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PALF–Hemp Hybrid Reinforced PLA Composites: A Systematic Review of Fibre Ratio, Interfacial Modification, and Mechanical Performance

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Abstract. *Natural-fibre-reinforced poly(lactic acid) (PLA) composites are investigated as sustainable alternatives to petroleum-based materials; however, the combined effects of pineapple leaf fibre (PALF), hemp fibre, hybrid ratio, interfacial modification, and processing remain insufficiently consolidated. This systematic review evaluates PALF–hemp hybrid-reinforced PLA composites, focusing on fibre ratio, total loading, alkali and silane treatments, tensile, flexural and impact performance, and fracture morphology. A Scopus search using a reproducible TITLE-ABS-KEY Boolean strategy identified 3,061 records. Following filtering, title–abstract screening, eligibility assessment, and hierarchical evidence classification, 30 studies were retained, comprising direct PALF–hemp/PLA evidence and related PALF-, hemp-, and hybrid-PLA systems. The findings indicate that mechanical performance is governed by a coupled composition–processing–interface–fracture–property relationship rather than fibre addition alone. The only direct PALF–hemp/PLA study reported improvements of 73.50% in tensile strength, 60.00% in flexural strength, and 58.40% in impact resistance following optimisation of fibre content, moulding temperature, and pressure. Supporting studies demonstrated that fibre length, orientation, surface treatment, matrix continuity, crystallinity, and void content also influence mechanical performance. Alkali and silane treatments generally improved interfacial adhesion and reduced water uptake, although moisture exposure could still cause substantial stiffness losses. Fracture observations associated effective interfaces with fibre rupture, matrix adhesion, crack deflection, and controlled pull-out, whereas weaker interfaces exhibited debonding, interfacial gaps, agglomeration, and void-assisted cracking. However, only one study directly investigated PALF–hemp/PLA composites, limiting the available evidence for establishing a generalisable optimum PALF ratio. Consequently, any apparent optimum remains specific to the reported formulation and processing conditions and requires independent experimental validation. Future research should distinguish fibre ratio from total loading, optimise each fibre component systematically, standardise processing and conditioning conditions, and validate multi-response performance through microscopy, physicochemical characterisation, durability testing, sensitivity analysis, and confirmation experiments.*

Keywords: *Pineapple leaf fibre; Hemp fibre; Poly(lactic acid); Hybrid biocomposites; Fibre loading.*

Type of the Paper: Review Article.

1. Introduction

The transition from petroleum-based polymers and synthetic reinforcements towards renewable composite systems has intensified the development of natural-fibre-reinforced biopolymers for lightweight structural, transportation, packaging, and additive-manufacturing applications. Poly(lactic acid) (PLA) is among the most widely investigated biodegradable

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matrices because it can be processed through extrusion, injection moulding, compression moulding, and fused-deposition modelling. Nevertheless, neat PLA remains constrained by brittleness, limited impact-energy absorption, and a strong dependence on thermal history and processing-induced defects. The incorporation of lignocellulosic fibres can increase stiffness, renewable content, and specific mechanical performance, but these benefits depend on whether the reinforcement remains intact, is uniformly dispersed, and forms an effective stress-transfer pathway with the PLA matrix.

Pineapple leaf fibre (PALF) is attractive because it combines agricultural-residue valorisation with considerable mechanical reinforcement potential. Anand et al. [1] showed that silane-treated PALF with a length of approximately 15–20 mm generated stronger fibre–matrix bonding and fracture-toughness values of 42–55 MPa, whereas shorter fibres were associated with crack proliferation and lower values of 15–32 MPa. The same study identified 20 mm PALF as the most favourable length for tensile, flexural, impact, and wear performance. Loading effects are similarly non-linear: Bindiganavile [2] reported that alkali-treated PALF performance increased up to 15 wt.%, reaching 78 MPa tensile strength and 122 MPa flexural strength, but higher contents promoted agglomeration, resin-deficient regions, and microvoid formation.

Hemp fibre provides a complementary reinforcement pathway through stiffness enhancement, load distribution, and formation of a load-bearing network. Its hydrophilic surface, however, creates a polarity mismatch with PLA and can produce poor wetting, interfacial debonding, and moisture-assisted deterioration. Çevik Elen et al. [3] found that incorporating 30 wt.% hemp into PLA improved tensile performance, while NaOH-treated hemp/PLA achieved a 54.3% increase in tensile strength relative to neat PLA. Valin Fernández et al. [4] further showed that cationisation with EPTA increased tensile strength by 615% relative to an untreated-hemp formulation, although the treated system ultimately approached rather than exceeded the performance of neat PLA.

The hybridisation of PALF and hemp is therefore conceptually attractive because the two fibres may perform complementary functions. PALF may support axial load bearing and crack bridging, whereas hemp may improve stiffness and reinforcement continuity. Hybridisation should not, however, be interpreted as automatically synergistic. A positive hybrid effect exists only when the combined response exceeds the proportional expectation derived from the corresponding single-fibre systems; otherwise, the result may be additive, property-balancing, or negative because of inadequate impregnation, dissimilar fibre dimensions, uneven stress distribution, or competition for the available PLA matrix.

Fibre ratio must also be distinguished from total fibre loading. Total loading determines the quantity of reinforcement and the amount of matrix available for wetting, whereas the PALF:hemp

ratio determines how a fixed reinforcement fraction is distributed between the two fibres. Related hybrid PLA evidence demonstrates this distinction. Janet et al. [5] maintained total fibre content at 10 wt.% and found that a hemp-rich formulation containing 7.5 wt.% hemp and 2.5 wt.% sisal achieved 53.19 MPa tensile strength, 83.24 MPa flexural strength, and 0.90 J impact energy. SEM revealed uniform distribution, fibre breakage, and crack deflection, indicating that relative composition modified both numerical performance and the fracture pathway.

Interfacial modification is central to translating fibre properties into composite-scale performance. Alkali treatment removes waxes and weakly bonded surface constituents, increasing roughness and mechanical interlocking, whereas silane can create chemically compatible bridges between hydroxyl-rich fibre surfaces and the polymer phase. Yet the strongest dry-state response may not yield the best durability. Bollino et al. [6] reported that 5 wt.% NaOH and GPTMS treatments reduced hemp-composite water uptake from 7.74% to 6.46% and 5.58%, respectively, at room temperature, while moisture exposure still reduced stiffness by approximately 50% after alkali treatment and 60% after silane treatment.

Fracture morphology provides the mechanism required to interpret numerical changes. Fibre rupture and matrix remnants on fibre surfaces generally indicate effective stress transfer, whereas clean pull-out, interfacial gaps, debonding, delamination, and resin-deficient regions indicate weak adhesion or poor consolidation. Controlled pull-out and crack deflection may nevertheless increase impact-energy dissipation, showing that the strongest interface is not necessarily the interface that maximises toughness.

Within the retained corpus, Raja et al. [7] provides the most direct evidence for the target PALF–hemp/PLA system. The compression-moulded composite was optimised through an enhanced Taguchi approach, Grey Relational Analysis, principal-component analysis, and computational validation. Reported improvements reached 73.50% in tensile strength, 60.00% in flexural strength, and 58.40% in impact resistance. Nevertheless, the wider literature remains dominated by PALF/PLA, hemp/PLA, PALF–hemp composites in non-PLA matrices, and related hybrid PLA systems. The optimum PALF:hemp ratio, total loading, treatment condition, and fracture-controlled balance among tensile, flexural, and impact performance therefore remain insufficiently validated.

This systematic review addresses that fragmentation by integrating direct and mechanistically relevant evidence within a fibre-ratio–interface–fracture–property framework. The review determines how PALF:hemp ratio, total fibre loading, alkali and silane treatments, and processing-induced interfacial structure govern tensile, flexural, impact, and fracture behaviour, while explicitly separating demonstrated target-system findings from bounded supporting evidence.

To clarify the conceptual positioning of the review, Fig. 1 connects the constituent system, controllable design variables, interfacial and structural consequences, fracture pathways, mechanical responses, and the central unresolved design problem.

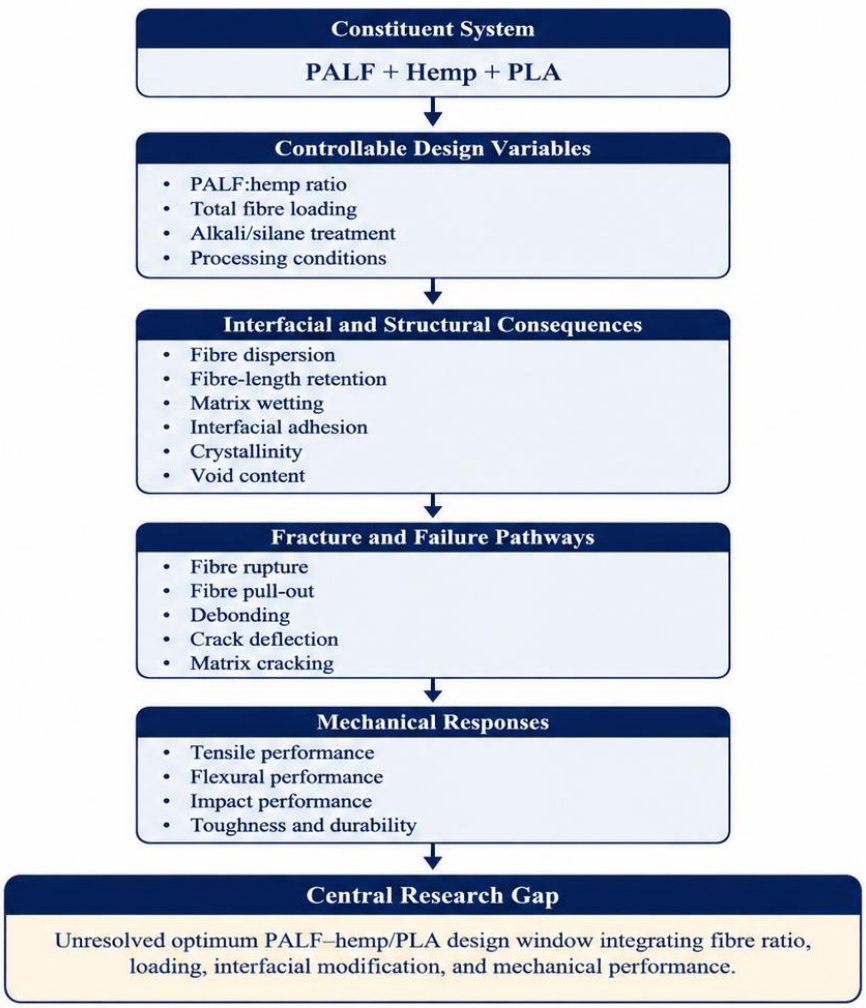


Fig. 1. Conceptual positioning of PALF–hemp hybrid reinforced PLA composites within a composition–interface–fracture–property framework.

2. Materials and methods

2.1 Review Design and Scope

This study was designed as a systematic literature review to identify, classify, and critically synthesise evidence on PALF–hemp hybrid reinforced PLA composites. The review followed the PRISMA 2020 reporting logic and adopted a composition–processing–interface–fracture–property framework in which PALF:hemp ratio, total loading, surface treatment, manufacturing conditions, interfacial structure, and failure morphology were treated as interconnected determinants of mechanical behaviour.

The primary material scope was restricted to composites involving PALF, hemp, and PLA. Because direct studies simultaneously combining both fibres in PLA were limited, the evidence was organised hierarchically. Tier 1 comprised direct PALF–hemp/PLA studies; Tier 2 included

PALF–hemp systems in other matrices; Tier 3 contained direct PALF/PLA and hemp/PLA evidence; and Tier 4 incorporated closely related hybrid PLA or interface-mechanistic systems. This approach separated demonstrated target-system performance from mechanistically transferable evidence.

The review addressed four questions: (RQ1) How do PALF:hemp ratio and total fibre loading affect tensile, flexural, and impact performance? (RQ2) How do alkali and silane treatments modify fibre–matrix adhesion and mechanical behaviour? (RQ3) Which fracture mechanisms explain improvement or deterioration? (RQ4) Which material, treatment, and processing conditions are needed to establish a validated PALF–hemp/PLA design window?

2.2 Search Strategy and Literature Sources

Scopus was used as the principal bibliographic source because it covers materials science, polymer engineering, composites, mechanical engineering, and sustainable manufacturing. Searches were conducted in title, abstract, and keyword fields using TITLE-ABS-KEY. British and American spelling variants, acronyms, botanical terminology, composite descriptors, mechanical-property terms, and fracture-related expressions were included to maximise recall.

```
TITLE-ABS-KEY ( "pineapple leaf fibre*" OR "pineapple leaf fiber*" OR "pineapple fibre*"
OR "pineapple fiber*" OR PALF OR "Ananas comosus" ) AND ( "hemp fibre*" OR "hemp fiber*"
OR "industrial hemp" OR "hemp reinforcement*" OR hemp OR "Cannabis sativa" ) AND (
"poly(lactic acid)" OR "polylactic acid" OR "poly lactic acid" OR polylactide OR PLA )
AND ( composite* OR biocomposite* OR "bio-composite*" OR "green composite*" OR "hybrid
composite*" OR "natural fibre reinforced composite*" OR "natural fiber reinforced
composite*" ) AND ( "mechanical propert*" OR "tensile strength" OR "tensile modulus" OR
elongation OR "flexural strength" OR "flexural modulus" OR "bending strength" OR "impact
strength" OR "impact resistance" OR "impact energy" OR toughness OR "fracture morphology"
OR fractograph* OR "fracture behaviour" OR "fracture behavior" OR "failure mechanism*" OR
"fibre pull-out" OR "fiber pull-out" OR debond* OR crack* ) AND ( LIMIT-TO ( SUBJAREA ,
"MATE" ) OR LIMIT-TO ( SUBJAREA , "ENGI" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND (
LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( EXACTKEYWORD , "Tensile Strength" )
OR LIMIT-TO ( EXACTKEYWORD , "Natural Fibers" ) ) AND PUBYEAR > 2020 AND PUBYEAR < 2027
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The final Scopus search was conducted on 5 August 2026, yielding 3,061 records. The large result set was expected because ratio, treatment, and fracture morphology are frequently reported in methods or results but may be absent from article titles. Search records were exported with bibliographic data and abstracts in APA-with-abstract format. English-language primary research articles were prioritised; review papers were used only for contextual interpretation or citation tracing and were not treated as primary experimental evidence.

2.3 Screening, Eligibility, and Inclusion Criteria

Screening was conducted progressively. Titles and abstracts were first assessed for correspondence with the target materials and analytical variables. Records were excluded when they concerned unrelated fibres, non-polymeric systems, fibre extraction without composite fabrication, or applications focused only on adsorption, electrical, acoustic, catalytic, filtration, or fire behaviour without relevant mechanical evidence.

A study was retained when it directly investigated PALF–hemp/PLA; examined PALF–hemp interaction in another matrix and provided transferable evidence; investigated PALF/PLA or hemp/PLA with relevant loading, treatment, processing, or fracture data; or supplied closely related hybrid-composite evidence required to interpret ratio, interface, and failure mechanisms. At least one mechanical response and one explanatory variable were required. Reviews, editorials, book chapters, brief conference summaries, corrections, duplicate records, and studies without identifiable material formulations were excluded.

Screening was conducted by one reviewer using the predefined inclusion and exclusion criteria. Titles and abstracts were assessed to identify potentially relevant studies, followed by further assessment of eligible records where the full text was available. Because the screening was conducted by a single reviewer, inter-reviewer disagreements did not arise. Uncertain eligibility decisions were resolved by rechecking the original articles against the predefined criteria. Duplicate records were identified by comparing bibliographic information, including titles, authors, and DOIs where available, and were removed before the screening process.

Following filtering, title–abstract screening, eligibility evaluation, and evidence-tier classification, 30 studies were retained. Because the supplied screening log reported the initial and final totals but not all intermediate counts separately, the aggregated exclusion count is presented in the PRISMA-aligned flow rather than reconstructed into unsupported subcategories.

The identification, screening, and hierarchical classification procedure is summarised in Fig. 2 which distinguishes the direct target-system evidence from the broader mechanistic evidence base.

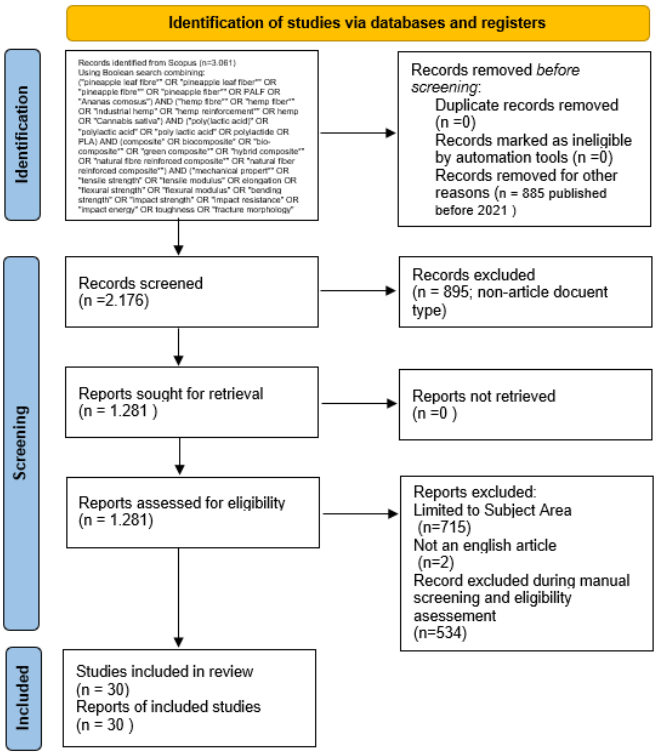


Fig. 2. PRISMA-aligned literature selection and evidence classification for the retained 30-study corpus.

2.4 Data Extraction and Synthesis Procedure

Data were extracted using a structured composition–processing–interface–fracture–property framework. Data extraction was performed by the same reviewer using the structured framework described above. Extracted information was checked against the original articles to ensure consistency in the recorded material compositions, processing conditions, mechanical properties, and associated units. Bibliographic information included authorship, year, journal, DOI, and evidence tier. Material variables included matrix type, PALF content, hemp content, total loading, ratio, fibre form, length, orientation, and stacking. Treatment variables covered chemical type, concentration, duration, washing, drying, and treatment sequence.

Processing information included compression moulding, extrusion, injection moulding, hand lay-up, hot pressing, and additive manufacturing. Where reported, temperature, pressure, screw or printing speed, infill, layer thickness, deposition spacing, and fibre placement were extracted because these factors alter fibre breakage, orientation, matrix impregnation, crystallinity, and void formation. Mechanical outcomes included tensile, flexural, and impact values, together with modulus, elongation, toughness, and load–displacement behaviour. Values were retained in their original units; impact values were not indiscriminately converted because studies used different geometries, notch conditions, and reporting bases.

Interfacial and fracture evidence was extracted from SEM, FTIR, XRD, DSC, water absorption, and fractured-surface descriptions. Particular attention was paid to matrix residues,

fibre rupture, pull-out, interfacial gaps, agglomeration, crack deflection, delamination, and porosity. The synthesis was thematic rather than meta-analytic because matrices, fibre architectures, processing routes, test standards, and reporting units were heterogeneous. Direct PALF–hemp/PLA evidence received the greatest interpretive weight.

To make the methodological procedure explicit, Table 1 links each review component with its operational criterion, extracted variables, and analytical function.

Table 1. Systematic review protocol and data-extraction framework

Review component	Operational criterion	Data extracted	Analytical function
Literature source	Scopus title, abstract, and keyword search	Bibliographic record, abstract, year, journal, DOI	Defines the searchable evidence base
Initial identification	Boolean combination of PALF, hemp, PLA, composite, mechanical, and fracture terms	3,061 retrieved records	Maximises recall and captures terminology variants
Material eligibility	PALF–hemp/PLA or hierarchically relevant evidence	Matrix, reinforcement type, evidence tier	Distinguishes direct from supporting evidence
Composition variables	Ratio, individual content, total loading, length, orientation, stacking	Weight/volume fraction, dimensions, architecture	Enables ratio- and loading-dependent synthesis
Treatment variables	Alkali, silane, compatibilisation, cationisation, related modification	Chemical, concentration, duration, sequence	Explains surface and adhesion effects
Processing variables	Moulding, extrusion, injection, hand lay-up, or additive manufacturing	Temperature, pressure, speed, layers, placement	Separates material effects from process-induced structure
Mechanical eligibility	Tensile, flexural, impact, modulus, elongation, or toughness	Value, unit, condition, percentage change	Provides principal performance evidence
Fracture and interface evidence	SEM, FTIR, XRD, DSC, void analysis, pull-out, rupture, debonding	Morphological and physicochemical observations	Connects numerical performance with mechanisms
Final synthesis	Study satisfied material, mechanical, and explanatory-variable requirements	30 retained studies	Provides the focused corpus for thematic review

3. Result and Discussion

3.1 Evidence Landscape and Characteristics of the Retained Corpus

The final corpus consisted of 30 studies published between 2021 and 2026 and was strongly concentrated in recent years. This recency reflects growing interest in natural-fibre hybridisation, biodegradable matrices, additive manufacturing, interfacial modification, and statistically assisted optimisation. Publication recency did not, however, correspond to equivalent target-system

directness: most studies investigated PALF or hemp separately, used another matrix, or employed a different hybrid partner.

Only one study directly combined PALF and hemp within PLA. Raja et al. [7] fabricated compression-moulded PALF–hemp/PLA and reported improvements of 73.50% in tensile strength, 60.00% in flexural strength, and 58.40% in impact resistance. Two additional studies combined PALF and hemp in other matrices and supplied evidence on NaOH or silane treatment, moisture affinity, and fracture morphology. A larger group examined PALF- or hemp-containing PLA systems, while the remaining studies were retained as mechanistic support.

The evidence corpus was heterogeneous in mechanical testing and reporting. Tensile and flexural strength were predominantly expressed in MPa, whereas impact behaviour was reported as J, J cm^{-2}, J m^{-1}, J m^{-2}, kJ m^{-2}, or percentage change. Fibre quantity was expressed as weight fraction, volume fraction, parts per hundred rubber, or composition ratio. This heterogeneity precluded pooled meta-analysis and required a hierarchical narrative synthesis.

To clarify the hierarchy and analytical function of the retained literature, Table 2 classifies the 30 studies according to material-system directness, contribution to the review, and principal limitation.

Table 2. Evidence classification and analytical roles of the retained studies

Evidence category	*Number*	*Representative systems*	*Analytical contribution*	*Principal limitation*
Direct PALF–hemp/PLA evidence (tier 1)	1	Compression-moulded PALF–hemp/PLA	Direct optimisation and tensile, flexural, and impact improvement	A single study cannot define a transferable optimum.
PALF–hemp evidence in other matrices (tier 2)	2	PALF–hemp thermoplastic; PALF–hemp/natural rubber	Hybrid interaction, treatment, interface, and moisture behaviour	Matrix chemistry differs from PLA.
PALF- or hemp-containing PLA-based evidence (tier 3)	8	PALF/PLA, hemp/PLA, PALF/PLA–PBAT, hemp/PLA–PBS	Loading, processing, treatment, crystallinity, and fracture evidence	Most studies contain only one target fibre.
Related hybrid PLA evidence (tier 4)	2	Hemp–sisal/PLA systems	Constant-loading ratio effects, compatibilisation, and SEM evidence	PALF is not included.
Mechanistic supporting evidence (Support Evidence)	17	PALF- and hemp-containing epoxy, polyester, polyethylene, and hybrid systems	Transferable mechanisms involving treatment, architecture, moisture, and fracture	Mechanical values are not directly equivalent to PLA.
Total	30	—	Supports hierarchical, mechanism-oriented synthesis	Direct target-system evidence remains limited.

The imbalance between direct target evidence and supporting literature is visualised in Fig. 3 which highlights the single direct PALF–hemp/PLA study within the 30-study corpus.

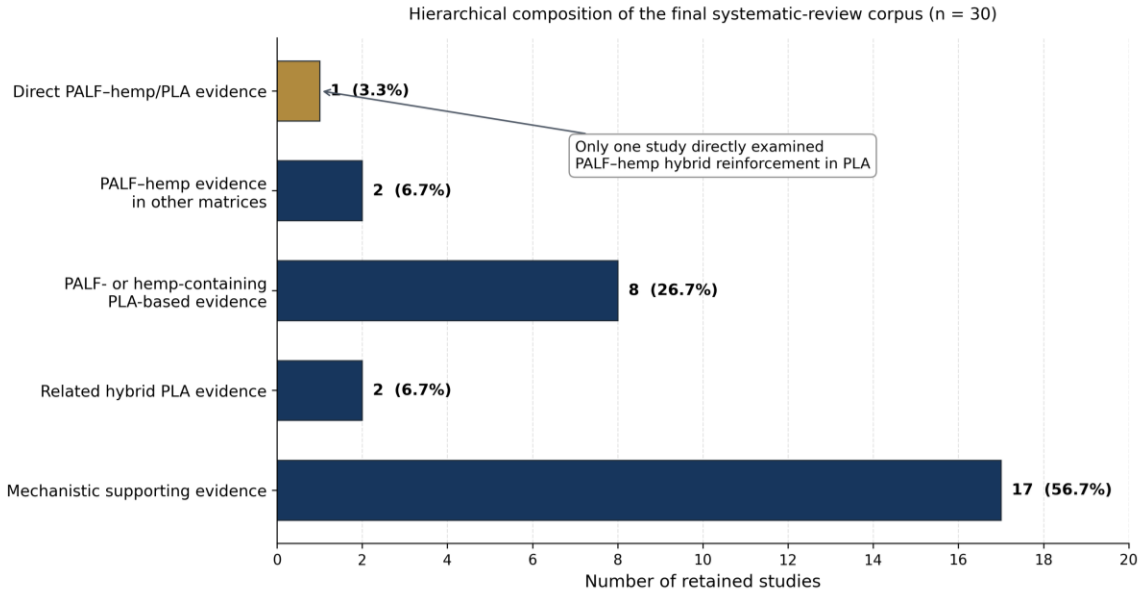


Fig. 3. Distribution of retained studies according to evidence classification (tier).

3.2 Effects of Fibre Ratio, Total Loading, and Processing Conditions

Fibre ratio and total loading emerged as distinct but interacting determinants of performance. The direct PALF–hemp/PLA study showed the potential magnitude of simultaneous composition and process optimisation: tensile improvement exceeded flexural improvement by 13.50 percentage points and impact improvement by 15.10 percentage points. The abstract did not report the complete ratio series or absolute values, however, which limits independent validation.

Related hybrid PLA evidence provides clearer ratio control. Janet et al. [5] held total fibre loading at 10 wt.% and obtained 53.19 MPa tensile strength, 83.24 MPa flexural strength, and 0.90 J impact energy at a hemp-rich ratio. Yuvaraj et al. [8] reported 84 MPa tensile strength and 79 MPa flexural strength in a compatibilised 30% hemp–sisal/PLA system. The higher loading did not produce a uniformly higher flexural response, emphasising the influence of fibre form, processing, and compatibilisation.

PALF-based single-fibre studies demonstrated that fibre loading and geometry influence composite performance, but their findings should not be interpreted as evidence of an optimum PALF hybrid ratio. Bindiganavile [2] identified an optimum PALF loading of 15 wt.% in an alkali-treated PALF/epoxy system, whereas Singh et al. [9] found that long PALF at 5 wt.% outperformed short PALF at 25 wt.%. Singh et al. [10] reported tensile and flexural strengths of 73.9 ± 1.3 MPa and 107.1 ± 4.3 MPa, respectively, for a PALF/PLA–PBAT composite containing

30 wt.% PALF. These findings illustrate the influence of fibre loading, geometry, and matrix composition but do not establish an optimum PALF ratio for hybrid-reinforced PLA composites.

Processing altered the reinforcement contribution even at similar nominal compositions. Layer-to-layer PALF/PLA printing increased tensile strength more strongly than flexural strength, while hemp/PLA printing became unstable when fibre or plasticiser content exceeded the processable range. Thus, the optimum loading is partly a processing threshold at which the matrix remains capable of wetting, separating, and consolidating both fibre populations.

The main ratio-, loading-, and processing-dependent outcomes are synthesised in Table 3, which distinguishes directly reported target-system evidence from representative supporting systems.

Table 3. Effects of fibre ratio, total loading, and processing on representative composite systems

STUDY	COMPOSITE SYSTEM	RATIO OR LOADING	PROCESSING ROUTE	PRINCIPAL RESULT	INTERPRETATION
RAJA ET AL. [7]	PALF–hemp/PLA	Optimised fibre content; ratio not fully reported	Compression moulding	Tensile +73.50%; flexural +60.00%; impact +58.40%	Direct evidence of simultaneous material/process optimisation.
JANET ET AL. [5]	Hemp–sisal/PLA	7.5:2.5 wt.% at constant 10 wt.% total	Micro-injection moulding	53.19 MPa tensile; 83.24 MPa flexural; 0.90 J impact	Demonstrates ratio effects at constant loading.
YUVARAJ ET AL. [8]	Hemp–sisal/PLA	30% total fibre with compatibiliser	Melt blending/injection moulding	84 MPa tensile; 79 MPa flexural; 98 Shore D	Higher loading required effective compatibilisation.
BINDIGANAVILE ANAND [2]	PALF/epoxy	Optimum at 15 wt.% PALF	Hand lay-up	78 MPa tensile; 122 MPa flexural; 17.8 kJ m−2 impact	Above-optimum loading caused agglomeration and microvoids.
SINGH ET AL. [9]	PALF/epoxy	Short fibre 25 wt.%; long fibre 5 wt.%	Hand lay-up	Long fibre at 5 wt.%: 35.72 MPa tensile; 56.19 MPa flexural	Geometry shifted the optimum-loading condition.
SINGH ET AL. [10]	PALF/PLA–PBAT	30 wt.% PALF	Extrusion–injection moulding	73.9 ± 1.3 MPa tensile; 107.1 ± 4.3 MPa flexural	Strong PLA-containing PALF performance.
SUVANJUMRAT ET AL. [11]	PALF/PLA	Three PALF layers under optimised deposition	Layer-to-layer additive manufacturing	Tensile +37.6%; flexural +15.86%	Controlled placement improved interlayer stress transfer.

Fibre loading is expressed as reported in the original studies. Absolute mechanical properties retain their original units. Percentage values must be interpreted according to the reference formulation and calculation method reported in each source and should not be directly compared across different matrices and test conditions.

To isolate the relative response of the only direct target-system study, Fig. 4 presents its tensile, flexural, and impact improvement profile on a common percentage scale. Fig. 4 presents the reported percentage values for tensile, flexural, and impact performance of the PALF–hemp/PLA composite investigated by Raja et al. [7].

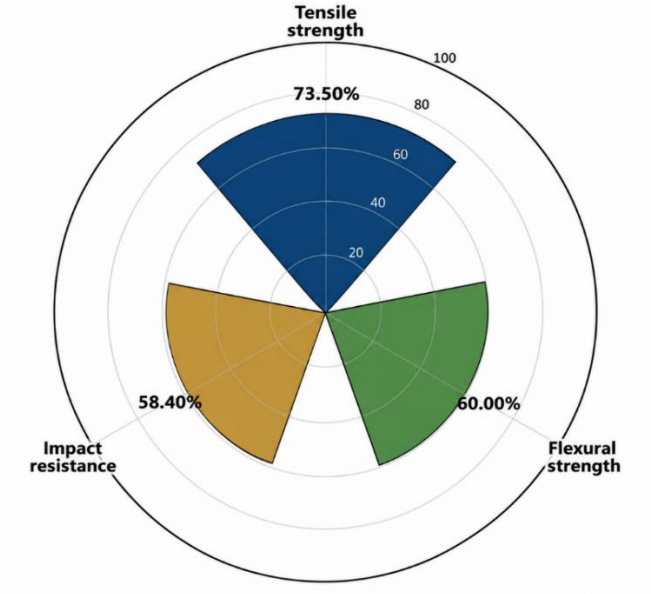


Fig. 4. Mechanical-performance improvement profile of the optimised PALF–hemp/PLA composite reported by Raja et al. [7].

Absolute values reported for representative PLA-based PALF and hemp systems are compared in Fig. 5. The graph is intended to show cross-system variation rather than establish a statistical ranking.

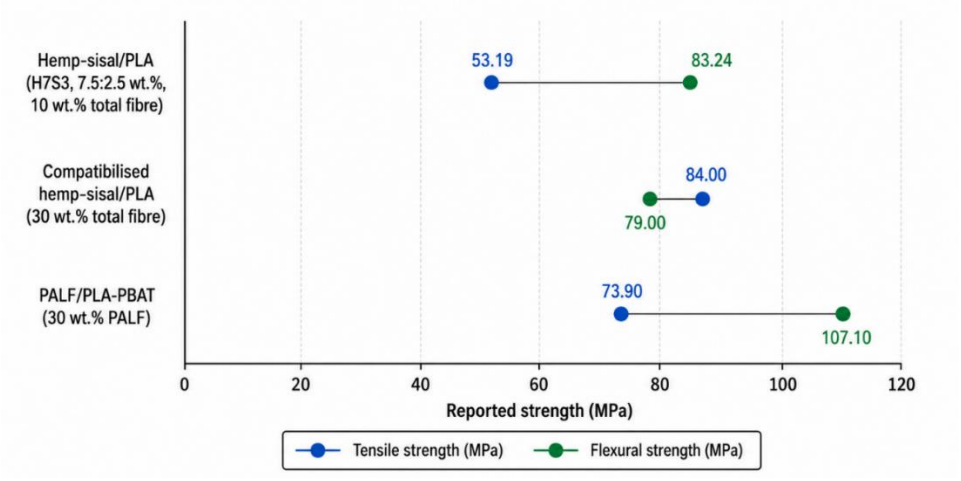


Fig. 5. Reported tensile and flexural strengths of selected hemp–sisal/PLA and PALF/PLA–PBAT composites, based on Janet et al. [5], Yuvaraj et al. [8], and Singh et al. [10]. The comparison is descriptive and does not establish a statistical ranking because fibre loading, matrix composition, processing routes, and test conditions differ among studies.

3.3 Effects of Interfacial Modification and Fracture Morphology

The retained studies consistently showed that intrinsic fibre strength cannot be translated into composite performance without an effective interface. Alkali treatment was the most frequently represented approach. Awad et al. [12] found that 5% NaOH produced different tensile and flexural optima in PALF hybrids, while Çevik Elen et al. [3] reported a 54.3% tensile-strength increase in NaOH-treated hemp/PLA relative to neat PLA.

More specialised chemistry produced larger within-study changes but required careful interpretation. EPTA cationisation increased hemp/PLA tensile strength by 615% relative to the poorly bonded untreated-hemp formulation, while GMA improved covalent interaction and dispersion. The increase was not a sixfold gain over neat PLA; the treated formulation recovered values comparable to the neat matrix.

Table 4. Interfacial modification and fracture-morphology evidence in the retained corpus

STUDY	SYSTEM AND MODIFICATION	REPORTED RESPONSE	FRACTURE/INTERFACIAL EVIDENCE	RELEVANCE
AWAD ET AL. [12]	OPF–PALF/bio-phenolic, 5% NaOH	33.3 MPa tensile; 99.8 MPa flexural at different ratios	Improved interaction following mercerisation	Treatment and ratio can generate response-specific optima.
ÇEVIK ELEN ET AL. [3]	Hemp/PLA, NaOH and APTES	NaOH formulation: tensile +54.3% vs neat PLA	Reduced water absorption after alkali treatment	Direct treatment-sensitive hemp/PLA evidence.
BOLLINO ET AL. [6]	Hemp composite, 5 wt.% NaOH or GPTMS	Water uptake reduced to 6.46% and 5.58% at room temperature	Moisture still reduced stiffness by approximately 50–60%	Conditioned performance must accompany dry testing.
VALIN FERNÁNDEZ ET AL. [4]	Hemp/PLA, EPTA and GMA	EPTA: tensile +615% vs untreated-hemp formulation	Improved adhesion, covalent interaction, dispersion	Demonstrates recovery from severe untreated-interface weakness.
KAILAS ET AL. [13]	PALF hybrid/epoxy, alkali plus plasma	Tensile +97.9%; flexural +70.21%; impact +22%	Reduced pull-out and delamination	Combined treatment improves stress transfer more than impact.
JANSINAK ET AL. [14]	PALF–hemp/natural rubber, silane	48.3 mJ m^{-2} adhesion; 6 MPa tensile	Reduced interfacial voids	Supports fibre-specific silane modification.

Combined alkali and plasma treatment increased tensile, flexural, and impact properties by 97.9%, 70.21%, and 22%, respectively, relative to alkali-only treatment. The much larger tensile and flexural gains indicate stronger stress transfer, whereas the smaller impact gain shows that interface strengthening does not translate proportionally to energy dissipation.

Fracture morphology provided the critical mechanism. Improved interfaces were associated with fibre rupture, matrix residues, crack deflection, fibril bridging, and reduced interfacial gaps. Weak interfaces produced extensive pull-out, smooth fibre surfaces, debonding, delamination, and voids. The optimal interface must therefore be strong enough to prevent premature debonding but not so brittle that cracks pass rapidly through the reinforcement and matrix.

The treatment–structure–property relationships are summarised in Table 4, which links reported mechanical changes with morphological or interfacial evidence and their relevance to PALF–hemp/PLA design. Percentage changes are relative to the reference conditions reported in the original studies, including neat PLA, untreated hemp/PLA, or alkali-only treatment, as applicable. Water uptake and stiffness changes refer to the reported treatment and conditioning conditions. Results from different matrix systems are not directly equivalent.

To compare the response specificity of selected treatments, Fig. 6 displays the reported percentage changes on a single axis while retaining the different reference conditions in the labels.

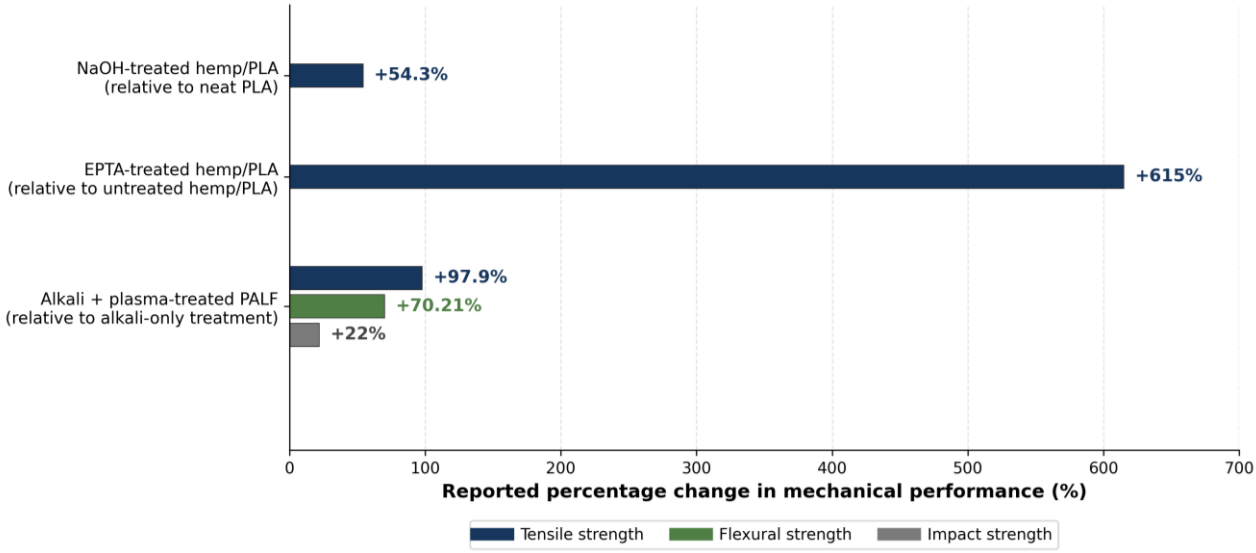


Fig. 6. Reported mechanical-property changes following interfacial modification relative to study-specific baselines: neat PLA for NaOH-treated hemp/PLA, untreated hemp/PLA for EPTA-treated hemp/PLA, and alkali-only treatment for alkali–plasma-treated PALF hybrids. Percentages are study-specific and not directly comparable across systems..

Fig. 7 presents a conceptual mechanistic synthesis proposed by the authors based on the reviewed literature, distinguishing weak, balanced, and strong-but-brittle interfaces and their expected fracture pathways and mechanical implications.

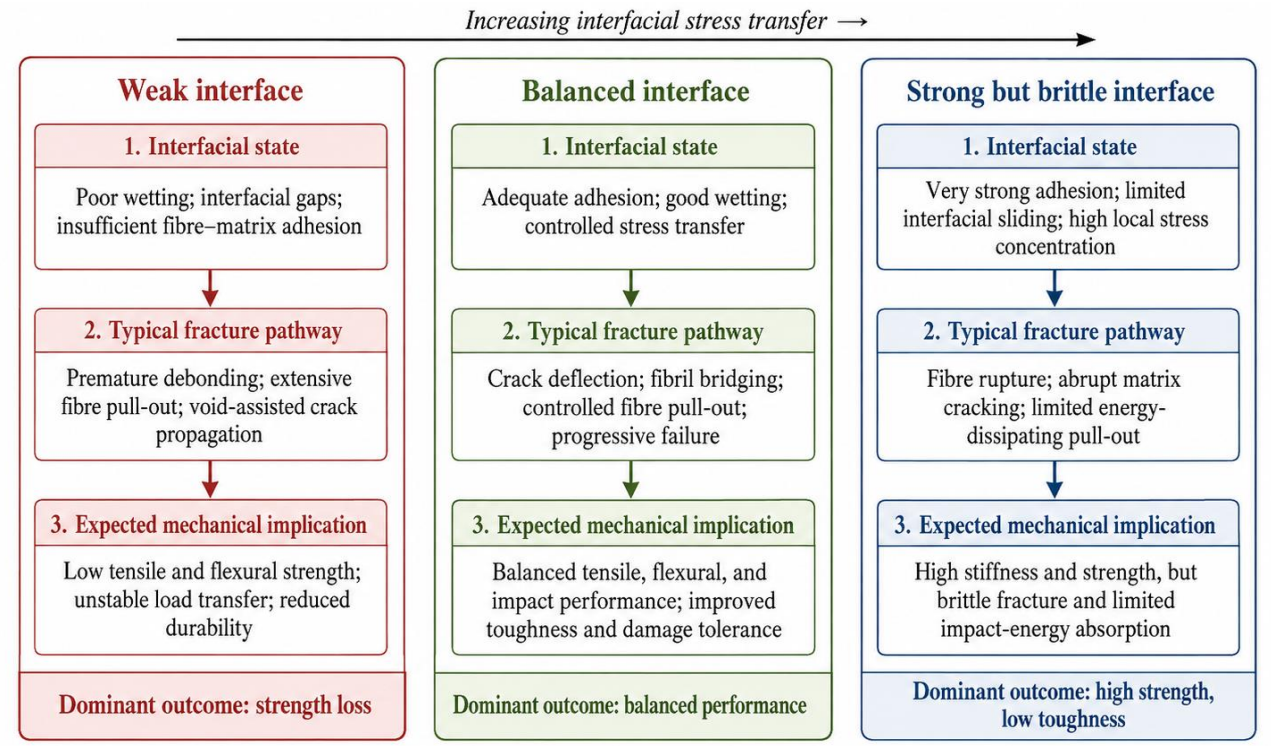


Fig. 7. Conceptual mechanistic synthesis proposed by the authors based on the reviewed literature, illustrating weak, balanced, and strong-but-brittle interfaces and their expected fracture pathways and mechanical implications. The diagram does not represent direct experimental results from this review.

3.4 Comparative Mechanical Performance, Moisture Resistance, and Design Trade-Offs

No single composition simultaneously maximised tensile strength, flexural strength, impact resistance, moisture stability, ductility, and processability. Tensile behaviour was particularly sensitive to fibre continuity and adhesion, whereas flexural performance depended strongly on outer-layer reinforcement, matrix compression, fibre orientation, and defect location. Impact results were difficult to compare because studies reported different quantities and units; they were therefore retained within their original test contexts.

Moisture resistance introduced a pronounced trade-off. Bollino et al. [6] showed that NaOH and GPTMS lowered water uptake, but substantial stiffness reduction still occurred after exposure. Saha et al. [15] found that an intermediate flax–hemp hybrid exhibited the lowest deterioration, with storage modulus decreasing by approximately 12% and glass-transition temperature by only 4 °C under wet conditions. Wang et al. [16] reported that severe weathering reduced tensile and flexural strengths by 23.58% and 13.59%, while impact strength increased to 18.23 ± 0.26 kJ m−2, suggesting moisture-induced plasticisation and altered energy absorption.

The most defensible target is therefore a balanced performance window in which static strength improves without excessive loss of impact energy, moisture stability, or manufacturing robustness. Such a window requires sufficient reinforcement continuity, adequate PLA for fibre wetting, fibre-specific treatment, and processing conditions that preserve fibre length while limiting void formation.

The principal mechanical, moisture, and morphological trade-offs are consolidated in Table 5 to distinguish maximum dry-state values from balanced and retained performance. Mechanical and durability results are reported in the original units and test contexts. Changes following moisture exposure or weathering are relative to the corresponding reference condition where specified in the original study. Cross-study comparisons are descriptive and do not establish a universal material ranking.

Table 5. Comparative performance and design trade-offs in representative retained studies

STUDY	COMPOSITE SYSTEM	PRINCIPAL MECHANICAL OUTCOME	MOISTURE/DURABILITY OUTCOME	MAIN TRADE-OFF
RAJA ET AL. [7]	PALF–hemp/PLA	Tensile +73.50%; flexural +60.00%; impact +58.40%	Not quantified in the abstract	Direct improvement, but optimum ratio remains incompletely reported.
JANET ET AL. [5]	Hemp–sisal/PLA, 10 wt.%	53.19 MPa tensile; 83.24 MPa flexural; 0.90 J impact	Minimal mass change during absorption testing	Hemp-rich ratio improved strength at low loading.
SINGH ET AL. [10]	PALF/PLA–PBAT, 30 wt.%	73.9 ± 1.3 MPa tensile; 107.1 ± 4.3 MPa flexural	Favourable density and water-related behaviour	Performance partly depends on matrix blending.
BOLLINO ET AL. [6]	Treated hemp composite	Treatments lowered water uptake	Stiffness decreased approximately 50–60% after exposure	Reduced uptake did not prevent degradation.
SAHA ET AL. [15]	Flax–hemp hybrid	Intermediate hybrid retained viscoelastic performance	Storage modulus −12%; Tg −4 °C	Balanced ratio improved wet-state retention.
WANG ET AL. [16]	Hemp sandwich laminate	Tensile −23.58%; flexural −13.59% after weathering	Impact increased to 18.23 ± 0.26 kJ m−2	Moisture reduced static strength but increased impact response.
UCPINAR ET AL. [17]	Hemp/PLA–PBS with MAH-g-PLA	Modulus and crystallinity increased; tensile strength not recovered	Thermomechanical properties improved	Compatibilisation improved some responses but not interface-controlled strength.

A direct numerical representation of treatment-dependent moisture behaviour is provided in Fig. 8 which compares water uptake at room temperature and 50 °C.

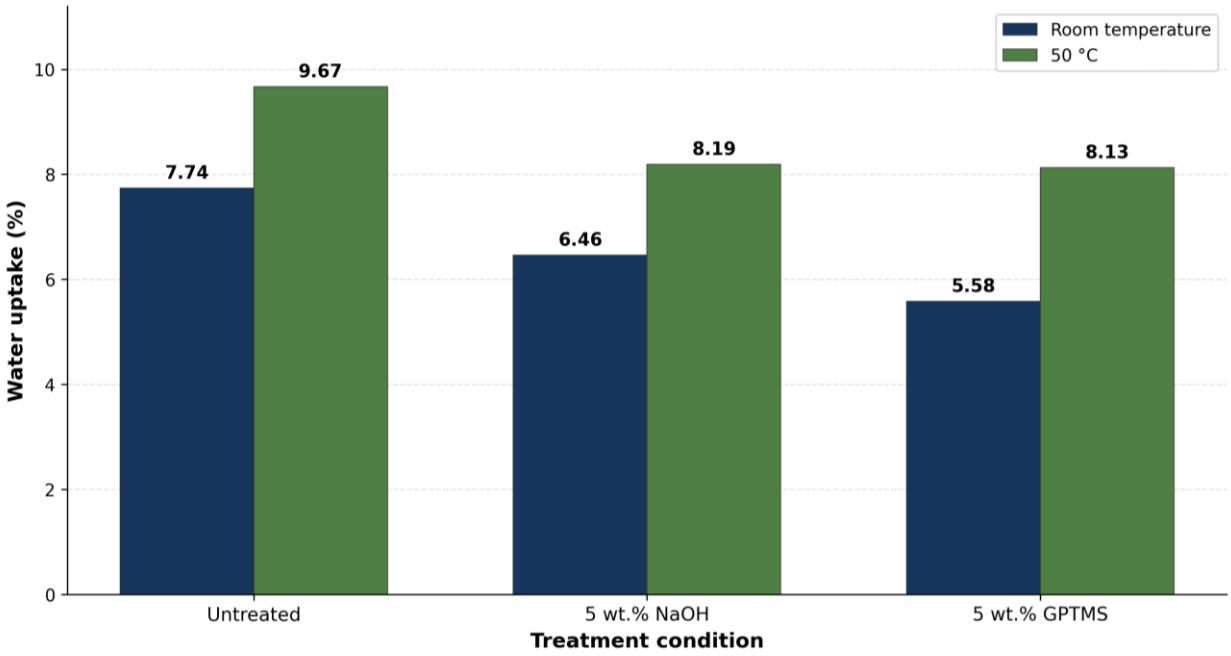
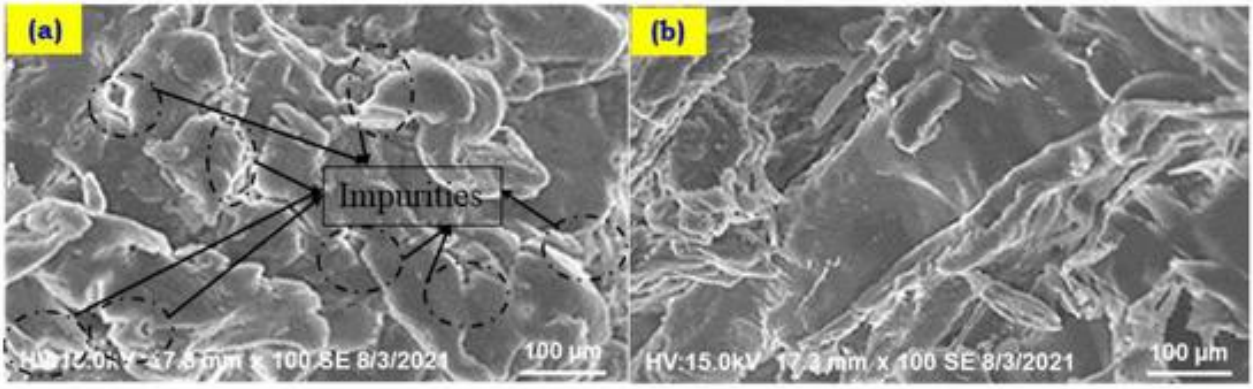


Fig. 8. Water uptake (%) of untreated and 5 wt.% NaOH- or GPTMS-treated hemp/epoxy composites at room temperature and 50 °C. Untreated composites serve as the reference at each temperature. Data are based on Bollino et al. [6].

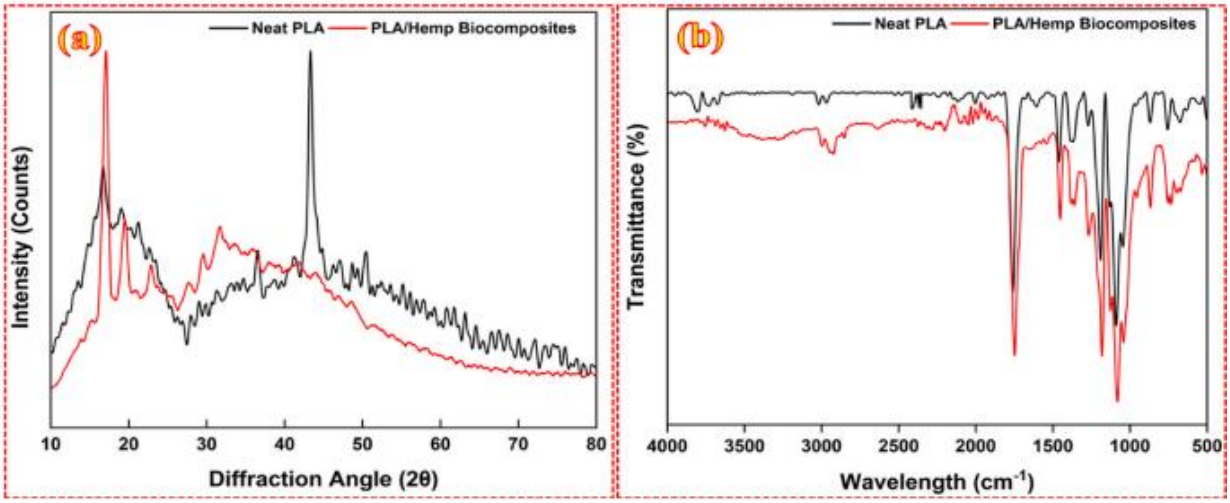
Beyond the quantitative trends, original corpus micrographs provide direct visual evidence of treatment-induced surface changes. Fig. 9 compares untreated and silane-treated PALF and is positioned here because it supports the interpretation of fibre-surface cleaning, roughness, and potential adhesion improvement.



Source: Anand et al. [1] . © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Fig. 9. SEM micrographs of pineapple leaf fibre: (a) without silane treatment and (b) with silane treatment.

Physicochemical characterisation further complements the mechanical and morphological evidence. Fig. 10 presents XRD and FTIR comparisons of neat PLA and PLA/hemp biocomposites, illustrating changes in crystalline response and chemical spectral features after reinforcement.



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Fig. 10. Characterisation of neat PLA and PLA/hemp biocomposites: (a) XRD patterns and (b) FTIR spectra.

3.5 Discussion

The retained evidence confirms that PALF–hemp hybridisation is mechanically feasible in PLA, but it does not yet support a universal formulation. The direct target-system study reported improvements of 73.50% in tensile strength, 60.00% in flexural strength, and 58.40% in impact resistance after simultaneous optimisation of fibre content, moulding temperature, and pressure; however, the complete PALF:hemp ratio series and absolute values required for independent reproduction were not available in the filtered abstract. Processing architecture alone produced unequal gains in PALF/PLA: layer-to-layer printing increased tensile and flexural strengths by 37.6% and 15.86%, demonstrating that nominal composition cannot be separated from fibre placement and consolidation. MAH-g-PLA increased crystallinity and modulus in hemp/PLA–PBS but failed to recover tensile strength because SEM still indicated inadequate adhesion, while NaOH and GPTMS reduced moisture uptake without eliminating 50–60% stiffness losses after conditioning. These findings show that PALF–hemp/PLA hybridisation should be interpreted as a property-balancing strategy governed by composition, processing, interface quality, fracture behaviour, and service environment rather than as an automatically positive hybrid effect.

To translate these evidence patterns into an actionable agenda, Table 6 connects the principal unresolved issues with their experimental consequences, required investigations, and expected validation outcomes.

Table 6. Principal research gaps and recommended investigations for PALF–hemp hybrid reinforced PLA composites

UNRESOLVED ISSUE	EVIDENCE-BASED CONSEQUENCE	REQUIRED FUTURE INVESTIGATION	EXPECTED VALIDATION OUTPUT
DIRECT EVIDENCE REMAINS LIMITED	Reported improvements cannot define a transferable optimum formulation.	Compare neat PLA, PALF/PLA, hemp/PLA, and PALF–hemp/PLA under identical processing and conditioning.	Separation of single-fibre, additive, and hybrid effects.
RATIO AND TOTAL LOADING ARE NOT ISOLATED	Improvement may arise from additional fibre rather than hybrid interaction.	Maintain constant total loadings while varying PALF:hemp ratio from 100:0 to 0:100.	Ratio–loading interaction maps.
FIBRE GEOMETRY AND ARCHITECTURE VARY	Optimum loading changes with length, form, orientation, and stacking.	Evaluate short, long, aligned, random, and layered fibres; measure length retention.	Architecture-specific design rules.
TREATMENTS ARE NOT FIBRE-SPECIFIC	One condition may improve one fibre while damaging the other.	Optimise concentration, duration, washing, and drying separately for PALF and hemp.	Fibre-specific treatment windows.
PROCESSING IS INCOMPLETELY LINKED TO STRUCTURE	Similar formulations can produce different dispersion, crystallinity, and voids.	Compare moulding, extrusion–injection, and additive manufacturing under controlled histories.	Repeatable processing–structure–property windows.
FRACTURE EVIDENCE IS INCONSISTENTLY INTEGRATED	Strength may be attributed to adhesion without proof of the failure mechanism.	Combine mechanical testing with SEM, FTIR, XRD/DSC, porosity, and fibre-length analysis.	Mechanistic distinction among pull-out, rupture, debonding, and cracking.
DRY-STATE TESTING DOMINATES	A dry optimum may fail after moisture or thermal ageing.	Conduct immersion, humidity ageing, thermal cycling, drying–rewetting, and retained-property testing.	Moisture-diffusion and aged-property retention data.
OPTIMISATION DEPENDS ON RESPONSE WEIGHTING	The selected optimum may change with performance priorities.	Apply mixture/factorial design, ANOVA, GRA/PCA or desirability, sensitivity analysis, and confirmation tests.	Robust optimum rankings with uncertainty.
SCALE-UP EVIDENCE IS SCARCE	Coupon-scale static data may not represent service behaviour.	Perform fatigue, repeated impact, pilot manufacturing, cost analysis, and LCA.	Application-specific feasibility and environmental justification.

Future research should progress through a controlled sequence rather than further isolated fibre-addition experiments. The need to separate composition from geometry is demonstrated by PALF systems in which short fibres required 25 wt.% loading to reach 20.85 MPa tensile and 42.70 MPa flexural strength, whereas long fibres achieved higher values of 35.72 and 56.19 MPa

at only 5 wt.%. Treatment results require explicit baselines: EPTA cationisation increased tensile strength by 615% relative to a poorly bonded untreated-hemp formulation, but the treated values were described as comparable to neat PLA. Durability must be incorporated during optimisation because an intermediate flax–hemp hybrid retained storage modulus and glass-transition temperature more effectively than the hemp-dominant system under wet conditions. A credible PALF–hemp/PLA design window should therefore be established through constituent standardisation, constant-loading ratio experiments, fibre-specific interfacial modification, controlled processing, multiscale characterisation, mechanical and environmental validation, statistical confirmation, and subsequent scale-up.

To present these priorities as a coordinated development pathway, Fig. 11 links constituent standardisation, ratio and treatment optimisation, processing control, interface characterisation, mechanical validation, durability assessment, and statistical confirmation to a validated design window.

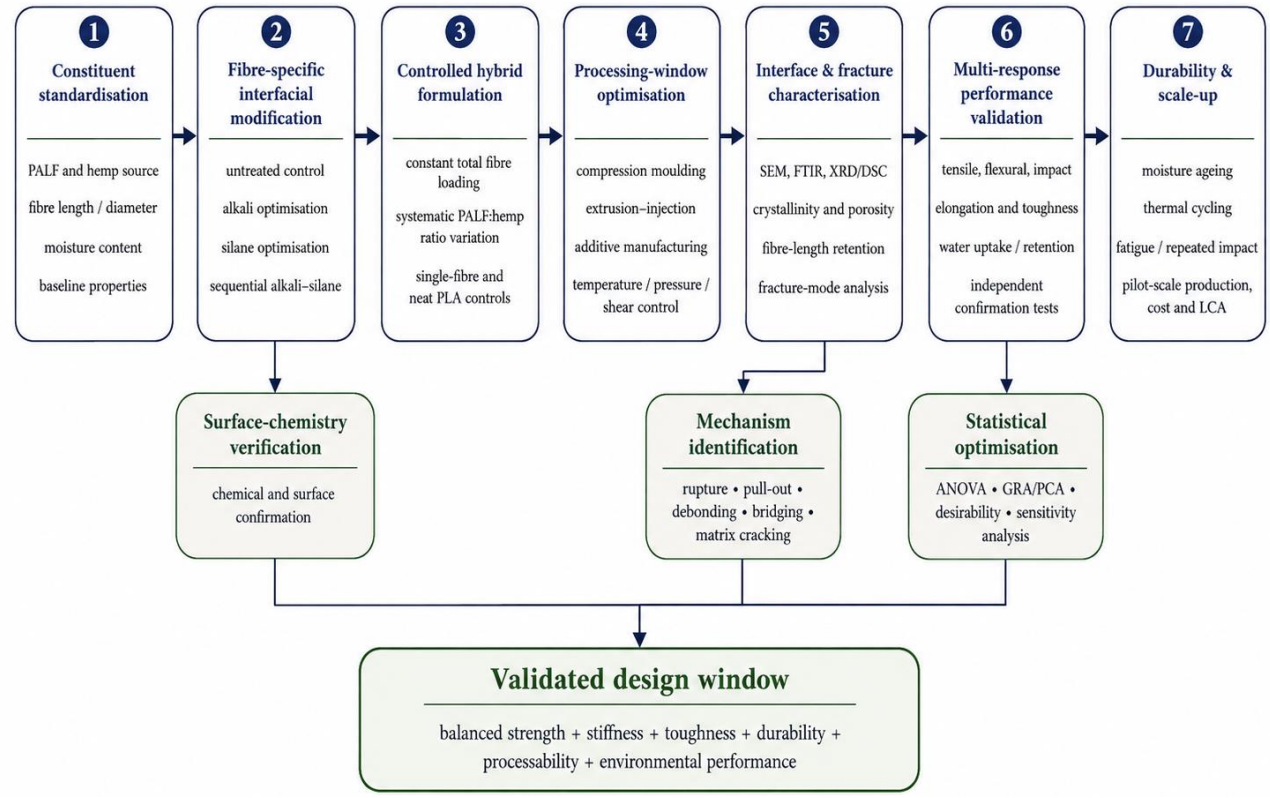


Fig. 11. Future research roadmap for PALF–hemp hybrid reinforced PLA composites.

4. Conclusions

This systematic literature review demonstrates that PALF–hemp/PLA composite performance is governed by an integrated composition–processing–interface–fracture–property relationship rather than by the simple addition of two fibres. The principal engineering challenge is to achieve simultaneous improvements in tensile strength, flexural strength, impact resistance, and durability without inducing agglomeration, insufficient wetting, fibre damage, interfacial

voids, or brittle failure. The only direct PALF–hemp/PLA study reported improvements of 73.50%, 60.00%, and 58.40% in tensile strength, flexural strength, and impact resistance, respectively. However, the limited direct evidence and insufficient reporting of the complete fibre-ratio series and absolute mechanical values prevent the establishment of a generalisable optimum PALF ratio. Any apparent optimum should therefore be considered specific to the formulation and processing conditions reported in that study until independently validated through further experiments.

Supporting evidence indicates that fibre loading, geometry, surface treatment, processing, and conditioning can substantially influence the apparent optimum. Long PALF at 5 wt.% outperformed short PALF at 25 wt.% in one study, while layer-to-layer PALF/PLA printing produced different improvements in tensile and flexural performance. Alkali and silane treatments generally reduced water uptake, although substantial stiffness losses could still occur following moisture exposure. These findings demonstrate that a formulation optimised for dry mechanical strength may not provide the best impact-energy absorption, moisture resistance, ductility, or retained mechanical performance.

The central research gap is the absence of a broadly validated PALF–hemp/PLA design window that independently establishes the effects of fibre ratio, total loading, fibre-specific treatment, architecture, and processing history. Future studies should maintain constant total fibre loading while systematically varying the PALF ratio, optimise PALF and hemp treatments separately, and include neat PLA and single-fibre controls. Mechanical testing should be integrated with SEM, FTIR, XRD/DSC, porosity, crystallinity, and fibre-length measurements to establish relationships between composition, interfacial characteristics, fracture mechanisms, and mechanical performance. Multi-response optima should then be verified through sensitivity analysis and confirmation experiments before proceeding to fatigue testing, scale-up, cost analysis, and life-cycle assessment. Accordingly, PALF–hemp hybridisation remains a promising property-balancing strategy, but its optimum composition and processing conditions remain experimentally unresolved.

Data availability statement

The Scopus search results and the final data-extraction table for the 30 included studies are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this manuscript. No commercial

organisation participated in the selection or interpretation of the reviewed studies. Any potential conflict arising before submission will be disclosed to the journal.

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