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Mechanical Behaviour of Sustainable Epoxy Hybrid Biocomposites Derived from Tea Bagasse and Banana Peel Residues

Khairum Bin Hamzah[1*], Fitri Ghanim Bin Mohammed [1], Irianto[2]

[1]Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia,

[2]Department-General Education, Faculty of Resilience, Rabdan Academy, Abu Dhabi, United Arab Emirates

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ABSTRACT

Agricultural and food-processing residues offer a renewable source of lignocellulosic reinforcement for polymer composites, but their environmental value must be considered together with functional performance. This study evaluates epoxy-based hybrid biocomposites containing tea bagasse (TB) and banana peel (BP) residues to identify compositions that balance residue utilisation with tensile, flexural and impact behaviour. Six formulations were prepared: neat epoxy and five composites containing 40 wt.% total residue with TB:BP ratios of 0:40, 10:30, 20:20, 30:10 and 40:0; the remaining 60 wt.% was epoxy resin. Residues were washed, water-soaked, sun-dried, ground and sieved before hand lay-up and ambient curing. Five replicate specimens per formulation were evaluated by tensile, three-point flexural and Charpy impact testing using the applicable ASTM procedures. Neat epoxy recorded the highest tensile (58.72 MPa) and flexural (275.53 MPa) strengths. Among residue-filled formulations, 0TB/40BP produced the highest tensile strength (16.18 MPa), whereas the balanced 20TB/20BP formulation achieved the highest flexural strength (94.53 MPa). The 10TB/30BP hybrid showed the best impact energy among the biocomposites (0.344 J), approaching the neat-epoxy value of 0.354 J. Increasing TB content generally reduced tensile and flexural performance, indicating that interfacial adhesion, particle geometry and void formation governed load transfer. The results demonstrate composition-specific rather than universal hybrid synergy. From a sustainability perspective, replacing 40 wt.% of the formulation with minimally processed residues may reduce demand for virgin resin and divert organic waste, although environmental superiority cannot be claimed without life-cycle, durability and end-of-life assessment. The 20TB/20BP and 10TB/30BP formulations are promising candidates for low-load, non-structural applications where flexural or impact performance, respectively, is prioritised.

Keywords: agricultural residues, banana peel, circular materials, hybrid biocomposites, tea bagasse

INTRODUCTION

The transition towards a circular economy requires material systems that retain value from biological residues while reducing dependence on virgin resources. Natural-fibre-reinforced polymer composites are increasingly investigated as lightweight materials because plant-derived reinforcements are renewable, widely available and potentially less resource-intensive than conventional synthetic fibres [1]. Nevertheless, renewable content alone does not establish sustainability. Recent assessments emphasise that environmental performance depends on cultivation or waste sourcing, processing energy, matrix selection, service life and end-of-life management [2]. In this context, the use of tea bagasse and banana peel as secondary raw materials is relevant because it simultaneously addresses organic-residue management and partial substitution of virgin epoxy resin.

Natural reinforcements contain cellulose, hemicellulose and lignin in proportions that influence stiffness, moisture affinity and interfacial behaviour. Recent reviews identify fibre geometry, dispersion, treatment, matrix compatibility and processing-induced porosity as major determinants of natural-fibre epoxy performance [3], [4]. Interfacial adhesion is particularly important because hydrophilic plant surfaces interact imperfectly with crosslinked polymer matrices; weak wetting promotes fibre pull-out, voids and premature failure, whereas appropriate physical or chemical treatment can improve stress transfer [5]. Consequently, the mechanical contribution of an agricultural residue is governed not only by its composition but also by its particle size, surface condition, distribution and loading fraction. Banana-derived reinforcement has been examined as continuous fibre, chopped fibre and particulate biofiller. Kumar et al. [6] demonstrated that treated banana-peel particles can modify the physical, mechanical, thermal and tribological behaviour of epoxy composites, with performance depending strongly on filler loading. Shahapurkar et al. [7] further showed that banana-fibre architecture and treatment significantly influence flexural response, with treated woven configurations outperforming several chopped and untreated arrangements. These findings confirm the technical potential of banana-derived reinforcement while also showing that favourable behaviour cannot be assumed at high residue content or with minimal surface treatment.

Hybridisation is intended to combine complementary reinforcement functions and offset the limitations of an individual constituent. Contemporary studies show that hybrid natural-fibre and particle systems may enhance selected properties when the reinforcements are well dispersed and strongly bonded, but excess filler can create agglomeration, hydrophilic sites and microvoids [8]. Similar composition-dependent behaviour has been reported for waste-filled epoxy systems: tea-waste addition may reduce tensile and flexural strength while increasing absorbed impact energy [9], whereas mechanically processed tea-stem powder at lower contents has improved tensile strength, hardness and fracture toughness [10]. Tea-waste epoxy cores have also been developed for lightweight sandwich structures, illustrating emerging engineering interest in this residue stream [11]. Beyond reinforcement selection, current sustainability literature stresses the need to compare life-cycle energy and emissions [12], consider renewable alternatives to petroleum-derived epoxy matrices [13], evaluate environmental and techno-economic feasibility [14], and assess the complete life cycle of natural-fibre polymer systems [15].

Despite these advances, the recent literature generally examines banana-derived reinforcement and tea-processing residues separately, applies relatively low filler contents, or combines the residue with conventional fibre architectures. Limited evidence is available on epoxy hybrid biocomposites that combine tea bagasse and banana peel while maintaining a fixed total residue content of 40 wt.%. The present study addresses this gap by comparing five TB:BP ratios against neat epoxy under tensile, flexural and impact loading. It asks whether hybrid composition can be adjusted to obtain a useful mechanical compromise while maximising residue utilisation. Sustainability is therefore treated as a material-design objective that must be balanced against performance, durability and life-cycle considerations, rather than as an automatic consequence of incorporating biomass [2], [1].

METHODOLOGY

Tea bagasse and banana peel residues were used as particulate lignocellulosic reinforcements in an epoxy matrix. Six formulations were produced (Table 1): neat epoxy and five biocomposites containing a constant 40 wt.% total residue and 60 wt.% epoxy. The TB:BP fraction was varied from 0:40 to 40:0 to isolate the effect of hybrid composition at constant total loading.

Table 1: Composite formulations by weight

Abbreviation	Tea Bagasse (%)	Banana Peel (%)	Epoxy Resin (%)
0TB0BP	0	0	100
10TB30BP	10	30	60
20TB20BP	20	20	60
30TB10BP	30	10	60

40TB0BP	40	0	60
0TB40BP	0	40	60

Mechanical performance was evaluated through tensile, three-point flexural and Charpy impact tests. Five replicate specimens were tested for each formulation. Results are reported as formulation means and interpreted comparatively; inferential significance is not asserted because complete ANOVA outputs and dispersion values are not presented in the current dataset.

Materials preparation and research design

The collected residues were washed to remove adhering contaminants, soaked in water for approximately 24 h, and sun-dried for 2-3 days. The dried materials were ground and sieved to obtain a more uniform particulate reinforcement. Tea bagasse and banana peel had mean particle sizes of approximately 231 and 429 micrometres, respectively. The required quantities were weighed, mixed with epoxy resin according to Table 1, placed in the moulds and cured at ambient conditions for 24 h. The relatively simple preparation route was selected to limit processing intensity, although the absence of chemical surface treatment may constrain fibre-matrix adhesion.

Composite sheets measuring 300 mm x 200 mm were fabricated to promote consistent material distribution. Cured sheets were cut into test specimens using a CNC router in accordance with the dimensional requirements of the selected test methods. Figures 1 and 2 show the moulds used for tensile/flexural and impact specimens.

Figure 1: Mould used for tensile and flexural specimens

Figure 2: Mould used for impact specimens

Specimen preparation and mechanical testing

After curing, specimens were cut with a CNC router to improve dimensional consistency. The specimen

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dimensions were checked before testing, and five replicates were evaluated for each formulation.

Tensile tests were conducted on a SHIMADZU Universal Testing Machine in accordance with ASTM D3039. Specimens measured 250 mm x 25 mm x 3 mm. Testing used a crosshead speed of 5 mm/min and a 100 kN load cell. Figure 3 shows the tensile-test setup.

Figure 3: Tensile-test setup

Flexural behaviour was evaluated on the SHIMADZU Universal Testing Machine using a three-point bending fixture in accordance with ASTM D790. Specimen dimensions were measured before testing and entered into the test programme. A 100 mm support span, 2 mm/min crosshead speed and 100 kN load cell were used. Figure 4 shows the flexural-test setup.

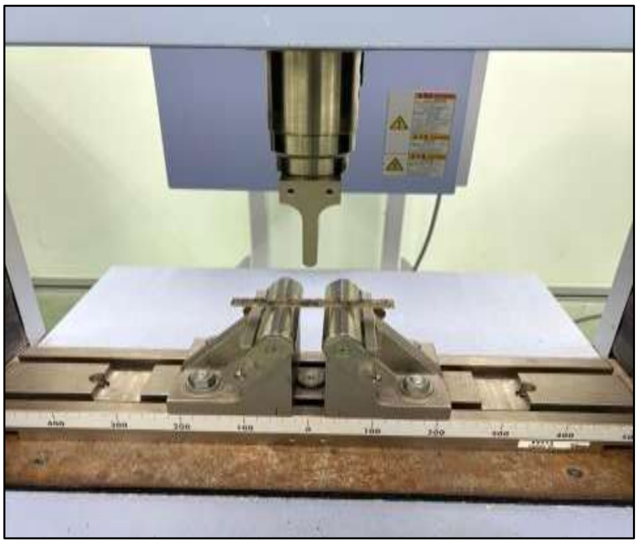

Figure 4: Three-point flexural-test setup

Impact resistance was evaluated using a Charpy impact-testing machine. Each specimen was positioned consistently in the fixture, and the energy absorbed during fracture was recorded in joules. Five specimens were tested per formulation. Figure 5 shows the impact-test apparatus. The exact impact-test standard, notch geometry and specimen dimensions should be confirmed in the laboratory record before submission to ensure complete reproducibility.

Figure 5: Charpy impact-testing apparatus

Data analysis

Data were organised in Minitab and summarised for each formulation using the five replicate measurements. The present manuscript reports the mean mechanical response for comparative interpretation. Claims of statistical significance, confidence intervals and homogeneous groupings were excluded because the underlying replicate values and complete ANOVA tables were not available for independent verification during manuscript preparation.

The results are presented for tensile, flexural and impact behaviour. Table 2 summarises the measured density and mean particle size of the constituent materials. The tea-bagasse particles were smaller and less dense than the banana-peel particles, which may have affected packing, wetting and stress transfer within the epoxy matrix.

Table 2: Physical characteristics of the constituent materials

Properties	**Banana Peel Fibres**	**Tea Bagasse Fibres**	**Epoxy Resin**
Density (g / cm^3)	0.323	0.277	1.2
Size of materials (µm)	429	231	-

Tensile behaviour

Figure 6 compares the mean tensile strength of all formulations. Neat epoxy recorded the highest value (58.72 MPa). Among the biocomposites, 0TB/40BP achieved the highest tensile strength (16.18 MPa), followed by 10TB/30BP (13.72 MPa) and 20TB/20BP (13.29 MPa). Strength decreased markedly at higher TB fractions, reaching 6.43 MPa for 30TB/10BP and 4.25 MPa for 40TB/0BP. The decline relative to neat epoxy indicates that, at 40 wt.% residue, the particles acted predominantly as discontinuities rather than efficient load-bearing reinforcement. The superior performance of BP-rich formulations may reflect the larger banana-peel particle size, improved mechanical interlocking, or compositional differences in the lignocellulosic residue. Conversely, the smaller TB particles may have increased the surface area requiring wetting and promoted agglomeration or void formation. This interpretation is consistent with recent work identifying dispersion and fibre-matrix adhesion as decisive controls in plant-fibre epoxy systems [3], [5], [4]. The lower strength at high tea-bagasse fractions also parallels the composition-dependent decline reported for jute/tea-waste epoxy composites [9]. Microscopy and void-content measurements are required to verify these proposed mechanisms.

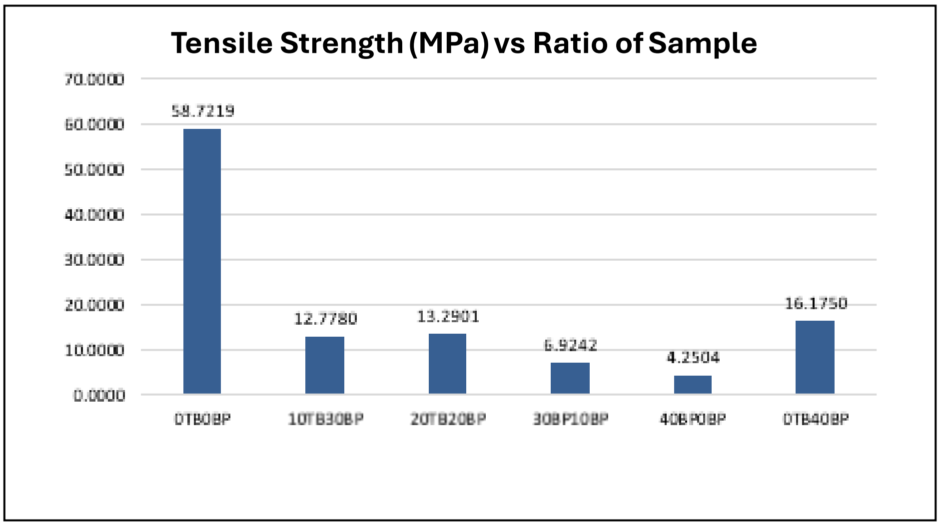

Figure 6: Mean tensile strength of the composite formulations

Flexural behaviour

Neat epoxy produced the highest flexural strength (275.53 MPa). Among the residue-filled materials, the balanced 20TB/20BP composition performed best (94.53 MPa), exceeding 0TB/40BP (72.35 MPa), 10TB/30BP (49.95 MPa), 30TB/10BP (40.46 MPa) and 40TB/0BP (22.80 MPa). The non-monotonic trend indicates that flexural performance was controlled by the interaction of the two residues rather than by BP content alone. The 20TB/20BP result is consistent with a composition-specific hybrid effect in bending, potentially arising from improved particle packing and crack-path tortuosity. Recent hybrid biocomposite research indicates that improvements depend on uniform filler dispersion and effective interfacial bonding, while agglomeration and microvoids can reverse the benefit [8]. Banana-fibre epoxy studies likewise demonstrate that architecture and treatment alter flexural strength substantially [7]. Here, the equal-ratio formulation exceeded both single-residue formulations, supporting a provisional positive hybrid interpretation for flexural loading; microstructural evidence is still required. Although all biocomposites remained below neat epoxy, the 20TB/20BP formulation retained approximately 34% of the control flexural strength while replacing 40 wt.% of the formulation with recovered residues. This trade-off may be acceptable for low-load panels, interior components or other non-structural products, subject to durability, moisture and safety validation.

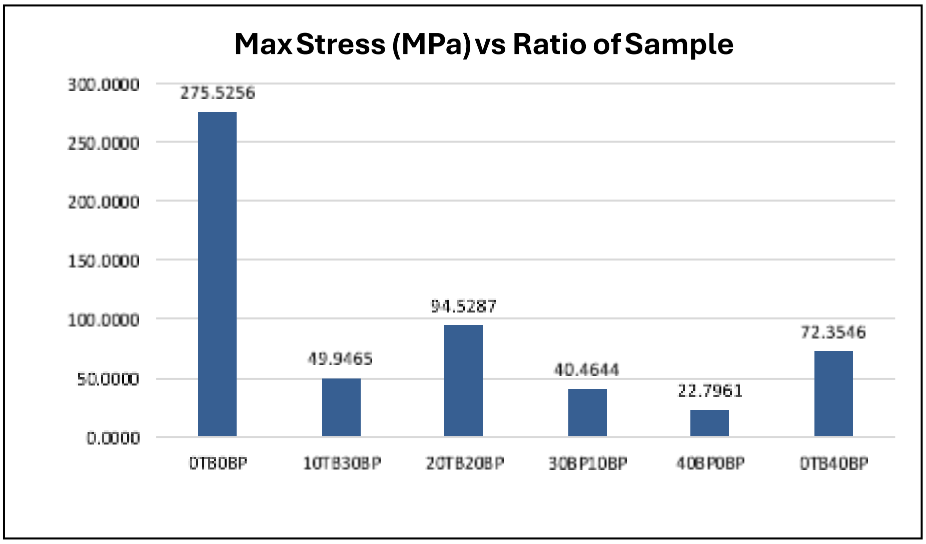

Figure 7: Mean flexural strength of the composite formulations

Impact behaviour

Neat epoxy absorbed 0.354 J. The 10TB/30BP hybrid achieved 0.344 J, followed by 30TB/10BP at 0.328 J, 0TB/40BP at 0.296 J and 40TB/0BP at 0.230 J. The 20TB/20BP formulation recorded the lowest value (0.180 J). Unlike the flexural response, therefore, the equal-ratio blend did not provide the best resistance to sudden loading. The strong impact response of 10TB/30BP suggests that a BP-rich hybrid may promote energy-dissipating mechanisms such as particle debonding, crack deflection and frictional pull-out. The low value for 20TB/20BP may instead reflect local agglomeration or porosity. Tea-waste epoxy research has similarly shown that absorbed impact energy can increase even when tensile and flexural strength decline [9], while mechanically processed tea-stem powder can improve fracture resistance at an appropriate loading [10]. These mechanisms remain hypotheses until fracture surfaces are examined. The contrasting flexural and impact optima demonstrate that sustainable formulation selection must be application-specific rather than based on a single aggregate ranking.

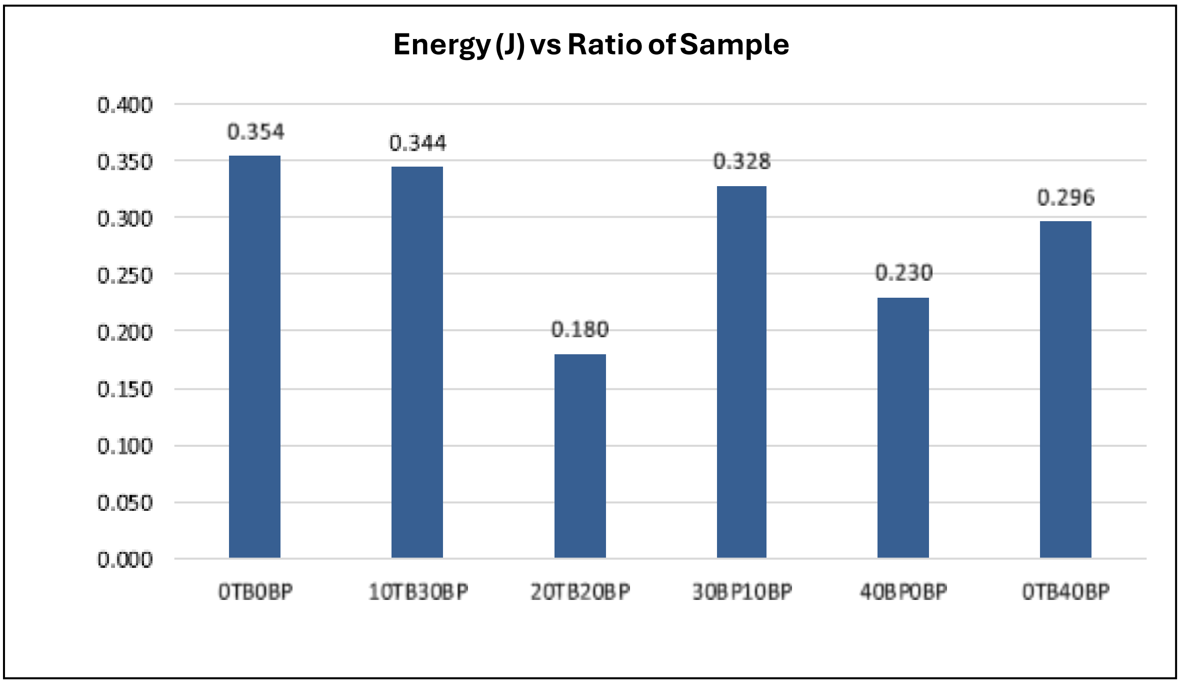

Figure 8: Mean impact energy of the composite formulations

Sustainability Implications

The principal sustainability contribution is the valorisation of two food-related residues at a combined loading of 40 wt.%. This approach may divert biodegradable waste and reduce the mass of virgin epoxy required per unit of composite. The water-based cleaning, sun-drying and ambient-curing route also avoids intensive chemical treatment. However, recent sustainability reviews caution that natural-based composites are not inherently environmentally superior; benefits depend on processing burdens, durability, functional performance and end-of-life pathways [1], [2], [12], [15]. The material remains a petroleum-derived thermoset and is not biodegradable. Bio-epoxy systems could reduce fossil feedstock dependence in future formulations, although their mechanical performance, curing requirements and renewable content must be evaluated carefully [13]. A cradle-to-grave life-cycle assessment and techno-economic assessment should therefore quantify residue collection, drying and grinding energy, resin displacement, manufacturing cost, product lifetime, and disposal or recovery options before comparative environmental claims are made [14].

STUDY LIMITATIONS AND FUTURE WORK

The analysis is limited by the absence of reported standard deviations and full inferential statistics, microstructural evidence, moisture uptake, thermal behaviour, durability and life-cycle indicators. Particle-size distributions and fibre chemical composition were also not characterised. Future work should report replicate-level data; quantify void content; use scanning electron microscopy and spectroscopy to evaluate interfaces; compare untreated and low-impact surface treatments; test water absorption, ageing and thermal stability; and conduct life-cycle and techno-economic assessments. The exact Charpy standard, notch condition and specimen geometry must also be verified from the laboratory record before submission.

CONCLUSION

Tea bagasse and banana peel residues produced composition-dependent mechanical responses in epoxy biocomposites containing 40 wt.% total residue. Neat epoxy remained strongest in tension and flexure. Among the biocomposites, 0TB/40BP gave the highest tensile strength, 20TB/20BP gave the highest flexural strength, and 10TB/30BP gave the highest impact energy. The different optimum formulations show that hybrid synergy depends on loading mode. Increased tea-bagasse content generally reduced tensile and flexural performance, most plausibly because of inadequate wetting, agglomeration or voids, although microstructural analysis is needed for confirmation. The findings support further development for low-load, non-structural applications and demonstrate a pathway for residue valorisation. Environmental superiority, however, remains conditional on durability and life-cycle evidence.

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