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Article

An experimental analysis on the low-velocity impact response of jute/epoxy biocomposites

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Abstract: This study investigates the low-velocity impact behavior of jute/epoxy biocomposites with varying fiber volume fractions 10% (JE10), 20% (JE20), and 30% (JE30). Samples were characterized by gradual force decrease and progressive damage mechanisms. All samples exhibited ductile failure behavior. Energy absorption capacity and peak forces decreased with increasing fiber content. JE10 achieved the highest energy absorption of 9.45 J and peak force of 772 N, while the JE30 composite showed the lowest values of 5.41 J and 690 N, respectively. However, the JE30 sample exhibited a faster energy dissipation rate, potentially advantageous for specific applications. Moreover, the study uncovered a complex interplay between impact duration, displacement, and fiber content, with higher fiber content leading to shorter impact durations and improved composite stiffness. These findings highlight the potential for tailoring the biocomposites' impact response through strategic manipulation of fiber content, potentially opening new avenues for designing eco-friendly materials with optimized impact resistance.

Keywords: low-velocity impact; jute/epoxy bio-composites; fiber content

1. Introduction

Natural fibers are eco-friendly and cost less than synthetic fibers, which are made from limited petroleum. Fibers can be either natural from plants, animals, and minerals, or man-made. People have used natural fibers like flax and wool since ancient times, with hemp being one of the oldest. A fiber is considered natural if its length-to-diameter ratio is more than 1:200. They are preferred for being non-toxic, easy to work with, and energy-efficient in production [1]. Natural fibers are used in construction, transportation, and everyday items, often mixed with other materials [2]. Natural fiber reinforced composites are renewable, biodegradable, and environmentally friendly [3,4]. The market for natural fiber composites was worth $4.46 billion in 2016 and is expected to grow significantly by 2024. The automotive sector is a major user, aiming to replace heavier glass fibers with lighter natural fibers. Understanding how these composites behave under different stresses, especially impacts, is critical as they can be damaged internally [5].

Choosing the right material is key for designers to make products cost-effective and perform well. They often use fiber composites instead of metals for lighter, stronger structures. Understanding how composite materials behave under sudden forces is crucial. The ability of a composite to absorb energy depends on its material, shape, size, and how it's impacted [6]. Impacts can be low, high, or hypervelocity;

low velocity impacts (LVI) can also cause hidden damage [7]. Impact speeds are grouped as low (1–10 m/s), high (100–1000 m/s), and hyper (over 1000 m/s). Metal handles low-speed impacts well, but composites can be secretly damaged [6]. Natural fiber composites have poor damage resistance in low-velocity impacts [8]. Damage from low-speed impacts might not be seen, yet it can weaken the material more than visible damage does [9].

Low-velocity impacts can cause delamination, fiber pull-out, and matrix cracking [10]. Factors like fiber orientation, stacking sequence, hybridization, and impactor geometry influence their response. Treatment of fibers, mixing with synthetic fibers, and adding nano-fillers can improve impact resistance. Impact energy, peak load, peak deformations, energy absorbed, and peak velocity are measured parameters [11]. LVI testing assesses the damage tolerance and resistance of materials. Impact energy (E_i) and absorbed energy (E_a) are key parameters. Force vs. time plots show features like peak force and maximum displacement. The load-time curve shows maximum load before major damage and severe internal damage [8]. Low-velocity impact testing is typically done using a drop tower. A high-speed camera is used to observe the bottom surface of the composite plate during impact. An automatic surface-to-surface contact is defined between the impactor and the composite plates [12]. NFCs can fail mechanically due to fiber debonding, breaking, and pull-out because of weak adhesion between fibers and the matrix. The hydrophilic nature of natural fibers can lead to poor mechanical performance when combined with hydrophobic polymers. Thermal treatment can improve physical properties but may reduce mechanical strength, such as the modulus of elasticity. Low-pressure plasma treatment, while effective, is challenging to implement on an industrial scale. The addition of certain treatments, like heavy wood distillate (HWD), can improve some mechanical properties but may not enhance impact strength. Some fiber treatments may not significantly impact resistance to water uptake. Pre-treatments on fibers like kenaf may have little effect on fungus resistance [13].

Jute fiber (*Corchronus capsularis*) composites are popular in many fields, including aerospace, because of their good properties [7]. Jute/MSO bio-composites provide weight saving, recyclability, and biodegradability compared to glass fibers [14]. Jute fibers are commonly used due to their low cost and mechanical performance [15]. Properties of Jute Fiber are summarized in **Table 1**.

Table 1. Properties of Jute fiber [2].

Content	**Character/Values**
Classification	These fibers are gathered from the bast or skin that surrounds the plant's stem. These fibers have very high tensile strength as compared to others. These fibers are used to make strong ramie, fabric, yarn, packaging, and paper
Chemical composition	Hemicellulose 14–20% Cellulose 61–71% Lignin 12–13%
Mechanical properties	Density: 1.23 g/cm^3, Diameter: 5–25 µm, Length: 0.8–6 mm, Tensile Strength: 187–773 MPa, Young's Modulus: 20–55 GPa, Elongation at Break: 1.5–3.1%, Moisture Content: 12%
Universal Production Pattern	2.1%
Manufacturing techniques	Polyester: Hand-Layup Fabrication.

	Polyurethane: Injection Molding and Extrusion. Epoxy: Hot Press Compression Molding.
Consumption pattern of natural fibers used in composites.	5%

Despite growing interest in natural fiber composites, the influence of jute fiber volume fraction on the low-velocity impact response, particularly in terms of energy absorption, impact duration, stiffness, and progressive damage mechanisms, remains insufficiently understood. This work provides the first systematic experimental assessment of the low-velocity impact behavior of jute/epoxy composites with varying fiber contents, revealing a unique trade-off between energy absorption and dissipation rate and offering a fiber-content-based approach for tailoring impact performance in sustainable composite materials. To cover the research gap, this research is driven by the necessity to produce relevant impact performance data for jute fiber epoxy composites with fiber contents of 10%, 20%, and 30% to ensure their safe and dependable use in actual engineering applications using a drop weight impact tester. The samples experienced an impact speed of 1.77 m per second. The history curves of impact generated were examined and analyzed to comprehend the impact behavior of Biocomposites. This consists of the force-time records, energy at maximum, and damage evolution under different levels of fiber loading and impact speed. Various additional experiments using various natural fibers were also analyzed to gain a better understanding.

2. Experimental

2.1. Materials

A two-component, solvent-less, transparent Lapox Metalam Clear System B Resin with Lapox Metalam Clear System B Hardener (Atul Ltd. India), Viscosity at 25° 800–1,200 mPas, Density 1.00–1.20 g/cc. The jute fabric mats were purchased from the local supplier based in Khulna, Bangladesh.

2.2. Resin blending

Lapox Metalam Clear System B Resin with hardener was used as the matrix for jute biocomposites. Curing was performed at higher temperatures between 40 °C and 60 °C. Curing at a higher temperature was recommended to achieve optimum bond strength. The adherents were thoroughly degreased with a good degreasing solvent, ensuring the surface is free from dirt, oil, grease, and moisture. The surface was wiped off with a clean cloth. Inadequately pre-treated substrates may not yield satisfactory results. The mixed mass is applied by brush on the surface to be coated. The viscosity at 25 °C was 300 and the mixed viscosity at 25 °C was 500.

2.3. Fiber Surface Treatment

The laboratory-grade solid NaOH pellets were purchased from the local market and dissolved in distilled water to create a 5% NaOH solution. In particular, 50 g of NaOH was gradually added to about 800 mL of distilled water while being constantly stirred, allowing the solution to drop to room temperature and the exothermic process to finish. After diluting the solution with distilled water to a final volume of 1 L. The jute mats were thoroughly washed with 5% NaOH solution for 24 h and dried under direct sunlight for 48 h. Woven drying was employed to ensure the removal of any sort of moisture from the fiber. This helps remove non-cellulosic components like lignin, hemicellulose, pectin, wax and oils present in Jute. It also helps improve the mechanical interlocking between fiber and matrix.

2.4. Composite Fabrication

Composite laminates were fabricated through a layer-by-layer stacking process using jute fiber mats as the preform. The resin impregnation was performed via hand lay-up, resulting in a uniform distribution of resin throughout the mat. The prepared samples were then placed in a mold and subjected to a pressure of approximately 4 mm to achieve the desired thickness. Three layers of jute mat were employed, where the fiber direction was maintained as (0/90). Three different percentages of fiber loading were considered to prepare the composites as 10%, 20%, and 30%. To conduct the drop tower impact test, specimens were cut from samples as per the ASTM D7136 standard with the dimensions of 150 mm × 100 mm using a CNC cutting machine. Prepared specimens are depicted in **Figure 1**.

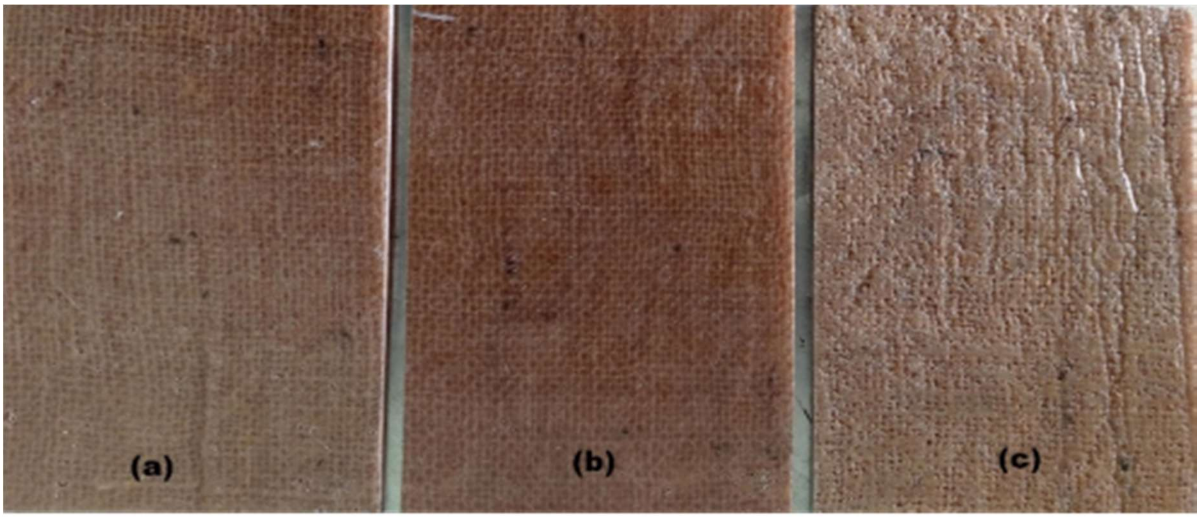


Figure 1: Jute/Epoxy composite Specimen for impact test using (**a**) 10% (JE10), (**b**) 20% (JE20), and (**c**) 30% (JE30) fiber loading.

2.5. Drop weight tower

In this study, an Instron CEAST 9350 drop tower impact system (Instron, Italy) was utilized to conduct a series of impact tests on specimens of various fiber percentages. The testing equipment consisted of three primary components: the cross head, tup holder, and instrumented tup. A 20 mm hemispherical striker was installed, and the total mass impactor of 6.166 kg was used to deliver a predefined amount of energy to the specimens. The incident energy was set at 10 J, and the striking velocity was controlled at 1.77 m/s. The positioning of the specimen was done in the specimen holder, and the impactor was then raised to the desired height from which it is made to fall on the specimen, thus, force was applied. The experiment took place under normal room temperature conditions. The higher the drop, the greater the potential energy of the impactor becomes. After the impactor assembly is dropped from a specific height, the potential energy changes into the impactor's kinetic energy. Details of the test conditions are provided in **Table 2**. The impact test history, including the impact force and time, was measured using the instrumented tips of the system.

Table 2. Test and sample conditions.

Specimen	Thickness (mm)	Indenter diameter (mm)	Indenter mass (kg)	Weight (g)	Energy (J)	Incident velocity (m/s)
JE10	4	20	6.166	74.35	10	1.87
JE20	4	20	6.166	53.43	10	1.87
JE30	4	20	6.166	73.74	10	1.87

3. Results and discussion

3.1. Impact response

The suggested Jute/Epoxy composite samples were tested in LVI to investigate their impact behavior as summarized in **Table 3** and visualized in **Figure 2**. The samples were subjected to controlled impact parameters, including velocity at start (1.76–1.77 m/s), velocity variation (0–0.16 m/s), and slow down percentage (0–9.1%). The impact response was characterized by measuring force, displacement, and energy parameters. The peak force ranged from 1034.351 N (JE10) to 1097.152 N (JE20). Ductility analysis revealed ductile behavior for JE10 (82.7%), JE20 (77.6%) and JE30 (65.7%). The impact velocity variation and the slowdown percentage influenced the impact response.

Table 3. Test outcomes for different examples of Jute/Epoxy Bio-composites.

Sample	User-defined break type	Velocity at start (m/s)	Velocity variation	Slow down (%)	Force at peak (N)	Ductility index percentage (%)	Ductility index comment
JE10	ND	1.76	0	0	1156.622	82.7	Ductile
JE20	ND	1.77	0	0	1097.152	77.6	Ductile
JE30	ND	1.77	0	0	1034.351	65.7	Ductile

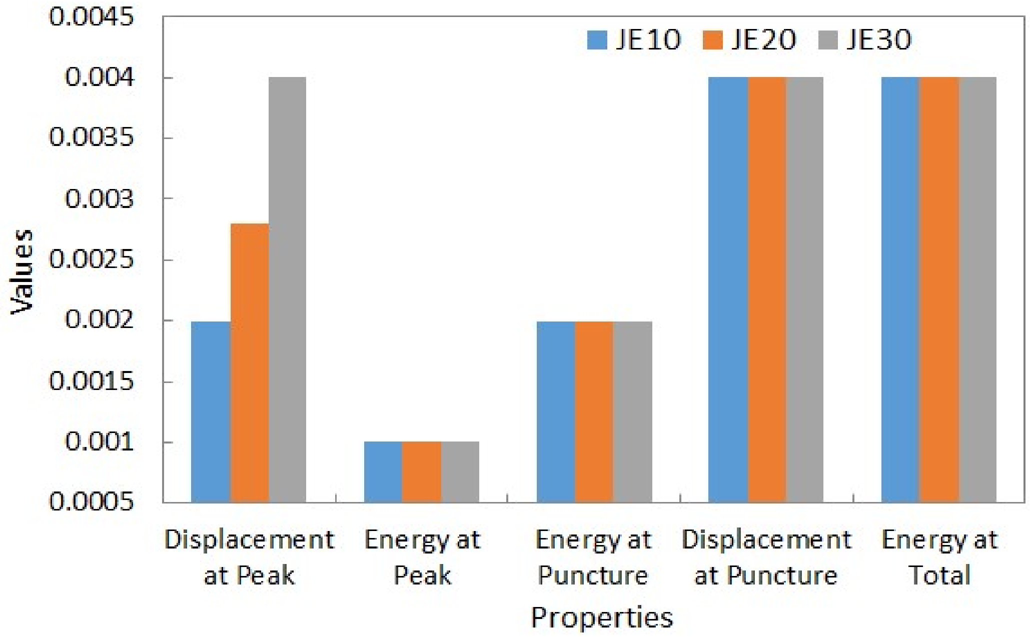
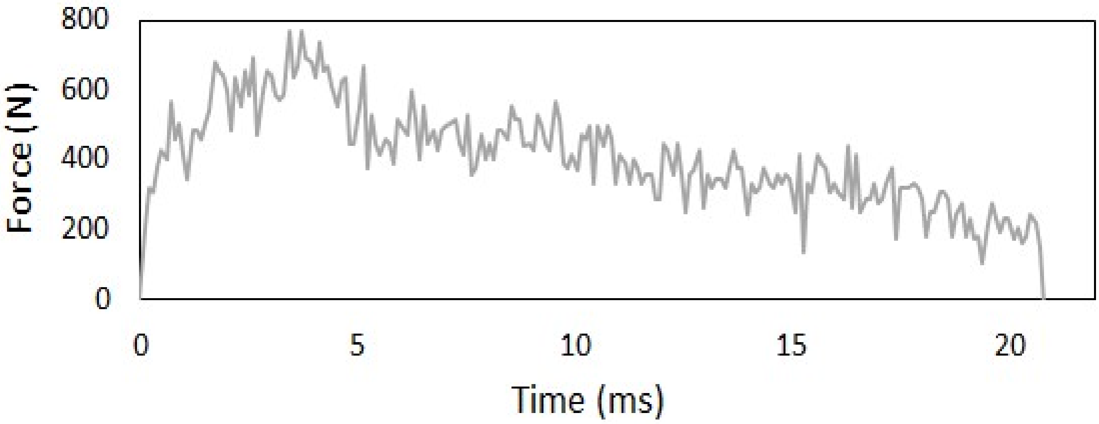


Figure 2. LVI test results for different fiber loading of jute.

It can be seen from **Figure 2** that a comparatively stiffer reaction under LVI loading was demonstrated by the sample containing 10% jute fiber, which showed the least displacement at peak impact. The maximum displacement increased with the increased of the fiber loading. This can be explained by changes in the composite's energy dissipation mechanisms and stiffness as the fiber content increased. Through mechanisms like fiber pullout, crack bridging, and better load distribution, the additional fibers can improve energy absorption. The increase in maximum displacement with higher jute fiber loading is attributed to reduced laminate stiffness and enhanced damage-based energy dissipation mechanisms such as fiber pull out, crack bridging, and interfacial debonding, a behavior widely reported for natural fiber composites under low-velocity impact loading [16,17].

Figure 3 shows typical force-time traces following drop weight impact tests on the biocomposites using Jute epoxy. The force-time curve for the JE10, as shown in **Figure 3a**, exhibits a relatively smooth increase in force until reaching a peak value of approximately 772 N at around 3.41–3.71 ms. After the peak, the force gradually decreases, suggesting a ductile failure behavior. Such behaviour is exhibited due to higher effective stiffness and more efficient fiber–matrix load transfer, which delays damage initiation. The force-time curve for the JE20 sample in **Figure 3b** shows a steep initial increase in force, reaching a peak value of around 742 N within the first 4.2 ms. After the peak, the force drops gradually, indicating a ductile failure behavior. The force-time curve for the JE30 sample, as shown in **Figure 3c**, is similar to that of the JE10 & JE20 samples, with a smooth increase in force until reaching a peak value of approximately 700 N at around 2 ms. After the peak, the force gradually decreases, suggesting a ductile failure behavior. It can be said that as the jute fiber content increases to 20% and 30%, the peak force decreases, likely due to fiber agglomeration, increased voids, and reduced interfacial bonding, leading to lower resistance to impact loading. The gradual post-peak force reduction observed in all samples confirms a predominantly ductile failure mechanism involving matrix cracking, fiber debonding, and fiber pull-out.

The observed smooth rise and gradual post-peak force decay for JE10-JE30, indicating ductile failure behavior, is consistent with reported low-velocity impact responses of natural fiber-reinforced composites, where progressive damage mechanisms such as matrix cracking, fiber debonding, and pull-out dominate rather than catastrophic fracture. The reduction in peak force with increasing jute fiber content has been widely attributed to fiber agglomeration, higher void content, and weakened fiber–matrix interfacial bonding, which reduces effective load transfer and impact resistance at higher fiber volume fractions [16,18]



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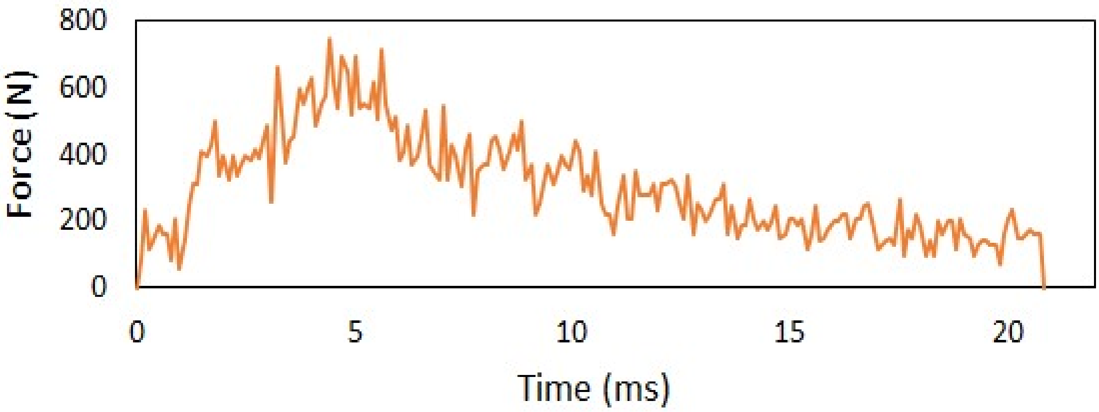

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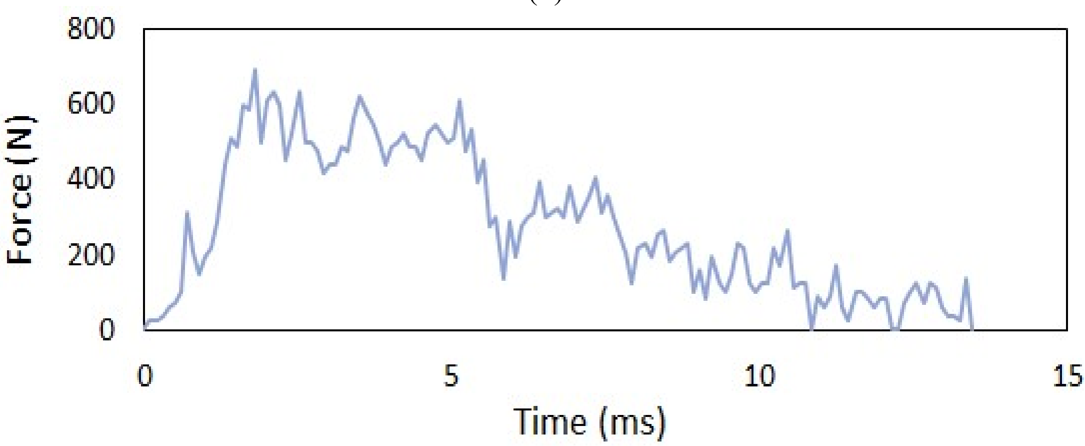


(**c**)

Figure 3. Force-Time graph for various composite samples (**a**) JE10, (**b**) JE20, (**c**) JE30.

3.2. Comparative analysis between force, displacement, absorbed energy, and time

The displacement curves for all samples are shown in **Figure 4**. The analysis revealed significant trends in impact behavior as jute fiber content increased. Notably, impact duration decreased, with JE30 showing a markedly shorter duration of 12 ms compared to the 25 ms observed in JE10 and JE20. The reduction in impact duration with increasing fiber loading indicates a stiffer composite response, as higher fiber loading accelerates force transfer and shortens the contact time between the impactor and the specimen.

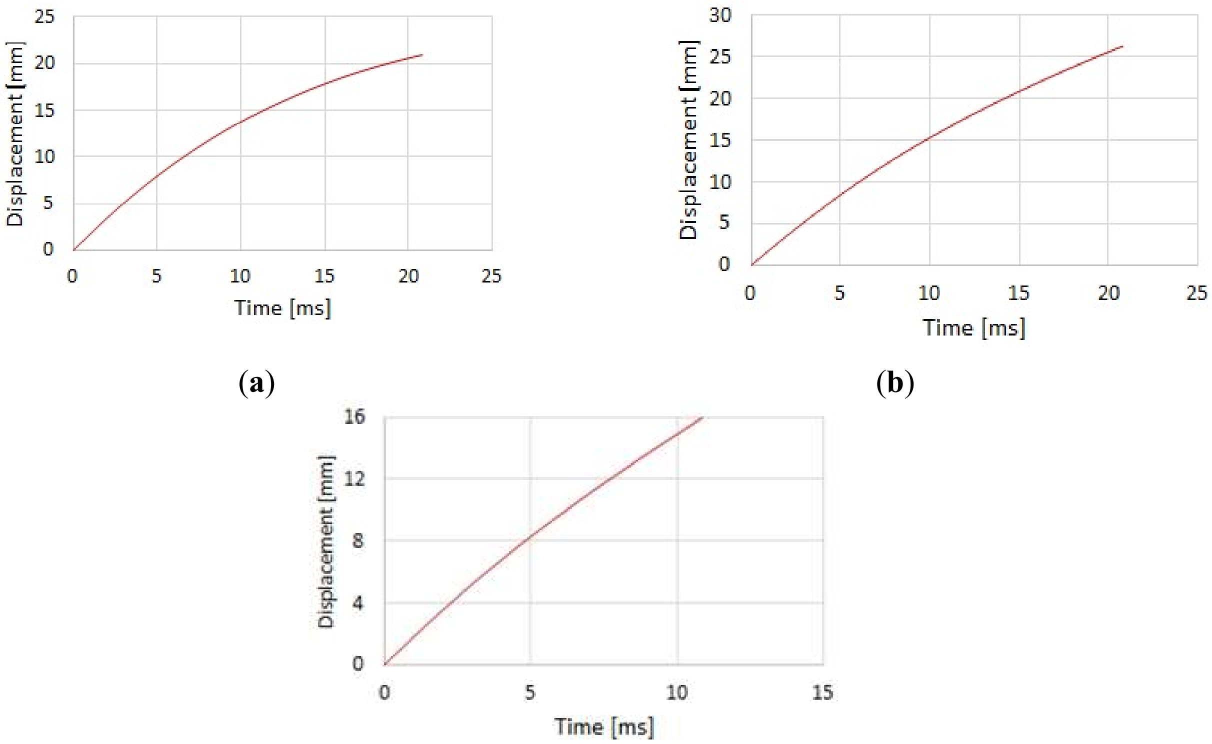
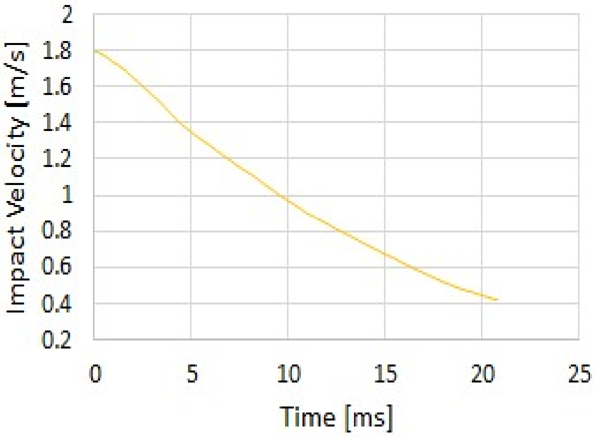


Figure 4. Displacement-Time graph for (**a**) JE10, (**b**) JE20, (**c**) JE30.

Figure 5 revealed a consistent initial impact velocity of approximately 1.8–2 m/s across all samples, followed by a rapid decrease over time. JE10 and JE20 exhibited similar velocity decay profiles throughout about 25 ms, while JE30 showed a steeper velocity reduction over a shorter 12 ms period. The similar velocity decay profiles of JE10 and JE20 indicate comparable contact stiffness and energy dissipation mechanisms during impact. This aligns with the displacement-time data, where JE30 demonstrated a notably shorter impact duration compared to JE10 and JE20. The steeper and shorter velocity reduction promotes faster momentum transfer and earlier rebound of the impactor.



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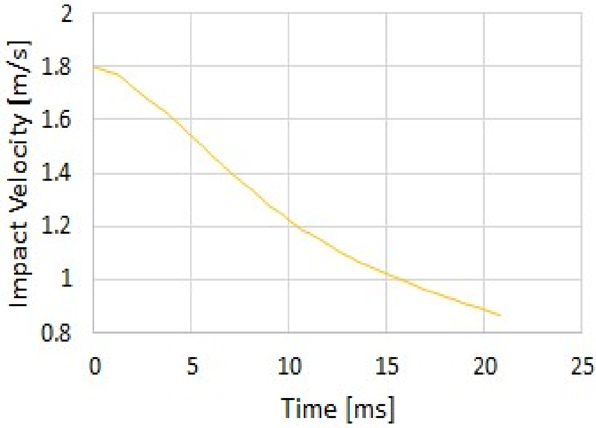

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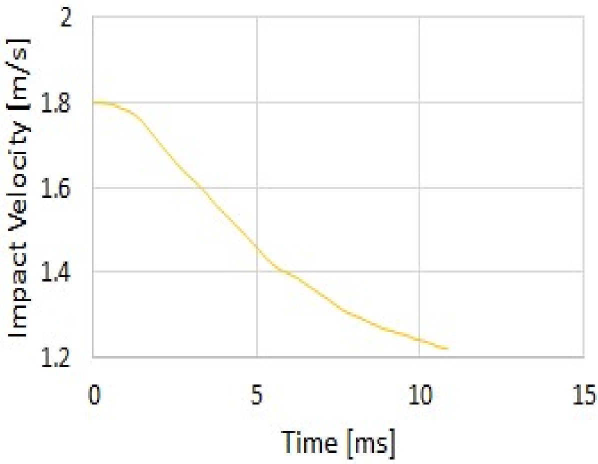
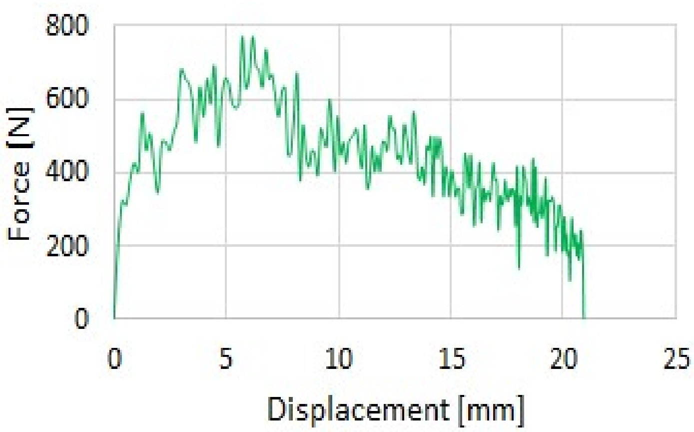


(**c**)

Figure 5. Impact Velocity-Time graph for (**a**) JE10, (**b**) JE20, (**c**) JE30.

Force-displacement dynamics in **Figure 6** showed a clear pattern, with peak forces diminishing as jute fiber loading increased. JE10 exhibited the highest peak force at 771 N, while JE30 had the lowest at 690 N.



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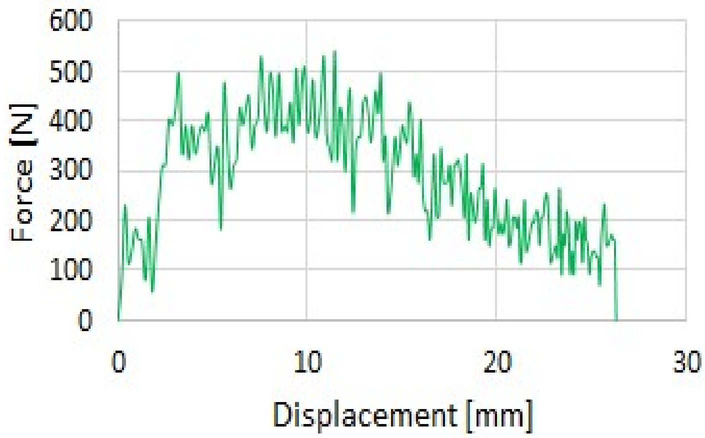

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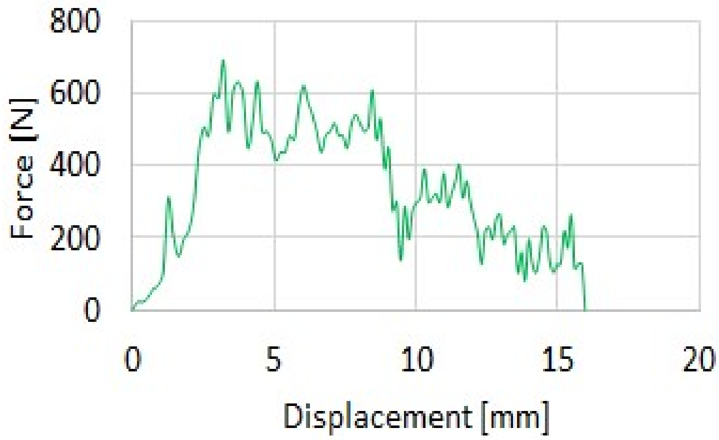
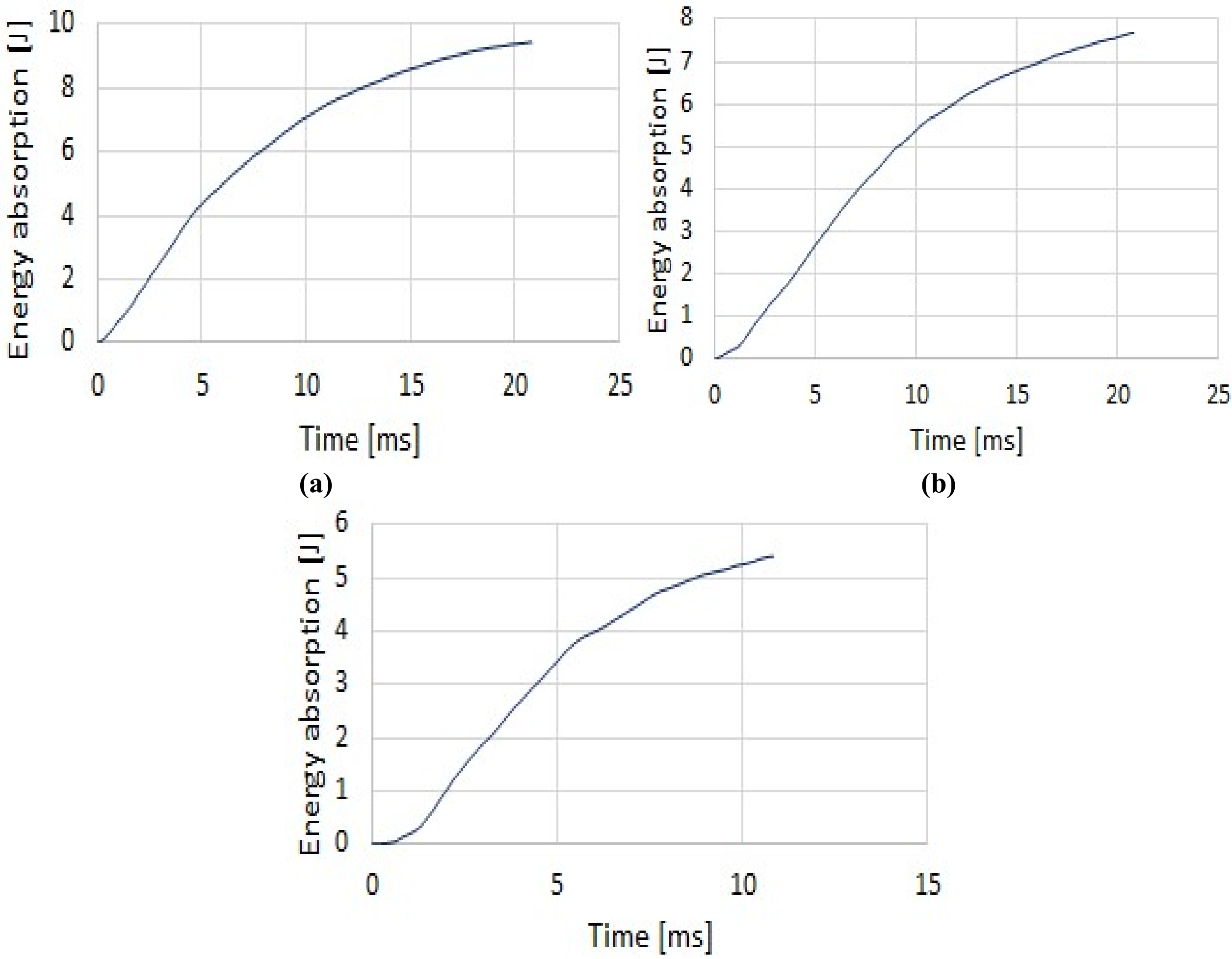


(**c**)

Figure 6. Force-Displacement graph for (**a**) JE10, (**b**) JE20, (**c**) JE30.

Energy absorption vs time graphs in **Figure 7** showed decreasing energy absorption from 9.45 J in JE10 to 5.41 J in JE30. However, JE30 demonstrated a faster initial rate of energy absorption. These findings highlight the complex relationship between jute fiber content and impact response in these bio-composites. The observed trends in impact duration, displacement, force resistance, and energy absorption suggest that jute fiber loading can be strategically manipulated to tailor the impact response characteristics of these materials.

The reported shortening of impact duration and steeper velocity decay at higher jute fiber loading (JE30) is consistent with low-velocity impact theory and experimental observations on natural-fiber composites, where increased fiber content raises contact stiffness, accelerates force transfer, and reduces contact time between the impactor and laminate [19,20].



(a) (b)

(c)

Figure 7. Energy Absorbed-Time graph for (a) JE10, (b) JE20, (c) JE30.

At the same time, the reduction in peak force and total absorbed energy with increasing fiber loading, despite a faster initial energy absorption rate, has been attributed in the literature to premature interfacial debonding, fiber agglomeration, and higher void content, which limit effective load transfer and shift energy dissipation toward rapid damage initiation rather than sustained resistance [21].

Similar correlations between force-displacement response, velocity decay, and energy absorption trends have been widely reported for natural fiber–reinforced laminates under low-velocity impact, confirming that fiber volume fraction can be used as a design parameter to tailor impact response characteristics [22,23].

3.3. Damage properties

A closer examination of the samples in **Figure 8** reveals distinct failure modes and damage patterns across the different V_f. The JE10, JE20, and JE30 samples all exhibit evidence of ductile failure, characterized by localized indentation and deformation around the impact site. This ductile behavior is corroborated by the gradual force decrease observed in their force-time curves, suggesting progressive damage mechanisms. The energy absorption capabilities of these samples can be attributed to their ductile failure modes. This allows for a more controlled dissipation of impact energy. JE10 demonstrates the highest total energy absorption value (approximately 9.45 J), followed by JE20 (9.09 J) and JE30 (5.41 J). This suggests that lower V_f offers advantages in terms of energy absorption capacity, with a decreasing trend as fiber content increases. All samples show relatively high peak forces, indicating good impact resistance across all fiber loadings.

These observations highlight the complex relationship between fiber content and impact response in jute/epoxy biocomposites. While all samples demonstrate ductile behavior, the lower fiber loadings (particularly 10%) appear to offer better overall performance in terms of energy absorption and peak force resistance. However, the higher fiber loading (30%) shows a faster energy dissipation rate, which could be advantageous in certain applications.

Figure 8. Post impact samples (**a**) JE10, (**b**) JE20, (**c**) JE30.

3.4. Comparison with other experiments

Table 4 lists the comparison of the present study with the published results.

Table 4. Comparative analysis of the present study.

Fiber	Loading	Matrix	Indenter diameter (mm)	Indenter mass	Impact velocity	Impact energy (J)	Peak force (N)	Damage characteristics	Ref.
Jute	50	PLA	19.8	3.6	-	2,5,10,12,15	1350	Linear relationship between delamination area and impact energy/indentation depth.	[24]
Jute	-	Methacrylated soybean oil (MSO)	19.8	23.11	-	25	265–3283	Laminates with higher thickness and aerial weight exhibited higher damage thresholds in terms of peak force and absorbed energy compared to thinner laminates.	[14]
Jute	7,10,12	Natural rubber	-	3.5	2.42, 3.70, 4.64	10. 24, 23.95, 37.67.	1295.66–4196.5	No delamination observed. JRJ exhibited more severe damage compared to JRRJ and JRJRJ based on depth of damage measurements.	[25]
Jute	33	Unsaturated polyester	20.7	1.926	1.5–2	2.199–3.852	-	Damage area and delamination increased with	[26]

								increasing temperature.	
Basalt & carbon	60	Epoxy	12.7	4.906	-	30.60.80.100.120.160	-	Damage was not clearly visible at lower energy of 20 J for CFRP and 60 J for BFRP.	[27]
Flax	40	Epoxy	20	3.1	-	3–5	1550	Fibre failure and plate penetration were observed at higher energies beyond 9J for both composites.	[28]
Flax	40	Epoxy	16	3.170	-	12.4 & 18.7	-	Thermoset showed sharper failure patterns indicative of brittle failure & thermoplastic composites showed more ductile perforation.	[29]
Flax & glass	44.9	Vinyl ester	19	23.11	1.469–2.082	25–50	-	Hybrid composite showed more delamination than non-hybrid.	[30]
Hemp	-	Epoxy	16	-	-	5,10,15,20,40	-	Better fiber/matrix adhesion for bio-epoxy observed through SEM.	[31]
Pineapple Leaf	30	PLA	12.7	3.602	1,2,3	16.25 & 15.74	1215.09	At 1 m/s impact velocity, visual observation shows the presence of barely visible impact damage (BVID).	[3]

The investigated experimental results of the fabricated samples indicate good impact resistance and energy dissipation capabilities associated with ductile failure modes, as corroborated by studies on flax, hemp, and other natural fiber composites [28,30,31].

The peak forces showed a decreasing trend with increasing fiber content (JE10: 772 N, JE20: 742 N, JE30: 690 N), which differs from some other studies where higher fiber content led to increased peak forces [26]. This suggests that optimal fiber volume fractions exist for achieving the desired balance between impact resistance and energy absorption capabilities.

The high total energy absorption values (5.95 J) indicate good impact resistance and energy dissipation capabilities associated with ductile failure modes, as corroborated by studies on flax, hemp, and other natural fiber composites [8,30].

The findings highlight the crucial role of fiber volume fraction in governing the impact behavior and damage characteristics of jute epoxy biocomposites. Optimal fiber volume fractions seem to exist for achieving the desired balance between impact resistance and energy absorption capabilities. Additionally, factors like fiber-matrix adhesion, laminate thickness, and hybrid compositions (e.g., combining natural and synthetic fibers) can influence the damage mechanisms and thresholds, as evidenced by various studies [25,27,29].

4. Conclusion

In this research, jute/epoxy bio-composites, prepared by hand layup method, were subjected to low-velocity impact for various fiber loadings and the results were analyzed. Samples were prepared with a jute/epoxy ratio of 10/90 (JE10), 20/80 (JE20), and 30/70 (JE30). In the drop tower impact test, it was found that all samples exhibited ductile failure behavior. Samples were characterized by gradual force decrease and progressive damage mechanisms. It is observed that the energy absorption capacity decreased with increasing V_f. The JE10 demonstrated the highest value (9.45 J), followed by JE20 (9.09 J) and JE30 (5.41 J). Peak forces also showed a decreasing trend with increasing V_f, contrary to some previous studies. The results revealed that energy absorption capacity and peak impact force decreased with increasing jute fiber content. Although the JE30 sample showed reduced energy absorption, it exhibited a faster energy dissipation rate and shorter impact duration. Overall, the findings confirm that jute fiber loading plays a critical role in governing the impact response of jute/epoxy biocomposites and can be effectively tailored to meet specific application requirements. From a practical perspective, lower jute fiber loadings are more suitable for energy-absorbing components such as automotive interior panels and protective casings, while higher fiber loadings may be advantageous in stiffness-dominated, low-deformation applications. Future research directions may include exploring the underlying mechanisms of these observed trends and investigating the optimal jute fiber loading for specific performance criteria.

Author contributions: Conceptualization, SD and NAS; Methodology, MASS and MSR; Software, SD and MSR; Validation, MASS, SBS and MAC; Formal analysis, MSR and SBS; Resources, MASS and SBS; Writing—original draft, SD, MASS and MSR; Writing—review & editing, MAC and SBS, NAS. All authors have read and agreed to the published version of the manuscript.

Availability of data: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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