exchanged natural fibers (e.g., cotton, wool, silk) for more durable and low-cost synthetic fibers (e.g., polyester, nylon, elastane). Now constituting 69% of the 132 million tonnes (approximately 91 Mt) of global fiber production in 2024, according to the 2025 Materials Market report, synthetic fibers make up almost every piece of fabric worn and used [1]. However, the discovery of microplastics (MPs) – plastics less than 5 mm in length – and chemical leaching in the 21st century has presented a significant scientific reversal that prompts the need to create fibers that are safer for human and ecological health while still matching synthetic fibers in terms of mechanical properties and durability.

Synthetic fibers are man-made plastic fibers typically formulated with harsh chemicals (e.g., PFAs, phthalates) and petroleum-based products that are known to be endocrine disruptors [2,3]. The increasing use of synthetic fibers poses significant health risks as MPs leach into our daily lives. For instance, a 2024 study found that microfibers seep into water systems during washing machine cycles [4]. Additionally, there are rising concerns surrounding whether the microfibers and their chemical additives can leach into human bodies during everyday wear [5].

It is important to note that almost every synthetic fiber has a natural alternative that can be used for long periods of time. Although these natural fibers have mechanical properties (e.g., tensile strength) and durability (e.g., thermal resistance) that fall short of man-made fibers, they are much safer for human and environmental health [6]. Furthermore, taking into account that the average US consumer annually contributes 81.5 lbs of clothing to landfills [7], it is important that fabrics be biodegradable – a benefit exclusively offered by natural fibers. Given that natural fibers are still a viable choice compared to synthetic fibers, further research needs to be focused

on specific modifications to natural fibers to make them possess stronger mechanical properties and long-term durability.

Contrary to most synthetic fibers, elastane (commonly known as Spandex) is the only synthetic fiber that has no natural alternative widely available in the commercial market. Elastane is known for its ability to stretch and recover that provides the form-fitting comfort expected in modern apparel. Elastane comprises approximately 1% of the 132 Mt of textiles produced annually, as opposed to the 59% of textiles which are solely synthetic polyester [1]. Although elastane is typically used in small percentages, it is present in approximately 80% of all clothing [8]. Despite the innovation of elastic fibers from recombinant DNA [9,10] and the reintroduction of natural rubber fibers [11] as elastane alternatives, the high cost and weaker properties of these alternatives prevent the widespread use of current alternative fibers. Nonetheless, environmentalists state that it is imperative to synthesize a safe, natural alternative to elastane. When companies use common synthetic fibers such as polyester, they are consciously choosing to utilize harmful plastic fibers as opposed to natural substances such as cotton or silk. However, when companies aim to increase the elasticity of their fabrics, they are compelled to use the synthetic fiber elastane due to a lack of low-cost, durable, natural elastic fiber alternatives.

This study aims to prove that it is possible to synthesize a natural alternative to elastane through the bioadditive-induced modifications of *Hevea brasiliensis* natural rubber (NR) fibers. These fibers were the most common and affordable elastic fiber used prior to the introduction of elastane. They either matched or surpassed the mechanical properties and durability of elastane. Tests show that the synthesized alternative fiber, BioLastane, can perform similarly to commercial elastane in terms of elongation at break, elastic recovery, tensile strength,

hydrophobicity, thermal resistance, sweat resistance, and chlorine resistance, thereby offering the textile industry a safer, greener alternative to elastane.

LITERATURE REVIEW

Thanks to the innovation of elastane, modern apparel has the ability to be flexible, lightweight, and durable. Despite the recent invention of elastane in 1959, the exceptional elasticity of the fiber (ranging from maximum elongation values of 200% to above 1000%) has rapidly allowed the fiber to become a staple element in undergarments, activewear, and even in medical compression garments and furniture upholstery [1,12].

The unique structure of elastane shapes the many elastic properties that make it a widely used elastic fiber. The segmented polyether-polyurea block copolymer structure of elastane consists of a long-chain, flexible polyether or polyester "soft" segment and a rigid, crystalline diisocyanate-based "hard" segment, as shown in **Figure 1** [12], according to the earliest online research of the fiber on *ACS Publications*. These “soft” and “hard” segments exist in an alternating pattern where the amorphous segments provide elastane with elasticity, whereas the rigid segments act as physical crosslinks which induce hydrogen bonding upon the elongation of the fiber; thus, the fiber rebounds into its original structure, allowing maximal elastic recovery. However, the strong bonds of the petroleum-based fiber make it highly non-biodegradable.

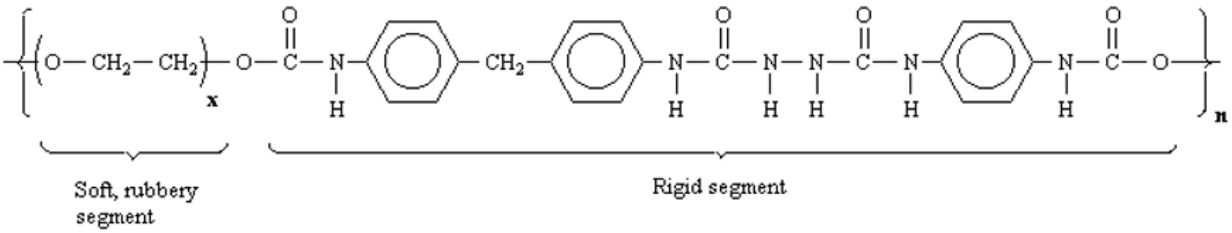


Figure 1. Molecular structure of elastane [12].

Although the chemical structure of elastane has not been altered since its invention, companies tailor the performance of elastane for specific uses. For example, swimwear will often include elastane that has been modified with toxic plasticizers (e.g., Di-2-ethylhexyl phthalate (DEHP)) and stabilizers (e.g., Hindered Amine Light Stabilizers (HALS)) to become more elastic and resistant to environmental factors (e.g., ultraviolet and chlorine exposure). These harsh chemicals bioaccumulate in human and aquatic systems and can lead to detrimental health effects.

Recently, the study of MP shedding and MP-related chemical exposure (e.g., plasticizers) sourced from plastic products, including elastane, has gained significant attention. A 2023 study of the health effects of MP exposure in South Korea highlights that one of the main sources of MPs in indoor and outdoor air is synthetic fibers; in fact, "recent human-biomonitoring data have revealed the presence of plastic fibers in lung tissue, suggesting that airborne microplastics can be deposited or accumulate in the lungs" [3]. Furthermore, plastic fibers do not pollute the environment solely through everyday wear, but also through household washing and textile waste. A 2024 *Environmental Pollution* study found that a 6 kg load of synthetic clothing can shed MP amounts ranging from 6 million to 8 million microfibers per washing machine cycle [4]. As these plastic microfibers leach during wash cycles, they travel through water treatment plants and are eventually deposited in landfills as sewage sludge. In addition to the 92 million tons of textile waste generated per year, sewage sludge exacerbates the accumulation of synthetic textiles and associated MPs and MP-related chemicals. These contaminants can biomagnify in aquatic ecosystems and persist in humans through paths other than direct dermal contact – such as MP inhalation and ingestion [13,14]. The increasingly high exposure to MPs is particularly

concerning, as emerging studies, such as Sun and Wang's evaluation of "Human Exposure to Microplastics and Its Associated Health Risks," have found that plastics disrupt several body systems (intestinal, reproductive, immune, nervous, and endocrine) due to high exposure to both the plastics themselves and the pollutants (e.g., additives, dyes, and plasticizers) that MPs carry [5].

In the past few years, several researchers have attempted to synthesize a natural alternative to elastane; however, their efforts have proven to be unsuccessful due to alternatives that are either too expensive or that lack the mechanical properties and high durability of elastane. In early 2025, two companies, Good Fibes and YULEX, introduced biodegradable alternatives to elastane. YULEX's prototype relies primarily on natural latex, the staple elastic fiber used prior to the invention of elastane. Despite being renewable, natural latex lacks the high elasticity and tensile strength of elastane, thus making it an unfavorable alternative [11]. Meanwhile, Good Fibes utilizes recombinant DNA technology to grow elastane-like fibers in laboratories [9]. Nevertheless, this process is expensive and resource-intensive because recombinant DNA is necessary. Another natural biodegradable elastane substitute was developed by students at the Fashion Institute of Technology (FIT) by using elastin – a naturally abundant elastic protein found commonly in aquatic organisms and mammals – to create a compostable elastic fiber [10]. However, FIT's prototype involves the high cost and strenuous extraction of elastin from biological tissue, which would be economically unfeasible at scale, especially since elastin is already in high demand in the cosmetic industry as it improves skin elasticity. Unlike polyester and nylon, elastane does not yet have a truly functional biodegradable counterpart, as achieving the same combination of extreme elasticity, strength, and biodegradability has proven to be scientifically and economically difficult. Although current alternatives to elastane are

infeasible for industry implementation, there lies the possibility of modifying current alternatives to elastane to create low-cost, sustainable elastic fibers.

Natural fibers typically consist of natural biomaterials that have been modified for textile applications [6]. Following the description of natural fibers, this study aims to use readily available biomaterials to modify *H. brasiliensis* natural rubber (NR) fibers. This modification will address the low elasticity and durability of NR fibers. Prior to the invention of elastane, NR fibers were frequently used in the manufacturing of elastic textiles. However, as elastic fibers were commonly used in athletic wear and swimwear, where they would be exposed to high heat, chlorine, and sweat, researchers noticed that NR fibers break down under these stressful conditions [15,16]. Additionally, NR is relatively hydrophilic and less elastic compared to synthetic elastane, thereby rendering elastane the more suitable material. Albeit, a 2019 study on *Ricinus communis* oil (castor oil, CO) shows that the ricinoleic acid in CO enables it to function as an effective plasticizer through esterification/epoxidation [17]. BioLastane incorporates unepoxidized CO, heated to 50°C to reduce the viscosity of CO and accelerate CO absorption into the hydrophilic natural rubber (NR) fibers. Due to the hydroxyl groups in ricinoleic acid, the CO additive still provides natural plasticity. Additionally, the durability of NR can be increased through reinforcement of *Medicago sativa* extract (alfalfa extract, AE). In 2024, researchers at the Lodz University of Technology found that *M. sativa* (alfalfa) can act as a source of functional bioadditives in NR [18]. As alfalfa is rich in sulfur and antioxidants (flavonoids, phenolic acids, and saponins), it can increase the tensile strength and aging resistance of NR under high-stress conditions. To maintain the goal of a low energy-intensive bioadditive reinforcement process, the NR is soaked in a 1:1 v/v emulsification of water-based AE and CO at 50°C. Lastly, as the bioadditives may not persist over long durations, the NR is cured using the industrial additives

zinc oxide (ZnO) and stearic acid (StA) [19], which react at temperatures above 60°C and act as a sealant for the bioadditives.

The research question remains: To what extent can BioLastane (a natural rubber alternative to elastane reinforced with castor oil, alfalfa extract, zinc oxide, and stearic acid) serve as a viable alternative to commercial elastane? As there lies a research gap in sustainable, low-cost alternatives to elastane, the answer to this question is imperative. Unlike previous alternatives, BioLastane is almost entirely made out of natural materials, with the exception of zinc oxide and stearic acid, which can be naturally sourced but are typically not. If BioLastane performs similar to or better than commercial elastane in terms of mechanical properties (elongation at break, elastic recovery, tensile strength) and durability (accelerating aging tests of hydrophobicity, thermal resistance, sweat resistance, and chlorine resistance), this study may represent a step forward in the path towards safer, greener synthetic fiber alternatives.

METHODOLOGY

To evaluate the effect of the bioadditives on the mechanical properties and durability of *H. brasiliensis* natural rubber (NR) fibers, the performance of the fibers under physical and chemical stress must be considered. The engineering goals include a naturally sourced fiber that has a high elongation at break, elastic recovery, tensile strength, hydrophobicity, thermal resistance, sweat resistance, and chlorine resistance. Five experimental groups are tested to evaluate the effects of each bioadditive: NR (control), NR-CO (CO reinforced NR), NR-AE (AE reinforced NR), NR-CO-AE (CO and AE reinforced NR), NR-CO-AE-Z (CO and AE reinforced vulcanized NR). The BioLastane product (NR-CO-AE-Z) is then directly compared to

commercial elastane (SPX). All formulated fibers are developed under standardized conditions and tested after 24 hours of synthesis.

Materials

NR latex is used as the base polymer. CO and AE are utilized as NR bioadditives, and ZnO and StA aid the vulcanization of the rubber fibers. Each fiber is formulated through a simulation of wet-spinning based off of the description of wet-spun polymer extrusion by the Research Institutes of Sweden [20]; view additional details on the wet-spinning simulation in the subsection Natural Rubber Fiber Fabrication. SPX fibers are externally sourced from a commercial elastane manufacturer. For each group, n = 3 fiber samples are synthesized (or sourced) and cut to a length of 5.0 cm prior to testing. The samples are prepared under identical environmental conditions (23 ± 2°C, atmospheric pressure) to minimize variability.

Natural Rubber Fiber Fabrication

The NR latex is extruded through a 31 G syringe tip submerged in a 5% v/v acetic acid coagulation bath, as seen in **Figure 2**. The fibers rest in the coagulation bath for 1 hour before being rinsed with deionized water to remove residual acid and minimize potential contamination. Fibers are then air-dried and dehydrated in a laboratory oven at 60°C for 2 hours before further modification.

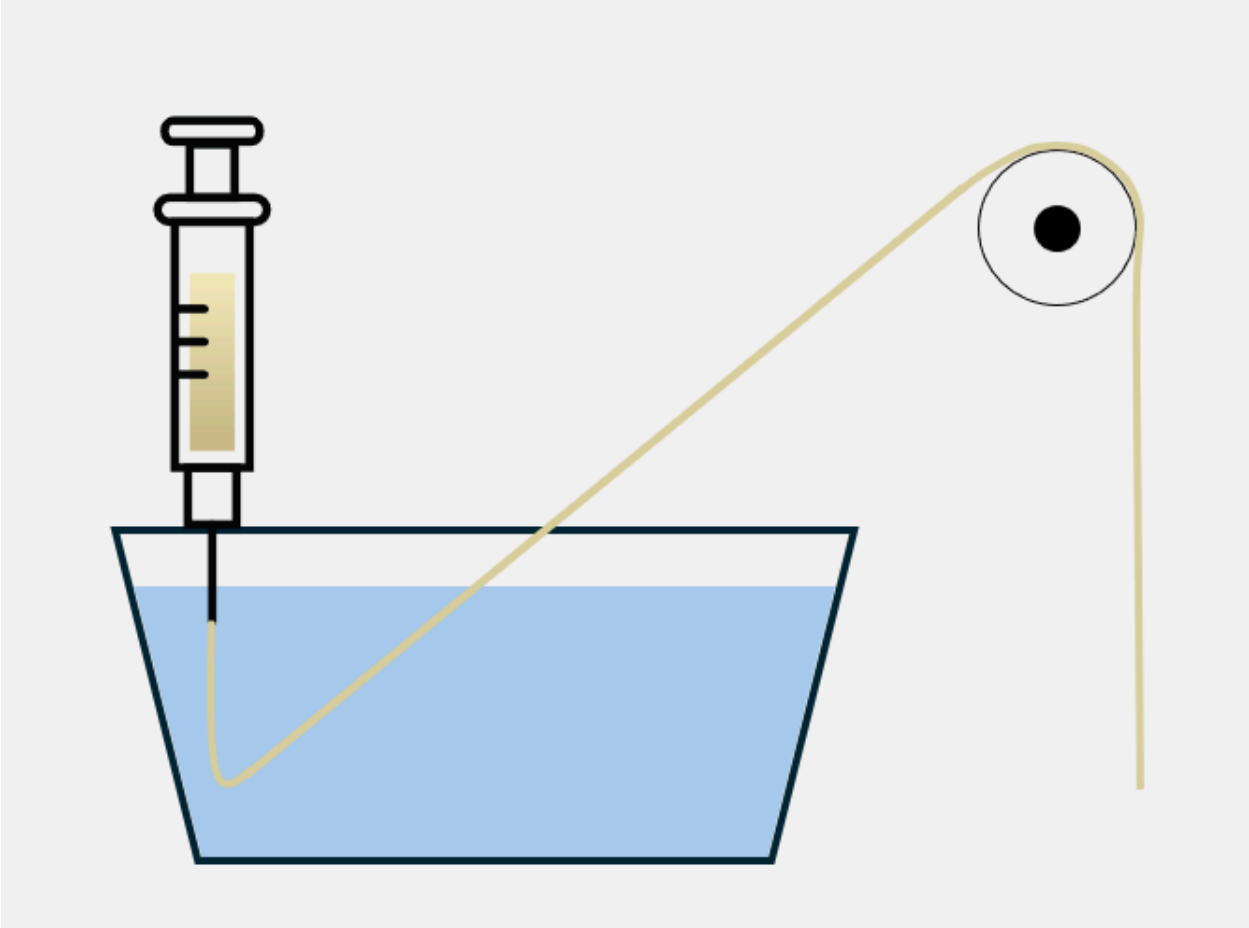


Figure 2. Simulation of wet-spinning NR fibers through latex extrusion via a 31 G syringe.

The next phase of the experiments is the bioadditive treatment reinforcement of each experimental group. The control (NR) fibers are not reinforced with bioadditives. Each experimental group is reinforced with bioadditives for 2 hours or until mass stabilization ($\Delta m <$ 0.01 g between measurements taken at least 15 minutes apart). NR-CO fibers are immersed in CO at 50°C (the maximum temperature at which CO can be heated without degradation), then cured at 60°C for 20 minutes. NR-AE fibers are immersed in AE at standardized conditions, then cured at 60°C for 2 hours or until hydration (whiteness) is no longer visible. NR-CO-AE fibers are immersed in a 1:1 volume ratio of emulsified CO and AE, then cured at 60°C for 2 hours or

until hydration (whiteness) is no longer visible. The BioLastane, NR-CO-AE-Z fibers, undergo the curing process of NR-CO-AE; subsequently, a vulcanization paste – 5 phr (parts per hundred) ZnO and 2 phr stearic acid – is uniformly applied to the surface of the BioLastane fibers and cured at 120°C for 1 hour until an amber coloration appears.

All fiber samples are conditioned for 24 hours at 23 ± 2°C to ensure equilibrium moisture content and thermal stabilization prior to mechanical testing. This step is necessary to reduce variability caused by differences in residual solvent evaporation or thermal expansion between samples.

Mechanical and Durability Testing

All testing procedures are derived from the International Organization for Standardization (ISO) standards. The elongation at break (%), elastic recovery (%), and tensile strength (MPa) are measured using a mechanical tester or universal testing machine (UTM), as shown in **Figure 3**.

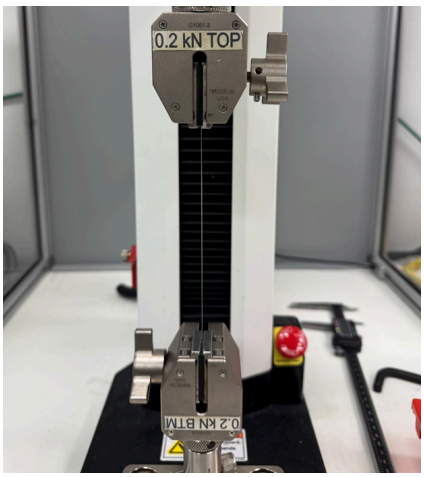


Figure 3. Mark-10 Series F Universal Testing Machine

Elongation at break (%) is measured through stretching each fiber until rupture.

$$\text{Elongation at break} = \frac{final\ length - initial\ length}{initial\ length} \times 100\ \%$$

Elastic recovery (%) is measured through stretching each fiber to 200% elongation (15 cm, 10 cm displacement) for 1 minute and releasing each for 3 minutes before the recovery length is measured.

$$\% \text{ Recovery} = \frac{elongated\ length - recovered\ length}{10\ cm} \times 100\%$$

Tensile strength (MPa) is measured by a uniaxial tensile test at a constant strain rate per fiber until failure. The maximum force at break (F) is recorded, and tensile strength was calculated using:

$$\text{Tensile Strength} = F / A$$

where A represents the cross-sectional area of the fiber measured prior to testing.

Surface hydrophobicity (°) of each fiber was measured using a simulation of a contact goniometer, where the droplet of water placed on each fiber is photographed and analyzed digitally. A 50 µL droplet of deionized water is placed on each fiber, and the water contact angle is recorded within 5 seconds of deposition, as shown in **Figure 4**.

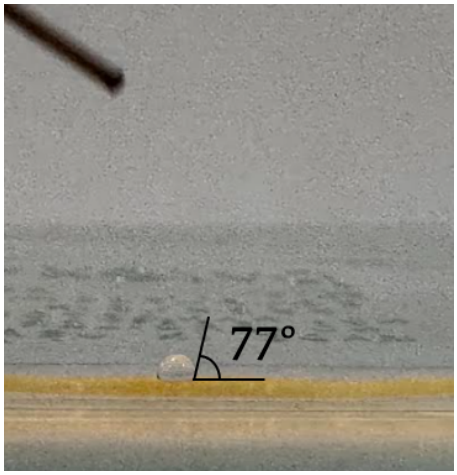


Figure 4. Contact angle goniometer simulation.

Thermal resistance (%) was measured through the elastic recovery of the samples after exposure to 150°C for 2 hours in a laboratory oven and allowed to cool for 1 hour.

Sweat resistance (%) was measured through the elastic recovery of the samples after the accelerated sweat aging induced by the submersion of the fibers in artificial sweat for 24 hours.

Chlorine resistance (%) was measured through the elastic recovery of the samples after accelerated chlorine aging induced by the submersion of the fibers in 50 ppm HOCl for 24 hours.

Risk Assessment and Safety Precautions

The hazardous chemicals used in this experiment were determined using Flinn Scientific Safety Data Sheets. It is hazardous to heat zinc oxide (ZnO) at extremely high temperatures. ZnO is hazardous to aquatic life with acute toxicity (Category 1, H400) and chronic toxicity (Category 1, H410) [21]. The EnvironMolds Liquid Latex Mold Making Rubber is hazardous to human health as it can cause skin corrosion/irritation (Category 2) and serious eye damage/ eye irritation (Category 2B). The EnvironMolds Liquid Latex Mold Making Rubber is hazardous to aquatic environments as an acute hazard (Category 3) [22]. The ZnO and EnvironMolds Liquid Latex Mold Making Rubber can release fumes when heated in a laboratory oven. Additionally, the laboratory oven has heated surfaces that can cause burns to skin. The laboratory oven also poses the risk of a combustion reaction of the heated materials. Hypochlorous acid is a potential eye irritant, therefore PPE will be used during interactions [23].

Data Collection and Analysis

For each test, three independent measurements (n = 3 per experimental and control groups) were recorded and averaged. The results were reported as mean values. Statistical comparisons between NR groups were conducted using a one-way ANOVA test to determine whether differences in fiber formulation produced significant changes in mechanical

performance. Additionally, BioLastane (NR-CO-AE-Z) was directly compared to commercial elastane (SPX) through Welch's t-test to determine its validity as a viable alternative.

All experimental groups follow a standard fiber length, diameter, drying time, and set of environmental conditions to ensure that observed differences were solely attributable to the bioadditive composition. All mechanical testing instruments were calibrated prior to use, and measurements were conducted using identical protocols across all trials to reduce variability.

The criteria used to evaluate each fiber are elongation at break, elastic recovery, tensile strength, hydrophobicity, thermal resistance, sweat resistance, and chlorine resistance. Higher elongation at break, elastic recovery, and tensile strength values signify a strong, elastic fiber. Additionally, water contact angles above 90° signify a hydrophobic fiber. Lastly, high elastic recovery values under thermal, sweat, and chlorine conditions indicate a durable fiber. See the Discussion section for more information about what these factors indicate about BioLastane's performance as a viable elastane alternative.

RESULTS

Trial data were utilized to generate the bar graphs shown below for each of the mechanical and durability tests (elongation at break, elastic recovery, tensile strength, hydrophobicity, thermal resistance, sweat resistance, and chlorine resistance). The horizontal axis of each graph represents the control group (NR) and the 4 experimental groups (NR-CO, NR-AE, NR-CO-AE, NR-CO-AE-Z). The vertical axis varies depending on the specific test being carried out. NR is represented by the darkest green bar, NR-CO by the bar shaded in the second-darkest shade of green, NR-AE by the second-lightest shade of green, NR-CO-AE by the lightest shade of green, BioLastane (NR-CO-AE-Z) by the navy bar, and elastane (SPX) by the

gray bar. In instances where the statistics across experimental groups exhibited differences less than 1%, axis breaks were utilized to accurately visualize differences between the sample means. Of course, the mean values and testing statistics are also readily accessible in the tables below. The summary statistics for each statistical test (one-way ANOVA test and Welch's T-Test) are included in these results, where $\alpha = 0.05$.

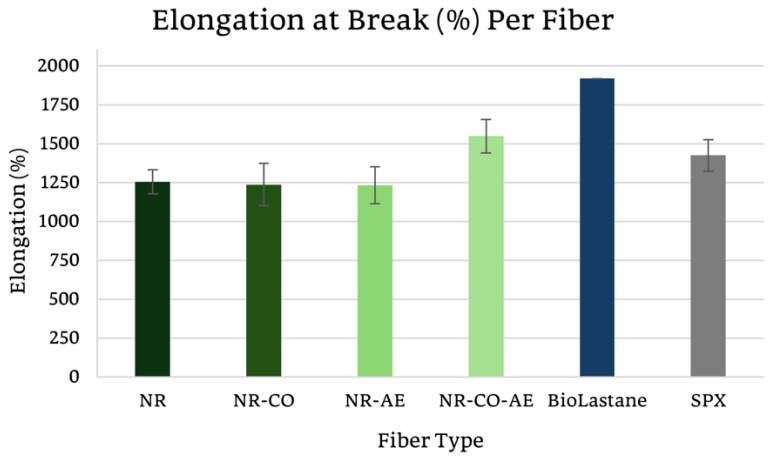


Figure 5. Elongation at break (%) per fiber in experimental and control groups at room temperature (25°C).

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1077134.747	5	215426.9493	21.19987644	1.41466E-05	3.105875239
Within Groups	121940.4933	12	10161.70778			
Total	1199075.24	17				

Table 1. Elongation at break (%) per fiber in experimental and control groups at room temperature (25°C), one-way ANOVA test summary statistics.

	NR-CO-AE-Z	*SPX (mm)*
Mean	1918	1424.666667
Variance	0	10146.33333
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	8.482942536	
P(T<=t) one-tail	0.006806714	
t Critical one-tail	2.91998558	
P(T<=t) two-tail	0.013613427	
t Critical two-tail	4.30265273	

Table 2. Elongation at break (%) per fiber in experimental and control groups at room temperature (25°C), Welch's t-test summary statistics.

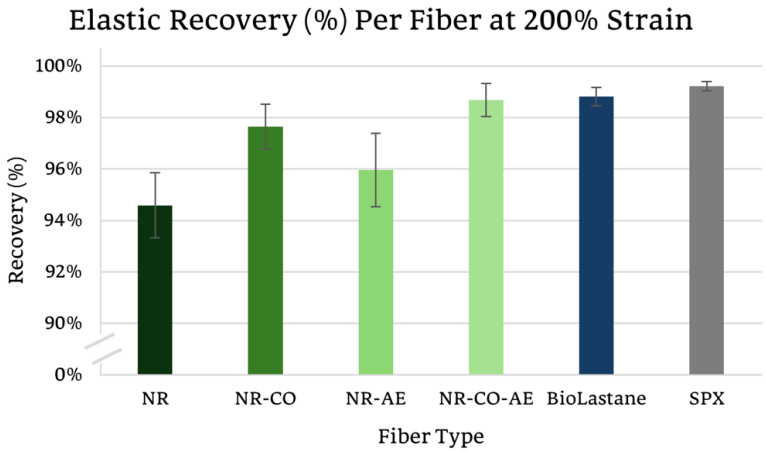


Figure 6. Elastic recovery (%) per fiber upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C).

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.005077276	5	0.001015455	12.21984115	0.000228632	3.105875239
Within Groups	0.000997187	12	8.30989E-05			
Total	0.006074463	17				

Table 3. Elastic recovery (%) per fiber upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C), one-way ANOVA test summary statistics.

	NR-CO-AE-Z	*SPX*
Mean	0.9881	0.99216667
Variance	0.00001263	3.5833E-06
Observations	3	3
Hypothesized Mean Difference	0	
df	3	
t Stat	-1.74929497	
P(T<=t) one-tail	0.089276194	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.178552388	
t Critical two-tail	3.182446305	

Table 4. Elastic recovery (%) per fiber upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C), Welch's t-test summary statistics.

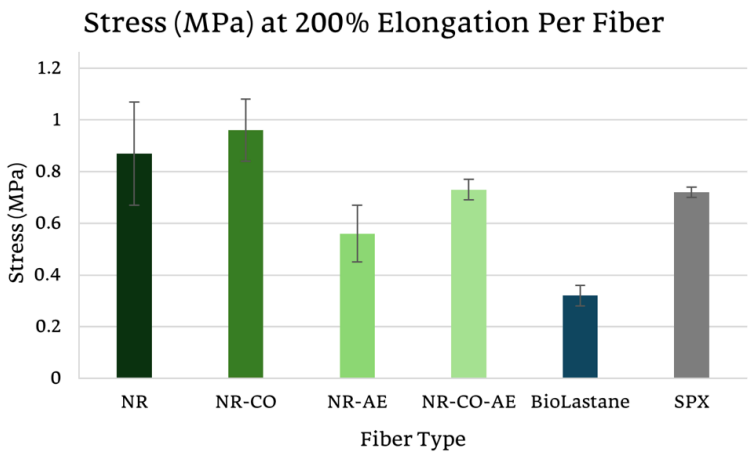


Figure 7. Tensile strength (MPa) per fiber after 1 minute of 200% strain in experimental and control groups at room temperature (25°C).

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.788844444	5	0.157768889	12.70621924	0.000189356	3.105875239
Within Groups	0.149	12	0.012416667			
Total	0.937844444	17				

Table 5. Tensile strength (MPa) per fiber after 1 minute of 200% strain in experimental and control groups at room temperature (25°C), one-way ANOVA test summary statistics.

	NR-CO-AE-Z	*SPX (mm)*
Mean	0.32	0.72
Variance	0.000266667	0.02806667
Observations	4	4
Hypothesized Mean Difference	0	
df	3	
t Stat	-4.752708206	
P(T<=t) one-tail	0.008838845	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.017677689	
t Critical two-tail	3.182446305	

Table 6. Tensile strength (MPa) per fiber after 1 minute of 200% strain in experimental and control groups at room temperature (25°C), Welch's t-test summary statistics.

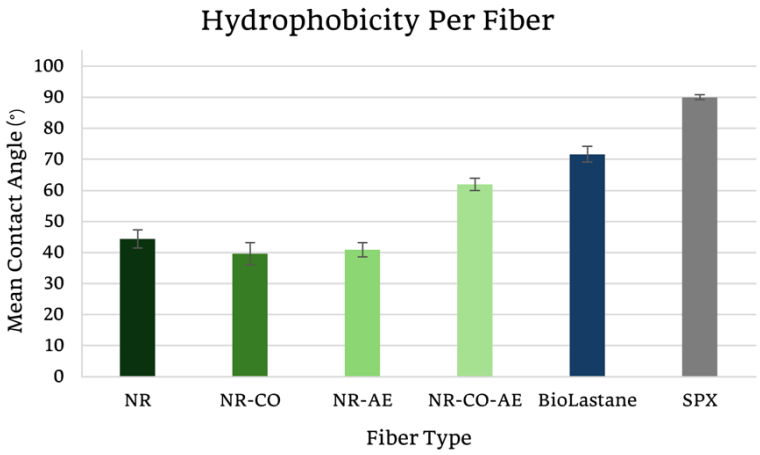


Figure 8. Hydrophobicity (°) per fiber within 5 seconds of 50 µL of deionized water exposure in experimental and control groups at room temperature (25°C).

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4033.25	5	806.65	180.930841	1.863E-06	4.38737419
Within Groups	26.75	6	4.45833333			
Total	4060	11				

Table 7. Hydrophobicity (°) per fiber within 5 seconds of 50 µL of deionized water exposure in experimental and control groups at room temperature (25°C), one-way ANOVA test summary statistics.

	NR-CO-AE-Z	*SPX*
Mean	54.125	67.625
Variance	1278.229167	2002.5625
Observations	4	4
Hypothesized Mean Difference	0	
df	6	
t Stat	-0.471383566	
P(T<=t) one-tail	0.327009372	
t Critical one-tail	1.943180281	
P(T<=t) two-tail	0.654018743	
t Critical two-tail	2.446911851	

Table 8. Hydrophobicity (°) per fiber within 5 seconds of 50 µL of deionized water exposure in experimental and control groups at room temperature (25°C), Welch's t-test summary statistics.

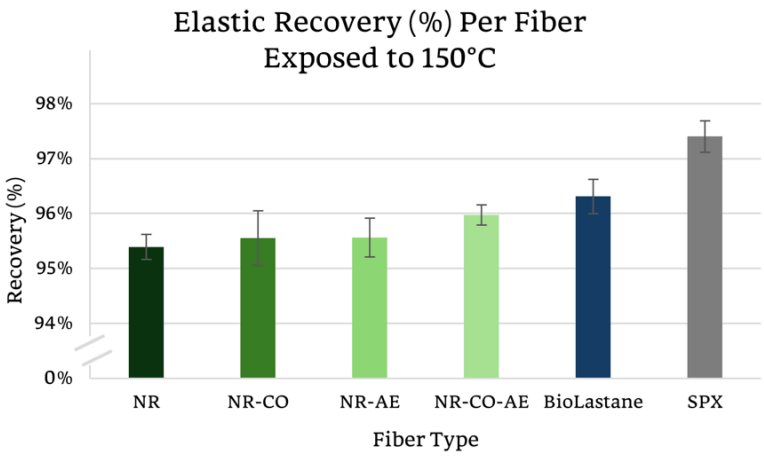


Figure 9. Thermal resistance measured in elastic recovery (%) per fiber exposed to 150°C upon 1 minute of 200% strain in experimental and control groups.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00084488	5	0.00016898	15.9345348	6.1716E-05	3.10587524
Within Groups	0.00012725	12	1.0604E-05			
Total	0.00097214	17				

Table 9. Thermal resistance measured in elastic recovery (%) per fiber exposed to 150°C upon 1 minute of 200% strain in experimental and control groups, one-way ANOVA test summary statistics.

	NR-CO-AE-Z	*SPX*
Mean	0.9631	0.974
Variance	9.93E-06	8.19E-06
Observations	3	3
Hypothesized Mean Difference	0	
df	4	
t Stat	-4.4351471	
P(T<=t) one-tail	0.005688292	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.011376584	
t Critical two-tail	2.776445105	

Table 10. Thermal resistance measured in elastic recovery (%) per fiber exposed to 150°C upon 1 minute of 200% strain in experimental and control groups, Welch's t-test summary statistics.

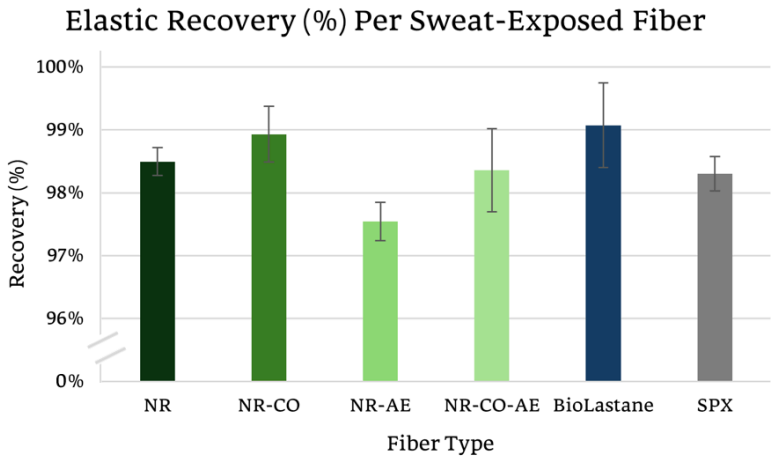


Figure 10. Sweat resistance measured in elastic recovery (%) per fiber exposed to artificial sweat upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C).

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000442016	5	8.84032E-05	4.082765876	0.02132921	3.105875239
Within Groups	0.000259833	12	2.16528E-05			
Total	0.000701849	17				

Table 11. Sweat resistance measured in elastic recovery (%) per fiber exposed to artificial sweat upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C), one-way ANOVA test summary statistics.

	NR-CO-AE-Z	*SPX*
Mean	0.990733333	0.983033333
Variance	4.54533E-05	7.34333E-06
Observations	3	3
Hypothesized Mean Difference	0	
df	3	
t Stat	1.835473423	
P(T<=t) one-tail	0.081887119	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.163774238	
t Critical two-tail	3.182446305	

Table 12. Sweat resistance measured in elastic recovery (%) per fiber exposed to artificial sweat upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C), Welch's t-test summary statistics.

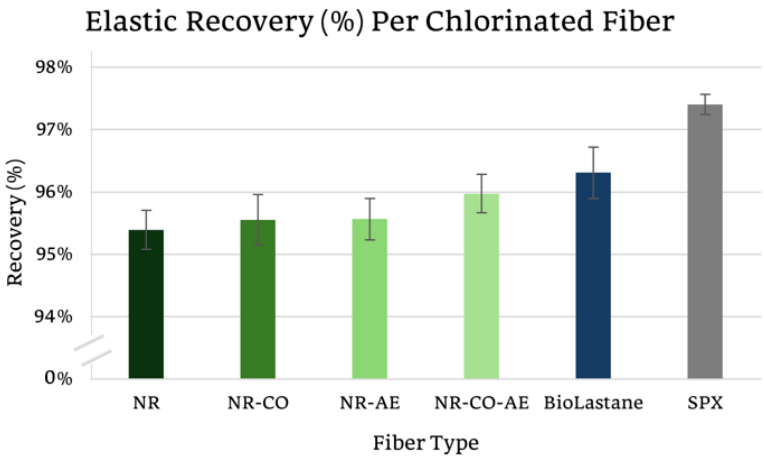


Figure 11. Chlorine resistance measured in elastic recovery (%) per fiber exposed to 50 ppm HOCl upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C).

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.002640531	5	0.000528106	47.76600171	1.65107E-07	3.105875239
Within Groups	0.000132673	12	1.10561E-05			
Total	0.002773204	17				

Table 13. Chlorine resistance measured in elastic recovery (%) per fiber exposed to 50 ppm HOCl upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C), one-way ANOVA test summary statistics.

	NR-CO-AE-Z	*SPX*
Mean	0.975233333	0.97913333
Variance	1.68933E-05	2.6433E-06
Observations	3	3
Hypothesized Mean Difference	0	
df	3	
t Stat	-1.52826969	
P(T<=t) one-tail	0.111953353	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.223906706	
t Critical two-tail	3.182446305	

Table 14. Chlorine resistance measured in elastic recovery (%) per fiber exposed to 50 ppm HOCl upon 1 minute of 200% strain in experimental and control groups at room temperature (25°C), Welch's t-test summary statistics.

Test Case	*NR*	*NR-CO*	*NR-AE*	*NR-CO-AE*	*NR-CO-AE-Z*	*SPX*
Elongation at Break (%)	1255.10%	1237.20%	1231.43%	1547.80%	1918.00%	1424.67%
Elastic Recovery (%)	94.59%	97.65%	95.96%	98.68%	98.81%	99.22%
Tensile Strength (MPa)	0.87	0.96	0.56	0.74	0.32	0.72

Figure 15. Mean values per experimental and control group for each mechanical test performed.

Test Case	*NR*	*NR-CO*	*NR-AE*	*NR-CO-AE*	*NR-CO-AE-Z*	*SPX*
Hydrophobicity (°)	42.50	42.25	40.50	61.00	71.75	90.00
Elastic Recovery (%)	94.59%	97.65%	95.96%	98.68%	98.81%	99.22%
Thermal Resistance (%)	95.39%	95.55%	95.56%	95.97%	96.31%	97.40%
Sweat Resistance (%)	98.50%	98.93%	97.54%	98.36%	99.07%	98.30%
Chlorine Resistance (%)	96.08%	95.64%	94.42%	97.22%	97.52%	97.91%

Figure 16. Mean values per experimental and control group for each durability test performed.

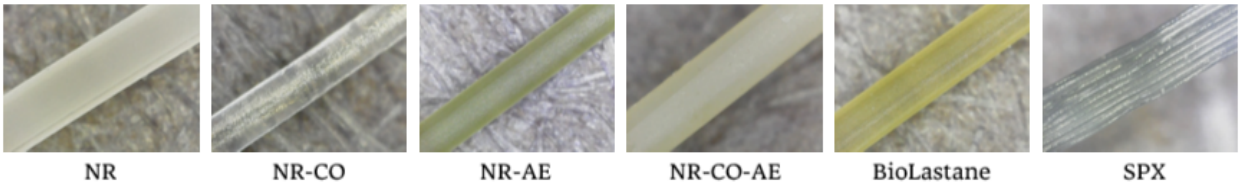


Figure 17. Natural rubber alternatives and elastane (SPX) micrographs.

DISCUSSION

The results obtained in this study contribute to meaningful discussion of the extent to which bioadditive-reinforced NR can serve as an elastane alternative. For ease of comprehension, this discussion has been broken into the following sections: mechanical performance, durability, and the limitations of this study.

Mechanical Performance

The mechanical performance of BioLastane encompasses a balance of both promising advancements and critical limitations when compared to commercial elastane. Elongation at break values show a statistically significant increase across the different experimental groups, according to the one-way ANOVA results (**Table 1**, $p = 1.415 \times 10^{-5}$, $\alpha = 0.05$). Additionally, the Welch's t-test comparison between NR-CO-AE-Z and SPX (**Table 2**, $p = 1.361 \times 10^{-2}$, $\alpha = 0.05$) and **Figure 5** further illustrate that BioLastane exhibits a significantly higher mean elongation at break (1918%) than elastane (1424.67%). This increase suggests that the incorporation of castor oil (CO) and alfalfa extract (AE) alongside zinc oxide (ZnO) and stearic acid (StA) increases the elasticity of NR. The role of ricinoleic acid as a plasticizing agent explains this increase in elongation as its hydroxyl functionality promotes intermolecular mobility within the polymer network [17].

Elastic recovery values present a different trend. The one-way ANOVA results indicate significant variation across groups (**Table 3**, $p = 2.286 \times 10^{-4}$, $\alpha = 0.05$); however, the Welch's t-test comparison between BioLastane and elastane does not show statistical significance (**Table 4**, $p = 1.786 \times 10^{-1}$, $\alpha = 0.05$), implying that BioLastane exhibits elastic recovery similar to elastane. **Figure 6** shows that BioLastane achieves a mean recovery value (98.81%) that is

comparable to elastane (99.22%). This similarity suggests that the utilization of ZnO and StA successfully increased crosslink density and, consequently, elastic recovery within the NR matrix. These interactions appear to mildly replicate the physical crosslinking behavior observed in elastane's segmented block co-polymer structure, where the strong attraction between the amorphous and rigid segments enables elastic recovery after deformation [12]. The ability of BioLastane to approximate the elastic recovery of elastane addresses a key limitation previously identified in natural rubber-based fibers.

Tensile strength results emphasize a notable weakness in BioLastane. The ANOVA results (**Table 5**, $p = 1.894 \times 10^{-4}$, $\alpha = 0.05$) and Welch's t-test (**Table 6**, $p = 1.768 \times 10^{-2}$, $\alpha = 0.05$) confirm a statistically significant decrease in tensile strength for BioLastane (0.32 MPa) compared to elastane (0.72 MPa), as shown in **Figure 7**. This reduction in tensile strength suggests that although the additives improve flexibility, they may disrupt the structural integrity of the NR matrix. The absence of highly ordered crystalline domains, a staple characteristic of elastane hard segments, likely limits the ability of BioLastane to withstand stress. This trade-off between elasticity and tensile strength relates to a common challenge in polymer engineering, where increasing flexibility often reduces polymer strength. Despite high elasticity, the lower tensile strength indicates that BioLastane does not yet achieve the balance of properties required for full functional to elastane.

Durability Performance

Durability testing addresses the main concern surrounding NR fiber use: degradation under high stress conditions. These tests evaluated the performance of BioLastane under environmental stressors relevant to common textile applications of elastane.

Hydrophobicity results do not show a statistically significant difference between BioLastane and elastane (**Table 8**, $p = 6.540 \times 10^{-1}$, $\alpha = 0.05$), although the ANOVA indicates variation across the bioadditive groups (**Table 7**, $p = 1.863 \times 10^{-6}$, $\alpha = 0.05$). **Figure 8** shows comparable contact angle values between BioLastane (71.75°) and elastane (90.00°). The lower water contact angle of BioLastane signifies a less hydrophobic material; however, this property may contribute to a more biodegradable fiber. Nonetheless, the balance of hydrophobicity and hydrophilicity offered by NR fibers may be more beneficial than that of highly hydrophobic synthetic elastane.

Thermal resistance results demonstrate statistically significant variation across groups (**Table 9**, $p = 6.172 \times 10^{-5}$, $\alpha = 0.05$). **Figure 9** indicates that BioLastane maintains relatively high elastic recovery upon exposure to accelerated thermal aging at 150°C. However, in comparison to elastane, the Welch's t-test indicates that elastane performs significantly higher under thermal stress as opposed to BioLastane (**Table 10**, $p = 1.138 \times 10^{-2}$, $\alpha = 0.05$). This difference is also reflected in Figure 9, where elastane maintains a higher elastic recovery after exposure to elevated temperature. The superior performance of elastane can be attributed to its segmented block copolymer structure, which has rigid hard segments that provide thermal stability and prevent permanent deformation under heat exposure [12]. In comparison, BioLastane relies on physically reinforced interactions rather than a fully engineered segmented structure, thus limiting its ability to fully replicate elastane's thermal resilience. [19]. This outcome suggests that although the thermal resistance of elastane is significantly superior to BioLastane, BioLastane can withstand thermal conditions relevant to elastane processing and use.

Sweat resistance and chlorine resistance results further attest to the durability of BioLastane. The ANOVA results for sweat resistance (**Table 11**, $p = 2.133 \times 10^{-2}$, $\alpha = 0.05$) and chlorine resistance (**Table 13**, $p = 1.651 \times 10^{-7}$, $\alpha = 0.05$) indicate significant differences across groups. However, Welch's t-test comparisons between BioLastane and elastane do not show statistically significant differences (**Table 12**, $p = 1.638 \times 10^{-1}$, $\alpha = 0.05$; **Table 14**, $p = 2.239 \times 10^{-1}$, $\alpha = 0.05$). **Figures 10 and 11** show that BioLastane maintains recovery values comparable to elastane under both conditions. Given the known susceptibility of natural rubber to degradation under sweat and chlorine exposure, the performance of BioLastane surpasses that of unmodified NR fibers, making it a more suitable elastane alternative [15,16]. The presence of antioxidant compounds in the alfalfa extract likely contributed to improved sweat and chlorine resistance by decreasing oxidative degradation [18]. These findings indicate that bioadditive reinforcement can address the durability limitations associated with NR fibers.

Figures 15 and 16 provide a consolidated comparison of mean mechanical and durability performance across all groups. Across the seven tests, BioLastane demonstrates competitive performance in most categories (5 out of the 7), with the exception of tensile strength and thermal resistance. This pattern further supports the conclusion that the bioadditive reinforcement improves multiple aspects of NR performance despite leaving specific limitations unresolved.

Limitations

Several limitations must be considered when interpreting these results. The BioLastane fibers were produced through syringe extrusion as opposed to industrial wet-spinning processes. This difference in fabrication likely influenced decreased BioLastane's fiber alignment and

structural uniformity – two critical factors in determining mechanical properties. The tensile strength and elasticity values reported in this study may therefore underestimate the true potential of BioLastane under optimized manufacturing conditions.

The study does not evaluate the potential release of chemical substances during wear, washing, or decomposition. The introduction of additives such as zinc oxide and stearic acid raises questions regarding long-term environmental and biological impacts. The formation of unintended reaction byproducts from additive interactions also remains unexamined. These factors are particularly relevant given the concerns surrounding chemical exposure from synthetic fibers and associated microplastics [3,5]. Further investigation into the chemical safety and degradation products of BioLastane is necessary to fully assess its viability as a sustainable alternative.

CONCLUSION

This study investigates the extent to which BioLastane can serve as a viable alternative to commercial elastane through the modification of natural rubber with castor oil, alfalfa extract, zinc oxide, and stearic acid. The results indicate that BioLastane achieves significant improvements in elongation at break and maintains comparable, if not superior, performance in elastic recovery and durability tests, including hydrophobicity, sweat resistance, and chlorine resistance. These findings demonstrate that the proposed bioadditive reinforcement can address several limitations of NR fibers and produce a natural material that approaches the functional performance of elastane.

However, BioLastane exhibits a significant reduction in tensile strength and thermal resistance compared to elastane. This limitation emphasizes the difficulty of replicating the

balance of elasticity, strength, structural integrity, and controlled degradability – where the material is not overly degradable but remains more degradable than elastane – achieved by synthetic segmented polymers.

The results suggest that although BioLastane represents a promising step toward sustainable elastic fibers, further optimization is required to enhance its mechanical strength without compromising flexibility and non-toxicity.

This study addresses the critical gap in the development of a low-cost, biodegradable alternative to elastane. As existing alternatives remain limited by cost, scalability, or insufficient performance, BioLastane offers a novel approach by using accessible biomaterials (CO and AE) and a low-energy modification process (bioadditive reinforcement through additive baths).

The findings of this study support the feasibility of this approach while identifying areas for continued research. Future work should focus on improving fabrication methods, enhancing tensile strength and thermal resistance, and evaluating the environmental and biological safety of the material. Through these advancements, it is hoped that BioLastane contributes to the development of safer and more sustainable textile materials.

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