Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 5	Month	: October
p-ISSN	: 1693-5462	Volume	: 23	Year	: 2025

Processing dates: received on 2025-9-21, reviewed on 2025-10-13, accepted on 2025-10-21 and online availability on 2025-10-30

Evaluation of mechanical and ballistic properties of abaca–polyester composites as a candidate material for bulletproof vests

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Abstract

This study aims to analyze the mechanical and ballistic properties of abaca (*Musa textilis*) fiber–reinforced polyester (BQTN 157) composites as an alternative candidate material for bulletproof vest panels. Variations in fiber orientation (bias-woven fiber, straight-woven fiber, and straight fiber) and fiber mass fractions (10%, 20%, and 30%) were applied to evaluate their influence on tensile strength, impact toughness, and ballistic response. The tensile test results revealed that the straight fiber alignment at a 10% mass fraction exhibited the best tensile strength of 54.12 MPa, strain of 0.021 mm/mm, the toughness of 43.90 kJ/m^2, and an elastic modulus of 2577 MPa. In the impact test, the same configuration achieved the maximum absorbed energy of 2.70 J. The ballistic testing with 9 mm FMJ projectiles (NIJ Level IIIA) demonstrated that all specimens with thicknesses of 15 mm and 20 mm experienced full penetration. The dominant failure mechanisms included delamination, fiber pull-out, matrix fracture, and shear plugging. These findings indicate that although abaca fiber composites possess good mechanical performance and sustainability advantages, further material engineering strategies—such as hybridization with synthetic fibers or the addition of ceramic/metallic layers—are required to enhance their ballistic resistance. Abaca–polyester composites require hybridization with synthetic fibers or additional protective layers to be viable for ballistic applications.

Keywords:
Abaca fiber, polyester resin, composites, mechanical properties, ballistic performance.

1 Introduction

Advances in material technology have driven the extensive use of composites across various sectors, including automotive, aerospace, construction, healthcare, and defense [1-3]. These materials exhibit a unique capability to absorb kinetic energy, making them promising candidates for protective applications such as body armor and bulletproof vests. In recent years, there has been growing interest in natural fibers as reinforcement materials for composites due to their abundant availability, relatively low cost, and environmentally friendly characteristics [4-6].

Several previous studies have extensively reported the use of flax, kenaf, and sisal fibers to improve the mechanical properties of polymer composites [2, 7]. The ballistic performance of these materials remains limited, indicating the need for further exploration of alternative fibers with distinct characteristics [8, 9].

Among various natural fibers, abaca (*Musa textilis*) stands out due to its relatively high tensile strength and abundant availability in Indonesia. These characteristics make abaca a promising candidate as reinforcement in composite materials [10, 11]. Its natural properties are influenced by the presence of lignin and extractives, which can hinder bonding with polymer matrices. Therefore, chemical treatments such as alkali treatment are often applied to improve fiber morphology, enhance interfacial adhesion to the matrix, and consequently increase its mechanical performance [12, 13].

Abaca fibers possess several advantages over other natural fibers, including relatively high tensile strength, good energy absorption capacity, and abundant availability in Indonesia [14]. The comprehensive studies that correlate the mechanical properties and ballistic performance of abaca fiber composites with variations in fiber orientation and mass fraction remain very limited [15-17].

In composite fabrication, the selection of the matrix plays a crucial role in determining material quality. Epoxy and polyester resins are among the most widely used types [15-18]. Specifically, BQTN 157 polyester resin was selected due to its low viscosity, cost-effectiveness, and ability to be processed at room temperature with the aid of a catalyst, making it suitable for natural fiber–based production [19, 20].

Bulletproof vests function by reducing the kinetic energy of projectiles and distribute it over a wider area, thereby causing the bullet to lose momentum before penetrating the protective layers [21]. The performance of such vests is typically evaluated using the standards established by the National Institute of Justice (NIJ), where Level IIIA requires materials to withstand 9 mm handgun projectiles at a specified distance. This standard is commonly used as a reference in ballistic testing of composite materials [22].

Several studies have reported the performance of natural fiber–based composites for ballistic protection applications. Pulungan demonstrated that carbon fiber–reinforced epoxy panels could absorb impact energy up to 138.77 J [23]. Marissa found that abaca fiber composites with a 25% mass fraction achieved tensile strengths of up to 47.6 MPa [24]. Meanwhile, Recardo reported that abaca fiber composites with an epoxy matrix were not sufficiently effective in resisting projectile penetration [25]. Based on these findings, it can be concluded that although abaca fibers show promising potential, further investigations are required, particularly with respect to fiber orientation, mass fraction, and appropriate matrix selection.

From the literature review, a research gap is evident in the utilization of abaca fibers as a primary material for bulletproof vest panels. Most studies have primarily focused on basic mechanical properties such as tensile and impact strength, while investigations into their ballistic performance remain limited. Furthermore, research on the effects of fiber orientation and mass fraction in polyester resin matrices is still scarce. Therefore, this study is designed to evaluate the mechanical properties (tensile and impact) as well as the ballistic response of abaca fiber composites with different fiber orientations (oblique weave, straight weave, and parallel alignment) and mass fractions (10%, 20%, and 30%).

2 Research methodology

This study employed an experimental approach consisting of three main stages: the fabrication of abaca fiber–reinforced polyester composites, the evaluation of their mechanical properties (tensile and impact), and the preparation of composite panels for subsequent ballistic testing. This sequence was designed to provide a comprehensive overview of the material’s characteristics, both in terms of mechanical performance and resistance to projectile penetration.

2.1 Time and location

The research activities were conducted at several different locations. Specimen fabrication was carried out at the Mechanical Engineering Laboratory, Faculty of Science and Technology, Universitas Samudra. Mechanical testing, including tensile and impact tests, was performed at the Integrated Laboratory of Universitas Samudra. Meanwhile, ballistic testing of the composite vest panels was conducted at the testing facility of the Mobile Brigade Unit (Brimob), Battalion B, Company 2, Bireum Bayeun, East Aceh.

2.2 Tools and materials

The equipment used in this study included a 9 mm Sig Sauer pistol for ballistic testing, a tensile testing machine, a Charpy impact testing machine, specimen molds, a grinder, a digital scale, a caliper, and other supporting tools such as plastic cups and stirrers. The materials employed consisted of abaca fibers obtained from East Aceh Regency, BQTN 157 polyester resin as the matrix, a catalyst, sodium hydroxide (NaOH) solution for fiber treatment, and mirror glaze as a mold release agent.

2.3 Samples preparation

The abaca fibers used in this study were harvested, cleaned, and dried before undergoing alkali treatment with NaOH solution to improve surface quality and enhance bonding with the matrix. The NaOH solution used had a concentration of 3%, with fibers immersed for 3 hours and subsequently dried under sunlight for one full day. After preparation, the fibers were arranged in three bias-woven, straight-weave, and straight alignment—and molded using the hand lay-up method. Polyester resin was poured and evenly distributed onto the fiber arrangement with the aid of a roller to ensure uniform resin penetration. This process produced specimens for tensile testing, impact testing, and composite vest panels. The steps of the abaca fiber preparation process are illustrated in Fig. 1.

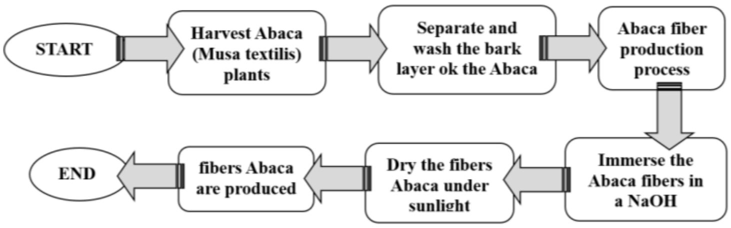

Fig. 1. Step abaca fibers production process.

The mechanical characteristics of the specimens were evaluated through tensile and impact tests. A total of three specimens were used in these tests. The composition and codes of the tensile test specimens are presented in Table 1, while the impact test results are shown in Table 2. For the ballistic test, the specimen codes are listed in Table 3.

Table 1. Codes and composition of tensile test samples abaca-polyester composite

Compositions (% mass)		Specimens code		
		Fiber orientations		
Fibers	Resin	Bias-woven fibers (Ta)	Straight-woven fibers (Tb)	Straight fibers (Tc)
10 %	90 %	Ta1.1	Tb1.1	Tc1.1
		Ta1.2	Tb1.2	Tc1.2
		Ta1.3	Tb1.3	Tc1.3
20 %	80 %	Ta2.1	Tb2.1	Tc2.1
		Ta2.2	Tb2.2	Tc2.2
		Ta2.3	Tb2.3	Tc2.3
30 %	70 %	Ta3.1	Tb3.1	Tc3.1
		Ta3.2	Tb3.2	Tc3.2
		Ta3.3	Tb3.3	Tc3.3

Table 2. Codes and composition of impact test samples

Compositions (% mass)		Specimens code		
		Fiber orientations		
Fibers	Resin	Bias-woven fibers (Ia)	Straight-woven fibers (Ib)	Straight fibers (Ic)
10 %	90 %	Ia1.1	Ib1.1	Ic1.1
		Ia1.2	Ib1.2	Ic1.2
		Ia1.3	Ib1.3	Ic1.3
20 %	80 %	Ia2.1	Ib2.1	Ic2.1
		Ia2.2	Ib2.2	Ic2.2
		Ia2.3	Ib2.3	Ic2.3
30 %	70 %	Ia3.1	Ib3.1	Ic3.1
		Ia3.2	Ib3.2	Ic3.2
		Ia3.3	Ib3.3	Ic3.3

Table 3. Codes of ballistic test specimens

Code	Fiber orientation	Thickness (mm)	Volume (cm^3)	Mass (g)
P15L	Straight	15	450	558
P15A	Woven	15	450	558
P20L	Straight	20	600	747
P20A	Woven	20	600	747

2.4 Experimental procedure

2.4.1 Tensile testing

Tensile testing of the composite material was carried out in accordance with ASTM D3039, as illustrated in Fig. 2. The purpose of this test was to determine the tensile strength of the material. The results provide an indication of the composite's ability to withstand tensile forces, which is an essential parameter for its use in protective applications.

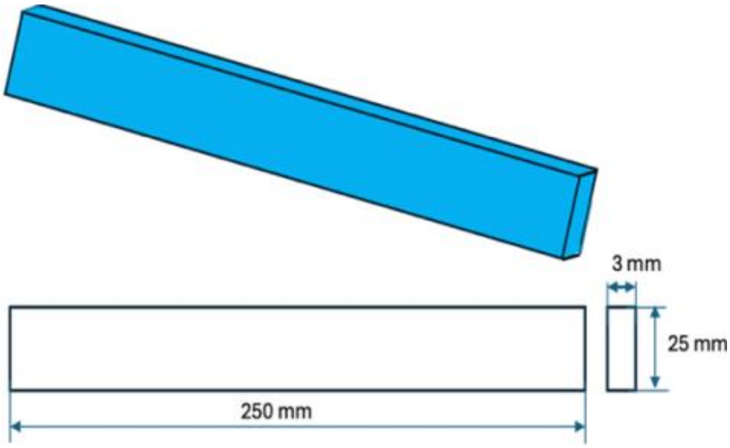

Fig. 2. Tensile specimen ASTM D3039.

2.4.2 Charpy impact testing

The Charpy impact test was conducted using the Charpy method in accordance with ASTM D6110-10, as illustrated in Fig. 3. This test aimed to determine the toughness of the material under sudden loading. The energy absorbed during impact was measured to evaluate the material's resistance to fracture, which represents a critical factor in the application of bulletproof vests.

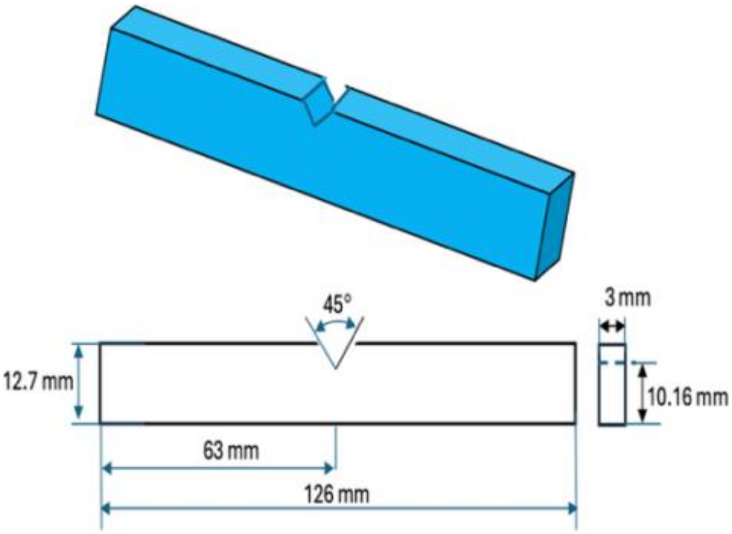

Fig. 3. Charpy impact specimen ASTM D6110-10.

2.4.3 Ballistic testing

The final stage involved ballistic testing, which was carried out in accordance with the NIJ Level IIIA standard. The composite panels were subjected to firing using a Sig Sauer 9 mm pistol with 9×19 mm ammunition at 10 meters. Each panel was shot once at the center point of its surface to evaluate the material's ability to resist projectile penetration. The results of this test serve as the basis for assessing the feasibility of abaca fiber-reinforced composites as an alternative material for bulletproof vest panels. Therefore, the ballistic test setup is shown in Fig. 4.

3 Results and discussion

3.1 Results of preparing specimens

The prepared specimens designated for tensile testing, Charpy impact testing, and ballistic testing are shown in Fig. 5, Fig. 6, and Fig. 7, respectively. These figures illustrate the specimen configurations that were fabricated according to the specific requirements of each testing method.

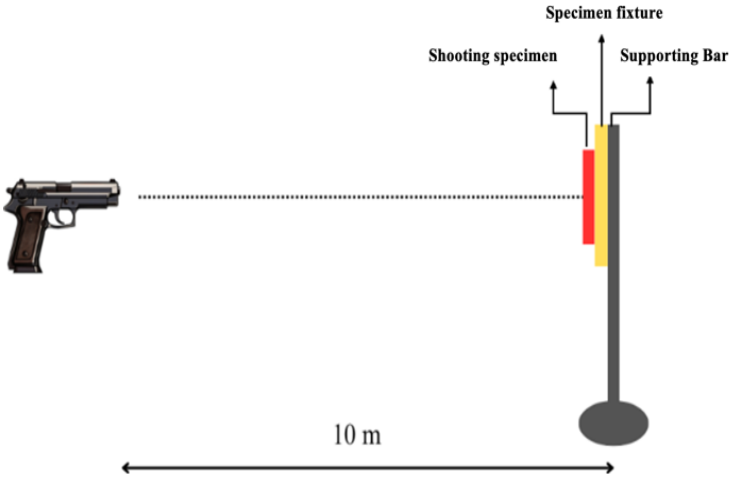

Fig. 4. Ballistic test setup.

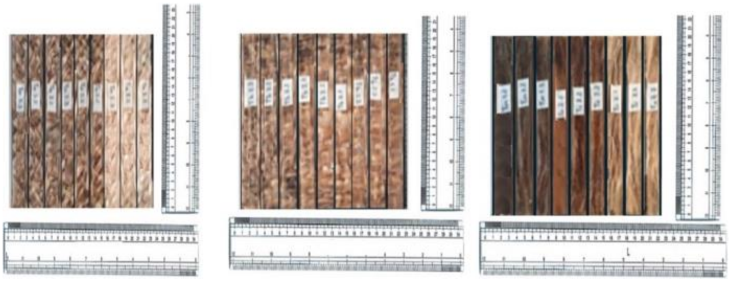

Fig. 5. Shows the produced tensile test specimens.

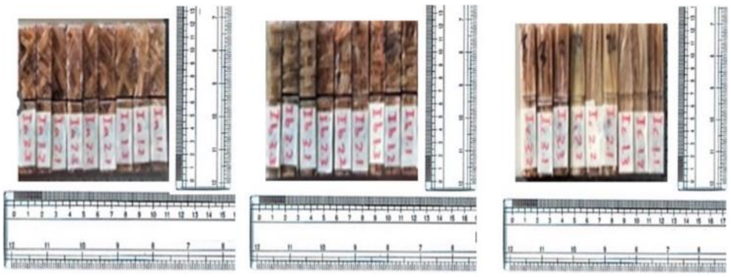

Fig. 6. Shows the produced impact test specimens.

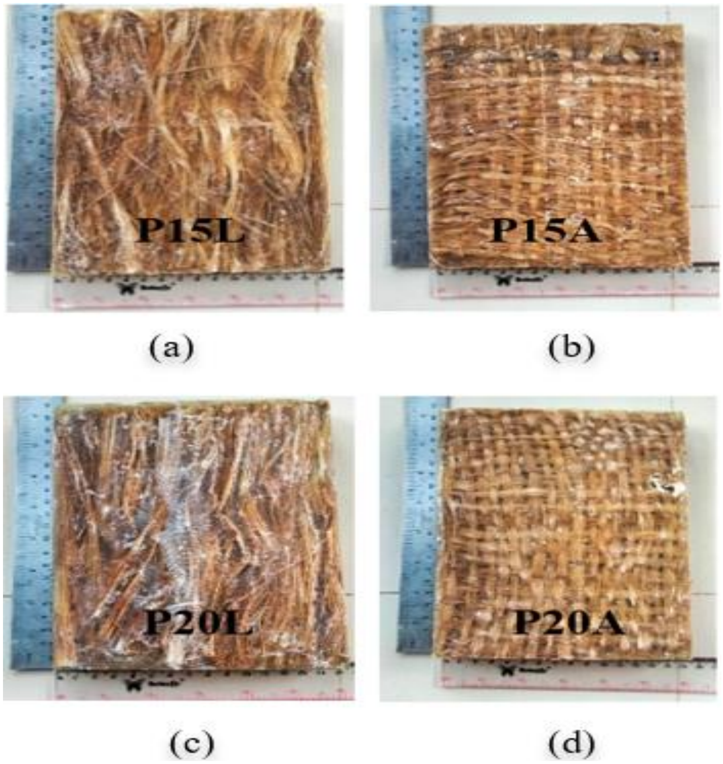

Fig. 7. Shows the produced ballistic test specimens: (a) P15L (b) P15A (c) P20L (d) P20A.

3.2 Results of tensile testing

3.2.1 Tensile testing of Ta specimens

Fig. 8 presents the stress–strain curves for specimens with bias-woven fiber orientation (Ta) at fiber mass fractions of 10%, 20%, and 30%. The curves exhibit linear elastic behavior up to the peak stress, followed by a decline in strength associated with material failure.

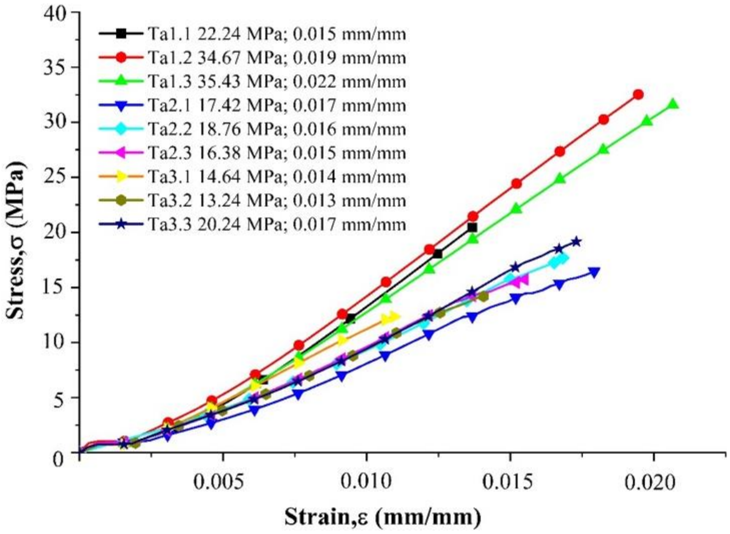

Fig. 8. Stress–strain graph of Ta specimens.

At a fiber mass fraction of 10%, the highest tensile strength was achieved by specimen Ta1.3, reaching 35.43 MPa at a strain of 0.022 mm/mm, followed by Ta1.2 at 34.67 MPa, while Ta1.1 reached only 22.24 MPa. These results indicate that at lower fiber content, the resin distribution is more uniform, thereby allowing more effective stress transfer from the matrix to the fibers. In contrast, at a 20% fiber mass fraction, a reduction in tensile strength was observed, with maximum values ranging from 16.38 to 18.76 MPa, and the best performance shown by specimen Ta2.2. This reduction can be attributed to insufficient resin coverage of the fibers, leading to the formation of voids and weakening of the fiber–matrix bonding. A similar trend was observed at a 30% fiber mass fraction, where the tensile strength further decreased within the range of 13.24–20.24 MPa. Among these, specimen Ta1.3 exhibited relatively better performance (35.43 MPa) compared to Ta3.2 (13.24 MPa), although still lower than the 10% variation. This finding confirms that increasing fiber content in inclined woven configurations does not necessarily enhance the mechanical strength but instead tends to reduce the material's performance due to the imbalance between fiber and resin composition. The decline in tensile strength observed at higher fiber contents aligns with the findings of Meriatna (2019), who showed that when the fiber volume in abaca–polyester composites increase, the resin can no longer completely wet the fibers, causing voids that weaken interfacial bonding [26].

3.2.2 Tensile testing of Tb specimens

Fig. 9 presents the stress–strain curves for specimens with straight-woven fiber orientation (Tb) at fiber mass fractions of 10%, 20%, and 30%. At a fiber mass fraction of 10%, the highest tensile strength was achieved by specimen Tb1.2, reaching 39.45 MPa at a strain of 0.034 mm/mm, followed by Tb1.3 at 31.34 MPa and Tb1.1 at 22.27 MPa. These results indicate that at lower fiber content, the resin was able to coat the fibers more uniformly, resulting in more effective stress transfer from the matrix to the fibers. For the 20% fiber mass fraction, the tensile strength tended to decrease, with values ranging from 19.25 to 29.18 MPa. The best performance was exhibited by specimen Tb2.1 with a tensile strength of 29.18 MPa, while Tb2.2 showed the lowest value at 19.25 MPa. This reduction is associated with insufficient resin wetting of the fibers, which promotes void formation and reduces the efficiency of stress transfer. The improved tensile behavior at lower fiber fractions corresponds with similar pattern was observed by Rangappa (2022), who explained that poor resin flow in woven natural fiber structures can reduce stress transfer efficiency and cause premature tensile failure [14].

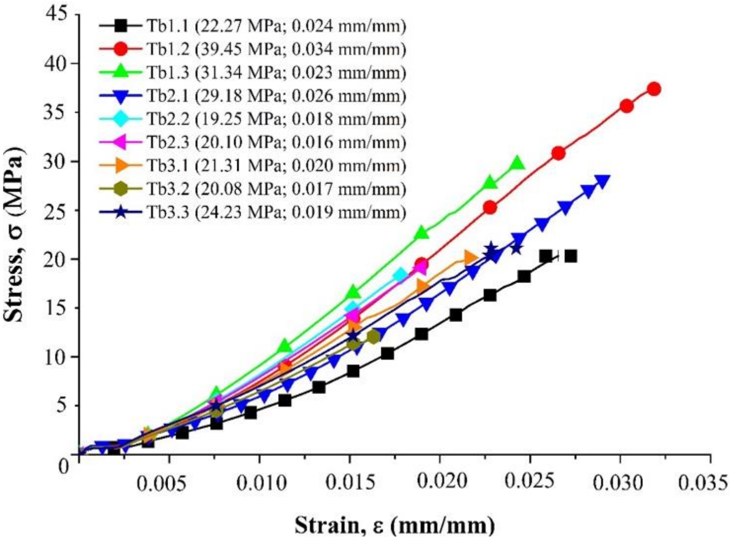

Fig. 9. Stress–strain graph of Tb specimens.

For the 20% fiber mass fraction, the tensile strength tended to decrease, with values ranging from 19.25 to 29.18 MPa. The best performance was exhibited by specimen Tb2.1 with a tensile strength of 29.18 MPa, while Tb2.2 showed the lowest value at 19.25 MPa. This reduction is associated with insufficient resin wetting of the fibers, which promotes void formation and reduces the efficiency of stress transfer. The strength reduction at higher fiber mass fractions is consistent with the work of Mylsamy (2024), who indicated that limited resin penetration at high fiber loadings increases interfacial voids and stress concentration points [12].

At a fiber mass fraction of 30%, the tensile performance became relatively inconsistent. The maximum stress values ranged between 21.31 and 24.23 MPa, with Tb3.3 showing the best performance (24.23 MPa). This condition confirms that excessive fiber content in the straight woven orientation leads to reduced mechanical strength due to non-uniform stress distribution and weak fiber–matrix interfacial bonding. The inconsistent tensile performance recorded at 30% fiber fraction agrees with Rangappa (2022), who noted that over-reinforced woven composites tend to develop fiber clustering and weak matrix adhesion, resulting in poor load distribution [14]. This observation is also in line with Meriatna (2019**)**, who stated that excessive abaca content causes resin starvation and weakens composite integrity [26].

3.2.3 Tensile testing of Tc specimens

Fig. 10 illustrates the stress–strain response of specimens with straight fiber mass fraction orientation (Tc) at fiber mass fractions of 10%, 20%, and 30%. The curves reveal a predominantly linear elastic behavior up to the maximum stress, after which the strength declines due to fiber or interfacial failure.

At 10% fiber content, specimen Tc1.1 recorded the highest tensile strength of 54.12 MPa at a strain of 0.021 mm/mm, followed by Tc1.3 (53.48 MPa) and Tc1.2 (51.63 MPa). This superior performance indicates that fibers aligned parallel to the loading axis provide efficient load transfer from the matrix to the reinforcement, thereby maximizing fiber contribution to tensile resistance. For the 20% fiber mass fraction, tensile strength decreased slightly compared to the 10% variation, with values ranging from 33.32 to 35.25 MPa. The best result was obtained by specimen Tc2.3 (35.25 MPa), while Tc2.2 exhibited the lowest strength (33.32 MPa). The reduction is attributed to insufficient resin penetration and heterogeneous fiber wetting, which limits the efficiency of stress transfer and increases susceptibility to interfacial debonding. At 30% mass fiber loading, tensile strength values further declined, ranging between 31.67 and 35.17 MPa. Specimen Tc3.3 achieved the highest strength (35.17 MPa), while Tc3.1 showed the lowest (31.67 MPa). Despite outperforming the bias-woven (Ta) and straight-woven (Tb) orientations, excessive fiber content in the straight (parallel) configuration promotes void formation and weakens fiber–matrix adhesion, preventing linear improvements in mechanical strength.

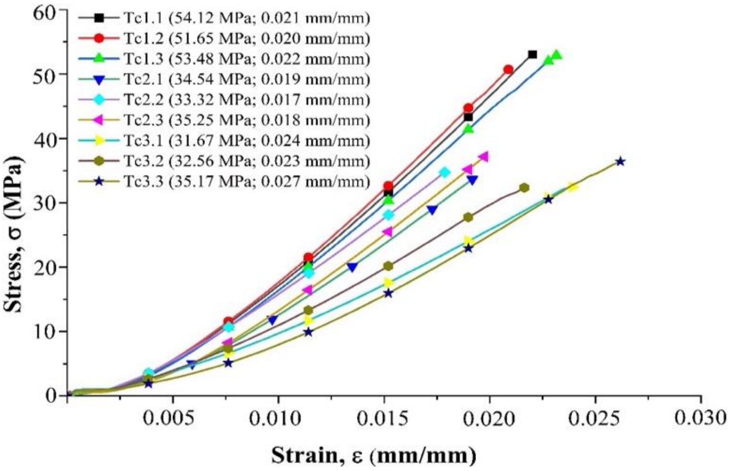

Fig. 10. Stress–strain graph of Tc specimens.

The superior tensile performance of the straight (parallel) fiber configuration supports the conclusion by Nayak (2021) that fiber alignment parallel to the loading direction enhances stress transmission and stiffness in natural fiber composites [22]. Similarly, Paglicawan (2020) demonstrated that abaca fiber composites with well-aligned reinforcement achieved high tensile strengths due to efficient load transfer and improved adhesion between fiber and matrix [24].

Overall, the straight fiber orientation (Tc) exhibited the greatest tensile strength among the three fiber architectures. This outcome underscores the efficiency of fiber alignment with the applied load direction, which facilitates direct stress transfer along the fibers. Consequently, the straight (parallel) configuration proves to be the most effective in optimizing the mechanical response of abaca fiber–reinforced composites. Table 4 presents the mechanical properties obtained from the tensile tests of each specimen.

Table 4 presents the mechanical properties obtained from the tensile tests for specimens Ta, Tb, and Tc. The data highlight the influence of fiber orientation and fiber mass fraction on the tensile behavior of abaca fiber–reinforced composites. Overall, the straight fiber orientation (Tc) consistently exhibits the highest tensile strength compared to the bias-woven (Ta) and straight-woven (Tb) configurations. In contrast, both Ta and Tb orientations demonstrate lower tensile performance, particularly at higher fiber fractions, which can be attributed to inadequate resin distribution, the formation of voids, and weakened fiber–matrix interfacial bonding. These findings confirm that fiber alignment straight to the loading direction enables more effective stress transfer, thereby enhancing the tensile properties of the composite. The finding that straight fiber orientation yields the highest tensile strength corresponds with Kurien (2023), who highlighted that proper fiber alignment and compatibility between fiber and matrix are essential for optimizing the mechanical performance of abaca-based composites [11].

Table 4. Mechanical properties the tensile test results

Specimens	Stress σ (MPa)	Strain ε (mm/mm)	Modulus E (MPa)
Ta1	30.78	0.019	1620.00
Ta2	26.28	0.016	1642.05
Ta3	16.04	0.014	1145.71
Tb1	31.02	0.027	1148.89
Tb2	22.84	0.020	1142.00
Tb3	21.87	0.019	1151.05
Tc1	53.08	0.021	2527.62
Tc2	34.37	0.018	1909.44
Tc3	33.13	0.024	1380.42

The comparison of tensile strength of abaca fiber composites with three different fiber orientations is presented in Table 5. The data clearly demonstrates that fiber orientation plays a decisive role in determining the mechanical performance of the composite. Among the three orientations, the straight (parallel) configuration exhibits the highest tensile strength due to its alignment with the loading direction, which facilitates more efficient stress transfer. In contrast, the inclined orientation shows the lowest tensile performance as the misalignment between fiber direction and applied load leads to non-uniform stress distribution. The straight weave orientation provides intermediate results, but its strength tends to decline at higher fiber fractions because of void formation and weakened fiber–matrix interfacial bonding. These findings emphasize that optimizing fiber orientation is crucial for achieving maximum mechanical efficiency in abaca fiber–reinforced composites. The finding that straight fiber orientation yields the highest tensile strength corresponds with Abdullah (2024) confirmed that unidirectional natural fiber composites show improved tensile properties because of more uniform load distribution and reduced interfacial stress concentrations [27].

In general, these results indicate that straight fiber orientation with a low mass fiber fraction (10%) represents the optimal configuration for enhancing the mechanical properties of abaca–polyester composites. The straight (parallel) orientation facilitates uniform stress distribution, while the low fiber fraction minimizes void formation due to resin limitations.

Table 5. Comparison of tensile strength of abaca fiber composites

Fiber orientation	Fiber fraction 10% (MPa)	Fiber fraction 20% (MPa)	Fiber fraction 30% (MPa)	General characteristics
Bias-woven fibers (Ta)	22.24 – 35.43	16.38 – 18.76	13.24 – 20.24	Misalignment with the applied load results in non-uniform stress distribution
Straight-woven fibers (Tb)	22.27 – 39.45	19.25 – 29.18	20.08 – 24.24	Excessive fiber content promotes void formation and weakens interfacial bonding
Straight fibers (Tc)	51.65 – 54.12	33.32 – 35.25	31.67 – 35.17	Fiber alignment parallel to the applied load enables the most efficient stress transfer

This research is consistent with the report by Marissa (2020), which demonstrated that abaca fiber composites with an epoxy matrix at a 25% volume fraction could achieve tensile strengths up to 47.6 MPa [24]. The discrepancy in values compared to the present study is primarily attributed to the type of matrix, as epoxy exhibits superior interfacial bonding capabilities compared to BQTN 157 polyester. Nonetheless, the trend regarding the influence of fiber orientation on tensile strength aligns with literature.

Furthermore, Meriatna (2019), reported that increasing the abaca fiber fraction does not necessarily improve mechanical strength due to the resin's limited ability to fully wet the fibers, ultimately reducing the effectiveness of the fiber–matrix bonding. A similar phenomenon was observed in this study, where higher fiber fractions (20–30% volume) resulted in lower tensile strength [26].

Compared with other natural fibers, the abaca–polyester composite with a straight orientation (54.11 MPa) is relatively competitive. According to Abdullah, kenaf–polyester composites exhibit tensile strengths around 11.39 MPa, while sisal–epoxy composites range from 32 to 36 MPa [27]. Therefore, although still lower than epoxy-based composites, the performance of straight (parallel) oriented abaca–polyester composites are comparable to that of kenaf and sisal fibers.

Based on the research of this study, it can be concluded that a parallel fiber orientation with a 10% fraction is the most efficient configuration, providing the best combination of tensile strength and elastic modulus. These results further underscore the potential of abaca fibers as a sustainable reinforcement material, although performance improvements may be achievable through the selection of matrices with superior interfacial bonding or via fiber hybridization strategies. This conclusion is consistent with the work of Mylsamy (2024) and Rangappa (2022), who noted that well-aligned and properly wetted fibers improve the overall tensile response of natural fiber composites [12,14].

3.3 Results of charpy impact testing

The ability of a material to resist sudden or dynamic loading is commonly defined as its impact strength, which reflects the material's toughness. In the Charpy impact test, a pendulum hammer is released to strike the specimen, and the energy absorbed during fracture is recorded as an indicator of the material's resistance to sudden failure. For abaca fiber–reinforced composites, this parameter is essential for evaluating their potential application in protective systems such as bulletproof panels. A higher absorbed energy value indicates a greater capacity of the composite to withstand sudden impact, thereby enhancing its effectiveness in protective applications. The role of fiber alignment and volume fraction in determining impact strength is consistent with Pulungan (2017), who demonstrated that the uniform distribution of fibers increases the ability of composites to absorb energy during impact [23].

3.3.1 Charpy impact testing of Ia specimens

Charpy impact tests on specimens with a bias-woven fiber orientation (Ia) at fiber mass fractions of 10%, 20%, and 30%. The parameters evaluated included absorbed energy (J) and impact toughness (kJ/m²). Table 6 presents the results of Charpy impact Ia.

For the 10% fiber fraction (Ia1), the average impact toughness reached 9.95 kJ/m², with an absorbed energy of 0.61 J. The highest value was observed in specimen Ia1.1, which absorbed 0.96 J of energy with a toughness of 15.57 kJ/m². This indicates that at a low fiber fraction, the resin can more effectively penetrate the fibers, resulting in a strong interfacial bond and enhanced energy absorption capability of the material. Nayak (2021) showed that well-oriented natural fibers can significantly enhance the material's resistance to dynamic and ballistic loads [22].

Table 6. Results of specimen impact testing (Ia)

Specimens	Energy (J)	Strength (kJ/m²)
Ia1.1	0.96	15.57
Ia1.2	0.58	9.40
Ia1.3	0.30	4.89
Average (Ia1)	0.61	9.95
Deviation standard (Ia1)	0.33	5,36
Ia2.1	0.71	11.51
Ia2.2	0.50	8.13
Ia2.3	0.48	7.73
Average (Ia2)	0.56	9.12
Deviation standard (Ia2)	0.13	2.08
Ia3.1	0.32	5.23
Ia3.2	0.45	7.34
Ia3.3	0.31	5.00
Average (Ia3)	0.36	5.86
Deviation standard (Ia3)	0.08	1.29

At a 20% fiber fraction (Ia2), the impact toughness decreased to 9.12 kJ/m², with an average absorbed energy of 0.56 J. The best-performing specimen in this group, Ia2.1, exhibited a toughness of 11.51 kJ/m². This reduction suggests limitations in resin penetration between fibers at higher fractions, leading to the formation of voids that reduce energy absorption. For the 30% fiber fraction (Ia3), impact performance further declined, with an average toughness of only 5.86 kJ/m² and absorbed energy of 0.36 J. The lowest-performing specimen, Ia3.3, recorded a toughness of 5.00 kJ/m². These results demonstrate that increasing the fiber fraction in a bias-woven orientation does not necessarily enhance mechanical properties, as interfacial bonding weakens due to insufficient resin coverage of the fiber surfaces. Overall, these findings confirm that a low fiber fraction (10%) in bias-woven orientation yields the best impact performance, whereas increasing the fiber fraction reduces toughness. These findings correspond with Meriatna (2019), who reported that increasing fiber content beyond 20% causes a reduction in impact energy absorption due to limited resin penetration and poor interfacial bonding [26]. Similarly, Pulungan (2017) found that lower fiber content leads to higher impact resistance because of better bonding uniformity and energy dispersion [23].

3.3.2 Charpy impact testing of Ib specimens

Table 7 presents the Charpy impact test results for specimens with straight-woven fiber orientation (Ib) at fiber fractions of 10%, 20%, and 30%.

Table 7. Results of specimen impact testing (Ib)

Specimens	Energy (J)	Strength (kJ/m^2)
Ib1.1	0.42	6.05
Ib1.2	0.70	11.38
Ib1.3	0.63	10.27
Average (Ib1)	0.58	9.24
Deviation standard (Ib1)	0.15	2.81
Ib2.1	0.45	7.45
Ib2.2	0.56	9.12
Ib2.3	0.36	5.95
Average (Ib2)	0.46	7.51
Deviation standard (Ib2)	0.10	1.59
Ib3.1	0.25	4.20
Ib3.2	0.40	6.54
Ib3.3	0.45	7.32
Average (Ib3)	0.37	6.02
Deviation standard (Ib3)	0.10	1.62

For the 10% mass fiber fraction (Ib1), the average toughness was recorded at 9.24 kJ/m², with an absorbed energy of 0.58 J. The highest value was observed in specimen Ib1.2, which absorbed 0.70 J of energy with a toughness of 11.38 kJ/m². This indicates that at a low fiber mass fraction, the fiber–matrix interactions are sufficiently effective, allowing the material to withstand impact energy efficiently. At a 20% fiber mass fraction (Ib2), impact performance decreased, with an average toughness of 7.51 kJ/m² and absorbed energy of 0.46 J. The best-performing specimen in this group, Ib2.2, exhibited a toughness of 9.12 kJ/m². This reduction suggests that as the fiber fraction increases, resin infiltration becomes limited, potentially leading to internal defects such as voids, which weaken the interfacial bonding. For the 30% fiber mass fraction (Ib3), the average toughness further declined to 6.02 kJ/m², with an average absorbed energy of 0.37 J. Specimen Ib3.1 recorded the lowest toughness at 4.20 kJ/m². This confirms that increasing the fiber fraction in the straight-woven orientation does not provide significant mechanical advantages and may even reduce the composite's ability to absorb impact energy. When compared to the bias-woven orientation (Ia), the straight-woven orientation (Ib) exhibited a similar trend, where the best performance occurred at a 10% fiber mass fraction, and increasing the mass fraction to 20% and 30% tended to decrease toughness. Therefore, the average toughness for the straight-woven orientation was slightly higher than that of the bias-woven orientation at low fiber fractions. The decrease in toughness with increased fiber loading supports the conclusions of Rangappa (2022), who explained that excessive reinforcement leads to micro voids and internal stress accumulation, weakening impact resistance [14]. Mylsamy (2024) also pointed out that a balanced fiber–resin ratio ensures adequate bonding and maximizes the material's capacity to absorb sudden energy [12].

3.3.3 Charpy impact testing of Ic specimens

Table 8 presents the Charpy impact test results for specimens with a straight fiber orientation (Ic) at fiber fractions of 10%, 20%, and 30%.

Table 8. Results of specimen impact testing (Ic)

Specimens	Energy (J)	Strength (kJ/m^2)
Ic1.1	0.82	13.31
Ic1.2	2.70	43.90
Ic1.3	2.38	38.64
Average (Ic1)	2.54	31.95
Deviation standard (Ic1)	1.01	16.35
Ic2.1	1.69	27.42
Ic2.2	1.46	23.66
Ic2.3	1.83	29.66
Average (Ic2)	1.66	26.91
Deviation standard (Ic2)	0.19	3.04
Ic3.1	1.02	16.54
Ic3.2	1.22	19.73
Ic3.3	1.08	17.45
Average (Ic3)	1.10	17.91
Deviation standard (Ic3)	0.10	1.64

For the 10% fiber mass fraction (Ic1), the average toughness reached 31.95 kJ/m² with an average absorbed energy of 2.54 J. Specimen Ic1.2 exhibited the best performance, achieving a toughness of 43.90 kJ/m², the highest value among all samples in this study. These results indicate that at a low fiber mass fraction, the straight fiber orientation is highly effective in transferring impact energy, as the fibers are aligned with the force direction, allowing deformation to be resisted more efficiently. For the 20% fiber mass fraction (Ic2), the average toughness slightly decreased to 26.91 kJ/m², with an absorbed energy of 1.66 J. Although still relatively high, this decreasing trend suggests the influence of a higher fiber fraction, where resin distribution becomes less uniform and some fiber areas are not fully bonded. This condition may lead to internal defects, reducing the efficiency of energy absorption. At the 30% fiber mass fraction (Ic3), impact performance further declined, with an average toughness of only 17.91 kJ/m² and absorbed energy of 1.10 J. Specimen Ic3.1 recorded the lowest toughness at 16.54 kJ/m². This substantial reduction confirms that increasing the fiber mass fraction in straight orientation diminishes impact properties due to limited resin infiltration and the emergence of porosity. The superior impact toughness of straight fiber specimens at 10% fiber fraction agrees with Nayak (2021), who found that parallel fiber alignment optimizes energy absorption in composite armor systems [22]. This observation is further validated by Pulungan (2017), who reported that unidirectional fiber arrangements enhance the absorbed impact energy compared with woven orientations [23].

Compared to the bias-woven (Ia) and straight-woven (Ib) orientations, the straight fiber specimens (Ic) consistently exhibited significantly higher toughness values, particularly at the 10% fiber mass fraction. This demonstrates that straight (parallel) fiber orientation is the most effective configuration for enhancing the material's resistance to impact loads. It can be concluded that abaca fiber composites with a straight orientation (Ic) and a 10% fiber mass fraction represent the optimal configuration for resisting impact energy, with a maximum toughness of 43.90 kJ/m². Increasing the fiber mass fraction to 20% and 30% reduces performance, although the values remain higher than those of both skewed and straight woven orientations. The decreasing impact toughness with increasing fiber fraction corresponds with Meriatna (2019), who found that excessive fiber volume introduces voids and poor resin wetting, resulting in lower impact resistance [26]. Additionally, Rangappa (2022) stated that higher fiber packing density disrupts stress distribution and lowers the composite's ability to absorb shock loads [14].

The Charpy impact test results across all fiber orientations indicate that fiber alignment and fraction critically influence energy absorption and toughness. For bias-woven fibers (Ia) and straight-woven fibers (Ib), the best performance occurred at a low fiber mass fraction (10%), with toughness values of 9.95 kJ/m² and 9.24 kJ/m², respectively, while increasing the fiber mass fraction to 20% and 30% led to decreased toughness due to limited resin penetration and void formation. In contrast, the straight fiber orientation (Ic) exhibited markedly superior performance, with a maximum toughness of 43.90 kJ/m² at a 10% mass fiber fraction and consistently higher values across all fractions compared to Ia and Ib. These findings demonstrate that straight fiber configuration is the most effective for enhancing the composite's resistance to impact loading, while higher fiber fractions generally reduce impact performance due to insufficient matrix infiltration and increased porosity. A low fraction of straight fibers (10%) represents the optimal configuration for maximizing energy absorption and impact toughness in abaca–polyester composites.

The present study corroborates previous findings on the critical role of fiber orientation and fraction in determining the impact performance of natural fiber composites. Pulungan (2017), highlighted that straight fibers aligned in volume with the loading direction significantly enhance energy absorption compared to complex woven patterns [23]. Similarly, Meriatna (2019), reported that increasing the fiber volume fraction does not necessarily improve mechanical properties, as higher fractions can induce void formation and reduce toughness, a trend observed in this study for 20% and 30% fiber fractions [26]. Moreover, Nayaka *et al.* (2021) emphasized that straight (parallel) fiber arrangements are essential for improving ballistic limits and composite toughness [22]. Consistent with these reports, the current findings indicate that a straight, parallel fiber configuration with a 10% fiber fraction yields the highest impact resistance and toughness in abaca–polyester composites. This configuration represents the optimal balance between effective fiber–matrix bonding and energy absorption, confirming the superiority of aligned fiber orientations over woven patterns for impact mitigation.

3.4 Results ballistic testing

Ballistic testing was performed to assess the resistance of abaca–polyester composite panels against projectile impact. Each panel was subjected to a single ballistic shot, with fiber orientations arranged either as straight (aligned) or woven.

The panels were manufactured with thicknesses of 15 mm and 20 mm to investigate the influence of both fiber orientation and panel thickness on impact resistance. Specimen performance, including penetration depth and material deformation, was systematically documented, providing a comparative assessment of straight versus woven fiber configurations under identical ballistic loading conditions (Table 9).

Table 9. Results ballistic testing fiber orientations

Code	Fiber orientations	Thickness (mm)	Weight (g)	Projectile penetrated
P15L	Straight	15	558	penetrated
P15A	Woven	15	558	penetrated
P20L	Straight	20	747	penetrated
P20A	Woven	20	747	penetrated

Ballistic testing on abaca fiber composites with straight (P15L, P20L) and woven (P15A, P20A) fiber orientations at thicknesses of 15 mm and 20 mm demonstrated that all specimens experienced complete penetration by the projectile (Table 9). These findings indicate that, in their current configuration, abaca fiber–reinforced composites are unable to meet the basic requirements of projectile stopping capability. The ballistic performance of the composites with straight and woven fiber orientations is illustrated in Fig. 11 and Fig. 12.

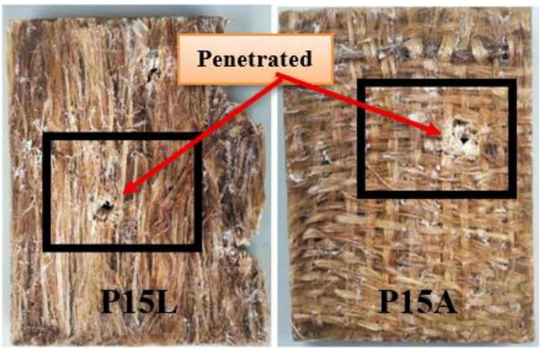

Fig. 11. Ballistic test results of specimens P15L and P15A.

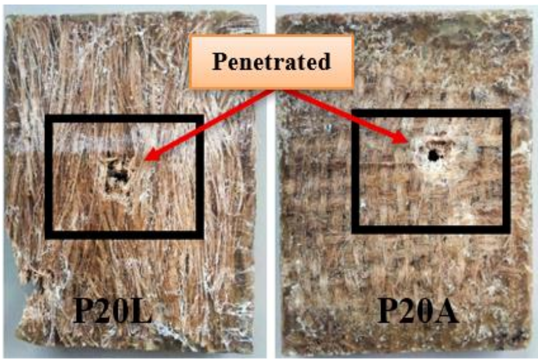

Fig. 12. Ballistic test results of specimens P20L and P20A.

According to NIJ Standard–0101.06, body armor rated at Level III must be capable of stopping a 9 mm Full Metal Jacket (FMJ) bullet traveling at approximately 373 m/s without penetration, while Level III requires resistance against a 7.62 mm NATO projectile at approximately 847 m/s. In this study, even the thickest panel (20 mm, 747 g) failed to prevent penetration, indicating that abaca composites in single-layer configurations do not meet the minimum NIJ Level III requirements [22].

The inability of the composite panels to stop projectiles, despite an increase in thickness from 15 mm to 20 mm, demonstrates that thickness alone is insufficient to improve ballistic performance. Critical factors include the tensile strength of abaca fibers, adhesion quality at the fiber–matrix interface, and the efficiency of load distribution between fibers. Although woven orientations are theoretically expected to enhance interlocking and frictional resistance, no significant improvement over straight orientations were observed in preventing projectile penetration. The inability of abaca–polyester composites to resist projectile penetration is consistent with the simulation results of Sirot (2023), who reported that abaca–epoxy composites could absorb substantial energy but still failed to stop 9 mm FMJ bullets due to weak fiber–matrix interfaces [25]. In contrast, Fonseca (2025) demonstrated that composites reinforced with aramid fabrics successfully met NIJ ballistic standards, underscoring the superior bonding and energy dissipation of synthetic fibers compared to natural ones [29].

Similarly, Kondor *et al.* (2025) demonstrated composites reinforced with Armor Aramid Fabric successfully resisted ballistic penetration according to NIJ Standard–0108.01, highlighting the superior interfacial bonding and energy dissipation of aramid composites [28]. In addition, Mandal *et al.* (2024) showed that para-aramid fiber–reinforced composites in polymer matrices maintained structural integrity under ballistic impact, further emphasizing the advantages of synthetic aramid fibers in armor applications [30].

Conversely, the present abaca composites showed premature failure mechanisms such as delamination, fiber pull-out, and brittle matrix fracture, all of which contributed to full penetration. Therefore, while abaca composites offer advantages in terms of sustainability and lightweight properties, their use in ballistic protection requires advanced engineering strategies, such as hybridization with aramid or UHMWPE fibers, ceramic/metal faceplates, or optimization of fiber volume fraction and resin densification, to meet NIJ standards for body armor applications.

4 Conclusions

This study demonstrates that fiber orientation and mass fraction significantly affect the mechanical properties of abaca–polyester composites. Based on the results of the tests that have been carried out, it can be concluded:

1. The straight fiber (parallel) alignment with a 10% mass fraction provided the best mechanical performance, with a best tensile strength of 54.12 MPa, strain of 0.021 mm/mm, and elastic modulus of 2577 MPa. An impact toughness of 43.90 kJ/m². In the impact test configuration, it achieved the maximum absorbed energy of 2.70 J.
2. Increasing the fiber mass fraction to 30% decreased the mechanical performance due to uneven resin distribution and void formation. The best mechanical performance, with a best tensile strength of 35.17 MPa, strain of 0.027 mm/mm, and an elastic modulus of 1303 MPa. An impact toughness of 17.45 kJ/m². In the impact test configuration, it achieved a maximum absorbed energy of 1.08 J.
3. Ballistic testing with 9 mm FMJ projectiles showed that all specimens with thicknesses of 15 mm and 20 mm experienced complete penetration, with no significant differences between straight and woven fiber orientations. The observed failure mechanisms included delamination, fiber pull-out, matrix fracture, and shear plugging. These results confirm that abaca–polyester composites do not yet meet NIJ standards for ballistic applications, although they possess potential as environmentally friendly base materials.

Furthermore, this study contributes to the initial understanding of the limitations of abaca fiber composites in ballistic applications and highlights the importance of further engineering strategies, such as hybridization with synthetic fibers, the addition of ceramic or metallic layers, and optimization of fiber fractions, to enhance ballistic resistance in future developments. Therefore, abaca–polyester composites, despite their environmental advantages, require hybridization with synthetic fibers or additional protective layers to be viable for ballistic applications.

Acknowledgments

The author would like to express sincere appreciation and gratitude to the Rector of Universitas Samudra for the opportunity and support provided through the Lecturer Research Scheme funded by DIPA Unsam in 2024, with LPPM contract number 34/UN54.6/PG/2024.

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