ADVANCED BALLISTIC MATERIALS: A COMPREHENSIVE REVIEW OF NATURAL AND SYNTHETIC FIBER COMPOSITES FOR BODY ARMOR APPLICATIONS

AROOJ SHAHID, MUMTAZ HASAN MALIK, TAYYAB NAVEED, MUHAMMAD UMAIR and IMRAN AHMAD KHAN

Department of Textile and Apparel Sciences, School of Design and Textiles, University of Management and Technology, Lahore 54770, Pakistan
School of Engineering and Technology, National Center of Composite Materials, National Textile University, Faisalabad, Pakistan
✉ *Corresponding author: I. A. Khan, imran.ahmad@umt.edu.pk*

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Body armor plays a crucial role in modern defense and law enforcement, offering lifesaving protection against ballistic threats. With the growing complexity of threats and the demand for improved wearer mobility, research has shifted toward optimizing materials for higher strength-to-weight ratios, enhanced energy absorption, and flexibility. This review comprehensively examines advancements in both natural and synthetic fibers used in soft and hard ballistic armor systems. Focus is given to their mechanical properties, structural configurations, and the incorporation of novel technologies, such as hybrid composites. The role of fabric architecture, surface treatments, and fiber-matrix adhesion in enhancing energy absorption is also discussed. The article concludes with future directions for the development of multifunctional, lightweight, and eco-friendly ballistic protection systems using emerging material technologies.

Keywords: ballistic protection, fiber composites, natural and synthetic fibers, hybrid composites, body armor systems

INTRODUCTION

Ballistic protection remains a paramount priority across military, law enforcement, and civilian security domains, necessitating continuous innovation in materials science and protective system engineering. Modern body armor is meticulously designed to mitigate the effects of high-velocity projectiles and sharp-edged threats by absorbing, dissipating, and redistributing kinetic energy, thereby preventing penetration and reducing the risk of blunt force trauma.[1] The escalating complexity of battlefield and urban conflict scenarios has intensified the demand for armor systems that not only provide superior protective performance, but also exhibit reduced weight, enhanced flexibility, and improved wearer comfort.[2] The performance demands have encouraged a surge in research, extending from conventional and high-performance fibers to advanced innovations, such as nanostructured composite materials, textile architecture enhanced with shear-thickening fluids, and hybridized fabric systems.[3,4] Previous ballistic protection materials used dense metallic plates, which provided protection, but restricted the wearer's mobility.[5] The beginning of soft body armor, normally made of high-performance fibers, offering a high comfort level, comparatively falls short in terms of ballistic resistance.[6] This gap has been addressed through advances in structural design modifications, the incorporation of nanomaterials, and the application of multi-phase hybridization techniques, thereby opening new horizons for the next generation of high-performance and lightweight ballistic composites.[7]

Among the various engineered fibers employed for ballistic protection, para-aramids (*e.g.*, Kevlar®, Twaron®) and ultra-high-molecular-weight polyethylene (UHMWPE) have established themselves as front-runners, because they offer outstanding strength relative to weight, absorb high energy, and withstand dynamic impacts.[8] These synthetic materials form the cornerstone of most modern soft and hard armor solutions. Concurrently, there is a growing resurgence of interest in renewable and eco-friendly natural fibers as viable reinforcements in ballistic composites. While natural fibers once lagged in mechanical strength, new surface treatments, chemical modifications, and improved bonding with polymers have greatly enhanced their durability and compatibility in

composites.[9] This dual trajectory, advancing both high-performance synthetics and optimizing sustainable alternatives, reflects a strategic shift toward multifunctional, lightweight, and environmentally responsible armor systems. Beyond improved mechanical protection, next-generation ballistic systems are being integrated with electronic sensors capable of detecting impacts and monitoring environmental conditions, thus helping the wearer to make data-driven decisions in high-risk environments.[10]

The objective of the present review is to give a comprehensive and comparative evaluation of the materials that are employed in ballistic protection systems from natural and synthetic fiber sources. In particular, the goals of this review are:

- To critically review mechanical properties, structural configurations, and ballistic performance of natural and man-made fibers that are employed in soft and hard armor;
- To investigate the effect of fabric construction, surface finishing, and bonding between the fiber and matrix on ballistic energy absorption;
- To observe and discuss new technologies, such as hybrid composite systems, that will increase protection and flexibility;
- To emphasize existing problems and future research directions for lightweight, multifunctional, and sustainable ballistic protection systems.

HISTORICAL EVOLUTION OF BALLISTIC MATERIALS

In earlier times, body armor was made from rigid natural materials, including leather, wood, and metal, such as bronze or iron chest plates. While effective for protection, these heavy constructions imposed considerable restrictions on mobility and often caused discomfort. One of the first known types of soft body armor was used in feudal Japan, where samurai wore silk clothing for armor protection.[11] In the early 20th century (World War I), the U.S. military tested silk armor for slow bullets, but found it failed against faster rounds.[12]

A breakthrough in ballistic protection came in the 1960s when DuPont developed Kevlar®, the first high-performance para-aramid fiber, which combined high tensile strength, flexibility, and light weight, transforming soft body armor for police and military use.[13,14] Soon after, other high-performance fibers, such as Twaron®, Technora®, and UHMWPE-based types like Dyneema® and Spectra® emerged, followed by materials like PBO, Vectran®, and M5, all offering excellent strength-to-weight ratios and strong resistance to heat, chemicals, and ballistic impacts.[15,16] The use of 3D woven fabrics and multi-axial knits has improved body armor by spreading impact forces more evenly.[17] Recent advances, such as shear-thickening fluids and nanomaterials, have boosted impact absorption significantly, without reducing flexibility.[18]

NATURAL FIBERS FOR BALLISTIC PROTECTION

Natural fibers, sourced from plants and animals, are being used as eco-friendly alternatives to synthetic materials in ballistic composites as they are biodegradable, lightweight, affordable, and have good strength for their weight.[19,20] Different plant-based fibers, such as jute, hemp, flax, ramie, banana, coir, and sisal, have been widely studied for personal protective equipment because they can help lower the environmental impact of synthetic fibers.[21]

Mechanical properties of natural fibers

The properties of plant-based fibers largely depend on factors like their cellulose content and the way cellulose microfibrils are arranged in the cell wall. Cellulose is a strong biopolymer that gives the fiber its strength, but the microfibrillar angle is also an important factor – it is the angle between the cellulose fibrils in the secondary cell wall and the fiber's length, and it affects how the fiber handles stress.[22] Natural fibers with smaller microfibrillar angles are usually stronger and stiffer. Table 1 compares the strength of different natural fibers. Their performance and durability mainly depend on their chemical composition, structure, defects, and cell size.[23,24] Notably, there exists a direct correlation between the cellulose content and the strength of the fiber, with higher cellulose levels generally resulting in superior mechanical performance.[25] Animal-derived fibers, such as wool and spider silk, are also being explored for their remarkable tensile properties and elasticity. Spider silk is well known for being tough and light, and it can absorb more energy for its weight than many

synthetic fibers. However, challenges in mass production and environmental stability have limited its widespread application thus far.[26]

Table 1
Mechanical characteristics of natural fibers

Fiber source	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	References
Bamboo	0.6-1.1	140-230	11-17		[27]
Jute	1.3-1.5	385-850	10-55	1.16-8.0	[28, 27]
Flax	0.6-1.5	88-1600	24-80	1.2-10	[29]
Hemp	1.4–1.6	310–900	30–80	1.6–6	[30]
Rice husk	1.4	19–135	0.3–2.6		[31]
Sisal	1.3–1.5	80–840	9–38	2–25	[32]
Cotton	1.5–1.6	45.5–1000	5.5–12.6	3–10	[33]
Spider silk	1.3	2000	30	30	[34]
Wool	1.3	1-1.7	2.3-3.4	35-45	[34]

Natural fiber surface treatment

Although natural fibers offer numerous environmental and economic advantages, their inherent hydrophilicity and heterogeneity pose challenges to mechanical consistency and interfacial bonding in composites.[35] To address these drawbacks, researchers have employed surface treatments, such as alkali treatment, silane coupling, enzymatic modification, and plasma techniques, to enhance fiber–matrix adhesion. These modifications effectively reduce water absorption and improve tensile strength, interfacial shear strength, and impact energy dissipation.[36]

Physical treatments

Among the most commonly employed physical methods for modifying the surface of natural fibers are corona discharge, thermal treatments, plasma exposure, and ultraviolet (UV) irradiation. These techniques primarily aim to individualize fiber bundles (filamentation) and to alter the outer fiber surface to enhance interfacial compatibility with polymer matrices. These treatments boost fiber–matrix bonding by changing the surface features, without affecting the fiber's internal structure.[37] However, due to the advanced equipment required for surface-level physical modifications, such treatments are generally more costly than chemical alternatives.[38] An overview of the primary effects of these physical treatments on natural fibers is presented in Table 2.

Table 2
Physical treatment of natural fibers and induced effects

Treatment method	Fiber used	Effects	Reference
Fiber beating	Eucalyptus cellulose fiber	Enhanced the internal porosity of the fiber structure	[39]
Heat treatment	Agave fiber	Boosted the fiber's crystallinity and rigidity	[40]
UV treatment	Cotton	Enhanced fiber swelling contributed to improved dye uptake and coloration efficiency	[41]
Plasma treatment	Cotton	Adjustments to the fiber's surface features were associated with a decrease in moisture affinity	[42]

Chemical treatments

Lignocellulosic fibers mainly consist of cellulose, hemicelluloses and lignin, with cellulose providing most of the fiber's mechanical strength. Chemical treatments are used to purify cellulose by removing surface impurities like oils, waxes, and other non-cellulosic materials. These chemical modifications are widely used to improve fiber–matrix interfacial adhesion either through covalent bonding or by reducing water affinity, thereby facilitating stronger mechanical interlocking at the interface. According to existing research, a wide range of chemical treatment strategies exhibit varying degrees of effectiveness. Generally, chemical treatments have demonstrated superior performance compared to physical methods in terms of enhancing fiber properties and composite compatibility. A

key challenge in natural fiber composites is the mismatch between the water-attracting fibers and the water-repellent polymer matrices. This disparity often results in weak interfacial adhesion, which in turn limits mechanical performance and compromises long-term durability due to poor moisture resistance.[43,44]

Several studies have compared the performance of treated and untreated natural fibers in composite structures under ballistic loading. For example, sisal, flax, and jute fibers treated with NaOH or silane have demonstrated up to 30% improvement in energy absorption during projectile impact tests. Notably, nettle and ramie fibers have displayed tensile properties that rival or exceed certain commercial synthetic fibers, making them particularly attractive for lightweight body armor applications.[45] When the hydroxyl (–OH) groups on natural fibers react with sodium hydroxide (NaOH), it triggers the formation and release of water molecules. As a result, the overall hydroxyl group content is reduced, which subsequently lowers the fiber's tendency to absorb moisture. In addition to this reaction, NaOH treatment partially removes non-cellulosic components, such as hemicelluloses, pectin, lignin, and surface waxes, thereby enhancing the fiber's purity and reactivity.[46] The chemical interaction pathway between the fiber and alkali is illustrated below, while Figure 1 highlights the structural and morphological changes induced by alkali treatment in natural fibers.

$$\text{Fiber–OH} + \text{NaOH} \rightarrow \text{Fiber–O–Na}^{+} + \text{H}_2\text{O} \qquad (1)$$

Eze *et al*. conducted a detailed investigation into the influence of hydrogen peroxide (H_2O_2) surface treatment on pineapple leaf powder (PALP) and its subsequent incorporation into high-density polyethylene (HDPE) composites. In their work, both untreated and H_2O_2-treated PALP were incorporated into HDPE at varying filler loadings (2, 4, 6, 8, and 10 wt%) using an injection molding process. The research found that PALP inclusion boosted critical mechanical properties, regardless of treatment. Notably, the elongation at break exhibited a decreasing trend with increasing PALP content, suggesting a trade-off between strength and ductility. Importantly, composites reinforced with peroxide-treated PALP consistently outperformed those with untreated PALP across all measured parameters. H_2O_2 treatment proved successful in strengthening the bonding between natural fiber fillers and the polymer matrix, leading to improved mechanical behavior. This reinforces the broader consensus in the literature that chemical surface modification of lignocellulosic fillers can significantly optimize fiber–matrix interactions and improve composite quality.[48]

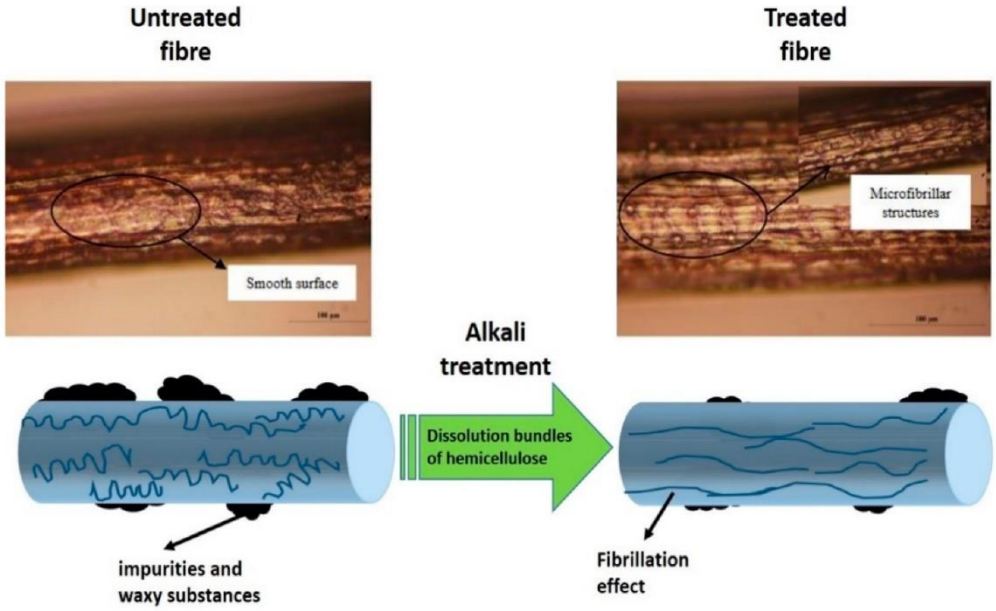

Figure 1: Schematic representation of natural fiber modification through alkaline treatment (adopted from ref. 47 with permission; Copyright 2022 MDPI Polymers (Open Access Creative Commons CC-BY-NC 4.0 license))[47]

(a) (b)

Figure 2: Visuals depicting contact angle measurements of (a) soap-washed wool fibers and (b) wool fibers exposed to peroxide treatment (adopted from ref. 49 with permission; Copyright 2022 MDPI Materials (Open Access Creative Commons CC-BY-NC 4.0 license))[49]

Another investigation reported that the peroxide-treated samples exhibited noticeably greater surface irregularities compared to untreated fibers. This was particularly evident in the contact angle measurements, where fiber strands were visibly embedded within the water droplet, as depicted in Figure 2. Thus, oxidative treatment makes the surface rougher, which can affect the interaction of fibers with other materials.[49] Liu *et al.* studied how treating corn stalk fibers from agricultural waste with a silane coupling agent could improve their use in composites. Fibers were treated with silane solutions of 1%, 5%, 9%, and 13%, and analyzed using FTIR and XRD. The 5% treatment showed the best results, increasing fiber crystallinity and removing hemicelluloses and lignin. Composites made with these treated fibers showed better impact resistance than those with untreated fibers. SEM images also showed a rougher surface after treatment, improving mechanical grip and bonding between fiber and matrix. This shows silane treatment can effectively improve the surface and strength of natural fiber composites.[50]

Acetylation is a widely adopted surface modification technique aimed at reducing the hydrophilicity of plant-based fibers while simultaneously enhancing their thermal stability. This process involves the substitution of hydroxyl (–OH) groups present on the fiber surface with acetyl (CH_3CO–) groups, resulting in the formation of a more hydrophobic exterior. Although these hydroxyl groups are primarily found in the non-cellulosic components, namely hemicelluloses and lignin, as well as to a lesser extent in cellulose, direct reaction with acetic acid is generally limited due to its low reactivity with cellulose. To overcome this limitation, acetic anhydride is commonly employed as a more effective acetylating agent. The reactions (presented below) can occur either with or without the presence of an acid catalyst and are typically carried out over a period of 1 to 3 hours. The pretreatment of fibers by immersion in acetic acid is sometimes utilized to enhance reactivity. In addition to decreasing the water absorption capability of natural fibers, acetylation enhances thermal resistance, which is important for composites exposed to high temperatures.[46] Extensive studies have been conducted on various fiber surface modification methods, with an overview of these treatment techniques presented in Table 3.

$$\text{Cellulose} - \text{OH} + CH_3COO \xrightarrow[H_2SO_4]{(CH_3CO)_2O} \text{Cellulose} - O - \underset{\underset{O}{\|}}{C} - CH_3 + H_2O \quad (2)$$

$$\text{Cellulose} - \text{OH} + CH_3 - \underset{\underset{O}{\|}}{C} - O - \underset{\underset{O}{\|}}{C} - CH_3 \longrightarrow \text{Cellulose} - O - \underset{\underset{O}{\|}}{C} - CH_3 + CH_3COOH \quad (3)$$

Table 3
Physical treatment of natural fibers and induced effects

Treatment method	Fiber used	Effects	Reference
Alkalization	Wool	Elevating the degree of polymerization improves the structural integrity and reactivity of the fiber.	[51]
	Sisal/Hemp	Incorporation of 40 wt% sisal and hemp fibers, treated with 10% NaOH solution, led to a noticeable improvement in flexural strength, indicating enhanced fiber–matrix interaction and mechanical reinforcement.	[52]
	Banana	Fibers subjected to a 5% NaOH treatment demonstrated superior mechanical properties compared to untreated or more heavily treated counterparts.	[53]
	Jute	The treatment removed hemicelluloses and increased fiber interlocking, enhancing adhesion and stress transfer, which improved tensile, flexural, and interlaminar shear properties.	[54]
Peroxide treatment	Eucalyptus cellulose fiber	Peroxide-treated fibers exhibit a greater degree of surface roughness.	[49]
	Pineapple leaf	Treated composites exhibited improved mechanical properties.	[48]
Silane treatment	Oil palm fiber	The composite exhibits increased thermal stability as a result of better fiber–matrix compatibility and structural reinforcement.	[55]
	Kenaf	Silane treatment eliminated lignin and hemicellulose from the fiber surface, resulting in improved interfacial bonding with the matrix.	[56]
	Pineapple leaf	Treated fibers exhibited reduced interfacial voids, leading to stronger fiber–matrix bonding and enhanced mechanical performance.	[56]
Esterification/Acylation	Biofiber (pineapple leaf fiber/sisal fiber)	Improved fiber–matrix interfacial adhesion enhances load transfer efficiency and structural performance of the composite.	[57]
	Grewia serrulata bast	Treated fibers demonstrated improved dimensional stability and increased resistance to moisture absorption.	[5859].

Beyond individual fiber types, blending or layering different natural fibers in hybrid composites offers a promising approach to improve mechanical strength and ballistic performance. Such hybridization allows material engineers to tailor stiffness, failure strain, and impact resistance by leveraging the complementary properties of different fiber types.[60]

In summary, natural fibers, when appropriately treated and structured, hold significant potential for application in personal ballistic protection, especially in hybrid or multilayer systems where their limitations can be mitigated. Ongoing advancements in fiber processing and bio composite design continue to push the boundaries of their applicability in high-performance armor.

SYNTHETIC FIBERS FOR BALLISTIC PROTECTION

Synthetic fibers have transformed personal protection thanks to their excellent strength and reliable performance under load. Para-aramid fibers, such as Kevlar® and Twaron®, are prized for being strong, lightweight, and resistant to heat and abrasion, and are woven or arranged unidirectionally to create flexible yet protective body armor.[61] Kevlar is about five times stronger than steel by weight, allowing armor to be both light and effective. It protects by spreading and absorbing impact energy as its molecules stretch and shift, making it ideal for soft armor in security and military gear. It also works well in extreme temperatures and resists fire and chemicals.[62] Still, Kevlar has some limitations, including sensitivity to sunlight and moisture, which can weaken its fibers over time. It also performs poorly under compressive loads, making it less effective on its own in composites facing complex or multidirectional forces.[63] Secondly, manufacturing Kevlar-reinforced composites is challenging because the fibers' smooth, chemically inert surface makes bonding with the matrix difficult. Methods like plasma treatment, silane agents, and nano-coatings are used to improve adhesion and stress transfer, but issues such as delamination and reduced performance after repeated impacts can still occur.[64] To address these drawbacks, researchers combine Kevlar with ultra-high-molecular-weight polyethylene (UHMWPE), carbon fibers, or shear-thickening fluids, creating hybrids that offer better impact resistance and longer-lasting structural strength.[65]

UHMWPE fibers like Dyneema® and Spectra® are lighter than para-aramids and can absorb more energy, while also resisting moisture, UV damage, and chemical attack, making them ideal for use in different harsh conditions. UHMWPE-based armor solutions are particularly favored in marine and tropical applications due to their excellent weather resistance. Poly(p-phenylene benzobisoxazole) (PBO), marketed as Zylon®, once held promise as the next-generation fiber due to its extremely high tensile strength. However, early failures in field-deployed vests due to environmental degradation raised serious concerns about their long-term stability. Nonetheless, Zylon® still garners research interest when encapsulated or hybridized with more stable fibers.[66,67] In recent years, M5 fiber, based on polyhydroquinone-diimidazopyridine (PIPD), has attracted attention due to its combination of high modulus, low density, and exceptional chemical stability. Its performance under ballistic conditions remains under investigation, particularly in high-strain-rate environments and in conjunction with ceramic hard plates.[31]

Aramid fibers are generally categorized into para-aramid (*e.g.*, Kevlar®, Twaron®), meta-aramid (*e.g.*, Nomex®), and copolymer aramid (*e.g.*, Technora®), based on their molecular configuration. Among these, para-aramid fibers are predominantly utilized in ballistic textiles and composite structures due to their outstanding mechanical strength and superior resistance to impact. Extensive research has focused on the development and optimization of para-aramid-based materials and composites. Nevertheless, the strong molecular alignment in aramid fibers creates a smooth, inert surface that hampers effective adhesion to polymer matrices.[68] Various surface modification methods have been investigated to improve the reactivity and bonding between aramid fibers and polymer matrices. These include both chemical and physical approaches, such as chemical etching, surface grafting, oxidative treatments, in-situ polymerization, application of coupling agents, thermal treatment, plasma processing, ion sputtering, electron beam exposure, gamma irradiation, corona discharge, and ultrasonic treatment.[69]

Different categories of synthetic fibers pose distinct challenges related to their economic viability, processing intricacies, and interfacial compatibility with composite matrices. For instance, aramid fibers typically exhibit low compressive strength and limited adhesion to standard resin systems. Enhancing fiber–matrix adhesion often involves surface modifications including ozone

functionalization, plasma treatment, and silane coupling.[70] Hybrid systems that combine aramids with UHMWPE or other synthetics have shown synergistic effects. These systems optimize both high energy dissipation and structural integrity, making them suitable for multilayered soft armor and vehicle protection applications.[71] Additionally, blending synthetic fibers with nano-reinforcements like carbon nanotubes or graphene oxide has resulted in increased mechanical performance without significantly increasing weight.[72] Synthetic high-performance fibers continue to play a pivotal role in the advancement of contemporary ballistic protection technologies. Ongoing innovations in hybrid composite structures and enhancements in fiber-matrix interfacial bonding are expected to further elevate the effectiveness and resilience of next-generation armor systems.

Table 4 presents the key physical and mechanical characteristics of various synthetic fibers used in ballistic protection. This comparative overview highlights the distinct benefits of each fiber type and supports informed selection for specific protective needs. Widely used in protective armor, para-aramid and UHMWPE stand out for their blend of low weight, strong tensile strength, high stiffness, and considerable elongation. While both materials exhibit similar mechanical profiles, UHMWPE generally demonstrates superior performance in terms of specific strength and stiffness, primarily because of its lower material density.

Table 4
Characteristics of synthetic fibers used in ballistic protection[73,74,75]

Fiber type	Fiber name	Density ($g.cm^{-3}$)	Tensile strength (GPa)	Tensile modulus (GPa)
Polyamide	Nylon 6	1.14	0.5	3
Glass	S-Glass	2.48	4.4	90
	E-Glass	2.63	3.5	68.5
	Standard	1.77	3.65	33.5
Para-Aramid	Technora, Teijin	1.39	3.0	70
	Twaron, Teijin	1.45	3.1	121
	Kevlar 29	1.44	2.97	70
	Kevlar 129	1.44	3.39	96
	Kevlar 49	1.44	2.97	113
UHMWPE	Spectra 900	0.97	2.4	73
	Spectra 1000	0.97	2.83	103
	Spectra 2000	0.97	3.34	124
	Dyneema	0.97	2.6	87
Aromatic polyester	Vectran	1.47	3.2	91
Poly-hydroquinone-diimidazopyridine (PIPD)	M5 Fiber	1.7	8.5-9.5	300-450

COMPARISON OF NATURAL AND SYNTHETIC FIBERS FOR BALLISTIC PROTECTION APPLICATIONS

Table 5 shows a comparison of natural and synthetic fibers used for ballistic protective clothing. Synthetic fibers such as aramid fibers, ultra-high-molecular-weight polyethylene, and carbon fibers have been the backbone of commercial ballistic protection systems due to their high specific modulus and excellent energy absorption. These properties help them absorb the energy from the projectiles and keep the structure intact when it is hit at a high speed.[76] However, their high production cost, reliance on non-renewable resources, environmental issues of disposal and recycling continue to be major constraints. Natural fibers like flax, hemp, kenaf, jute, sisal, ramie, banana, and pineapple leaf fiber (PALF) have become the focus of growing interest for being sustainable, as these are low-density, biodegradable, renewable, cost-effective, and eco-friendly.[77] However, their ballistic resistance is typically lower than that of high-performance synthetic fibers due to lower tensile strength, higher moisture uptake, and variability in fiber properties. Still, they have good potential for lightweight and eco-friendly protective systems.

Table 5
Comparison of natural and synthetic fibers for ballistic protective clothing [78]

Property	Natural fibers	Synthetic fibers
Examples	Flax, hemp, jute, kenaf, ramie, sisal, banana, pineapple leaf fiber (PALF), coir	Kevlar®, Twaron®, UHMWPE (Dyneema®, Spectra®), carbon fiber, basalt fiber, nylon, PBO (Zylon®)
Source	Renewable, plant-based	Petroleum-based or mineral-derived
Density (g/cm³)	1.2–1.6	0.97–2.0
Specific strength	Moderate	High to very high
Tensile strength	Moderate	Very high
Young's modulus	Moderate	High
Impact resistance	Moderate	Excellent
Ballistic performance	Suitable for low- to moderate-threat applications; often used in hybrid composites	Excellent; widely used for military and law enforcement body armor
Energy absorption capacity	Good due to cellular structure; lower than advanced synthetic fibers	Excellent due to high tensile strength and toughness
Weight	Lightweight	Lightweight (especially UHMWPE) to moderate
Flexibility and comfort	Good comfort and breathability	Generally good; depends on fiber architecture
Moisture absorption	High; may reduce mechanical performance in humid conditions	Very low (UHMWPE) to moderate (aramid)
Thermal stability	Moderate; susceptible to thermal degradation	Excellent (aramids, carbon fiber, basalt); UHMWPE has lower melting temperature
Chemical resistance	Limited; sensitive to moisture, alkalis, fungi, and UV exposure	Generally excellent; varies with fiber type
Durability	Moderate	Excellent
Environmental sustainability	Renewable, biodegradable, low carbon footprint	Non-biodegradable (except some emerging bio-based synthetics); higher environmental footprint
Cost	Low	Moderate to high
Processing	Easy to process but requires surface treatment for improved fiber–matrix adhesion	Well-established industrial processing techniques
Major advantages	Eco-friendly, renewable, biodegradable, low cost, low density, good vibration damping	Superior strength, high ballistic resistance, excellent durability, consistent quality
Major limitations	Moisture sensitivity, variability in properties, lower ballistic efficiency, lower durability	Higher cost, non-renewable origin, recycling challenges, environmental concerns
Typical applications	Hybrid ballistic composites, vehicle panels, helmets, protective inserts, research on sustainable armor	Soft body armor, hard armor plates, military helmets, shields, aerospace and defense applications

BALLISTIC PERFORMANCE FACTORS

The ballistic efficiency of fiber-reinforced armor systems is determined by an interplay of intrinsic material properties and structural design features. Key factors include fiber strength, fabric weight, weave pattern, yarn alignment, and friction between yarns, and understanding how these factors work together is crucial for designing advanced protective systems.[79]

Weave design plays a key role in how fiber-based armor performs, with patterns like plain, twill, satin, and basket weaves affecting yarn crimp and force distribution. Plain weaves, with their tight interlacing, offer better stability and resist yarn pull-out. In contrast, twill and satin weaves offer increased flexibility, but generally exhibit reduced impact resistance.[80] Recent research indicates that 3D woven and multilayer warp-knitted fabric architectures exhibit superior performance compared to conventional 2D counterparts, primarily due to their improved through-thickness reinforcement and more efficient energy dissipation mechanisms.[81]

Yarn crimp plays a significant role in energy transfer. High crimp structures delay strain wave propagation due to initial yarn straightening, which can reduce the efficiency of energy absorption. On the other hand, crimp-free fabrics, such as unidirectional (UD) layers, allow fibers to engage directly on impact, resulting in higher ballistic performance and less deformation.[82]

The resistance generated between adjacent yarns plays a significant role in determining the protective efficiency of textile armor structures under ballistic impact. Elevated frictional forces inhibit lateral slippage between yarns, thereby promoting greater yarn participation in absorbing and dispersing impact energy. Surface treatments, like polyurethane coatings or nano-silica finishes, can effectively enhance inter-yarn friction, resulting in improved energy dissipation during ballistic events.[83] Notably, the inclusion of shear thickening fluids (STFs) between layers has been shown to significantly increase inter-yarn friction under strain, improving multi-hit resistance without compromising flexibility.[84]

Layer orientation and stacking order are key to armor performance, with cross-ply and multi-axial layouts reducing directional weaknesses and spreading stress more evenly. Tests show these designs can absorb 20–30% more energy than purely unidirectional layers and adjusting layer count and fabric weight allows protection levels to be tailored while keeping the armor lighter and less bulky.[85] Furthermore, stitching and lamination are also important for keeping fabric armor intact during impacts. While too much stitching can create weak spots, well-planned seam designs help prevent layers from separating. Research shows patterns like diamond or perimeter stitching can reduce trauma in soft armor.[86]

From the above discussion, it is clear that the ballistic performance of protective materials is multifactorial and depends on fiber properties, fabric architecture, areal density, and finishing techniques. It should be remembered that optimal performance could only be obtained through a system approach, wherein every item is carefully selected and engineered to be effective in energy absorption. Some parameters that influence perspectives such as yarn orientation, weave structure, inter-yarn friction, and post-treatment processes are the most critical in defining materials' dimensions on their way to withstanding and dissipating the impact forces encountered during use. Looking ahead, combining multifunctional materials are expected to produce more efficient and highly targeted ballistic protection systems.

COMPOSITE SYSTEMS AND HYBRID MATERIALS

Recently, ballistic protection has moved toward advanced composites that combine high-performance fibers with polymer matrices to improve impact resistance, stiffness, and durability in different environments. These panels embed strong fibers in thermoset or thermoplastic resins, helping spread impact energy efficiently. With their light weight, high strength, and design flexibility, fiber-reinforced composites have become a core material in both soft and hard armor systems.[87] Hybrid composites combine different fiber types in one matrix to improve ballistic performance. For example, combining aramid with UHMWPE or carbon fibers creates a balance of toughness, flexibility, and impact resistance, often leading to better bonding between layers, more efficient energy absorption, and less delamination. Tests show that hybrids like Kevlar/basalt and UHMWPE/glass can perform up to 40% better than composites made from a single fiber type.[88] Additionally, the matrix material also plays a vital role in determining the ballistic composite's performance. In this context, epoxy and polyester resins have long been favored for their ability to bond well with fibers and transfer stress effectively. However, thermoplastic matrices, such as polycarbonate, polypropylene, and polyetherimide, are increasingly being adopted due to their advantages in recyclability, enhanced toughness, and ability to recover shape after impact.[89]

Advancements in nanotechnology have significantly contributed to the performance enhancement of composite materials used in ballistic applications. Introducing nanofillers, such as carbon nanotubes (CNTs), graphene oxide, and nano-silica, into fiber-reinforced polymer systems has led to notable gains in tensile strength, thermal resistance, and fracture toughness. For example, research has shown that Kevlar/epoxy laminates modified with CNTs demonstrate superior specific energy absorption under ballistic impact compared to their unreinforced counterparts.[90] Moreover, the strength of adhesion between reinforcing fibers and enclosing matrix is a key determinant of the composite armor’s overall protective performance. To enhance this adhesion, various surface modification techniques, such as fiber functionalization, plasma treatment, and the application of coupling agents,

are commonly employed. These strategies strengthen the chemical interaction at the fiber-matrix interface, thereby minimizing debonding under impact and enabling a greater number of fibers to actively contribute to absorbing and dissipating projectile energy.[91] The arrangement of layers within hybrid composite structures plays a vital role in determining their failure behavior and ballistic resistance. Optimizing the stacking sequence, such as positioning high-stiffness fibers like carbon on the strike face, followed by layers of energy-absorbing materials like aramid or UHMWPE, has been shown to effectively distribute impact forces and delay penetration. This configuration leverages the rigidity of the outer layers to blunt the projectile while allowing the underlying ductile layers to dissipate energy. In multi-hit conditions, such strategically layered composites exhibit superior damage tolerance and maintain their protective performance more effectively than uniform, single-material panels.[92]

A plain-woven hybrid fabric incorporating both Kevlar and carbon fibers (Fig. 3a, b) merges the advantages of each material, delivering excellent tensile strength, rigidity, and impact resistance. Due to these properties, it serves effectively as a reinforcement material in composite structures that demand superior mechanical behavior, such as rally car body panels and canoe hulls. Figure 3c illustrates a 3×1 twill-woven Kevlar–carbon hybrid fabric, which offers enhanced surface coverage during composite fabrication. This configuration is commonly employed to strengthen and stiffen composite components, while also providing resistance to wear, making it suitable for use in applications like kayaks, racing seats, structural panels, and similar high-performance elements. Additionally, Kevlar and carbon fibers can be hybridized in braided (as shown in Fig. 3d), ring-shaped sleeve forms to meet specific structural reinforcement requirements.

Recent research is increasingly directed toward the development of sustainable ballistic materials, particularly bio-hybrid and recyclable composites. Natural fibers such as flax and jute, when combined with biodegradable polymer matrices like polylactic acid (PLA), have demonstrated encouraging impact resistance, while significantly lowering environmental impact. Although their ballistic performance currently falls short of that achieved by conventional synthetic composites, ongoing material optimization positions bio-hybrids as viable candidates for protective applications in low- to medium-threat environments.[94]

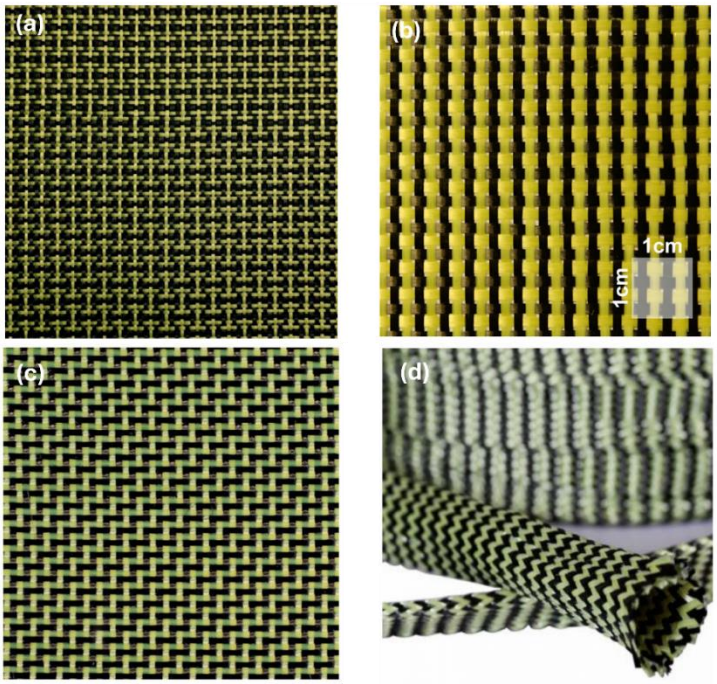

Figure 3: (a) Plain hybrid weave of Kevlar/Carbon fabric with high density, (b) Plain hybrid weave of Kevlar/Carbon fabric with low density, (c) Twill hybrid Kevlar–carbon fabric, (d) Braided hybrid Kevlar–carbon fabric (Copyright 2022 MDPI Polymers (Open Access Creative Commons CC-BY-NC 4.0 license))[93]

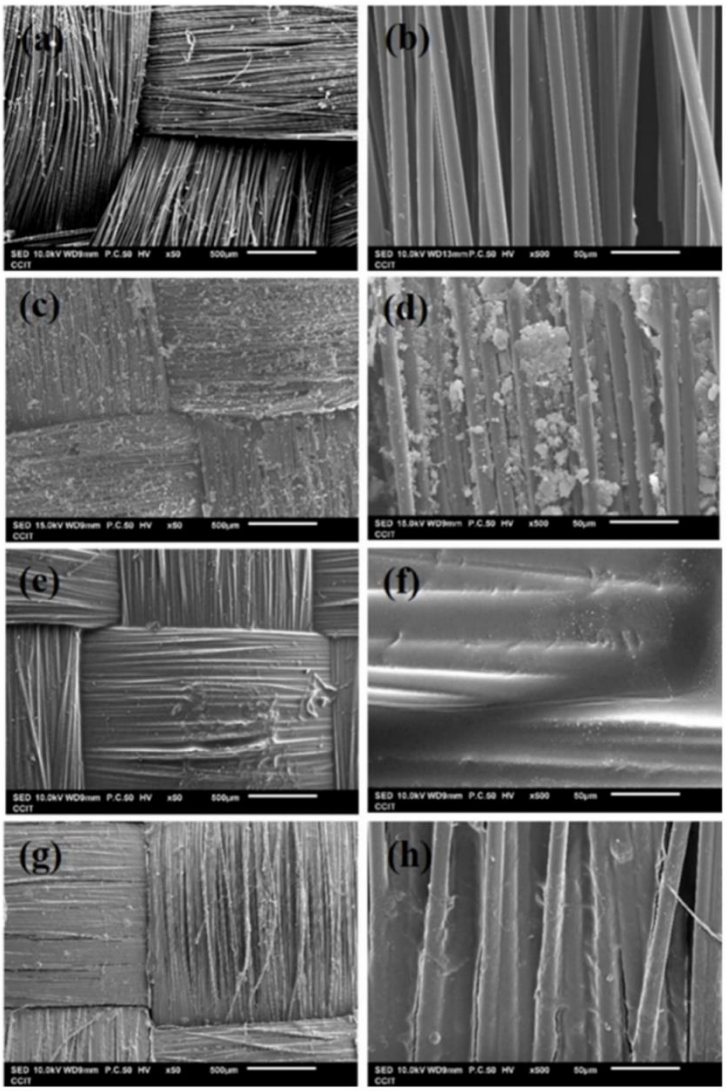

Figure 4: Scanning electron micrographs showing: (a, b) untreated Kevlar plates; (c, d) shear-thickening fluid (STF) impregnated Kevlar plates; (e, f) epoxy-coated Kevlar plates; and (g, h) polyurea elastomer-coated Kevlar plates (Copyright 2022 MDPI Polymers (Open Access Creative Commons CC-BY-NC 4.0 license))[95]

Recently, new materials like shear thickening fluids (STFs) have been explored to improve the ballistic performance of woven fabrics. STFs have drawn attention for being non-toxic and having good heat resistance. It is usually a fluid or gel made of fine particles such as silica or calcium carbonate in a liquid like polyethylene glycol or ethanol, and it thickens instantly when hit due to changes in viscosity under shear stress. Research has demonstrated that treating high-performance fibers like Kevlar or UHMWPE with STF can significantly improve their ability to absorb impact energy. This is primarily because STF increases inter-yarn friction, which reduces yarn movement and distributes impact forces more effectively.[34] Microscopic images (Fig. 4) show that plain Kevlar fabric has a 2D woven structure with yarn filaments about 10 μm in diameter (Fig. 4a, b). After impregnation with STF (Fig. 4c, d), the STF is seen filling some inter-yarn gaps, though not completely. In the case of epoxy treatment (Fig. 4e, f), the resin fully penetrates and fills the spaces, forming a dense 3D composite structure. Kevlar coated with polyurea elastomer (Fig. 4g, h) shows partial coverage, but some interstitial gaps remain, likely due to the use of a diluted polyurea solution that limits complete infiltration.[95] Furthermore, the inclusion of small quantities of silicon carbide as a secondary phase within STF has been found to boost stab resistance in aramid fabrics treated with the fluid.[34]

To summarize, composite and hybrid material systems have played a central role in the evolution of ballistic protection technologies, providing unequaled versatility for tailoring mechanical and structural performance. By manipulating fiber types, matrix compositions, and stacking sequences,

scientists and engineers can design armor systems that remain lightweight and resist impact to a high degree. The synergistic combination of different reinforcement materials in hybrid laminates provides the opportunity to balance often conflicting properties – the rigidity versus ductility versus energy absorption – needed for protective solutions tailored to the specific threat. Moreover, the application of nanomaterials and interfacial engineering techniques has markedly improved the interfacial load transfer efficacy and failure resistance of such systems. Looking ahead, developments in smart matrices that can themselves heal, sense damage, or adapt to external stimuli with sustainability and recyclability will drive ballistic composites into the next generation. These advancements not only present the promise of better protection, but also foreshadow the development of "green" ballistic composites.

Role of epoxy matrix in ballistic composites

Epoxy resin is one of the most widely used thermosetting matrix materials for fiber-reinforced ballistic composites, which is applied to bind the reinforcing fibers together and to impart structural integrity and stress transfer between the fibers during ballistic loading. The typical values of tensile strength of the epoxy resins range between 40 and 90 MPa, and the values of tensile modulus between 2.5 and 4.5 GPa. Moreover, the epoxy resins have polar functional groups that enable them to form good interfaces with synthetic fibers such as glass, carbon, and aramid fibers, and natural fibers such as kenaf, flax, sisal, and jute fibers. They also have low shrinkage while curing, good chemical resistance, and have dimensional stability, making them appropriate for structural and semi-structural armor panels.[96]

In a composite armor system, the matrix is not necessarily the primary energy absorber (this role is played by the fibers), but rather it plays a major role in energy transfer to and dispersion through the fibers, and it also contributes to secondary energy dissipation mechanisms, such as matrix cracking, fiber-matrix debonding, and delamination.[97] An epoxy matrix that is well bonded to the fibers will help distribute stress more evenly among the fibers and prevent localized fiber failure, thus increasing the energy absorption capabilities of the composite.[98] The positive attributes and inherent limitations of epoxy as a matrix material, in comparison with alternative matrix systems, are summarized in Table 6.

Table 6
Advantages and disadvantages of epoxy as a matrix material for ballistic composites

Aspect	Advantages	Disadvantages
Fiber adhesion	Excellent bonding to both synthetic (glass, carbon, aramid) and natural (kenaf, flax, sisal, jute) fibers due to polar functional groups	Interfacial bonds can degrade under moisture ingress, particularly with hydrophilic natural fibers
Mechanical performance	High strength and stiffness relative to other thermosets (*e.g.*, polyester, vinyl ester)	Inherently brittle; limited plastic deformation capacity under high strain-rate impact
Impact/multi-hit behavior	Good stress transfer delays localized fiber failure	Prone to catastrophic matrix cracking; poor multi-hit performance compared to thermoplastic matrices
Environmental resistance	Good chemical, moisture, and dimensional stability	—
Processing shrinkage	Low cure shrinkage, reducing residual stress and microcracking	Longer curing times; some formulations require elevated-temperature post-curing
Manufacturing flexibility	Compatible with hand lay-up, VARTM, compression molding	More energy- and time-intensive processing compared to thermoplastic matrices
Cost	Lower cost than specialty thermoplastic resins	Higher cost than polyester or vinyl ester resins
Toughness	Can be enhanced via tougheners (rubber particles, thermoplastic modifiers, nanoclay, CNTs)	Requires additional formulation/modification to achieve adequate toughness, increasing complexity and cost

ENERGY ABSORPTION MECHANISMS

A deep understanding of how fiber-reinforced composites manage and dissipate impact energy is essential for developing efficient ballistic protection systems. The performance of body armor is influenced not only by the tensile strength of the reinforcing fibers, but also by the complex energy dissipation mechanisms that occur during impact. These include processes such as yarn straightening, fiber elongation, yarn slippage, cracking within the matrix, separation at the fiber-matrix interface, and eventual fiber breakage. Each of these mechanisms contributes to the overall energy absorption capacity of the composite system under ballistic loading.[99] In woven fabric composites, yarn de-crimping serves as an initial mechanism for absorbing impact energy. Upon projectile contact, the wavy or crimped yarns begin to straighten, allowing for early-stage energy dissipation prior to fiber elongation. This action helps to delay the peak stress response and facilitates a wider distribution of impact forces. However, in unidirectional (UD) or low-crimp fabric configurations, this effect is significantly reduced, and alternative mechanisms, such as fiber stretching, matrix cracking, or interfacial debonding, play a more prominent role in energy absorption.[100]

The resistance of ballistic materials heavily relies on fiber stretching and tensile deformation. Advanced fibers like aramids and ultra-high molecular weight polyethylene (UHMWPE) can endure considerable elongation prior to failure, allowing them to dissipate impact energy effectively due to their high tensile strength. When struck, stress waves travel both along and across the yarns, triggering a rapid response in nearby fibers and promoting a more efficient spread of the absorbed energy throughout the fabric.[101] Another important mechanism contributing to ballistic protection is yarn pull-out, especially evident in fabrics with loose weaves or stitched layers. Upon impact, individual yarns slide through the textile structure, and the resulting friction resists this movement, transforming part of the projectile's kinetic energy into thermal energy. Research indicates that modifying yarn surfaces through coatings can raise inter-yarn friction levels, thereby increasing the force required for yarn extraction and enhancing the fabric's capacity to absorb impact energy.[102,103]

On the microscale, energy dissipation in composite armor systems is largely influenced by matrix cracking and failures at the fiber–matrix interface. The development of microcracks aids in dispersing impact energy across a broader region, while debonding between fibers and the surrounding matrix helps to alleviate localized stress peaks, reducing the likelihood of early fiber rupture. Enhancing the bond strength at this interface can delay structural collapse, enabling greater fiber participation in load bearing and improving the overall impact resistance of the composite.[104] Fiber breakage takes place once the tensile strength of the material is surpassed. Although it marks the terminal phase of the energy absorption process, the rupture itself can absorb a significant amount of energy, particularly in high-tenacity fibers. The overall ballistic performance, reflected in parameters such as back face deformation and trauma depth, is governed by the interplay and progression of all these energy-dissipating mechanisms.[105] Advancements in computational modeling, particularly through finite element analysis (FEA) and multiscale simulation techniques, have provided valuable insights into the dynamic behavior of ballistic materials. Modern FEA frameworks incorporate parameters such as fiber kinematics, interface mechanics, and projectile characteristics to accurately replicate fabric responses during impact events. These simulation tools have greatly enhanced the speed and precision of developing and validating advanced armor systems.[106]

In essence, the process of energy dissipation in ballistic armor involves a complex, multiscale interplay of physical mechanisms, from large-scale fabric stretching and yarn pull-out to microscopic phenomena, such as matrix cracking and interfacial debonding. Each of these contributes to the gradual absorption of kinetic energy, effectively delaying structural failure during high-velocity impacts. The overall performance of an armor system depends not only on how it absorbs energy, but also on how well its materials work together in the overall design. With ongoing research, armor is expected to move from purely passive protection to adaptive systems that react to different threats. This could involve smart materials, layered designs, and real-time response features to improve protection while keeping weight low and mobility high.

Models of energy absorption

Besides experimental characterization, theoretical modelling of the dissipation of kinetic energy of the projectile in the fiber/composite system is necessary to understand the ballistic performance. There

are several models that describe this process, ranging from single-fiber wave propagation theory to composite-level energy-balance approaches.

Wave propagation (transverse deflection) model

This basic model was developed for a single fiber under transverse impact. A transverse wave radiates outwards from the point of impact at a speed that depends on the strain of the fibers, whilst a longitudinal strain wave moves ahead of it at the sound velocity in fibers. The material in the transverse wave is pulled toward the point of impact, and energy is absorbed in the stretching of the fibers in the wave from the front of the wave to the point of impact. This model has set the groundwork for subsequent composite-level treatments and underscores the importance of the sonic velocity of fibers, which is equivalent to the modulus-to-density ratio; the higher the velocity, the more energy that can be dissipated over a larger area and in a shorter time.

Cunniff model (non-dimensional velocity model)

Cunniff proposed a non-dimensional parameter ("Cunniff velocity", Uc). One figure of merit that includes fiber tensile strength, failure strain, modulus, and density is used to predict the ballistic limit velocity.

$$Uc = (\sigma \cdot \varepsilon / 2\rho)^{1/2} \times (E/\rho)^{1/2} \quad (4)$$

where σ is the tensile strength, ε is the strain to failure, E is the modulus, and ρ is the density. This is a model often used to compare and rank fibre systems on a common basis, as it considers both the speed of the wave and the energy stored per unit mass.

Energy balance model

The total energy (E_{total}) dissipated in ballistic impact is usually divided into several dissipative processes:

$$E_{total} = E_{fiber\ breakage} + E_{delamination} + E_{matrix\ cracking} + E_{friction} + E_{deformation} + E_{kinetic} \quad (5)$$

This phenomenological framework has been widely adopted in composite ballistic studies and allows the quantification of the contribution of each failure mode to the total energy absorbed and is often evaluated by post-impact damage analysis.

Phenomenological/empirical models

Models like the modified Lambert–Jonas equation show that some relation exists between residual projectile velocity (V_r) and impact velocity (V_i), which are the two most commonly used parameters:

$$V_r = a(V_i^p - V_{50}^p)^{1/p} \quad (6)$$

where a and p are empirical fitting constants to be determined by experiments for a specific fiber/composite system. The energy absorption efficiency of various armor panels under various impact velocities is characterized and compared widely by using this model.

These models, when combined, contribute to understanding the reasons behind synthetic fibers being generally superior to natural fibers in terms of dynamic energy absorption and to design hybrid composite architectures that aim to reconcile mechanical properties with sustainability.

ADVANCED TRENDS IN BALLISTIC MATERIALS

New developments in textiles and materials are making it possible to create body armor that offers both high protection and wearer comfort. Beyond resisting ballistic threats, current designs target better movement, cooling, temperature management, and electronics integration. Advances like shear-thickening suspensions, nanoscale reinforcements, complex 3D weaves, and adaptive smart fabrics are at the forefront of this progress.[107]

STFs have emerged as a transformative innovation in the field of soft body armor. These non-Newtonian fluids maintain fluid-like, low-viscosity behavior under normal motion, but rapidly transition to a rigid state when subjected to sudden stress or impact. This unique property enables them to dissipate kinetic energy effectively during ballistic or stab events. When applied to high-performance textiles, such as aramid or UHMWPE fabrics, STFs can substantially enhance protective performance, while maintaining the material's inherent flexibility. For instance, experimental findings reported in 2022 demonstrated that Kevlar fabrics treated with STF formulations exhibited approximately 35% greater energy absorption compared to their untreated counterparts.[108]

Nanotechnology is playing a pivotal role in the evolution of advanced armor materials, offering enhancements across multiple functional domains. The integration of nanostructures, such as carbon nanotubes (CNTs), graphene oxide (GO), and boron nitride nanosheets, into polymer matrices and fiber reinforcements has led to marked improvements in mechanical strength, thermal stability, and electrical conductivity. For example, Aramid composites modified with CNTs demonstrate superior tensile performance and enhanced interfacial adhesion, while graphene-based surface treatments contribute to increased hardness and resistance to wear. Furthermore, the incorporation of nanoparticles into shear-thickening fluids has been shown to amplify their rheological behavior, enabling greater energy dissipation and improved load distribution under high-strain-rate impacts.[109]

Three-dimensional (3D) woven and knitted textiles represent a significant advancement in the design of high-performance protective materials. Unlike conventional two-dimensional fabrics, 3D textile architectures incorporate through-thickness reinforcement, resulting in improved resistance to delamination and superior energy distribution across multiple axes. Innovations such as 3D angle interlock weaves and auxetic structures, which exhibit lateral expansion when stretched longitudinally, offer enhanced protection against ballistic threats while preserving flexibility and mobility. These engineered textiles have demonstrated potential in minimizing deformation and increasing the structural robustness of soft armor systems.[110]

The emergence of smart textiles is transforming the functional scope of ballistic protection systems. By embedding sensors, conductive fibers, and energy-harvesting components into protective garments, researchers have developed armor capable of real-time monitoring and adaptive behavior. Such technologies can track vital signs, detect impacts, or modify their behavior when triggered. Ballistic panels fitted with piezoelectric sensors capture impact information and relay it to remote monitors. Likewise, shape-memory polymers and electroactive textiles can change firmness or form, helping armor adapt to new conditions or dangers.[111,112]

Along with new technologies, sustainability is becoming important in armor design. Researchers are testing bio-based and recyclable materials instead of traditional synthetic composites. Natural fibers like flax and hemp combined with bio-resins or nanocellulose are being developed to provide good strength for low-impact uses. These green composites could be ideal for civilian protection and light military gear, offering an eco-friendly option without losing performance.[113]

Modern armor design is increasingly driven by the need for multiple functions. New protective gear must block ballistic threats while also providing chemical resistance, flame protection, UV shielding, and antimicrobial effects. Balancing these features with low weight and flexibility is a major research challenge. Advances in hybrid coatings, fiber spinning, and nanoscale surface treatments are helping to combine these functions into lightweight armor systems.[114]

Material innovation goes hand in hand with digital technology like AI, modeling, and 3D printing in creating next-generation armor. They help simulate impacts, predict failures early, and speed up the creation of complex protective designs. Combining digital methods with new materials is changing how personal and vehicle armor is developed, making the process faster and smarter.[115]

In summary, ballistic materials are evolving quickly thanks to advances in smart technologies, new materials, and sustainable design. Innovations now include nanotech composites, shear-thickening fluids, 3D textiles, and sensor-enabled fabrics. The focus is shifting toward multifunctional armor that balances protection with features like thermal control and chemical resistance. Meanwhile, digital tools like AI modeling and 3D printing speed up design and production. Future armor is set to be lighter, smarter, and greener to meet changing threats and societal needs.

CONCLUSION

This review provides a comprehensive and forward-thinking overview of materials used in ballistic protection, bridging traditional methods with innovations. Unlike earlier works that focused mainly on common synthetic fibers and their properties, it offers a wider perspective by comparing natural and synthetic fibers, advanced hybrids, and innovative surface treatments, emphasizing performance, sustainability, and adaptability. The paper explores less-studied topics like bio-based composites, eco-friendly fiber modifications, and nanotech-enhanced matrices, highlighting their role in civilian and low-threat applications. It also draws attention to promising approaches, such as controlling inter-yarn friction, 3D reinforcement designs, and smart materials that enhance energy absorption without sacrificing comfort or flexibility.

The use of digital tools like finite element modeling, AI, and real-time sensors is driving a shift toward smarter, more adaptive armor systems. This blend of technologies encourages collaboration across textile engineering, materials science, and computational simulation, paving the way for next-generation protective materials that are lightweight, high-performing, and eco-friendly. This review offers a forward-looking framework for designing armor that meets today's complex security demands. Future research should focus on scalable production, balancing cost and performance, and integrating multiple functions to move ballistic protection beyond passive gear into a new age of intelligent, resilient defense.

REFERENCES

[1] G. Asgedom, K. Yeneneh, G. Tilahun and B. Negash, *Heliyon*, **11**, e41286 (2025), https://doi.org/10.1016/j.heliyon.2024.e41286

[2] D. B. Sitotaw, D. Ahrendt, Y. Kyosev and A. K. Kabish, *Autex Res. J.*, **22**, 96 (2022), https://doi.org/10.2478/aut-2021-0013

[3] K. Bilisik and M. Syduzzaman, in "Protective Textiles from Natural Resources", edited by Md. I. H. Mondal, Woodhead Publishing, 2022, pp. 689-749, https://doi.org/10.1016/B978-0-323-90477-3.00027-4

[4] National Research Council, Division on Engineering and Physical Sciences, National Materials Advisory Board, "Materials Research to Meet 21st-Century Defense Needs", The National Academies Press, 2003

[5] A. Pai and C. R. Kini, *Thin-Walled Struct.*, **179**, 109664 (2022), https://doi.org/10.1016/j.tws.2022.109664

[6] M. I. Tamjid, M. A. Abtew and C. Kopot, *J. Compos. Sci.*, **9**, 337 (2025), https://doi.org/10.3390/jcs9070337

[7] U. Mawkhlieng, A. Majumdar and A. Laha, *RSC Adv.*, **10**, 1066 (2020), https://doi.org/10.1039/c9ra06447h

[8] C. Ralph, L. Baker, E. Archer and A. McIlhagger, *Text. Res. J.*, **93**, 5168 (2023), https://doi.org/10.1177/0040517523119436

[9] S. Nagaraja, P. B. Anand, K. Mohan Kumar and M. I. Ammarullah, *RSC Adv.*, **14**, 17594 (2024), https://doi.org/10.1039/d4ra00149d

[10] A. T. Patil, B. Vidhale and A. Titarmare, in Procs. *2024 International Conference on Intelligent Systems for Cybersecurity* (ISCS), 2024, https://doi.org/10.1109/ISCS61804.2024.10581013

[11] M. El Messiry, "Protective Armor Engineering Design", CRC Press, 2019, https://doi.org/10.1201/9780429057236

[12] S. Ul-Islam and B. S. Butola, "Advanced Textile Engineering Materials", Wiley Scrivener, 2018, https://doi.org/10.1002/9781119488101

[13] K. Bilisik, M. Syduzzaman, G. Erdogan and M. Korkmaz, in "Functional and Technical Textiles", edited by S. Maity, K. Singha and P. Pandit, Woodhead Publishing, 2023, pp. 71-139, https://doi.org/10.1016/B978-0-323-91593-9.00023-7

[14] P. Singh Deora, M. Khurana, Priya, R. Avtar Muhal, D. Upadhyay, C. Goswami *et al.*, *Mater. Today Proc.*, **60**, 2230 (2022), https://doi.org/10.1016/j.matpr.2022.03.209

[15] A. Nawaz Khan, M. Gupta, P. Mahajan, A. Das, R. Alagirusamy *et al.*, *Text. Prog.*, **53**, 183 (2022), https://doi.org/10.1080/00405167.2022.2087400

[16] U. Mawkhlieng and A. Majumdar, *Text. Prog.*, **51**, 139 (2019), https://doi.org/10.1080/00405167.2019.1692583

[17] J. Hu, "3-D Fibrous Assemblies: Properties, Applications and Modeling of Three-Dimensional Textile Structures", Woodhead Publishing, 2008

[18] R. Chamola, S. Das, D. S. Ahlawat, Y. K. Mishra, M. S. Goyat *et al.*, *J. Mater. Sci.*, **59**, 747 (2023), https://doi.org/10.1007/S10853-023-09201-Z

[19] A. Przybek, *Materials*, **18**, 3803 (2025), https://doi.org/10.3390/MA18163803

[20] M. Y. Khalid, A. Al Rashid, Z. U. Arif, W. Ahmed, H. Arshad *et al.*, *Results Eng.*, **11**, 100263 (2021), https://doi.org/10.1016/J.RINENG.2021.100263

[21] A. Ari, M. Karahan, H. A. M. Ahmed, O. Babiker, R. M. A. Dehşet *et al.*, *AATCC J. Res.*, **10**, 163 (2023), https://doi.org/10.1177/24723444221147365

[22] S. M. Surid, K. M. Maraz, S. Shahida, A. Ahmed, R. A. Khan *et al.*, *Mod. Concepts Mater. Sci.*, **4** (2021), https://doi.org/10.33552/MCMS.2021.04.000592

[23] P. Pradhan, A. Purohit, I. Mohanty, H. Jena, B. B. Sahoo *et al.*, *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.*, **237**, 5653 (2023), https://doi.org/10.1177/09544062231167674

[24] P. Pradhan, A. Purohit, J. Singh, C. Subudhi, S. Sangita *et al.*, *J. Inst. Eng. India Ser. E*, **103**, 339 (2022), https://doi.org/10.1007/S40034-022-00243-7

[25] S. H. Kamarudin, M. S. Mohd Basri, M. Rayung, F. Abu, S. Ahmad *et al.*, *Polymers*, **14**, 3698 (2022), https://doi.org/10.3390/POLYM14173698

[26] C. Belbéoch, J. Lejeune, P. Vroman and F. Salaün, *Environ. Chem. Lett.*, **19**, 1737 (2021), https://doi.org/10.1007/S10311-020-01147-X

[27] Ş. Yıldızhan, A. Çalık, M. Özcanlı and H. Serin, *Eur. Mech. Sci.*, **2**, 83 (2018), https://doi.org/10.26701/EMS.369005
[28] N. M. Nurazzi, M. M. Harussani, H. A. Aisyah, R. A. Ilyas, M. N. Norrrahim *et al.*, *Funct. Compos. Struct.*, **3**, 024002 (2021), https://doi.org/10.1088/2631-6331/ABFF36
[29] L. Mohammed, M. N. M. Ansari, G. Pua, M. Jawaid, M. S. Islam *et al.*, *Int. J. Polym. Sci.*, **2015**, 243947 (2015), https://doi.org/10.1155/2015/243947
[30] H. Yan Cheung, M. P. Ho, K. T. Lau, F. Cardona, D. Hui *et al.*, *Compos. B Eng.*, **40**, 655 (2009), https://doi.org/10.1016/J.COMPOSITESB.2009.04.014
[31] K. D. S. Do Prado and M. A. D. S. Spinacé, *Mater. Res.*, **18**, 530 (2015), https://doi.org/10.1590/1516-1439.311514
[32] M. Saxena, A. Pappu, R. Haque and A. Sharma, in "Cellulose Fibers: Bio- and Nano-Polymer Composites", edited by S. Kalia, B. S. Kaith, and I. Kaur, Springer, 2011, pp. 589-659, https://doi.org/10.1007/978-3-642-17370-7_22
[33] S. Radoor, A. Jayakumar, S. Siengchin, J. Karayil, J. M. Shivanna *et al.*, in "Plant Fibers, their Composites, and Applications", edited by S. M. Rangappa, S. Siengchin, and J. Parameswaranpillai, Elsevier, 2022, pp. 379-390, https://doi.org/10.1016/B978-0-12-824528-6.00003-5
[34] M. Karhankova, M. Adamek, L. Krstulović-Opara, V. Mach, P. Bagavac *et al.*, *J. Compos. Sci.*, **8**, 415 (2024), https://doi.org/10.3390/JCS8100415
[35] M. Puttegowda, *Discover Appl. Sci.*, **7**, 1 (2025), https://doi.org/10.1007/S42452-025-06981-8
[36] M. M. Kabir, H. Wang, K. T. Lau and F. Cardona, *Compos. B Eng.*, **43**, 2883 (2012), https://doi.org/10.1016/J.COMPOSITESB.2012.04.053
[37] D. P. Ferreira, J. Cruz and R. Fangueiro, in "Green Composites for Automotive Applications", edited by C. J. R. Verbeek and S. G. Kazarian, Woodhead Publishing, 2018, pp. 3-41, https://doi.org/10.1016/B978-0-08-102177-4.00001-X
[38] N. S. A. Yaro, M. H. Sutanto, N. Z. Habib, M. Napiah, A. Usman *et al.*, *Constr. Build. Mater.*, **324**, 126618 (2022), https://doi.org/10.1016/J.CONBUILDMAT.2022.126618
[39] Y. Chen, J. Wan, X. Zhang, Y. Ma, Y. Wang *et al.*, *Carbohyd. Polym.*, **87**, 730 (2012), https://doi.org/10.1016/J.CARBPOL.2011.08.051
[40] A. Langhorst, M. Ravandi, D. Mielewski and M. Banu, *Ind. Crop. Prod.*, **171**, 113832 (2021), https://doi.org/10.1016/J.INDCROP.2021.113832
[41] M. Zuber, K. M. Zia, I. A. Bhatti, Z. Ali, M. U. Arshad *et al.*, *Int. J. Biol. Macromol.*, **51**, 743 (2012), https://doi.org/10.1016/J.IJBIOMAC.2012.07.001
[42] K. Kolářová, V. Vosmanská, S. Rimpelová and V. Švorčík, *Cellulose*, **20**, 953 (2013), https://doi.org/10.1007/S10570-013-9863-0
[43] R. A. Lima, D. K. Cavalcanti, J. S. S. Neto, H. M. Costa, M. D. Banea *et al.*, *Polym. Compos.*, **41**, 314 (2020), https://doi.org/10.1002/PC.25371
[44] A. Verma, A. Parashar, N. Jain, V. K. Singh, S. M. Rangappa *et al.*, in "Biofibers and Biopolymers for Biocomposites: Synthesis, Characterization and Properties", edited by S. M. Rangappa, S. Siengchin, and J. Parameswaranpillai, Springer, 2020, pp. 1-34, https://doi.org/10.1007/978-3-030-40301-0_1
[45] S. Islam, M. B. Hasan, M. Kodrić, K. Z. M. A. Motaleb, F. E. Karim*et al.*, *SPE Polymers*, **6**, e10173 (2025), https://doi.org/10.1002/PLS2.10173
[46] I. Elfaleh, F. Ababassi, M. Habibi, F. Ahmed and M. Guedri, *Results Eng.*, **19**, 101271 (2023), https://doi.org/10.1016/J.RINENG.2023.101271
[47] N. M. Nurazzi, M. R. Asyraf, A. Khalina, N. Abdullah, H. A. Aisyah *et al.*, *Polymers*, **13**, 646 (2021), https://doi.org/10.3390/POLYM13040646
[48] I. O. Eze, I. O. Igwe, O. Ogbobe, H. C. Obasi and U. L. Ezeamaku, *Eur. J. Adv. Eng. Tech.*, **4**, 617 (2017), www.ejaet.com
[49] A. Arbelaiz, T. Yurramendi, A. Larruscain, A. Arrizabalaga, A. Eceiza *et al.*, *Materials*, **17**, 4912 (2024), https://doi.org/10.3390/MA17194912/S1
[50] Y. Liu, L. V. Xueman, J. Bao, J. Xie, X. Tang *et al.*, *Carbohyd. Polym.*, **218**, 179 (2019), https://doi.org/10.1016/J.CARBPOL.2019.04.088
[51] L. Y. Mwaikambo and M. P. Ansell, *J. Appl. Polym. Sci.*, **84**, 2222 (2002), https://doi.org/10.1002/app.10460
[52] J. Naveen, M. Jawaid, P. Amuthakkannan and M. Chandrasekar, in "Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites", edited by M. Jawaid, M. Thariq, and N. Saba, Woodhead Publishing, 2019, pp. 427-440, https://doi.org/10.1016/B978-0-08-102292-4.00021-7
[53] V. K. Balla, K. H. Kate, J. Satyavolu, P. Singh, J. G. D. Tadimeti *et al.*, *Compos. B Eng.*, **174**, 106956 (2019), https://doi.org/10.1016/J.COMPOSITESB.2019.106956
[54] A. Lakshmanan, R. K. Ghosh, S. Dasgupta, S. Chakraborty, P. K. Ganguly *et al.*, *J. Ind. Text.*, **47**, 640 (2018), https://doi.org/10.1177/1528083716667259.

[55] R. Agrawal, N. S. Saxena, K. B. Sharma, S. Thomas, M. S. Sreekala *et al*., *Mater. Sci. Eng. A*, **277**, 77 (2000), https://doi.org/10.1016/S0921-5093(99)00556-0
[56] M. Asim, M. Jawaid, K. Abdan and M. R. Ishak, *J. Bionic Eng*., **13**, 426 (2016), https://doi.org/10.1016/S1672-6529(16)60315-3
[57] S. Mishra, S. Mishra, A. K. Mohanty, L. T. Drzal, S. Parija *et al*., *Compos. Sci. Technol*., **63**, 1377 (2003), https://doi.org/10.1016/S0266-3538(03)00084-8
[58] G. T. Mahesha, S. B. Shenoy, V. M. Kini and N. H. Padmaraja, *Mater. Today Proc*., **5**, 138 (2018), https://doi.org/10.1016/J.MATPR.2017.11.064
[59] I. Elfaleh, *Results Eng*., **19**, 101271 (2023), https://doi.org/10.1016/J.RINENG.2023.101271
[60] O. Olanrewaju, I. O. Oladele and S. O. Adelani, *Hybrid Adv*., **8**, 100378 (2025), https://doi.org/10.1016/j.hybadv.2025.100378
[61] M. Syduzzaman, S. E. Chowdhury, N. M. Pritha, A. Hassan, S. Hossain *et al*., *Results Mater*., **24**, 100639 (2024), https://doi.org/10.1016/j.rinma.2024.100639
[62] D. K. Rajak, P. H. Wagh and E. Linul, *Materials*, **15**, 4790 (2022), https://doi.org/10.3390/MA15144790
[63] S. Palola, J. Vuorinen, J. W. M. Noordermeer and E. Sarlin, *Coatings*, **10**, 556 (2020), https://doi.org/10.3390/coatings10060556
[64] M. I. Haque Protyai, F. M. Adib, T. I. Taher, M. R. Karim, A. Bin Rashid *et al*., *Hybrid Adv*., **6**, 100245 (2024), https://doi.org/10.1016/j.hybadv.2024.100245
[65] S. Gürgen and M. C. Kuşhan, *Compos. Part A Appl. Sci. Manuf*., **94**, 50 (2017), https://doi.org/10.1016/j.compositesa.2016.12.019
[66] B. Yuan, B. Yang, P. Xu and M. Zhang, *ACS Nano*, **19**, 1981 (2025), https://doi.org/10.1021/acsnano.4c14912
[67] L. Tang, M. Jia, M. He, Q. Liu, Y. Lin *et al*., *SusMat*, **4**, e245 (2024), https://doi.org/10.1002/SUS2.245
[68] X. Peng, H. He, Y. Liu, M. Ma, Y. Shi *et al*., *Polym. Compos*., **46**, 9540 (2025), https://doi.org/10.1002/PC.29577
[69] B. Zhang, L. Jia, M. Tian, N. Ning, L. Zhang *et al*., *Eur. Polym. J*., **147**, 110352 (2021), https://doi.org/10.1016/J.EURPOLYMJ.2021.110352
[70] D. K. Rajak, P. H. Wagh and E. Linul, *Materials*, **15**, 4790 (2022), https://doi.org/10.3390/MA15144790
[71] C. Li, J. Song, W. Xing, L. Wang, Y. Cui *et al*., *Polym. Adv. Technol*., **34**, 205 (2023), https://doi.org/10.1002/PAT.5878
[72] Z. Latif, M. Ali, E. J. Lee, Z. Zubair and K. H. Lee, *J. Compos. Sci*., **7**, 441 (2023), https://doi.org/10.3390/JCS7100441
[73] Z. Benzait and L. Trabzon, *J. Compos. Mater*., **52**, 3241 (2018), https://doi.org/10.1177/0021998318764002
[74] K. Bilisik, *Text. Res. J*., **87**, 2275 (2017), https://doi.org/10.1177/0040517516669075
[75] S. Wu, P. Sikdar and G. S. Bhat, *Def. Technol*., **21**, 33 (2023), https://doi.org/10.1016/J.DT.2022.06.007
[76] J. Luo, *Matter*, **9**, 102496 (2026), https://doi.org/10.1016/J.MATT.2025.102496
[77] M. Syduzzaman, S. E. Chowdhury, N. M. Pritha, A. Hassan, S. Hossain *et al*., *Results Mater*., **24**, 100639 (2024), https://doi.org/10.1016/J.RINMA.2024.100639
[78] V. Mahesh, S. Joladarashi and S. M. Kulkarni, *Def. Technol*., **17**, 257 (2021), https://doi.org/10.1016/J.DT.2020.04.002
[79] D. H. Elgohary, *J. Text. Inst*., **116**, 535 (2025), https://doi.org/10.1080/00405000.2024.2343162
[80] A. Patti and D. Acierno, *Macromolecules*, **3**, 665 (2023), https://doi.org/10.3390/MACROMOL3030037
[81] X. Wang, *Compos. Sci. Technol*., **68**, 444 (2008), https://doi.org/10.1016/J.COMPSCITECH.2007.06.016
[82] A. Joshi, A. Mishra and V. K. Saxena, *Compos. Part A Appl. Sci. Manuf*., **185**, 108314 (2024), https://doi.org/10.1016/J.COMPOSITESA.2024.108314
[83] Y. Chu, M. R. Rahman, S. Min and X. Chen, *Mech. Mater*., **148**, 103421 (2020), https://doi.org/10.1016/J.MECHMAT.2020.103421
[84] G. F. Serra, L. Oliveira, S. Gürgen, R. J. A. de Sousa, F. A. O. Fernandes *et al*., *Adv. Colloid Interface Sci*., **327**, 103157 (2024), https://doi.org/10.1016/J.CIS.2024.103157
[85] M. K. R. Hashim, M. S. Abdul Majid, M. R. Mohd Jamir, F. H. Kasim, H. A. Alshahrani *et al*., *Materials*, **15**, 6121 (2022), https://doi.org/10.3390/MA15176121
[86] T. Luo, Z. Chao, L. Jiang, S. Chen, S. Li *et al*., *J. Sci.: Adv. Mater. Devices*, **10**, 100941 (2025), https://doi.org/10.1016/J.JSAMD.2025.100941
[87] S. Doddamani, S. M. Kulkarni, S. Joladarashi and M. K. A. K. Gurjar, *Int. J. Lightweight Mater. Manuf*., **6**, 450 (2023), https://doi.org/10.1016/J.IJLMM.2023.01.003
[88] M. M. Alzahrani, K. A. Alamry and M. A. Hussein, *Results Chem*., **15**, 102199 (2025), https://doi.org/10.1016/J.RECHEM.2025.102199
[89] R. R. Dias, N. M. Meliande, H. G. Kotik, C. G. Camerini, I. M. Pereira *et al*., *J. Compos. Sci*., **8**, 385 (2024), https://doi.org/10.3390/JCS8100385
[90] M. S. Nitin and S. Suresh Kumar, *Polym. Compos*., **43**, 782 (2022), https://doi.org/10.1002/PC.26409

[91] I. Goda, E. Padayodi and R. N. Raoelison, *J. Compos. Mater.*, **58**, 3077 (2024), https://doi.org/10.1177/00219983241283958
[92] O. Ojo, M. O. Olaleke, K. K. Alaneme and A. O. Dahunsi, *Next Mater.*, **8**, 100565 (2025), https://doi.org/10.1016/J.NXMATE.2025.100565
[93] Ș. Ursache, C. Cerbu and A. Hadăr, *Polymers*, **16**, 127 (2023), https://doi.org/10.3390/POLYM16010127
[94] U. K. Sanivada, G. Mármol, F. P. Brito and R. Fangueiro, *Polymers*, **12**, 2373 (2020), https://doi.org/10.3390/POLYM12102373
[95] C. H. Shih, J. L. You, Y. L. Lee, A. Y. Cheng, C. P. Cha *et al.*, *Polymers*, **14**, 5026 (2022), https://doi.org/10.3390/POLYM14225026
[96] J. Gu, Y. Bai, Z. Zhao and C. Zhang, *Polymer*, **295**, 126744 (2024), https://doi.org/10.1016/J.POLYMER.2024.126744
[97] K. Rana, Z. Sajid, A. H. Baluch and P. Špatenka, *Appl. Compos. Mater.*, **33**, 103 (2026), https://doi.org/10.1007/S10443-026-10485-Y
[98] B. S. Baskar, G. Subbiah, P. Priya, J. Guntaj, M. Kumar *et al.*, *Results Eng.*, **26**, 105587 (2025), https://doi.org/10.1016/J.RINENG.2025.105587
[99] O. O. Ojo, M. O. Olaleke, K. K. Alaneme and A. O. Dahunsi, *Next Mater.*, **8**, 100565 (2025), https://doi.org/10.1016/J.NXMATE.2025.100565
[100] Q. H. Pham, C. Ha-Minh, T. L. Chu, T. Kanit, A. Imad *et al.*, *Int. J. Solids Struct.*, **239-240**, 111436 (2022), https://doi.org/10.1016/J.IJSOLSTR.2022.111436
[101] N. S. Gaikwad, D. D. Deshmukh and S. P. Kakade, *Smart Mater. Manuf.*, **3**, 100084 (2025), https://doi.org/10.1016/J.SMMF.2025.100084
[102] Z. Yi, M. Ali, X. Gong, H. Dai, D. Zhongmin *et al.*, *Text. Res. J.*, **89**, 4717 (2019), https://doi.org/10.1177/0040517519832845
[103] B. K. Dejene and A. D. Gudayu, *J. Ind. Text.*, **54** (2024), https://doi.org/10.1177/15280837241253614
[104] D. S. Silva, R. F. Pereira Jr., B. S. Avila de Cêa, A. Ben-Hur da Silva Figueiredo, S. N. Monteiro *et al.*, *J. Mater. Res. Technol.*, **36**, 2700 (2025), https://doi.org/10.1016/J.JMRT.2025.04.001
[105] A. K. Hamzat, M. S. Murad, I. A. Adediran and E. Asmatulu, *Adv. Compos. Hybrid Mater.*, **8**, 1 (2025), https://doi.org/10.1007/S42114-024-01192-Y
[106] Z. Zhao, H. Dang, C. Zhang, G. J. Yun, Y. Li *et al.*, *Compos. Part A Appl. Sci. Manuf.*, **110**, 113 (2018), https://doi.org/10.1016/J.COMPOSITESA.2018.04.020
[107] M. I. Tamjid, M. A. Abtew and C. Kopot, *J. Compos. Sci.*, **9**, 337 (2025), https://doi.org/10.3390/JCS9070337
[108] T. M. Zelelew, A. N. Ali, G. Kidanemariam, G. A. Kebede, E. G. Koricho *et al.*, *Smart Mater. Struct.*, **34**, 033004 (2025), https://doi.org/10.1088/1361-665X/ADBDB2
[109] M. Syduzzaman, A. Hassan, H. R. Anik, M. Akter, M. R. Islam *et al.*, *ChemNanoMat*, **9**, e202300205 (2023), https://doi.org/10.1002/CNMA.202300205
[110] Y. Liu, C. Huang, H. Xia and Q. Q. Ni, *Mater. Des.*, **212**, 110267 (2021), https://doi.org/10.1016/J.MATDES.2021.110267
[111] R. Nayak, L. Wang and R. Padhye, in "Electronic Textiles: Smart Fabrics and Wearable Technology", edited by T. Dias, Woodhead Publishing, 2015, pp. 239-256, https://doi.org/10.1016/B978-0-08-100201-8.00012-6
[112] H. A. Colorado, C. A. Cardenas, E. I. Gutierrez-Velazquez, J. P. Escobedo, S. N. Monteiro *et al.*, *J. Mater. Res. Technol.*, **27**, 3900 (2023), https://doi.org/10.1016/J.JMRT.2023.11.030
[113] B. Maleki, P. G. Kargar, S. S. Ashrafi, B. Maleki, P. G. Kargar *et al.*, in "Cellulose - Biobased Solutions for Society", edited by A. Rodriguez, IntechOpen, 2025, https://doi.org/10.5772/INTECHOPEN.1009464
[114] S. Das, K. Prathasana, P. A. Nitin, K. R. L. J. Priya, V. Mathivanan *et al.*, *Zastita Materijala*, **66**, 5 (2025), https://doi.org/10.62638/ZASMAT1202
[115] L. Zhou, *Sensors*, **24**, 2668 (2024), https://doi.org/10.3390/S24092668