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Natural Fiber Epoxy-Based Composite Ballistic Impact Performance Capabilities for Armor System Design: A Comprehensive Review

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Abstract

The utilization of natural fibers to reinforce epoxy not only reduces its environmental impact but also enhances its mechanical characteristics. Numerous studies have examined the influence of natural fibers on impact properties. However, to the authors' knowledge, a thorough review consolidating all findings considering the effect of the reinforcement conditions on the overall performance has not yet been produced. Consequently, this review paper seeks to deliver a comprehensive evaluation of the effects of various natural fibers under diverse global conditions on standard impact tests and the ballistic impact testing of epoxy-based composites. This work systematically reviews and thoroughly discusses the performance enhancement and deteriorations observed in impact tests, the optimal weight percentage, the type of fiber used, morphological analysis, ballistic performance, cost considerations, and the density of such potential epoxy-based composites. The findings indicate that all examined fibers can dramatically enhance traditional impact tests. In terms of ballistic impact testing, the results revealed the existence of numerous bio-based alternatives to synthetic Kevlar, which is typically employed as a secondary layer in multilayered armor systems. All these bio-based alternatives satisfy the NIJ-level III standard (a ballistic resistance rating established by the National Institute of Justice) requirements and are more economical and lighter than Kevlar. Thus, the necessity for Kevlar is diminished. Morphological analysis indicated that the primary source of energy dissipation was the separation of the fibrils.

Keywords: Multilayered armor system; Natural fibers; Ballistic performance; Ballistic impact, Izod impact, Charpy impact, Epoxy.

1. Introduction

In recent years, there has been a significant transition towards utilizing natural fibers in place of synthetic alternatives, attributed to their remarkable attributes such as availability, cost-effectiveness, low density, and biodegradability[1-3].Beyond these characteristics, natural fibers also demonstrate mechanical properties that are comparable to those of conventional fibers [4]. Moreover, the proper utilization of the available natural agro waste has become crucial for the sustainable industry and circular economy particularly for the developing countries where an abundant amount of agro waste are available with potential mechanical properties[5, 6]. The desired mechanical properties of natural fibers can be a key driver for generating totally new green products in various industrial applications [7]. The beneficial characteristics of the available natural fibers have drawn the interest of engineers in integrating them with various plastics, including thermosetting resins like epoxy and polyester [8]as well as thermoplastics such as polypropylene (PP), high-density polyethylene (HDPE), and poly(vinyl chloride) (PVC) [9, 10].The literature reviews included the effect of natural fibers on Izod impact, Charpy impact, and ballistic impact strength of green epoxy composites are very limited. Consequently, the structure of the current review articles will be organized as follows. Section 2 will address the impact of various natural fibers on traditional impact tests (Izod and Charpy) concerning epoxy composites, detailing the extent of improvement that fibers can contribute to the epoxy matrix and identifying the optimal fiber percentage. Section 3 will provide an in-depth analysis of the effects of these natural fibers on ballistic impact performance, including a microscopic examination following the ballistic tests. Furthermore, this section will compare epoxy-natural fiber composites (utilized as an intermediate layer in multilayered armor systems) with Kevlar, focusing on aspects such as

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penetration depth, density, and cost. All strength values will be systematically tabulated to facilitate researchers in accessing these metrics for future investigations.

2. The Effect of Natural Fibers on Charpy and Izod Impact Strength of Epoxy Composites

Epoxy resin is recognized for its resistance to creep and corrosion, excellent performance at elevated temperatures, minimal shrinkage, and favorable electrical characteristics. Furthermore, its mechanical properties can be readily modified [11]. Consequently, epoxy is extensively utilized in a variety of applications, including the encapsulation of electronic components, coatings, adhesives, and laminated circuit boards [12]. However, epoxy resin does have certain limitations, such as low impact resistance and low fracture toughness [13]. As a result, many researchers have investigated the impact of incorporating tough, flexible natural fibers on the results of impact strength tests.For instance, Nascimento, et al. [14]demonstrated that the Charpy impact strength of epoxy polymer could be enhanced by incorporating 10, 20, and 30 vol.% of 15 mm long mallow fiber.Similarly,Reddy, et al. [15]explored the effects of 20 wt.% of three varieties of natural fibers—prosopis juliflora, abuliton indicum, and tapsi—in a straw form on the Izod impact strength of epoxy. Their findings indicated that all three fiber types contributed to an increase in impact strength, with abuliton indicum achieving an impressive enhancement of 217%.Maleque, et al. [16]investigated the influence of woven Pseudo-stem banana fiber on the impact strength of an epoxy matrix. The composites were fabricated using a hand lay-up technique. The results indicated a notable improvement of approximately 40% attributed to the incorporation of the fiber. Different lengths (10, 20, and 30 mm) and volume fractions (ranging from 5% to 30%, in increments of 5) of Calotropis Gigantea fiber were employed to reinforce the epoxy. The findings revealed beneficial effects on the impact resistance of the epoxy composite, irrespective of the volume percentage and fiber length. Notably, a volume fraction of 25% with a fiber length of 30 mm exhibited the highest Izod impact resistance, achieving an enhancement of around 135%. Additionally, the researchers expanded their studies to explore the impact of hybrid reinforcement on the impact characteristics of epoxy.Jawaid, et al. [17]employed a hand lay-up technique to create multilayer composites using empty fruit bunch fibers (EFB) and jute (J) combined with epoxy. The epoxy-to-fiber ratio was set at 60:40. The results indicated that the hybrid fiber significantly improved the notched Izod impact resistance, irrespective of the layering sequence. The optimal layering configuration was found to be EFB/J/EFB, which resulted in a 30% increase in impact resistance. Furthermore, the presence of a coupling agent positively influenced the impact strength. Mishra and Biswas [18]examined the impact strength of epoxy composites reinforced with a bidirectional jute fiber mat at varying loadings (12-45 wt.%, in increments of 12) in accordance with ASTM D 256 testing standards. A significant increase of 350% was noted when 48 wt.% of jute was incorporated into the epoxy matrix. Rua, et al. [19]investigated the effect of eleven layers of fique fiber (150 g) on the Charpy impact strength of the epoxy matrix, resulting in a 17% enhancement in impact strength. Yang, et al. [20]employed two volume percentages (30 and 60) of two varieties of silk to enhance the Charpy impact strength. Both 30 and 60 vol.% of Bm and Ap silk fibers contributed to the improvement in strength. Notably, an extraordinary increase of 450% in the impact resistance of the epoxy matrix was recorded when 60 vol.% of Bm-SFRP was integrated into the matrix. **Table 1**shows the effect of different natural fiber loadings on the impact strength of epoxy.

3. Ballistic Impact Test

Following the observation of the beneficial effects of natural fibers in traditional impact tests, specifically the Izod and Charpy tests, researchers have redirected their focus to investigate the effects of these fibers on a different type of impact assessment, namely the ballistic impact test. This test is employed to assess the performance of multilayered armor systems concerning ammunition. The multilayered armor system (MAS) generally comprises three distinct layers. The first layer is constructed from high-strength ceramic materials, specifically engineered to absorb the kinetic energy generated by projectiles effectively. The second layer, which may consist of Kevlar or a bio-polymeric composite (as elaborated in later sections), is designed to partially absorb the kinetic energy of incoming projectiles while also containing any ceramic debris and shrapnel. The third layer, made from aluminum alloy, acts as a penetration barrier by undergoing plastic deformation upon impact, thereby preventing bullets and fragments from penetrating further. Behind all these layers lies a clay witness, which simulates the human body. For the MAS to be deemed successful in testing, the indentation in the clay witness must not exceed 44 mm after a high-velocity projectile (approximately 850 m/s) strikes the MAS, following the NIJ standard level III (7.62 × 51 mm NATO ammunition) [22, 23]. The experimental setup is depicted in **Figure 1(a)**, while a schematic diagram illustrating the three layers along with their dimensions is provided in **Figure 1(b).**

Table 1. The effect of different natural fiber loadings on the impact strength of epoxy.

Matrix	Fiber Type	(wt.% or vol.%)	Optimum loading %	Best Improvement (as %)	Test Type/ Standard	Reference
Epoxy	Mallow	0 vol.%	30	842%	Charpy ASTM D6110	[14]
		10 vol.%				
		20 vol.%				
		30 vol.%				
Epoxy	prosopis juliflora	0 wt.%	20	159%	Izod ASTM D256	[15]
		5 wt.%				
		10 wt.%				
		15 wt.%				
		20 wt.%				
		25 wt.%				
	abuliton indicum	0 wt.%	25	217%		
		5 wt.%				
		10 wt.%				
		15 wt.%				
		20 wt.%				
		25 wt.%				
	tapsi	0 wt.%	25	55%		
		5 wt.%				
		10 wt.%				
		15 wt.%				
		20 wt.%				
		25 wt.%				
Epoxy	Pseudo-stem banana fiber	NA/ Woven Fiber	Only one vol.%	40%	BS 2782	[16]
Epoxy	Calotropis Gigantea	0 vol.%	25 vol.%	135%	Izod ASTM D256	[21]
		5 vol.%				
		10 vol.%				
		15 vol.%				
		20 vol.%				
		25 vol.%				
		30 vol.%				
Epoxy	Empty fruit bunch fibers/jute	40vol.%	40vol.%	30 %	Izod impact ASTM D256	[17]
Epoxy	Bidirectional jute fiber	0wt.%	48	350%	Izod impact ASTM D256	[18]
		12 wt.%				
		24 wt.%				
		36 wt.%				
		48 wt.%				
Epoxy	Woven Fique	150g fiber:250g epoxy	150g fiber:250g epoxy	17%	Charpy ASTM E23-00	[19]
Epoxy	*B. mori/Bm silk*	30	60 vol..% Bm	450%	Charpy	[20]
		60				
	A. pernyi/Ap	30				
		60				

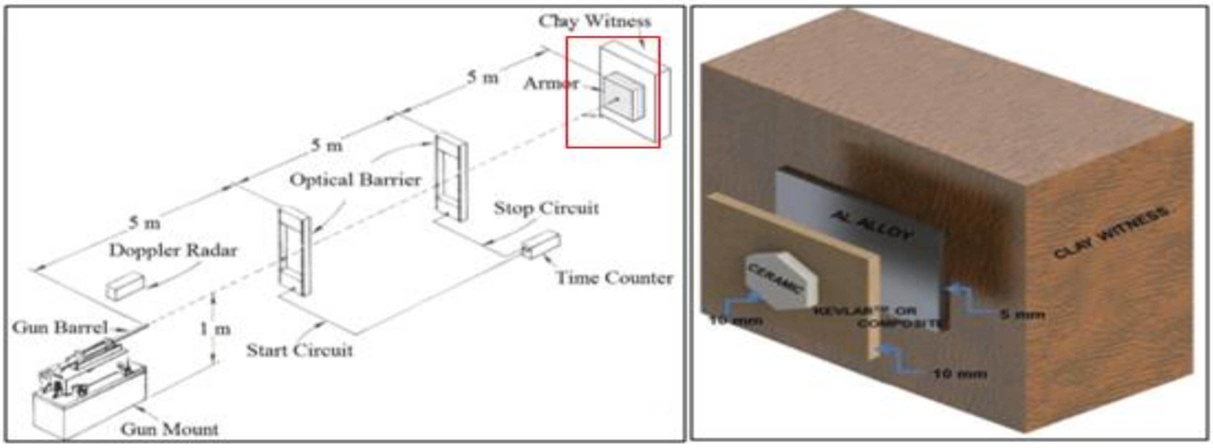

Figure 1. Schematic illustration of ballistic impact setup (a) and (b) better representation of multilayered armor system (red square in (a))[24].

3.1. The Performance of Natural Fibers Reinforced Epoxy Matrix under Ballistic Impact Test

In the past two decades, researchers have increasingly turned to natural fibers combined with polymers as a substitute for aramid fibers (Kevlar) in the multilayered armor. For instance, 30 vol.% of fabric malva and 30 vol.% of hybrid reinforcement (malva and jute) (70:30) were used to reinforce the epoxy matrix by Nascimento, et al. [25]to enhance the ballistic resistance of the second layer of the multilayer armoring system.The woven fibers were positioned within a steel mold, followed by the introduction of epoxy mixed with a hardener, and a pressure of 5 MPa was subsequently applied. Their findings revealed that both 30 vol.% jute and jute/malva composites met the requirements specified in the N.I.J. 0101.04 standard. The average indentation depth recorded from five replicates in the clay witness was 21.48 ± 1.64 mm and 23.16 ± 3.117 mm after impact with the multilayer armor system, which included epoxy-30 vol.% malva and epoxy-30 vol.% jute/malva layers, respectively. This depth remained below the 44 mm threshold, indicating the suitability of these natural fibers for use as the intermediate layer in multilayer armor systems. Furthermore, their statistical analysis indicated no significant difference in performance between synthetic Kevlar and natural composites. The primary failure mechanism observed was delamination, as illustrated in **Figure 2**.

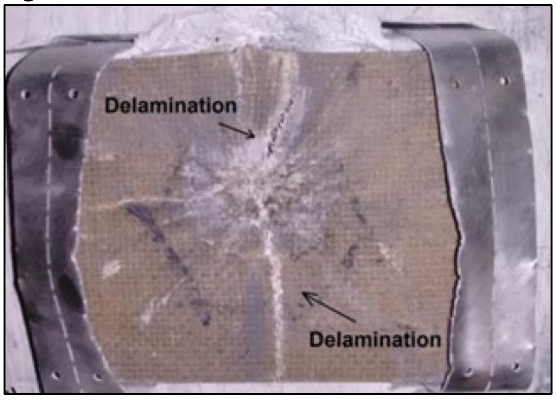

Figure 2.Delamination of epoxy-30 vol. jute/malva layer[25].

Luz, et al. [26] developed three variations of the intermediate layer for the armor system. These layers consisted of 16 layers of Kevlar, a composite of 30 vol.% jute fabric and epoxy, and a plain epoxy layer, each with a thickness of 10 mm. The jute/epoxy composite was produced following the methodology outlined by Nascimento, et al. [25]. Each sample was subjected to 10 ballistic tests according to the NIJ 0101.06 standard using 7.62 × 51 mm ammunition, and then the average of the penetration depth in the clay witness was calculated. The penetration depth was 23 ± 3 mm for Kevlar™, Kevlar absorbed the lowest amount of energy (0.06 kJ), then it was followed by jute/epoxy composite (0.16 kJ)) and plain epoxy plate dissipated the highest amount of energy (0.19 kJ). The fracture of Epoxy/ 30 vol.% jute fabric composite presented in **Figure 3** proves that energy dissipated in the composite.

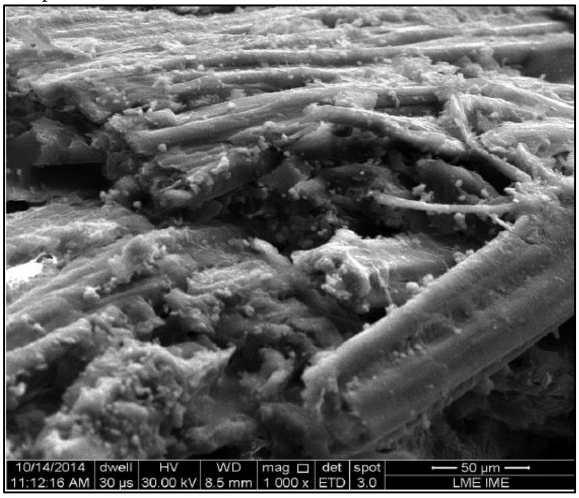

Figure 3. SEM micrographof fracturedepoxy/ 30 vol.% jute composite due to the observed energy.

Monteiro, et al. [23] utilized a hand lay-up technique to incorporate 30 vol.% of ramie fiber with epoxy, applying a pressure of 0.53 MPa. The effects of this fiber on the ballistic performance of epoxy were assessed according to the NIJ standard (class III). Their findings indicated that the ramie/epoxy composite exhibited a reduced penetration depth in comparison to 18 layers of conventional Kevlar (refer to **Table 2**). Nevertheless, the density of the 30 vol.% ramie/epoxy composite (1.23 g/cm³) surpassed that of Kevlar (1.09 g/cm³). Additionally, the incorporation of ramie fiber could lead to a cost reduction of 95%. The ramie fiber played a crucial role in capturing ceramic fragments and dissipating the remaining kinetic energy. The epoxy matrix experienced fracture during the testing, suggesting that excess energy was absorbed by the brittle epoxy as seen in **Figure 4**.

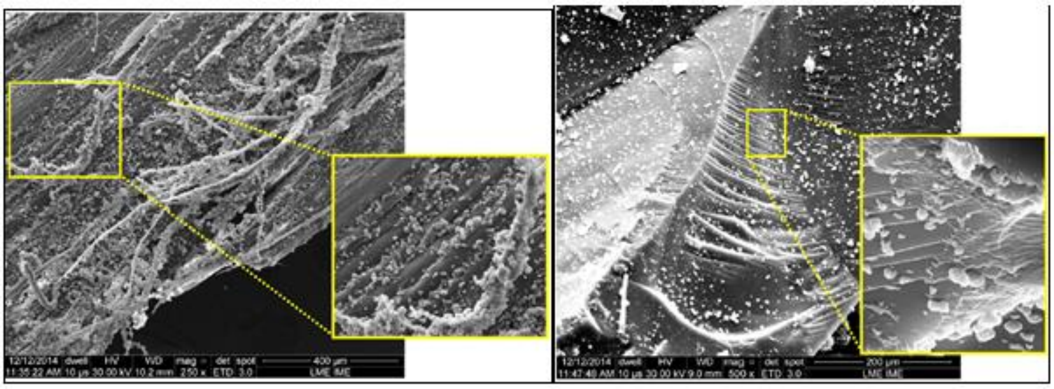

Figure 4. (Left) ceramic fragments stopped by ramie fiber, (right) fractured epoxy.

Rohen, et al. [27]conducted an investigation into the ballistic performance of sisal fiber, utilizing 30 vol. % of sisal to reinforce the epoxy. Their findings were compared against those of traditional Kevlar (16 layers) and a plain epoxy plate. The study revealed that both the sisal/epoxy composite and the plain epoxy plate exhibited enhanced resistance to ballistic impacts, as indicated in **Table 2**. The primary mechanism for energy dissipation was identified as the separation of the fibrils, while another contributing factor was the fracture of the epoxy, illustrated in **Figure 5**.

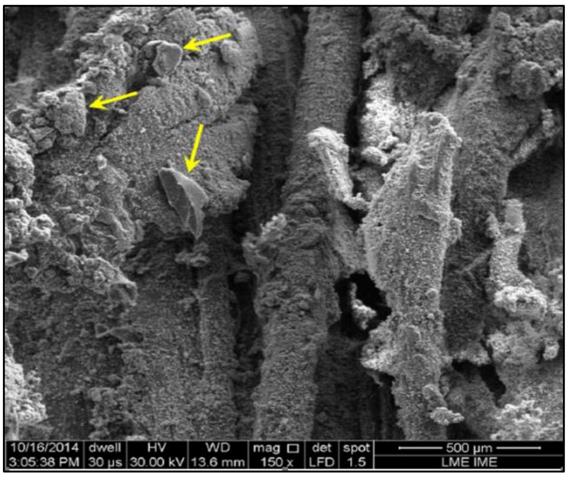

Figure 5.SEM of the fractured region of sisal/epoxy composite. Yellow arrows indicate fractured epoxy.

Cruz, et al. [28]evaluated the impact of three distinct configurations: 16 layers of aramid fabric, a plain epoxy plate, and a composite made of 30 vol.% giant bamboo fiber and epoxy, on the penetration depth in clay samples, in accordance with the NIJ-level III standard referenced in earlier research. The findings indicated that the penetration depth for both the plain epoxy plate and the bamboo/epoxy composite was less than that of the aramid fiber, as shown in **Table 2**. Furthermore, the bamboo/epoxy composite not only exhibited a reduced penetration depth but also offered advantages in terms of lower cost and density, as detailed in the subsequent sections. Nascimento, et al. [29] examined the impact of a 30 vol.% pure mallow fiber layer and a 30 vol.% hybrid layer composed of jute and mallow fiber on the indentation depth of epoxy composites. Two different ratios of the hybrid fiber were employed: one consisting of 70% mallow and 30% jute, and the other comprising 50% mallow and 50% jute. The results indicated that the natural fiber layers exhibited performance comparable to that of the conventional Kevlar layer when matched for thickness. This finding suggests that these bio-composites fulfill the requirements set forth by the NIJ standard. The testing conditions were consistent with those of prior studies. Monteiro, et al. [30] introduced a novel alternative for intermediate layers in the MAS. Their approach involved the use of plain epoxy reinforced with 30 vol.% of aligned and continuous curaua fiber. A comparison was made between the penetration depths of plain epoxy and its composite with Kevlar, revealing that both the epoxy and the curaua/epoxy composite exhibited a lower indentation depth than that observed in the MAS with Kevlar. All relevant values are presented in **Table 2**.de Oliveira Braga, et al. [31] reinforced epoxy resin by incorporating 30 vol.% curaua non-woven fiber fabric as shown in**Figure 6**. Subsequently, a ballistic test was conducted following the NIJ standard using 7.62 × 51 mm ammunition. The resulting composite exhibited good ballistic performance, successfully fulfilling the NIJ criteria. Similar to other bio-composites utilized in MAS, the curaua non-woven fiber/epoxy composite is significantly more cost-effective than Kevlar fabric.

A new composite material, comprising 30 vol.% ramie fiber-epoxy, was created as an alternative intermediate layer to replace Kevlar, as reported by de Oliveira Braga, et al. [32]. This composite exhibited ballistic performance that is comparable to that of Kevlar, achieving an indentation depth of 18 ± 2, while also presenting benefits such as reduced cost and enhanced environmental sustainability. Four types of intermediate layers were produced using epoxy combined with different configurations of 30 vol.% piassava fiber, including long scattered fiber, short scattered fiber, long aligned fiber oriented in a single direction, and long aligned fiber arranged in multiple directions. Each layer achieved the required ballistic performance as indicated in Table 2; however, their effectiveness did not match that of Kevlar. Conversely, these materials are more cost-effective and environmentally friendly [33]. The epoxy composite containing 30 vol.% piassava fibers, which are short and randomly distributed, exhibited an indentation depth that was most comparable to that of aramid fibers. Garcia Filho and Monteiro [34]employed various volume percentages of long continuous piassava (10, 20, 30, 40, and 50) in a single direction to create the intermediate layer of the MAS. The fiber is illustrated in Figure 7. Additionally, a volume percentage of 50 was applied in two directions. The cross-ply configuration demonstrated enhanced ballistic impact performance. Their findings, presented in Table 2, indicate that the piassava/epoxy composite serves as a promising material for the second layer in the MAS.

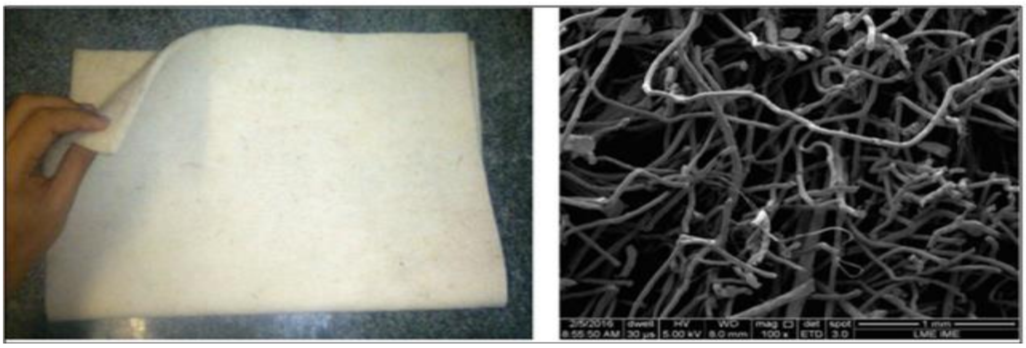

Figure 6.(left) Curaua fiber non-woven fabric and (right) SEM micrograph of Curaua fabric[31].

Various volume percentages (15, 30, 40, and 50) of fique fabric as shown in Figure 8 were integrated with epoxy byOliveira, et al. [35]. Their findings indicated that the fique fabric/epoxy composite could serve as a substitute for the Kevlar layer in the armor system, as detailed in **Table 2.** Notably, the 15 vol.% formulation exhibited the most favorable ballistic performance following NIJ-level III standards. Additionally, all formulations resulted in a decrease in both cost and weight.

Demosthenes, et al. [36]reinforced the second layer of the epoxy MAS by incorporating three volume percentages (10, 20, and 30) of buriti fabric, as illustrated in **Figure 9**. Consistent with previous studies, the hand layup technique was employed to fabricate the intermediate layer. The sample with 10 vol.% exhibited the least indentation depth in the clay witness.

Various volume percentages of coir mantle fiber, extracted from coconut fruit, specifically 10%, 20%, and 30%, were utilized to enhance the epoxy matrix in a study conducted by Luz, et al. [37].The objective was to evaluate their performance in ballistic testing and to compare these composites with the performance of Kevlar. The findings indicated that the coir fiber/epoxy composite could serve as a viable alternative to Kevlar. The ballistic test was performed according to NIJ 0101.06 class III. The results regarding the indentation depth in the clay witness for the composites are detailed in Table 2. The table reveals that as the fiber volume percentage increased, the indentation depth also increased. Nevertheless, the differences in indentation among the composites were not substantial. Observations from the SEM test, illustrated in Figure 10, indicated occurrences of fiber pull-out and fiber rupture.

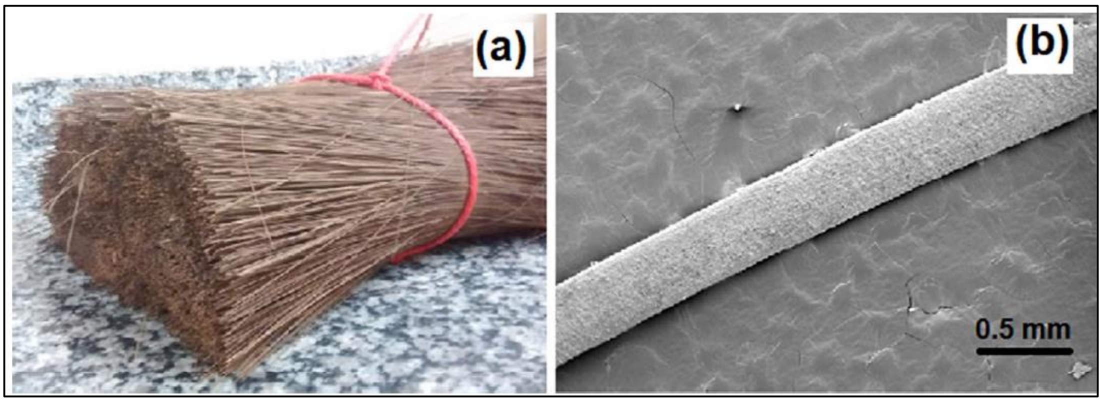

Figure 7. (a) a Bundle of piassava fiber and (b) a single fiber SEM[33].

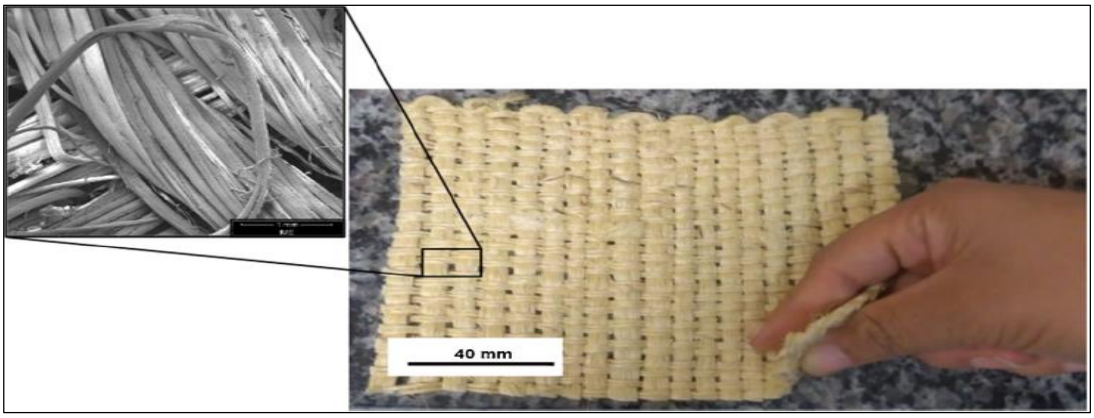

Figure 8.Fique fabric and its SEM micrograph at 80X magnification[35].

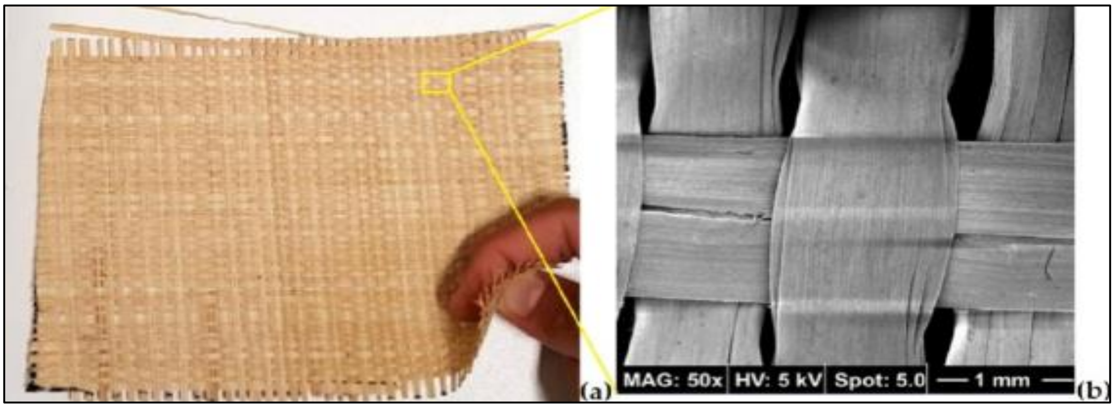

Figure 9.Buriti fabric and its SEM micrograph [36].

Monteiro, et al. [38]investigated the impact of incorporating 30 vol. % of two distinct types of fibers on the ballistic performance of an epoxy matrix, which served as the secondary layer of a multi-layered armor system (MAS). The fibers utilized were either raw bagasse or extracted bagasse, the latter being a byproduct of sugarcane juice extraction as shown in **Figure 11**. Furthermore, the researchers compared the ballistic performance of the developed composites—30 vol.% raw bagasse/epoxy and 30 vol.% extracted bagasse/epoxy—against 18 layers of Kevlar. All evaluations were conducted in accordance with NIJ class III standards, utilizing 7.62 x 51 mm ammunition weighing 9.7 g. The indentation depth (as shown in **Table 2**) recorded in the clay witness was averaged from 10 replicates for the epoxy composites and 15 for the Kevlar samples. The raw bagasse/epoxy composites did not meet the NIJ standards, whereas both the Kevlar and extracted bagasse/epoxy plates successfully complied with the NIJ requirements, exhibiting nearly equivalent performance. Notably, the bagasse/epoxy plate was significantly more cost-effective than the Kevlar alternative.

Nascimento, et al. [39]created a composite consisting of a 10 mm layer composed of 30 vol.% mallow fiber integrated with an epoxy matrix. This composite was subsequently employed in the MAS as a substitute for Kevlar. The indentation observed in the clay witness was remarkably similar to the performance of Kevlar under ballistic impact. The testing was conducted in accordance with the NIJ-level III standard, and the composite was fabricated as described byLuz, et al. [37]. The fiber in the second layer effectively captured the fragments from the ceramic layer (the first layer), as evidenced by the SEM micrograph shown in **Figure 12**.

A load of 5 tons was applied for 24 hours to a steel mold filled with either 30 vol.% curaua fibers combined with 70 vol.% epoxy or with curaua fibers coated with graphene oxide to enhance their adhesion to the polymer. The resulting plate had a thickness of 10 mm. Ballistic testing of these composites was performed following the NIJ-level III standard. The penetration depths observed in the composites are detailed in **Table 2**. It was noted that the curaua fibers coated with graphene oxide and epoxy exhibited inferior ballistic performance under identical testing conditions. Scanning electron microscopy (SEM) analysis (**Figure 13**) revealed the occurrence of fragment capture, fibril separation, and the pull-out phenomenon. These observed phenomena significantly influenced energy absorption [40].

A composite material was created using 30 vol.% of coir fiber and pineapple leaf fiber (PALF) as reinforcement in epoxy. The methodology employed was consistent with that outlined in the study of [37]. To assess the ballistic capabilities of the composite, a ballistic test was conducted in accordance with NIJ level III standards. The results indicated that the PALF/epoxy composite exhibited superior ballistic performance compared to the coir fiber/epoxy composite, as detailed in **Table 2**[41].

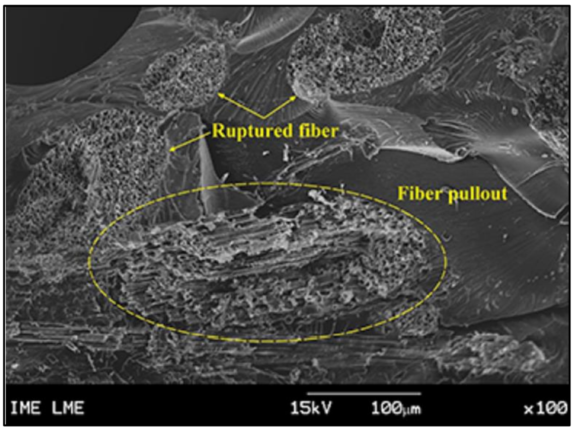

Figure 10. Pull out and rupture of the fiber[37].

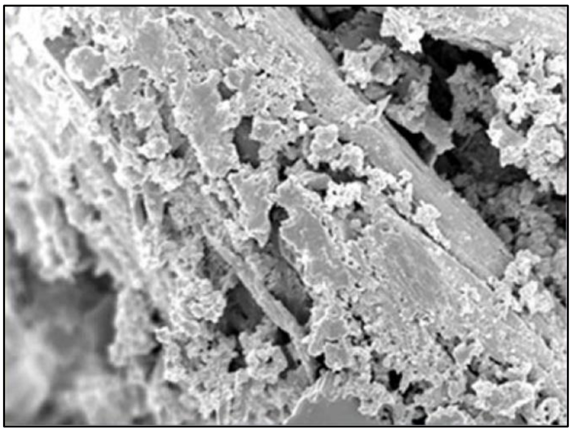

Figure 11. Ceramic particles captured by mallow fiber [39].

Figure 12.Extracted fiber of sugarcane

3.2. A Comparison of the Penetration Depth between Different Types of 30 Vol.% Natural Fibers/Epoxy Composites with Kevlar

This section is dedicated to analyzing the penetration depth observed in the clay witness of various natural fiber/epoxy composites at a volume fraction of 30%, in conjunction with 18 plies of synthetic Kevlar, following a ballistic test conducted in accordance with NIJ level 3 standards. The results of this comparison are illustrated in **Figure 14**. It is evident that ramie fabric fiber achieved the most favorable outcome, with a penetration depth of 17 mm. Furthermore, eight types of fibers, including giant, ramie fiber, ramie fabric, sisal, coir, pineapple leaves, piassava, and jute fabric, exhibited penetration depths that were less than that of Kevlar, which measured 21 mm. Conversely, raw bagasse fiber recorded the highest penetration depth at 39 mm within the clay witness, surpassing all other fiber types. Other fibers, such as malva, mallow, fique, Buriti, and curaua, demonstrated greater indentation than Kevlar; however, they still complied with the NIJ level III requirements.

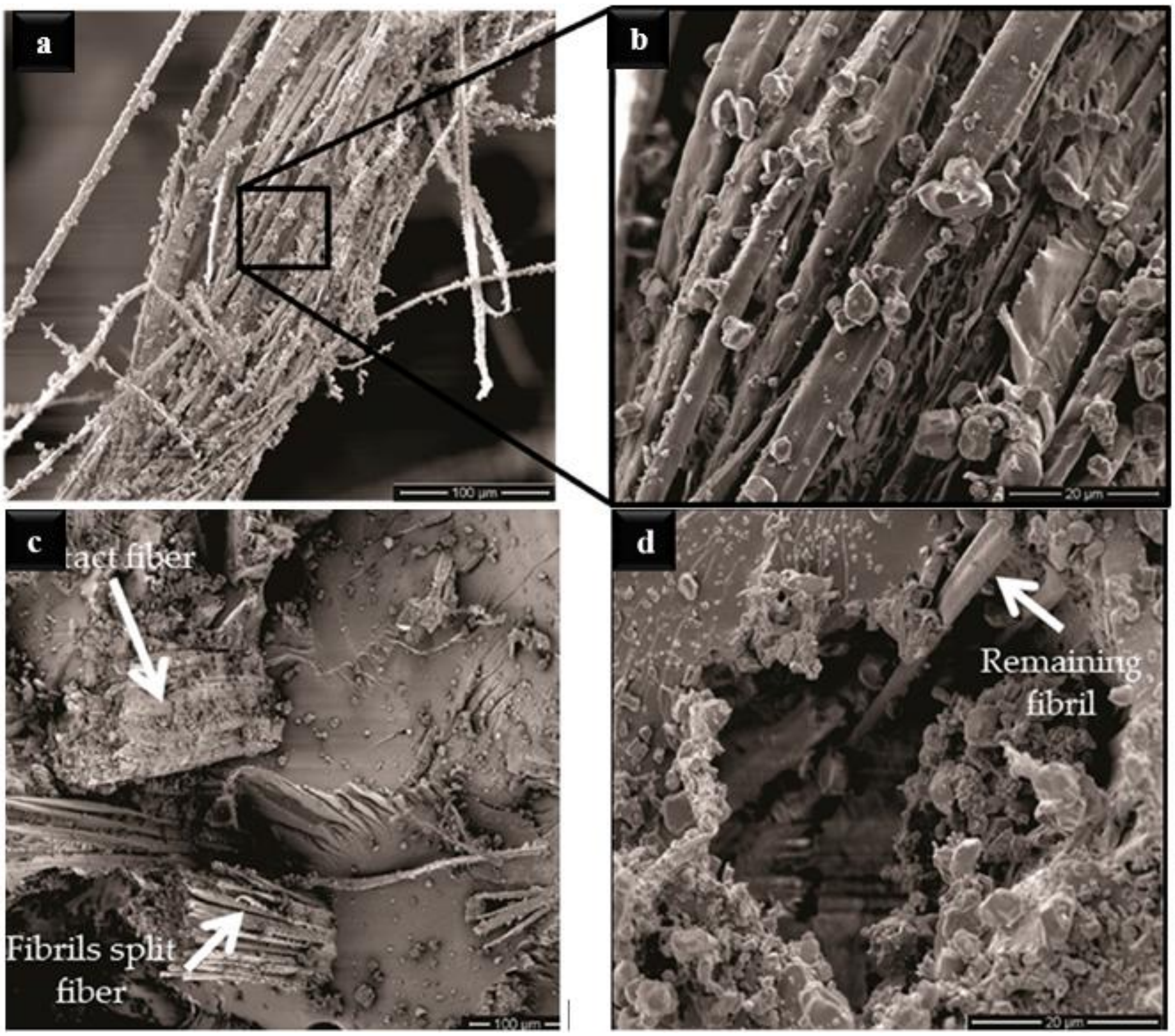

Figure 13. (b) is a magnification for (a) to prove that Curaua can stop ceramic fragments, (c) fibrlis separation, (d) fiber pull out during the impact test [40].

Table 2. The indentation depth of the 7.62 mm bullet in the clay witness according to NIJ-Level III standard.

No.	**The intermediate layer**	**Penetration depth (mm)**	**Reference**
1	Epoxy -30 vol.% malva	21.48 ± 1.6	[25]
	Epoxy -30 vol.% jute/malva	23.16 ± 3.1	
2	Kevlar™ (16 piles)	23 ± 3	[26]
3	Kevlar™ (18 piles)	21 ± 3	[23]
4	Aramid fiber plies (16 piles)	22.67 ± 2.79	[27]
5	Aramid fabric plies (16 piles)	22.67 ± 2.79	[28]
6	Epoxy-30 vol.% jute fabric	21 ± 3	[26]
7	Epoxy-30 vol.% pure jute fabric	20.7 ± 3.1	[29]
8	Plain epoxy plate	20 ± 1	[26]
9	Plain epoxy plate	19.84 ± 1.09	[27]
10	Plain epoxy plate	19.84 ± 1.09	[28]
11	Plain epoxy plate	20.69 ± 1.65	[30]
12	Epoxy-30 vol.% mallow fiber	22.4 ± 1.3	[39]
13	Epoxy- 30 vol.% pure mallow fabric	21.5 ± 1.6	[29]
14	Epoxy-30 vol.% ramie fabric	17 ± 1	[23]
15	Epoxy-30 vol.% ramie fibers	18 ± 2	[32]
16	Epoxy-30 vol.% curaua fiber	25.6 ± 0.2	[40]
	Epoxy-30 vol.% curaua coated with graphene oxide	27.4 ± 0.3	
17	Epoxy-30 vol.% curaua fiber	17.13 ± 1.57	[30]
18	Epoxy-30 vol.% curaua non-woven fabric	28 ± 3	[31]
19	Epoxy-10vol. % coir mantle	21 ± 2	[37]
	Epoxy-20 vol.% coir mantle	22 ± 2	
	Epoxy-30 vol.% coir mantle	24 ± 6	
20	Epoxy-30 vol.% coir fiber	31.6 ± 2.7	[41]
21	Epoxy-30 vol.% raw bagasse	39 ± 8	[38]
	Epoxy-30 vol.% bagasse fiber	21 ± 1	
22	Epoxy-30 vol.% Pineapple leaves	18.2 ± 2.7	[41]
23	Epoxy-30 vol.% sisal fiber	18.18 ± 2.06	[27]
24	Epoxy- 30 vol.% giant bamboo	17.58 ± 1.88	[28]
25	Epoxy-30 vol.% (70 mallow/30 jute)	23.2 ± 2.4	[29]
	Epoxy-30 vol.% (50 mallow/50 jute)	23.7 ± 2.4	
26	Epoxy-10 vol.% piassava	18.3 ± 1.9	[34]
	Epoxy-20 vol.% piassava	16.8 ± 0.7	
	Epoxy-30 vol.% piassava	19.8 ± 3.9	
	Epoxy-40 vol.% piassava	17.3 ± 1.9	
	Epoxy-50 vol.% piassava	15.6 ± 0.8	
	Epoxy-50 vol.% piassava (2 directions)	18.4 ± 2.4	
27	Epoxy-30 vol.% piassava (long and aligned/2D)	26.5*	[33]
	Epoxy-30 vol.% piassava (long and aligned-1D)	23.5*	
	Epoxy-30 vol.% piassava (long and randomly scattered)	26.5*	
	Epoxy-30 vol.% piassava (short and randomly scattered)	21.5*	
28	Epoxy-15 vol.% Fique Fabric	20.00± 3.56	[35]
	Epoxy-30 vol. % Fique Fabric	21.60 ± 3.68	
	Epoxy-40 vol. % Fique Fabric	21.00 ± 4.58	
	Epoxy-50 vol. % Fique Fabric	23.30 ± 5.07	
29	Epoxy -10 vol.% Buriti Fabric	18.9 ± 1.9	[36]
	Epoxy -20 vol.% Buriti Fabric	21.0 ± 1.9	
No.	Epoxy -30 vol.% Buriti Fabric	25.0 ± 3.3	

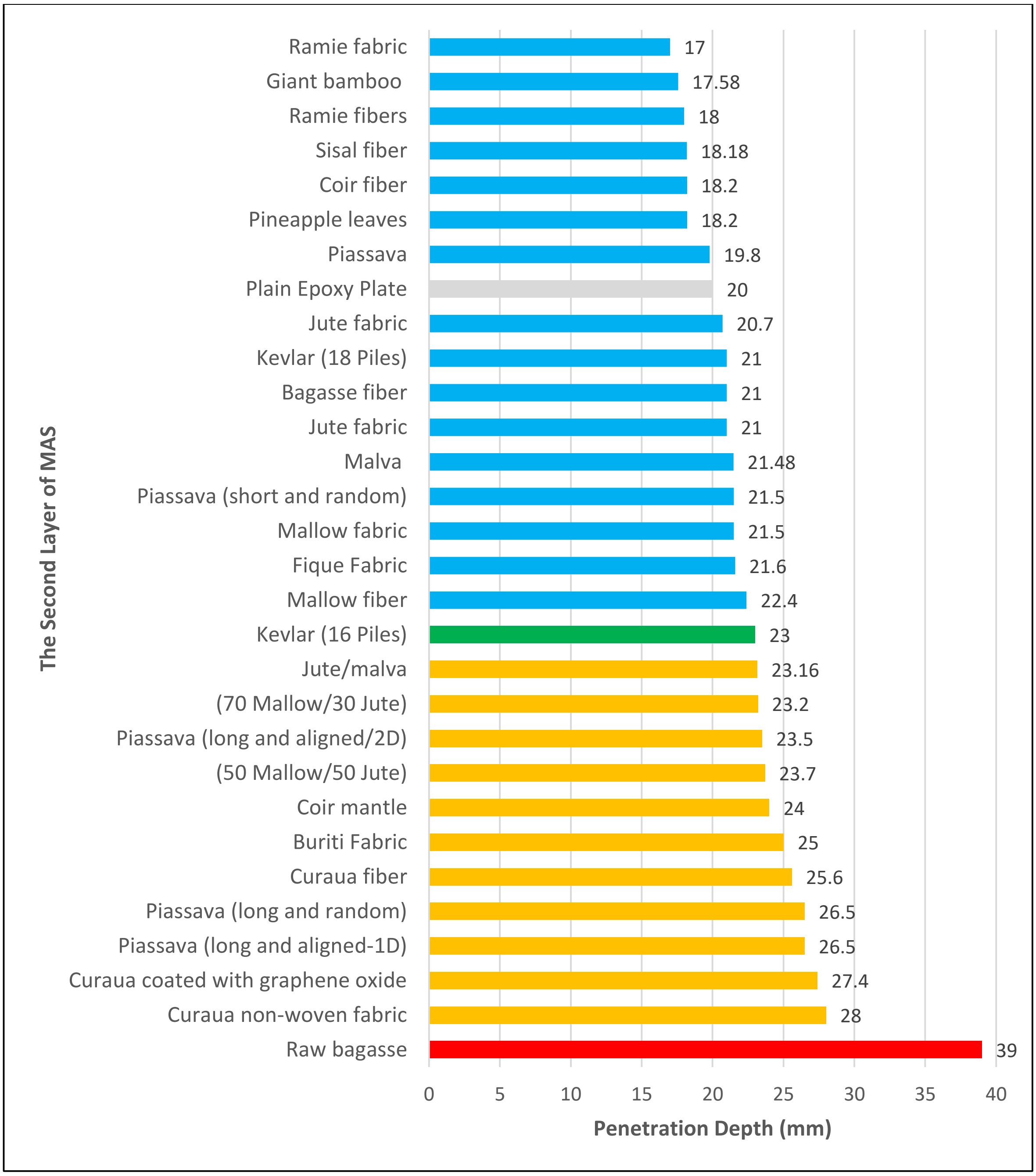

Figure 14. The penetration depth in an ascending order in the clay witness after using different types of bio-composites as anintermediate layer in theMAS.

3.3. The cost of the alternative layers to Kevlar

Table 3 presents the cost of a 30 vol.% natural fiber-epoxy intermediate layer in the MAR, expressed in US dollars per kilogram. It is readily apparent that there exists a considerable disparity between the cost of Kevlar fiber and that of other natural intermediate layers. In general, fabric fibers tend to be more costly than those derived from mallow and ramie. The research conducted by [26]and [30]highlights a significant variation in epoxy costs. The most economical fibers identified were curaua at $2.1 per kilogram and giant bamboo at $2.2 per kilogram, both of which are remarkably less expensive than Kevlar. This represents a cost reduction of approximately 2427% when considering the average price of Kevlar, calculated as ((47.69+63.6)/2). Although jute ($18.12/Kg), ramie ($20.88/Kg), and mallow ($19.3/Kg) fabrics are relatively high-priced, they remain approximately 166% less expensive than Kevlar.

Table 3. The cost of different intermediate layers in the MAS.

The intermediate layer	Cost (US$/Kg)	Reference
Kevlar™	47.69	[26]
Kevlar™	63.60	[23, 28]
Plain epoxy plate	19.35	[26]
Plain epoxy plate	2.80	[27]
Epoxy-30 vol.% jute fabric	16.05	[26]
Epoxy-30 vol.% jute fabric	18.12	[29]
Epoxy-30 vol.% mallow fiber	5.17	[39]
Epoxy- 30 vol.% mallow fabric	19.3	[29]
Epoxy-30 vol.% ramie fabric	20.88	[23]
Epoxy-30 vol.% ramie fibers	13.9	[32]
Epoxy-30 vol.% curaua fiber	2.1	[30]
Epoxy-30vol.% coir mantle	11.5*	[37]
Epoxy-30 vol.% bagasse fiber	11.40	[38]
Epoxy- 30 vol.% giant bamboo	2.2	[28]
Epoxy-30 vol.% (70 mallow/30 jute)	18.92	[29]
Epoxy-30 vol.% (50 mallow/50 jute)	18.7	
Epoxy-30 vol. % fique fabric	16.6	[35]
-The cost for some intermediate layers is calculated according to the costs available in their papers. -This table does not take into account the year and the region of the production which means that the epoxy and Kevlar might be different from one year to another or from region to another.		

3.4. The density of the alternative layers to Kevlar

Table 4 provides a comparison of the densities of the intermediate layers within the MAS. The literature presents several density values for Kevlar (Aramid fabric), specifically 1.08, 1.09, 1.14, and 1.44, which are relatively close to one another. To streamline the comparison, the average density of these values, calculated to be 1.19 g/cm³, is illustrated in **Figure 15**. Additionally, an average density was computed for curaua fiber, as two values are reported in the literature, and this average is also depicted in **Figure 15**. The densities of all intermediate layers are lower than the average density of Kevlar, except for the layers made from ramie fabric and mallow fabric. Notably, the difference in density between Kevlar and the epoxy-30 vol.% ramie fabric and epoxy-30 vol.% mallow fabric is only 3%, which is considered negligible. Furthermore, the density of epoxy-30 vol.% ramie fiber is the lowest among the samples, being 23% less than that of Kevlar.

Table 4. The density of different intermediate layers in the MAS.

The intermediate layer	Density (g/cm^3)(as a plate)	Reference
Kevlar™	1.08 ± 0.03	[26]
Kevlar™	1.09	[23]
Aramid fabric (Kevlar)	1.14	[27]
Aramid fabric	1.44	[28]
Epoxy-30 vol.% jute fabric	1.13± 0.07	[26]
Epoxy-30 vol.% mallow fiber	1.22	[39]
Epoxy- 30 vol.% mallow fabric	1.19	[29]
Epoxy-30 vol.% ramie fabric	1.23	[23]
Epoxy-30 vol.% ramie fibers	0.97	[32]
Epoxy-30 vol.% curaua fiber	1.05*	[40]
Epoxy-30 vol.% curaua fiber	0.98	[30]
Epoxy-30vol.% coir mantle	1.08	
Epoxy-30 vol.% bagasse fiber	1.03	
Epoxy-30 vol.% sisal fiber	1.12	[27]
Epoxy- 30 vol.% giant bamboo	1.09	[28]
Epoxy-30 vol.% (70 mallow/30 jute)	1.18	[29]
Epoxy-30 vol.% (50 mallow/50 jute)	1.17	
Epoxy-30 vol.% piassava	1.15*	[34]
Epoxy-30 vol.% Fique Fabric	1.06	[35]
Epoxy -30 vol.% Buriti Fabric	1.04*	[36]
*These values are calculated in this paper. Epoxy density (1.1 g/cm^3) was taken from [40]. The density of the fiber was taken from their original values. Piassava fiberdensity was taken as an average value from the references [33, 34]		

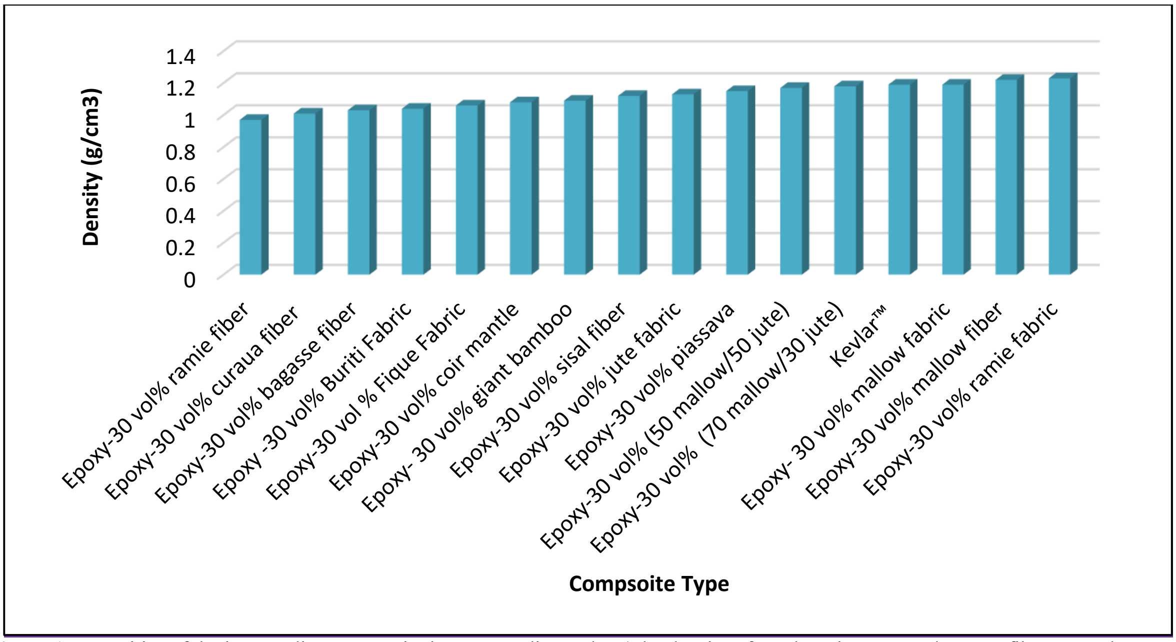

Figure 15. Densities of the intermediate composite in an ascending order. (The density of Kevlar, piassava, and curaua fiberswas taken as an average from different papers).

4. Conclusions

This study examined a variety of articles concerning the incorporation of natural fibers to improve traditional impact tests (Izod and Charpy) for epoxy polymer materials. Following the identification of enhancements in these standard tests, the research broadened its scope to include an analysis of additional literature regarding the influence of natural fibers on ballistic impact performance. Several conclusions can be drawn from this review. The natural fibers discussed in this review consistently demonstrated beneficial effects on the strength of the Izod and Charpy impact. Notably, the mallow fiber at a concentration of 30 wt.% achieved an impressive 842% increase in Charpy impact strength, while adding fique woven resulted in a modest improvement of 17%.Bio-epoxy composites utilized as second layer in the MAS exhibited potential as substitutes for synthetic Kevlar. Over ten varieties of 30 vol.% natural fiber-epoxy composites showed equal or reduced penetration depths compared to Kevlar in the clay witness following ballistic testing. All natural composites evaluated met the NIJ-level III standard, as the penetration depth in the clay witness remained below the threshold of 44 mm after the ballistic tests were conducted. The primary mechanism for energy dissipation was identified as the separation of fibrils, with additional energy loss occurring due to the epoxy fracture, as evidenced by SEM micrographs. The densities of all intermediate layers were lower than that of Kevlar, with ramie and mallow fabrics closely matching Kevlar's density. However, the density of the epoxy-30 vol.% ramie fiber was found to be 23% less than that of Kevlar. A notable cost disparity exists between bio-composites and Kevlar, with the 30 vol.% giant bamboo-epoxy composite emerging as the most economical alternative, resulting in a cost reduction of 2427%.

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Declaration of conflicting interests

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