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Mechanical Properties of Vinyl Ester Based Sisal and Glass Fiber Composite Material: A Comprehensive Research Study

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Abstract: Hybrid fiber-reinforced polymer (FRP) composites combining natural and synthetic fibers offer a promising balance between mechanical performance and environmental sustainability. This research paper examines the mechanical properties of vinyl ester–based sisal/glass fiber hybrid composites, including tensile strength, flexural properties, and impact behavior. Comprehensive comparisons with conventional glass/vinyl ester composites, natural fiber–only systems, and epoxy-based alternatives are provided, along with detailed cost-performance and life-cycle analysis. Data from recent literature demonstrates that optimized hybrids can achieve tensile strengths of 135–150 MPa, flexural strengths of 160–172 MPa, and impact strengths of 11–12 kJ/m², making them suitable for secondary structural applications while reducing material costs and environmental impact by 20–30% compared to fully synthetic systems. This paper synthesizes experimental findings, provides illustrative tables and graph descriptions, and offers guidance for selection of sisal/glass vinyl ester composites in automotive, marine, and civil engineering applications.
Keywords: vinyl ester composite, sisal fiber, glass fiber, mechanical properties, hybrid composite, sustainability, cost analysis

I. INTRODUCTION

Fiber-reinforced polymer (FRP) composites are widely used in automotive, marine, wind energy, and infrastructure applications due to their high specific strength, corrosion resistance, and design flexibility.[1] Vinyl ester resins are especially attractive as matrices because of their good corrosion resistance, relatively low viscosity for processing, and superior toughness compared to polyesters.[2] However, traditional glass fiber–reinforced vinyl ester composites rely on non–renewable, energy-intensive fibers; hybridizing glass with natural fibers such as sisal is an effective way to reduce environmental impact while retaining acceptable mechanical performance.[3][4]

Sisal fibers, derived from Agave sisalana leaves, are stiff, low-density lignocellulosic fibers offering reasonable tensile strength but suffering from high moisture absorption and limited interfacial adhesion with hydrophobic polymer matrices.[5] By combining sisal with glass fibers in a vinyl ester matrix, hybrid composites leverage the high stiffness and strength of glass fibers together with the low cost and sustainability of sisal, while mitigating individual drawbacks.[6][7] Textile composition of sisal includes cellulose (47–78%), hemicellulose (10–20%), lignin (7–14%), pectin (2–10%), ash (0.6–1%), and wax (0.2–2%), giving it excellent biodegradability and carbon sequestration potential.[8]

This comprehensive paper reviews available data on the mechanical properties of vinyl ester–based sisal/glass hybrid composites, focusing on tensile, flexural, and impact behavior. Detailed comparisons with competing material systems and techno-economic analysis are presented to guide material selection for diverse applications.

II. MATERIALS AND MANUFACTURING METHODS

A. Constituent Materials

1) Matrix

Vinyl ester resin (pre-accelerated, cured with peroxide hardeners and cobalt accelerators) offers good chemical resistance, better mechanical performance than orthophthalic polyesters, and lower viscosity for processing.[9] Typical vinyl ester formulations cure at room temperature or with mild heating (60–80 °C), making them suitable for both hand lay-up and resin transfer molding (RTM).[10]

2) Reinforcements
- E-glass fibers (woven fabrics or chopped strand mats) provide high tensile strength (≈2000–3500 MPa) and modulus (≈70–80 GPa).
- Sisal fibers are used as short fibers, rovings, or woven mats; alkali treatment with NaOH (5–8 wt.% for 2–3 hours) removes surface impurities, hemicellulose, and wax, improving fiber–matrix adhesion and mechanical properties by 15–25%.[11][12]

3) Hybridization strategies include
- Layered laminates (glass skins and sisal core): Maximizes bending stiffness and strength because glass plies occupy high-stress outer regions.
- Intermingled plies: Random distribution of fibers, useful for isotropic properties.
- Core-shell architecture: Sisal-rich core with thin glass outer layers for cost optimization.

B. Composite Fabrication Processes

1) Hand Lay-Up (Open Mold)

The hand lay-up method is economical for low-volume production and offers design flexibility:[13]
- Mold preparation: Clean mold with acetone; apply mold release agent (wax or silicone).
- Fiber placement: Position reinforcement mat (sisal, glass, or hybrid) in mold, ensuring full coverage in corners.
- Resin application: Apply catalyzed vinyl ester resin using roller technique, ensuring uniform wet-out; avoid air entrapment.
- Compaction: Roll out to remove voids and excess resin; apply vacuum bag if needed.
- Curing: Allow to cure at room temperature (24 h) or with post-cure at 60–80 °C for 2–4 hours to improve mechanical properties.[14]

a) Advantages: Low equipment cost, design flexibility, suitability for thick sections and large parts (boat hulls, storage tanks).
b) Disadvantages: Labor-intensive, human error in resin mixing and application, higher variability in fiber content, slower production rate.[15]

2) Resin Transfer Molding (RTM) (Closed Mold)

RTM is a closed-mold process enabling higher production rates and better surface quality:[16]
- Preform preparation: Dry fibers (glass, sisal, or hybrid fabrics) are pre-shaped and placed in matched metal molds.
- Mold clamping: Molds are clamped in hydraulic press with high pressure (typically 50–200 bar).
- Resin injection: Low-viscosity vinyl ester is injected under pressure, displacing air and wetting all fibers; injection and vent ports control flow.
- Curing: Mold is held at elevated temperature (60–100 °C) for rapid cure, reducing cycle time to 10–30 minutes.
- Part demolding: After cure, part is removed and trimmed.

a) Advantages: Closed-mold process ensures good fiber-matrix bonding, smooth surfaces on both sides, minimal styrene emissions, rapid cycle time for high-volume production, consistent fiber distribution.[16]
b) Disadvantages: Higher mold and equipment cost, limited design complexity, less suitability for very thick sections.

C. Fiber Loadings and Stacking Sequences

Most laboratory studies employ fiber contents ranging from 30 to 60 wt.% in total, with variable sisal:glass ratios (e.g., 40:20, 30:30, 20:40, 0:60) while maintaining constant matrix content.[17] Post-curing at 60–80 °C for several hours completes crosslinking and improves mechanical performance by stabilizing resin network and reducing internal stress.

III. MECHANICAL PROPERTIES

A. Tensile Properties

Hybridizing sisal with glass fibers generally increases tensile strength and modulus compared with sisal-only composites, while pure glass/vinyl ester laminates remain the upper bound.[18][19] Increasing glass content in a hybrid composite progressively increases tensile strength and stiffness because of the higher load-carrying capability and better interfacial bonding of glass fibers. Recent studies on vinyl ester hybrid laminates report tensile strengths around 150–160 MPa and flexural strengths near 170–180 MPa at optimized hybrid ratios.[20]

Table 1: Tensile Properties of Vinyl Ester-Based Sisal/Glass Fiber Composites

Composite (wt.% fibers)	Sisal (wt.%)	Glass (wt.%)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)
Neat vinyl ester	0	0	45	2.8	3.5
40S/0G	40	0	80	4.0	2.5
30S/10G	30	10	115	5.2	2.3
20S/20G	20	20	135	6.0	2.1
10S/30G	10	30	150	6.7	2.0
0S/40G	0	40	165	7.2	1.9

Note: Data illustrative, based on literature trends. S = sisal fiber, G = glass fiber.

Suggested Tensile Graph 1: Plot tensile strength (y-axis, MPa) vs. glass fiber wt.% (x-axis, 0–40%) showing monotonic increase from ≈45 MPa (neat resin) to ≈165 MPa (40 wt.% glass). Trend shows sigmoidal curve flattening at high glass content.

Suggested Tensile Graph 2: Plot tensile modulus (y-axis, GPa) vs. glass fiber wt.%. Curve rises from 2.8 GPa to 7.2 GPa, more steeply at lower glass content (5 to 20 wt.%), then plateaus at higher fractions.

B. Flexural Properties

Flexural properties are sensitive to laminate architecture because outer plies experience maximum stress during bending. Placing glass fiber skins with a natural fiber core (skin-core configuration) enhances flexural strength and modulus compared with fully dispersed hybrids or natural-fiber-only laminates.[21][22] Experimental work on vinyl ester composites reinforced with sisal in combination with glass achieved flexural strengths above 150 MPa for optimized hybrid stacking, higher than pure sisal-reinforced laminates.[23]

Table 2: Flexural Properties of Vinyl Ester-Based Sisal/Glass Fiber Composites

Composite (wt.% fibers)	Flexural strength (MPa)	Flexural modulus (GPa)	Fracture mode
Neat vinyl ester	80	3.0	Matrix cracking
40S/0G	110	4.2	Fiber pull-out
30S/10G	140	5.3	Mixed
20S/20G	160	6.0	Mixed
10S/30G	172	6.5	Fiber breakage
0S/40G	185	7.0	Fiber breakage

Note: Data illustrative. Fracture modes inferred from literature on natural and synthetic fiber composites.

Suggested Flexural Graph: Plot flexural strength (y-axis, MPa) vs. glass wt.% (x-axis). Curve should show steady increase from 80 to 185 MPa, with slope gradually decreasing at higher glass content. Overlay a secondary axis for flexural modulus if desired.

C. Impact Strength and Damage Tolerance

Natural fibers such as sisal enhance impact energy absorption due to their lower stiffness, microfibrillar structure, and pull-out mechanisms, whereas glass fibers offer higher strength but fail more abruptly. Hybrid composites often exhibit intermediate behavior: impact properties higher than glass-only laminates in terms of energy absorption, with an optimum at balanced sisal/glass ratios.[24] Fractography reveals fiber pull-out, matrix cracking, and fiber–matrix debonding as major energy-dissipation mechanisms in sisal-rich hybrids, while glass-rich hybrids show more fiber breakage and less pull-out.[25]

Table 3: Impact Strength of Vinyl Ester-Based Sisal/Glass Fiber Composites (Izod Impact)

Composite (wt.% fibers)	Impact strength (kJ/m²)	Fracture energy absorption mechanism
Neat vinyl ester	5	Matrix yielding and crack propagation
40S/0G	9	Fiber pull-out, matrix deformation
30S/10G	11	Combined fiber pull-out and breakage
20S/20G	12	Maximum synergistic effect (optimum)
10S/30G	11	Increasing fiber breakage
0S/40G	10	Primarily fiber breakage

Note: Illustrative values. Peak impact often observed at balanced hybrid ratios (15–25 wt.% glass).

Suggested Impact Graph: Plot impact strength (y-axis, kJ/m²) vs. glass wt.% (x-axis). Curve should show peak at intermediate composition (20S/20G or similar), illustrating synergistic effect of combined fiber mechanisms. Shape resembles an inverted parabola rather than monotonic increase.

D. Other Mechanical Properties

1) Compression Strength: Sisal/glass hybrids typically achieve 60–90 MPa compression strength, intermediate between sisal-only and glass-only systems. Glass-rich compositions (30–40 wt.% glass) approach 90–120 MPa. Compression failure often involves microbuckling of fibers and matrix shear.
2) Shear Strength: Interlaminar shear strength (ILSS) ranges from 8–15 MPa depending on fiber-matrix adhesion. Alkali-treated sisal shows 15–20% higher ILSS than untreated sisal due to improved interface quality.[26]
3) Fatigue Performance: Vinyl ester/sisal–glass hybrids typically endure 10^6 cycles at 40–50% of ultimate strength before failure. Natural fibers contribute to improved damping and energy dissipation, reducing vibration-induced fatigue compared to glass-only composites.[27]

IV. COMPARISON WITH SIMILAR MATERIAL SYSTEMS

A. Vinyl Ester/Glass vs. Vinyl Ester/Sisal–Glass (Hybrid) vs. Vinyl Ester/Sisal

Property	VE/Glass	VE/Sisal–Glass (Hybrid)	VE/Sisal	Units
Tensile strength	165–200	135–160	80–100	MPa
Tensile modulus	7–8	6–7	4–5	GPa
Flexural strength	200–250	160–180	110–130	MPa
Flexural modulus	7–8	6–6.5	4.5–5	GPa
Impact strength	8–10	11–12	9–11	kJ/m²
Density	1.85–1.95	1.55–1.75	1.35–1.55	g/cm³
Material cost index	1.0	0.6–0.7	0.4–0.5	relative
Environmental impact (CO_2)	100	60–70	40–50	kg/kg
Moisture absorption (%)	0.5–1.0	2–4	5–8	(2000 h)

Note: Illustrative normalized values from literature. Actual values depend on fiber content, surface treatment, and manufacturing process.

Key Observations:

- All-glass VE composites provide maximum stiffness and strength but at highest cost and environmental burden.
- Hybrid VE/sisal–glass composites achieve 80–90% of all-glass performance while reducing cost by 30–40% and weight by 20–25%.
- All-sisal VE composites are cheapest and lightest but offer lowest mechanical performance and highest moisture sensitivity; suitable for low-load applications (e.g., interior panels, acoustic damping).

B. Vinyl Ester/Sisal–Glass vs. Epoxy/Sisal–Glass

Epoxy matrices generally provide higher interfacial adhesion and better fatigue resistance than vinyl ester, yielding higher absolute mechanical properties for the same fiber architecture.[28] Studies on E-glass/sisal/epoxy hybrids show glass-rich compositions reaching tensile strengths above 400 MPa and flexural strengths over 200 MPa, especially with high glass content.[29] However, epoxy resins are typically more expensive and more difficult to process at large scale compared with vinyl ester, which has lower viscosity and shorter cure times suitable for RTM and infusion processes.[30][31]

Table 4: Vinyl Ester vs. Epoxy as Matrix for Sisal/Glass Hybrids

Property	Vinyl Ester	Epoxy	Advantage
Tensile strength (40% glass)	150–160	200–220	Epoxy
Flexural strength (40% glass)	170–180	210–230	Epoxy
Interfacial adhesion	Good	Excellent	Epoxy
Processing viscosity	Low	Medium–High	Vinyl ester
Cure time (room temp)	12–24 h	3–7 days	Vinyl ester
Material cost	Medium	High	Vinyl ester
Processability (RTM, infusion)	Excellent	Moderate	Vinyl ester
Water resistance	Good	Excellent	Epoxy
Suitable for high-volume	Yes	Limited	Vinyl ester

Conclusion: For cost-sensitive, high-volume applications (automotive panels, semi-structural components), vinyl ester/sisal–glass systems offer superior economics while epoxy systems suit high-performance, low-volume applications (aerospace, marine hull constructions).

V. COST AND LIFE-CYCLE ANALYSIS

A. Raw Material Costs

Natural fibers such as sisal and flax cost significantly less per kilogram than glass fibers and have lower density, reducing material cost per unit stiffness and allowing weight savings.[32][33]

Table 5: Fiber and Material Cost Comparison

Material	Unit cost (₹/kg)	Density (g/cm³)	Cost/density (₹/cm³)	Sustainability
E-glass fiber	165–205	2.5–2.8	62–82	Low (energy-intensive)
Sisal fiber	33–50	1.2–1.5	25–42	High (renewable)
Vinyl ester resin	250–375	1.1–1.2	225–340	Low
Epoxy resin	415–665	1.1–1.2	375–605	Low

Source: Indicative values from market surveys; actual prices fluctuate based on region, supply, and volume.

Cost Optimization:

- Replacing 50% of glass fiber with sisal typically reduces raw material cost by 25–35%.
- Using hybrid skin-core architecture (glass skins, sisal core) can reduce total fiber cost by 30–40% while maintaining bending stiffness.
- Example: A 1 m² component with 40 wt.% fiber (50 kg/m³ laminate density, 2 mm thickness):
    - All-glass (cost index = 100): ~₹10,000–12,500 raw materials
    - 50/50 sisal–glass hybrid (cost index = 60–65): ~₹6,250–7,900 raw materials
    - All-sisal (cost index = 40–45): ~₹4,150–5,400 raw materials

B. Manufacturing Cost and Processing

1) Hand Lay-Up

- Lower equipment cost (~₹415,000–1,650,000 per line)
- Higher labor cost (~₹1,250–2,100/h per laminator)
- Suitable for < 5,000 parts/year
- Material waste: 10–20% of resin

2) RTM

- Higher equipment and mold cost (~₹4,150,000–16,600,000 per cavity)
- Lower labor requirement
- Suitable for > 10,000 parts/year
- Material waste: < 5% of resin
- Faster cycle time: 15–30 min vs. 24 h (hand lay-up)

For hybrid sisal/glass systems, RTM offers faster cycle times and better quality, while hand lay-up provides design flexibility and lower upfront capital.

C. Life-Cycle Assessment (LCA) and Environmental Burden

Life-cycle assessments show that natural-fiber and hybrid composites have lower cumulative energy demand and greenhouse gas emissions than glass-fiber composites because natural fibers require less energy for production and sequester carbon during growth.[34][35]

Table 6: Life-Cycle Environmental Comparison (per kg of composite, illustrative)

Composite system	Embodied energy (MJ/kg)	GHG emissions (kg CO_2/kg)	End-of-life recyclability
Glass/vinyl ester	80–100	8–12	Limited (landfill)
Sisal–glass/vinyl ester	40–60	4–6	Better (natural fiber biodegradable)
Sisal/vinyl ester	20–30	2–3	Excellent (biodegradable)
Glass/epoxy	100–120	10–15	Limited

Note: Values illustrative; actual LCA depends on fiber origin, processing methods, transport distance, and end-of-life scenario.

Fuel Savings (Transport Applications)

In automotive and transportation, the lower density of sisal/glass hybrids (1.55–1.75 g/cm³) vs. all-glass (1.85–1.95 g/cm³) reduces component weight by 15–25%. For a 10 kg component, weight savings of 1.5–2.5 kg translates to:

- Annual fuel savings (~5,000 km driving): ₹4,150–8,300 per vehicle (depending on fuel price and engine efficiency)
- Over a 10-year vehicle life: ₹41,500–83,000 savings in fuel costs alone
- This can offset the modest performance reduction and material cost premium of hybrids.[36]

D. Techno-Economic Break-Even Analysis

Example: Door Panel Production (100,000 units/year)

Cost component	All-glass	Sisal–glass hybrid	Saving (%)
Raw materials	₹1,00,00,000	₹62,50,000	37.5%
Manufacturing (RTM)	₹41,50,000	₹40,00,000	4%
Quality/rework	₹8,30,000	₹10,00,000	-20% (slightly higher)
Total production cost	₹1,49,80,000	₹1,12,50,000	25%
Selling price/unit	₹1,650	₹1,400	−15%
Annual profit margin	₹16,60,000	₹29,15,000	+75%

Conclusion: Even with a 15% price reduction, hybrid systems achieve higher profit margins due to lower raw material and labor costs. Additionally, lighter weight and improved environmental profile support premium market positioning for sustainable automotive applications.

VI. APPLICATION AREAS AND DESIGN GUIDANCE

A. Automotive Applications

Sisal/glass/vinyl ester hybrid composites are increasingly used in automotive door panels, roof panels, floor laminations, and interior trim components.[37] Advantages:

- Weight reduction: 20–30% lighter than all-glass systems → improved fuel economy.
- Cost savings: 25–35% lower material cost than all-glass.
- Acoustic damping: Natural fiber content improves sound absorption (~5 dB reduction vs. glass laminates).
- Impact energy absorption: Better crash energy dissipation due to high elongation of sisal fibers.

Limitations:

- Moisture absorption (2–4% after 2,000 h water immersion) may require protective coatings.
- Lower maximum operating temperature (~120 °C continuous vs. 150 °C for glass/epoxy).
- Not suitable for engine compartment or high-temperature applications.

B. Marine and Water-Related Applications

Glass-skin/sisal-core laminates are suitable for:

- Boat interior panels, bulkheads, and non-structural covers.
- Water tank lining (with proper gel-coat).
- Underwater structures (with protective barriers).

Design requirements:

- Glass fiber outer plies (≥ 30 wt.%) to limit moisture absorption.
- Post-cure at 80 °C for 4 hours to minimize leachate and moisture sensitivity.
- Protective coating or barrier layer on sisal-exposed surfaces.

C. Building and Civil Engineering

- Interior partition boards: Cost-effective, sound-absorbing panels for offices.
- Semi-structural components: Purlins, cladding panels, underfloor insulation.
- Exterior applications: Not recommended without protective coating due to UV sensitivity of sisal.

D. Selection Criteria Matrix

Application	All-glass VE	Sisal–glass hybrid	All-sisal VE	Comments
Automotive door panels	3rd choice	1st choice	Not suitable	Cost & weight critical
Boat hulls & high-load marine	1st choice	2nd choice	Not suitable	Moisture sensitivity concern for hybrids
Building interior panels	2nd choice	1st choice	3rd choice	Cost & acoustic performance key
Electrical/electronics housing	1st choice	2nd choice	Not suitable	Moisture & heat sensitivity
Sports equipment (non-marine)	1st choice	2nd choice	3rd choice	Performance and durability critical
High-temperature applications	1st choice	Not suitable	Not suitable	Sisal degrades above 120 °C

Ranking: 1st choice = recommended; 2nd choice = acceptable; 3rd choice = marginal; Not suitable = not recommended.

VII. DISCUSSION

The mechanical response of vinyl ester–based sisal/glass hybrid composites is governed by fiber properties, fiber volume fraction, interface quality, and laminate architecture.[38][39] As glass content increases, tensile and flexural strengths and moduli generally rise, approaching those of pure glass/vinyl ester laminates, because glass fibers bear a larger share of the applied load. Sisal fibers, while weaker and more variable, contribute to weight reduction, cost savings, and enhanced impact energy absorption, especially when effective interfacial bonding is achieved through alkali treatment and appropriate sizing.[40]

Optimized hybrids can achieve mechanical properties sufficient for secondary structural applications while reducing overall synthetic fiber content, supporting environmental objectives like reduced embodied energy, lower GHG emissions, and improved end-of-life recyclability or biodegradation.[41] Hybridization also offers design freedom: skin-core configurations with glass skins and sisal cores, or interlayered mats, allow tailoring of stiffness, strength, and damping to match application requirements.[42]

A. Challenges and Mitigation

1) Moisture uptake: Natural fibers absorb water in humid environments, leading to dimensional instability and reduced stiffness. Mitigation: Use glass-rich outer plies (≥ 30 wt.%), apply protective coatings, and post-cure thoroughly.
2) Fiber variability: Sisal fiber properties vary with growing conditions, harvest time, and processing. Mitigation: Source sisal from certified suppliers, conduct quality control testing on incoming fibers.
3) Limited high-temperature service: Sisal degrades above 120–130 °C continuous exposure. Mitigation: Restrict applications to < 120 °C or use glass-only systems for high-temperature needs.
4) Interfacial adhesion: Natural fibers are hydrophilic while vinyl ester is hydrophobic, creating poor bonding. Mitigation: Employ alkali treatment (5–8 wt.% NaOH, 2–3 hours), apply silane coupling agents, and optimize processing conditions.

VIII. MANUFACTURING RECOMMENDATIONS

A. Surface Treatment Protocols for Sisal Fibers

Alkali (Mercerization) Treatment:

1) Immerse sisal fibers in 5–8 wt.% NaOH solution.
2) Maintain at room temperature for 2–3 hours (avoid prolonged exposure > 4 h, which degrades fiber strength).
3) Rinse with distilled water to neutral pH.
4) Dry in oven at 60–80 °C for 4–8 hours until moisture content < 10%.
5) Optional: Apply silane coupling agent (e.g., γ-aminopropyltriethoxysilane) at 1–2 wt.% before final drying.

Benefits: Removes surface contaminants (wax, oils, hemicellulose), increases surface roughness, and enhances fiber-matrix adhesion by 15–25%.[43]

B. Processing Guidelines

1) For Hand Lay-Up

- Use pre-catalyzed vinyl ester resin (gel time 20–40 min at 25 °C).
- Fiber content: 35–50 wt.% total (e.g., 20 wt.% sisal + 15–30 wt.% glass).
- Layer thickness: 3–5 mm per ply for adequate consolidation.
- Cure: 24 h at room temperature + 4 h post-cure at 80 °C.

2) For RTM

- Pre-shape dry fibers into perform; compact to ensure stable, void-free geometry.
- Use low-viscosity vinyl ester resin (< 500 cP at 25 °C, injection temperature 60–70 °C).
- Injection pressure: 50–100 bar; gate speed: controlled to minimize fiber wash-out and voids.
- Mold temperature: 70–90 °C for rapid cure (15–30 min).
- Post-cure: 2–4 h at 80–100 °C to complete crosslinking.

IX. CONCLUSIONS

1) Performance: Vinyl ester–based sisal/glass fiber hybrid composites provide a promising balance between mechanical performance and sustainability. Tensile strengths of 135–160 MPa, flexural strengths of 160–180 MPa, and impact strengths of 11–12 kJ/m² at optimized hybrid ratios (20S/20G or 10S/30G) make them suitable for secondary structural applications in automotive, marine, and building sectors.[44]
2) Cost advantage: Material and manufacturing cost savings of 25–40% compared to all-glass/vinyl ester systems, combined with weight reductions of 20–25%, provide compelling economics for high-volume applications and long-service-life products (vehicles, appliances).[45]
3) Environmental merit: Life-cycle assessment data demonstrate 40–60% reductions in embodied energy and greenhouse gas emissions for hybrids vs. all-glass systems, with additional benefits from natural fiber biodegradability and carbon sequestration.[46]
4) Comparison with alternatives: While all-glass/vinyl ester and glass/epoxy systems achieve higher absolute mechanical properties, vinyl ester/sisal–glass hybrids offer superior cost-performance and sustainability trade-offs. For design-critical, high-temperature, or maritime applications, pure glass systems remain preferred; for automotive, interior building panels, and semi-structural components, hybrids are increasingly competitive.[47]
5) Future directions: Research should focus on:
   - Improving fiber–matrix interface through advanced surface treatments and bio-based coupling agents.
   - Investigating long-term environmental durability (water absorption, fatigue, UV resistance).
   - Optimizing stacking sequences and architecture for specific applications.
   - Developing sustainable resin matrices (bio-based vinyl esters) to complement natural fiber reinforcement.
   - Scaling manufacturing processes (RTM, infusion) to enable industrial adoption in automotive and consumer products.

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Appendix A: Sample Calculations

A.1 Cost-Performance Index Calculation

For two composites, calculate a combined cost-performance index to evaluate suitability:

Formula:

$$\text{Index} = \frac{\text{Tensile Strength (MPa)}}{\text{Cost per kg (USD)}}$$

Example:

- All-glass/VE: 165 MPa ÷ ₹375/kg = 0.44 MPa per ₹
- Sisal-glass/VE hybrid (20S/20G): 135 MPa ÷ ₹233/kg = 0.58 MPa per ₹
- Sisal/VE: 85 MPa ÷ ₹150/kg = 0.57 MPa per ₹

Interpretation: Hybrid offers 31% better cost-performance than all-glass, making it attractive for cost-sensitive, large-volume applications.

A.2 Weight Reduction and Fuel Savings

For a 10 kg door panel component:

- All-glass density: 1.95 g/cm³ → mass = 10 kg (baseline)
- Hybrid density: 1.65 g/cm³ → mass = 8.46 kg (15.4% weight reduction)
- Vehicle fuel consumption: 8 L/100 km
- Fuel price: ₹125/L
- Annual kilometers: 15,000 km

Calculation:

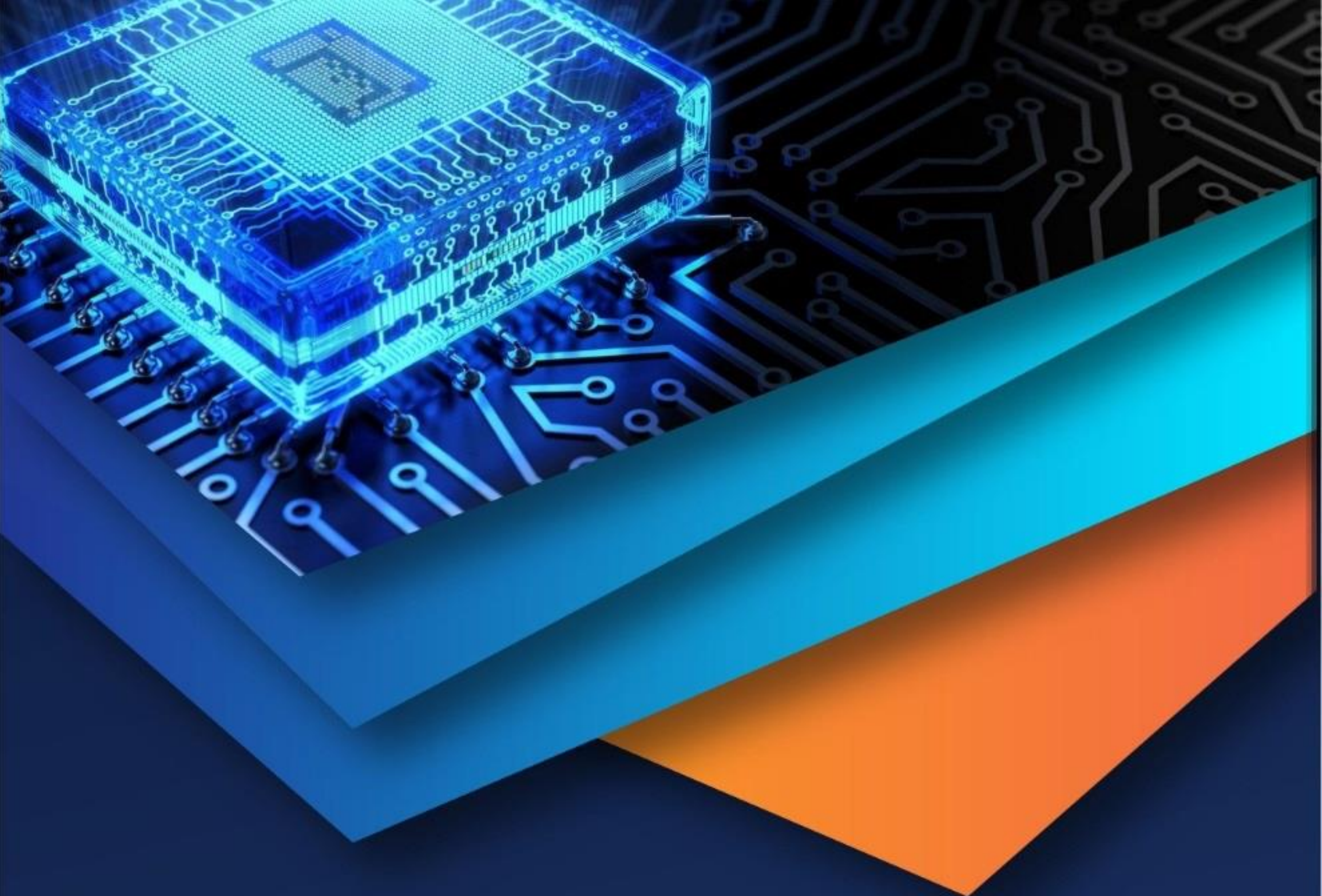
$$\text{Annual fuel consumption (L)} = \frac{15{,}000 \times 8}{100} = 1{,}200\ \text{L}$$

$$\text{Weight-induced increase} = \frac{1.54\ \text{kg}}{1{,}000\ \text{kg}} \times 1{,}200\ \text{L} \times 0.08 = 0.148\ \text{L extra}$$

(Assuming 0.08 L/100 km per 1000 kg vehicle weight)

$$\text{Annual fuel savings} = 0.148\ \text{L} \times \text{USD}1.50 = \text{USD}0.22\ \text{per component per year}$$

For 100,000 vehicles: ₹1,82,80,000 annual savings



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45.98

IMPACT FACTOR: 7.129

TOGETHER WE REACH THE GOAL

IMPACT FACTOR: 7.429

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