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A REVIEW ON THE POTENTIAL OF INDONESIAN NATURAL FIBERS AS BALLISTIC COMPOSITE MATERIALS

Fajar Paundra[1,2], Puji Basuki[1,3], Indah Puspitasari[1,4], Kuncoro Diharjo[1*]

[1]Doctor of Mechanical Engineering, Faculty of Engineering, Universitas Sebalas Maret
[2]Mechanical Engineering, Faculty of Industrial Technology, Institut Teknologi Sumatera
[3] Mechanical Engineering, Faculty of Engineering, Universitas Pandanaran
[4] Mechanical Engineering, Politeknik Negeri Madiun

Email: kuncorodiharjo@staff.uns.ac.id

Abstract

Ballistic composites are key materials in protective applications designed to absorb and dissipate the impact energy of projectiles. Currently, the reliance on synthetic materials such as aramid fibers (Kevlar) and ultra-high molecular weight polyethylene (UHMWPE) faces challenges including high production costs, environmental impact, and import dependency. Indonesia, with its abundant natural fiber resources such as ramie, abaca, bamboo, and sisal, has great potential to develop sustainable and self-reliant ballistic composite materials. This review aims to systematically examine the potential of Indonesian natural fibers as ballistic composite materials by analyzing their mechanical properties, comparing them with ballistic requirements, and identifying key challenges and development strategies. The study concludes that although natural fibers exhibit promising mechanical properties, they face major limitations such as hydrophilic nature and variability in characteristics. However, chemical treatments and surface engineering (such as reinforcement with SiO_2, CNT, or SiC) have been shown to improve fiber–matrix interfacial performance, thereby opening opportunities for the utilization of Indonesian natural fibers in effective and environmentally friendly ballistic composites.

Key words: Ballistic, natural fibre, SiO_2, CNT, SiC

INTRODUCTION

Ballistic composites are advanced materials widely used in protective applications. These materials function to absorb and dissipate the impact energy from projectiles (Silva et al., 2025). The global defense industry requires reliable and effective protection components, and the development of ballistic composite materials continues to be a major focus of research in many countries. Figure 1 illustrates various applications of ballistic composites.

Figure 1. Applications of composites in ballistic protection: (A) gloves, (B) bulletproof vest, (C) wheels, (D) helmet, (E) combat vehicle, (F) shield (Gaikwad et al., 2025).

However, conventional materials such as aramid fibers (Kevlar) and Ultra High Molecular Weight Polyethylene (UHMWPE) have several limitations. These materials require complex and costly production processes (Alzahrani et al., 2025; Joshi et al., 2024). In addition, synthetic materials often cause significant environmental impacts. Dependence on imported materials can also pose challenges to a nation's defense resilience.

Indonesia possesses abundant and diverse natural fiber resources. Several types of natural fibers—such as ramie, bamboo, coconut coir, pineapple leaf fiber, kenaf, and sisal—exhibit promising tensile strength and stiffness (Farhan Sidik et al., 2024). The mechanical properties of these natural fibers have the potential to be utilized as reinforcements in composite materials. The use of these local resources can serve as a sustainable alternative solution.

Nevertheless, the utilization of Indonesian natural fibers for ballistic applications still faces several challenges. The inherent hydrophilic nature of the fibers and the variability in their characteristics remain major obstacles. Previous studies have shown that chemical treatments and surface engineering can improve the interfacial bonding between fibers and the matrix (Vishwash et al., 2025). This review seeks to analyze various such methods to optimize composite performance.

Therefore, this review aims to systematically examine the potential of Indonesian natural fibers as ballistic composite materials. The study will analyze the mechanical properties of various local natural fibers and compare them with ballistic material requirements. The findings of this review are expected to provide guidance for further research to support Indonesia's defense industry self-reliance.

BALLISTIC MECHANISM

The bullet-resistant capability of materials is rigorously evaluated using internationally recognized standards such as the NIJ (National Institute of Justice) Standard 0101.06, which aims to protect against firearm threats for personal body armor under ballistic impact (NIJ Standard - 0101.06, 2008). This standard specifies the minimum performance requirements for ballistic testing configurations. The key parameters measured in these tests include ballistic limit velocity (V50), energy absorption, depth of penetration (DOP), and backface signature (BFS) (NIJ Standard - 0101.06, 2008; Suresh Kumar et al., 2022). The ballistic testing in this study focuses on Level IIIA protection using a 9 mm handgun. The distance between the specimen and the muzzle is 5 meters, while the chronograph (velocity measurement device) is positioned 2.5 meters away (NIJ Standard - 0101.06, 2008). An illustration of the testing setup is shown in Figure 2.

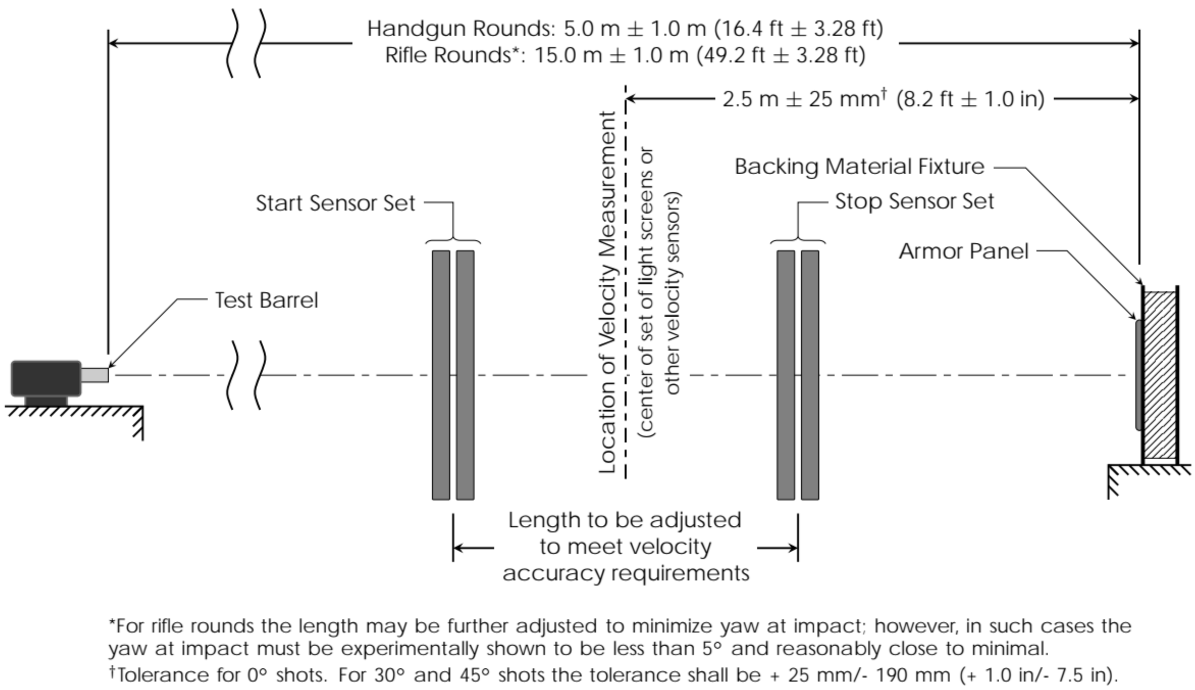

Figure 2. Ballistic testing standard based on NIJ (NIJ Standard - 0101.06, 2008)

After conducting ballistic testing in accordance with the NIJ standard, the following equation can be used to determine the ballistic parameters (Ismail et al., 2024):

$$\text{Impact Energy} = \frac{1}{2}(mv_i^2) \quad (1)$$

$$\text{Residual Energy} = \frac{1}{2}(mv_r^2) \quad (2)$$

$$E\ abs = \frac{(mv_i^2 - mv_r^2)}{2} \quad (3)$$

$$V50 = \sqrt{v_i^2 - v_r^2} \quad (4)$$

Where :

v_i = *impact velocity* (m/s)
v_r = *Residual impact* (m/s)
m = Mass bullet (kg)
E^{abs} = Absorb energy (joule)
v_{50} = Ballistic limit (m/s)

V50 is defined as the impact velocity of a projectile that has a 50% probability of penetrating the target. It is calculated as the average of the highest partial penetration velocities and the lowest complete penetration velocities of the projectile–target combination within a specific velocity range (Nilakantan & Nutt, 2014). The NIJ test determines the suitability of materials used in combat armor panels. To achieve a certain performance level, the material must withstand a specified bullet velocity; for example, some composites successfully resist bullet velocities of 482.5 m/s ± 5, meeting the NIJ Level II standard, while others only reach Level II (367 m/s) and fail to meet Level IIIA (436 m/s) (NIJ Standard – 0101.06, 2008).

Energy absorption is another key parameter used to evaluate the ballistic impact behavior of hybrid composites. This energy is calculated based on the reduction in the projectile's kinetic energy after impact, representing the energy absorbed by the target plate through deformation and damage (Gaikwad et al., 2025).

The depth of penetration (DOP) is measured using a caliper, while the backface signature (BFS) is an important indicator of trauma resistance. According to NIJ standards, the maximum DOP must not exceed 44 mm (1.73 in) to prevent significant bodily trauma caused by projectile penetration. Measured BFS values, for example, in the range of 13–13.5 mm or 17.5–19 mm, are considered within acceptable limits. During testing, Doppler radar and optical barriers are used to measure bullet velocity before and after impact. After testing, samples are examined to identify damage patterns—including delamination, matrix cracking, and fiber pull-out—to better understand the energy absorption mechanisms (Olaleye et al., 2024).

NATURAL FIBRE

Indonesia, as a country with abundant biodiversity, holds tremendous potential for the development of sustainable natural fibers. Various plants such as ramie, kenaf, bamboo, coconut coir, and pineapple leaf fibers have long been recognized and utilized, both in traditional practices and modern industrial applications. The advantages of these fibers lie not only in their strength, biodegradability, and environmental friendliness but also in their economic value, which can drive the growth of a green and sustainable industry. Exploring and optimizing the potential of each natural fiber is therefore a strategic step toward achieving raw material self-sufficiency and creating high value-added products that can compete in the global market(Braga et al., 2018).

Natural fibers are readily available across Indonesia and possess competitive mechanical properties, making them promising alternatives for environmentally friendly composite reinforcement materials. Several notable examples include ramie, which exhibits high tensile strength up to 938 MPa and an elastic modulus of 128 GPa; kenaf, widely cultivated in Sumatra and Kalimantan, with tensile strength around 930 MPa; and bamboo, abundant throughout the archipelago, offering low density and tensile strength up to 862 MPa. In addition, coconut coir—commonly found in coastal regions—and pineapple leaf fibers from areas such as Lampung and Central Java also show significant potential, despite variations in their mechanical characteristics. The diversity of these fibers provides Indonesia with a strategic advantage in developing natural fiber–based composite materials, particularly for engineering applications that demand an optimal balance between strength, lightness, and environmental sustainability(Ojo et al., 2025).

Indonesia's vast geographical landscape and tropical climate create ideal conditions for the cultivation of a wide range of natural fiber–producing plants(Farhan Sidik et al., 2024). Each region has its own distinctive fiber resources: ramie is primarily grown in West and Central Java; kenaf is cultivated in Sumatra and Kalimantan; bamboo thrives across nearly all islands, from Java to Sulawesi; while coconut coir is abundant in coastal areas such as Bali, Lampung, and North Sulawesi. Pineapple leaf fibers are also widely available in agricultural regions like Lampung and Central Java as by-products of the fruit industry. This broad distribution not only ensures a continuous and locally sourced raw material supply but also supports regional economic development through community-based fiber processing industries. With proper cultivation management, technological innovation, and industrial integration, Indonesia has the potential to become a leading producer of sustainable natural fibers in the Asia-Pacific region(Kannan et al., 2025).

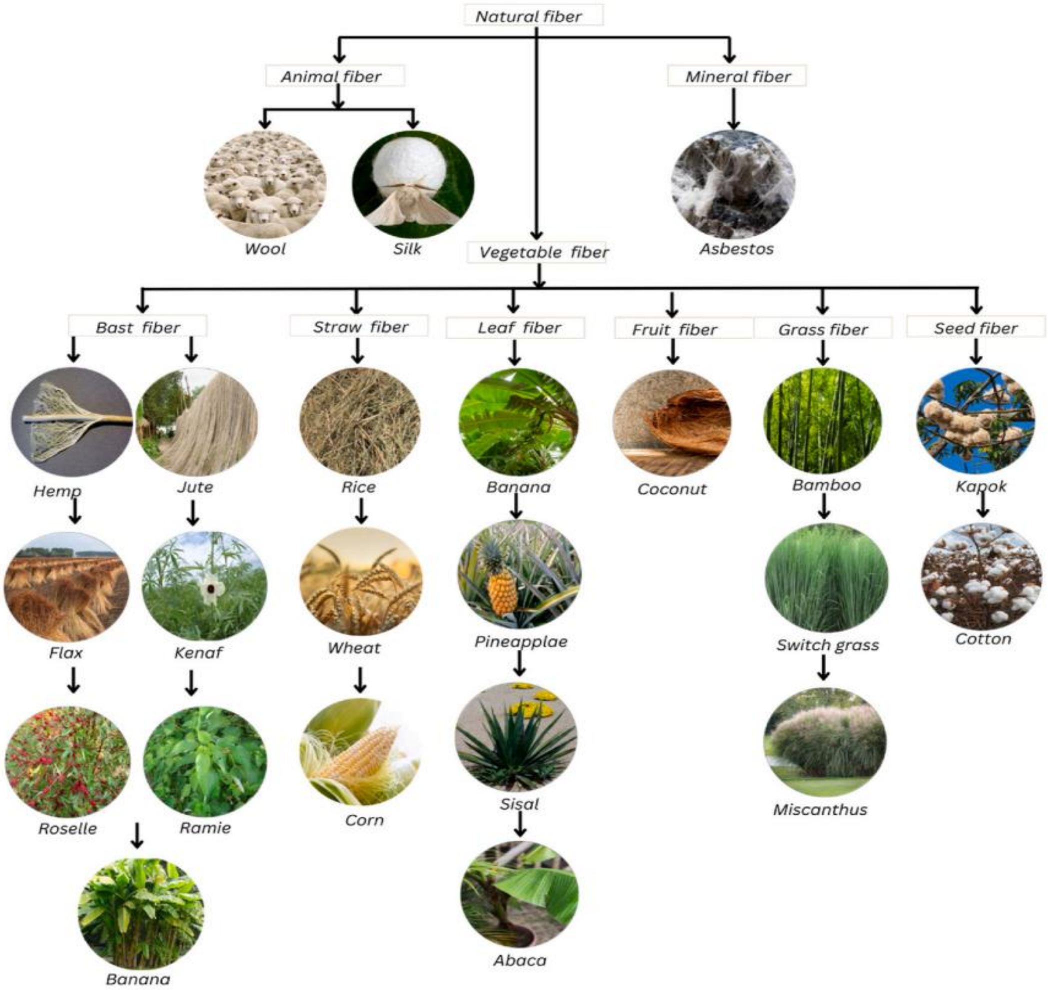

Figure 3. Types of natural fibers (Mohan Kumar et al., 2023)

Table 1 shows the mechanical properties and main local sources of several Indonesian natural fibers, highlighting their potential as reinforcement materials in composite applications. It can be observed that each fiber type exhibits distinct mechanical characteristics depending on its microstructure and regional growth conditions. Ramie fiber demonstrates the highest tensile strength, reaching up to 938 MPa, and an elastic modulus of up to 128 GPa, making it suitable for high-strength composite applications. Kenaf fibers, widely cultivated in Sumatra and Kalimantan, also show excellent tensile properties (up to 930 MPa) with relatively low density, offering a good balance between strength and lightness. Bamboo fibers, which are abundant across Indonesia, possess moderate tensile strength (503–862 MPa) and stiffness (35.91 GPa), while being one of the lightest natural fibers. In contrast, coconut coir fibers exhibit lower tensile strength (95–286 MPa) and stiffness (2–6 GPa) but provide high toughness and impact resistance, making them valuable for energy-absorbing structures. Pineapple leaf fibers, available mainly in Lampung and Central Java, display a wide range of tensile strength (170–1627 MPa) and modulus values, influenced by their fiber extraction and processing methods. Overall, the data confirm that Indonesia's diverse natural fibers offer a broad spectrum of mechanical performance suitable for various composite engineering applications, from lightweight panels to impact-resistant structures.

Table 1. Mechanical properties and main local sources of Indonesian natural fibers

Type of fibre	Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Main local source	Ref
Ramie	1,50	400-938	28,4-128	Jawa Tengah, Lampung	(Mudi & Shaw, 2025)
Kenaf	1,20-1,45	427–930	21,3-53	Sumatera, Kalimantan	(Ojo et al., 2025)
Bamboo	0,6-1,1	503-862	35,91	all Indonesia	
Coconut coir	1,15	95-286	2–6	Sulawesi, Jawa Barat	(Irawan et al., 2025)
Pineapple leaf fibre	1,44-1,52	170–1627	23,7-82,5	Lampung, Jawa Tengah	(Hartono et al., 2022)

IMPROVE THE STRENGTH OF NATURAL FIBER

Efforts to enhance the strength of natural fiber–based composites have become a key focus in developing natural fiber ballistic materials that can compete with synthetic counterparts(Alzahrani et al., 2025). One widely studied strategy involves optimizing the layering sequence configuration, applying alkali treatment to the fibers, and incorporating nanoparticles into the polymer matrix. Adjusting the layering sequence enables better load distribution and improved resistance to delamination and interlayer cracking. Alkali treatment helps remove lignin, hemicellulose, and surface impurities from the fibers, thereby improving interfacial bonding between the fiber and the matrix. Meanwhile, the addition of nanoparticles such as nano-silica, nano-clay, or nano-Al_2O_3 enhances the mechanical and thermal properties of the composite by reinforcing the microstructural bonding within the matrix(Jiang & Qian, 2022). The combination of these three approaches has proven effective in improving the tensile strength, impact resistance, and stiffness of natural fiber composites, making them more promising for various structural and engineering applications.

a. Layering Sequence Configuration

The arrangement of layer sequences plays a crucial role in determining a material's response to impact. While synthetic fibers (such as Kevlar or aramid) are widely used due to their proven impact resistance, natural fibers (such as kenaf or ramie) can be integrated to reduce environmental impact and production costs. Configurations in which synthetic fibers are placed on the front layers and natural fibers on the back layers have been investigated, showing that the layering sequence significantly influences ballistic performance. For example, variations in the arrangement of woven bamboo and woven E-glass have demonstrated notable differences in the ballistic limit that can be sustained (Ali et al., 2019). The following studies present examples of ballistic composites that combine natural and synthetic fibers.

Table 2. Hybrid composites

Reinforcement	matrix	Ballistic test	Ref
Bamboo & woven E-glass	Unsaturated polyester (UP),	Able to withstand bullets	(Ali et al., 2019)
ramie fibre & MAS ceramic	Epoxy resin	Able to withstand bullets	(Mujiyono et al., 2023)
Fique fibre & Alluminium	Epoxy resin	Able to withstand bullets	(Pereira et al., 2019)
Caraura fibre & Kevlar aramid	Neat polyester	Able to withstand bullets	(Braga et al., 2018)

b. Alkali Treatment

Natural fibers tend to be hydrophilic, which hinders strong adhesion with hydrophobic polymer matrices (Mudi & Shaw, 2025). Alkalization (mercerization) enhances the surface roughness of the fibers and facilitates better fiber–matrix interaction by removing lignin and hemicellulose. Meanwhile, silanization further improves interfacial bonding, leading to better thermal stability and tensile strength of the composite. This improved adhesion is crucial for reducing delamination under impact conditions.

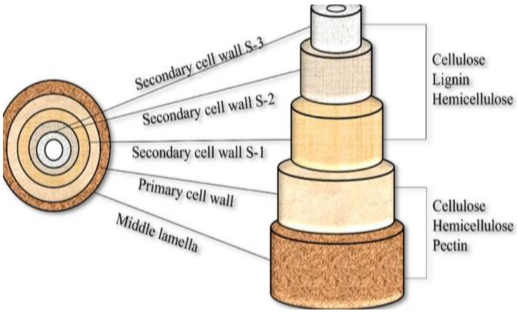

Figure 4. Structure of natural fibers (Mundhe, 2024)

Natural fibers generally consist of three main structural regions: the middle lamella, primary cell wall, and secondary cell wall (S1, S2, S3). The middle lamella is rich in pectin and lignin, acting as a natural adhesive between cells, while the primary and secondary walls are composed of cellulose, hemicellulose, and lignin with different microfibril orientations. The S2 layer is the most significant in determining the mechanical strength of the fiber, as it contains cellulose microfibrils aligned parallel to the fiber axis.
Chemical treatments such as alkalization remove portions of lignin, hemicellulose, and pectin from the outer layers, thereby opening pores and exposing cellulose microfibrils. This process increases surface roughness and surface energy, enabling stronger mechanical and chemical bonding with the polymer matrix. Consequently, proper surface treatment can enhance interfacial bonding, improve stress transfer efficiency, and strengthen the composite's resistance to delamination and dynamic loading, such as impact (Mundhe, 2024).

Table 3. The effect of alkali treatment on natural fiber composites

Treatment	fibres	Effect	Ref
Alkali 10% for 3 h	Jute	Increases elastic modulus by 35%	(Ojo et al., 2025)
Alkali 6% for 48 & 144 jam	Kenaf	Prolonged immersion may cause fiber brittleness	(Mudi & Shaw, 2025)
Alkali 5% for 2h	Sanse-viera	Enhances mechanical strength	(Mardiyati et al., 2023)
3% alkali for 2h	Flax	Removes impurities from the fiber surface	(Ismail et al., 2024)
2% alkali for 2h	Agave	Improves mechanical per-formance	(Haq et al., 2024)

c. Nanoparticle Addition

The hybridization strategy of natural fibers and nanoparticles is an effective approach to enhance the performance of ballistic composite materials. Natural fibers such as ramie, kenaf, and bamboo contribute to environmental sustainability and are abundantly available in Indonesia, while nanoparticles such as SiC, SiO_2, and CNB can significantly improve the mechanical strength of the composite.

The figure 5 illustrates the mechanism of crack propagation and energy absorption in a natural fiber-reinforced composite containing SiO_2 nanoparticles. When an external impact or stress is applied, cracks begin to form and propagate through the matrix. However, the presence of SiO_2 nanoparticles dispersed between the fiber layers enhances adhesion and interfacial bonding between the fibers and the polymer matrix.

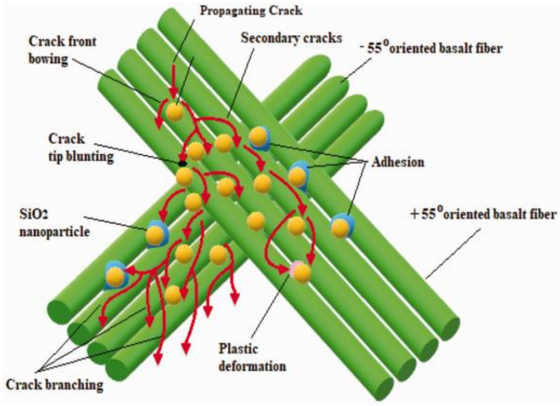

Figure 5. Illustration of nanoparticles (Demirci, 2020)

As cracks reach the fiber interface, the nanoparticles act as barriers, causing crack deflection, branching, and tip blunting, which significantly increase the energy required for crack propagation. The diagram also shows plastic deformation around the fibers, which helps dissipate impact energy and delays catastrophic failure. The ±55° fiber orientation contributes to a multidirectional load distribution, further improving the composite's toughness and impact resistance.

Overall, this microstructural mechanism demonstrates how nanoparticle reinforcement strengthens the fiber–matrix interface, reduces crack propagation speed, and enhances the mechanical and ballistic performance of hybrid natural fiber composites.

The combination of these reinforcements within an epoxy polymer matrix can produce a hybrid material with a balance of high mechanical strength, low density, and sustainability. To further enhance performance, nanoparticles such as nano-silica, Al_2O_3, or carbon nanotubes are often incorporated into the matrix to improve fiber–matrix interfacial bonding, increase hardness, and ensure more uniform impact energy distribution. Consequently, this hybridization strategy offers great potential for developing ballistic composite materials that not only exhibit superior bullet resistance but also align with the principles of sustainable and environmentally friendly material design.

Table 4. Addition of nanoparticles to composites

Nano partikel	matrix	penguat	Result	ref
Silicon Carbide (SiC), Aluminum oxide (Al_2O_3), *Multiwalled carbon nanotubes* (MWCNTs) 0,5%	*The epoxy resin* (Araldite AY105) and hardener (Hardener HY 2962)	Kevlar armaid	Composites with 0.5% MWCNT showed the highest impact resistance	(Mourad et al., 2020)
SiC & Boron Carbide (B_4C)	*Resin Epoxy* (Araldite AY105)	Aluminium 5083 & UHMWPE.	SiC exhibits excellent ballistic performance	(Chao et al., 2025)
Powder Al, Silika Koloidal, SiC, Gamma Alumina,	Epoxy (Pro-set LAM-125) + Hardener (LAM-229)	Kevlar 49 (20 layers) + Al 5086-H32	Macro-scale approaches such as biomimetic structures and gradients can yield even more dramatic performance improvements for high-end ballistic applications.	(Mourad et al., 2020)
SiO_2	Bisphenol A (DGEBA) epoxy resin	Basalt fibre	Increases impact strength	(Demirci, 2020)

CONCLUSIONS

In conclusion, Indonesian natural fibers—including ramie, abaca, sisal, bamboo, and coconut coir—possess significant potential as sustainable reinforcements for ballistic composites due to their promising mechanical properties, such as tensile strength and stiffness. However, their widespread adoption is hindered by inherent challenges, primarily their hydrophilic nature and variability in properties, which can compromise performance. To overcome these limitations, reinforcement strategies such as chemical treatments and nanomaterial enhancements (e.g., silica, carbon nanotubes, or silicon carbide) have shown effectiveness in improving fiber-matrix adhesion and boosting composite strength and energy absorption. Nevertheless, further focused research is essential to optimize processing, standardize ballistic testing according to international norms, and comprehensively evaluate performance under varied impact conditions. Ultimately, advancing such composites supports Indonesia's strategic move toward defense industry self-reliance, reducing dependency on imported materials while sustainably leveraging abundant local resources.

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