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ENHANCING MECHANICAL PERFORMANCE OF RECYCLED POLYMER COMPOSITES THROUGH NATURAL FIBRE REINFORCEMENT AND OPTIMISED INTERFACIAL ADHESION

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ABSTRACT
Recycled polymers offer opportunities to reduce plastic waste and dependence on virgin materials, yet variable composition and processing degradation often limit their mechanical reliability. Natural fibre reinforcement provides a renewable strengthening strategy, although weak fibre–matrix adhesion, moisture sensitivity and inconsistent dispersion can undermine performance. This study proposes an integrated evaluation of natural fibre reinforcement and interfacial optimisation in recycled polymer composites. Selected recycled matrices and fibre formulations are compared across controlled reinforcement contents, surface treatments and compatibiliser concentrations. Tensile, flexural and impact testing assess mechanical performance, while microscopy examines fibre dispersion, interfacial bonding, pull-out and fracture behaviour. Moisture absorption and thermal characterisation establish whether mechanical gains introduce durability or processing limitations. Experimental comparisons distinguish reinforcement effects from improvements associated with interfacial modification, accounting for feedstock variability, fibre dimensions and manufacturing conditions. Statistical analysis evaluates reproducibility and identifies formulation trade-offs rather than assuming universal improvements. The proposed approach supports evidence-based material selection by linking processing, interface quality and mechanical response. Application-specific validation and lifecycle assessment remain necessary before claiming suitability for structural service or environmental advantages over alternative materials under comparable operating conditions.

Keywords:
Recycled polymers; Natural fibres; Polymer composites; Interfacial adhesion; Mechanical performance; Compatibilisation.

1. INTRODUCTION

1.1 Recycled Polymers and the Need for Reliable Engineering Materials
Plastic waste recovery supports the return of discarded materials to productive use and can reduce demand for virgin polymer feedstocks [1]. Mechanical recycling preserves material value through sorting, cleaning and reprocessing, but the resulting recyclate does not necessarily reproduce virgin polymer behaviour. Previous thermal and mechanical exposure can alter molecular structure, while contamination and incompatible polymer mixtures introduce variability [2]. Consequently, nominally similar batches may differ in flow behaviour, strength and resistance to deformation. These differences complicate processing control and the manufacture of components with predictable performance. Material recovery therefore requires attention to engineering reliability alongside collection volumes and recycled content. Suitable applications depend on reproducible properties, documented processing conditions and evidence that components satisfy their intended requirements. Environmental benefits also require contextual assessment because sorting, washing, additives, processing energy and service life affect the overall balance [1]. Recycled content alone does not establish lower environmental impact than a functionally equivalent alternative material.

1.2 Natural Fibre Reinforcement and the Interfacial Challenge
Natural fibres provide potential reinforcement because their low density, renewable origin and availability support lightweight composite development [3]. Fibres such as flax, hemp and jute can increase stiffness and contribute to strength when their dimensions, orientation and distribution permit effective load sharing [4]. However, fibre properties vary with plant source, extraction, storage and preparation, making consistent composite production challenging. Moisture absorption can promote swelling and interfacial deterioration, while incomplete drying can introduce processing defects. Compatibility presents another difficulty: hydroxyl-rich fibre surfaces are hydrophilic, whereas commonly recycled polyolefins are comparatively hydrophobic [5]. Limited wetting and weak bonding can therefore restrict stress transfer between the matrix and reinforcement. Interfacial adhesion influences whether loading produces fibre fracture, debonding, pull-out or matrix deformation [6]. Surface

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treatments and compatibilisers can improve this relationship, although excessive treatment may damage fibres or change processing behaviour. Increasing fibre content can also promote agglomeration, void formation and reduced matrix continuity. Consequently, reinforcement requires coordinated control of fibre characteristics, interface quality and manufacturing conditions rather than an assumption that additional fibres invariably improve performance [4].

1.3 Study Aim, Research Questions and Contribution

This study evaluates how natural fibre reinforcement and interfacial modification influence the mechanical performance of recycled polymer composites. It examines how reinforcement content, surface treatment and compatibilisation affect tensile, flexural and impact properties relative to appropriate matrix and untreated reinforcement controls. A further question concerns whether observed gains remain consistent across recycled feedstock batches and conditioning environments. The contribution is a controlled comparison connecting processing conditions, structural observations and mechanical response, with manufacturing variability considered explicitly. Microscopy and moisture assessment provide complementary evidence without independently proving improved interfacial strength. Application suitability rests on measured properties and relevant service requirements, rather than reinforcement content alone. Establishing these comparisons first requires an account of matrix behaviour, fibre structure and stress transfer mechanisms that explains why reinforcement and interface modification warrant joint evaluation.

2. MATERIAL BEHAVIOUR AND REINFORCEMENT MECHANISMS

2.1 Recycled Matrix Characteristics and Processing History

Recycled polymers retain the consequences of their original manufacture, service exposure and reprocessing. Chain scission can reduce molecular weight and entanglement, while oxidation introduces chemical changes that influence melt behaviour and mechanical integrity [5]. Depending on polymer chemistry and exposure conditions, competing reactions can produce different property changes; degradation therefore requires measurement rather than inference from recycling history alone [6]. Contaminants, residual additives and incompatible polymer fractions introduce further variation between feedstock batches. These compositional differences must be distinguished from changes in crystallinity, orientation and residual stress generated during moulding and cooling [7]. A change in stiffness, for example, does not independently demonstrate molecular degradation. Melt flow measurements provide useful processing information but cannot uniquely identify molecular structure or contamination. Thermal analysis identifies transitions and 113rystallization behaviour, while baseline mechanical testing establishes the response of the unreinforced matrix. Together, these measurements define the starting material against which reinforcement is assessed. Without this 113rystallization113, apparent fibre benefits may instead reflect differences in feedstock composition, thermal history or specimen preparation across experimental groups.

2.2 Natural Fibre Structure and Stress Transfer

Natural fibres contain cellulose within a surrounding structure that includes hemicellulose, lignin and other constituents. Cellulose contributes axial stiffness, while composition, microfibril arrangement, defects and morphology influence fibre strength and moisture response [8]. Fibre dimensions matter: sufficient embedded length permits interfacial shear stresses to transfer load from the polymer into the reinforcement. Aspect ratio, orientation and loading consequently influence whether fibres carry substantial stress or behave primarily as discontinuities [9]. Processing can shorten fibres, meaning initial dimensions do not necessarily describe the reinforcement present in moulded specimens. Poor dispersion and excessive loading can create agglomerates, voids and regions with inadequate matrix coverage. Where bonding is insufficient, interfacial debonding and pull-out can limit strength or initiate premature failure [10]. However, pull-out and matrix deformation can absorb fracture energy, so suppressing these mechanisms does not automatically improve toughness. Stronger bonding may shift failure towards fibre fracture, while severe treatment can weaken fibres themselves. Mechanical interpretation therefore considers strength, stiffness and energy absorption together, supported by representative fracture observations and measured fibre characteristics.

2.3 Interfacial Modification and Performance Trade-Offs

Interfacial modification seeks to improve compatibility between natural fibres and the selected recycled matrix. Surface treatments can remove surface constituents or alter roughness and wettability, while coupling agents and compatibilisers promote interactions between otherwise dissimilar phases [11]. Depending on the chemistry, adhesion can involve improved wetting, mechanical interlocking and chemical interactions; none should be assumed without evidence. Treatment concentration, duration and washing conditions influence the resulting surface. Excessive treatment can damage fibre structure, and retained chemicals or moisture can compromise processing and reproducibility [12]. Compatibiliser concentration also requires control because additives can

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change matrix flow, 114rystallization and mechanical response independently of adhesion. Matrix controls help separate these effects. Optimisation therefore balances strength and stiffness against toughness, moisture resistance, processing demands and treatment burden [13]. The preferred interface is application dependent rather than simply the strongest achievable bond. These mechanisms establish the basis for selecting materials, defining experimental controls and preparing reproducible composites whose measured performance can be compared meaningfully across formulations.

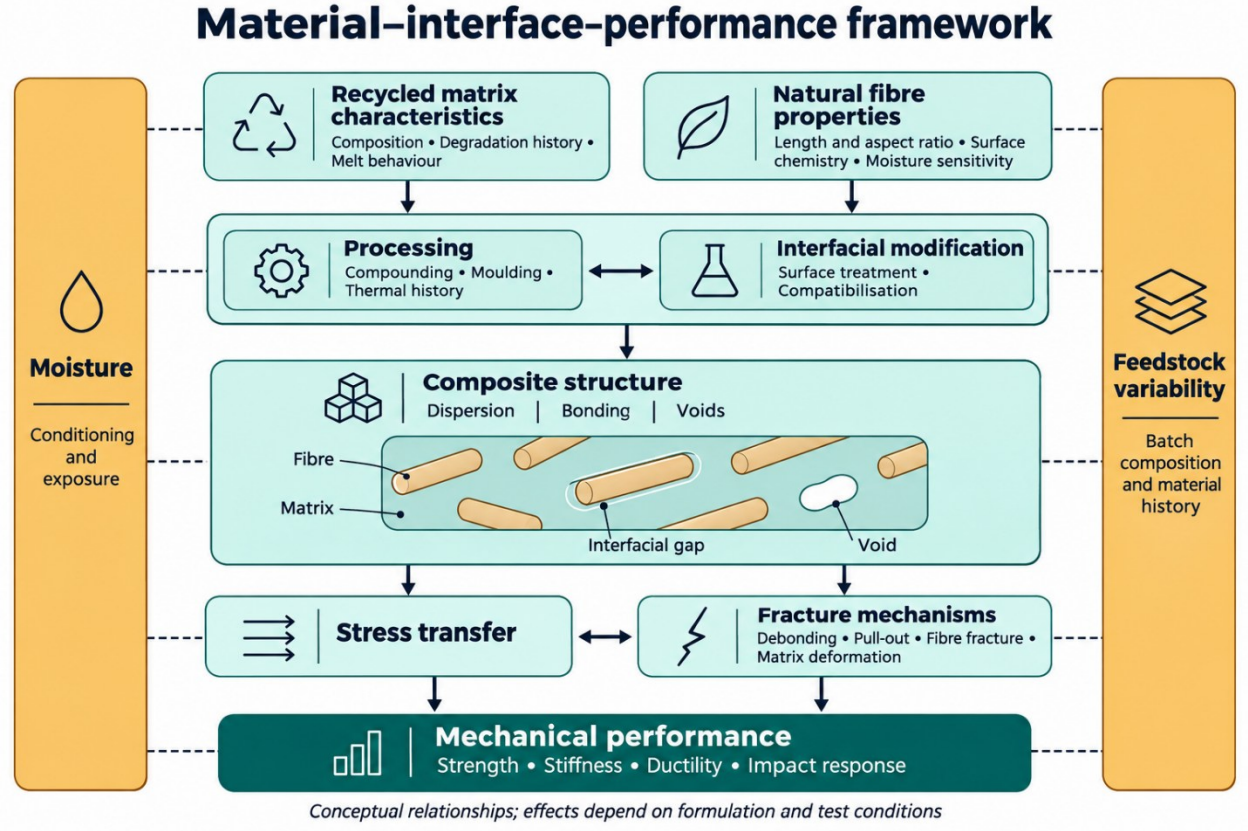


Figure 1. Material–interface–performance framework.

3. MATERIALS, EXPERIMENTAL DESIGN AND COMPOSITE MANUFACTURING

3.1 Recycled Polymer Acquisition and Feedstock Characterisation

The protocol uses mechanically recycled polypropylene from a documented post-consumer recovery stream. Supplier records identify collection periods, sorting procedures, previous processing and known contamination. Each delivery receives a batch identifier, and batches remain separate during initial characterisation to preserve information about feedstock variability. Sorting removes visible foreign materials, while washing, drying and sealed storage follow documented procedures appropriate to the contamination profile. Polymer identity is checked using infrared spectroscopy, supported by thermal analysis where mixed polymer contamination is suspected [12]. Melt flow measurements characterise processing behaviour under consistent temperature and load conditions [13]. Baseline density, thermal transitions and mechanical properties establish differences between batches before reinforcement. Blending occurs only under a documented rule, with constituent batch proportions retained. Samples from every batch are archived for subsequent investigation. These controls prevent nominal material labels from concealing differences that could otherwise be mistaken for reinforcement effects during comparisons between independently manufactured composite formulations.

3.2 Fibre Selection, Preparation and Initial Characterisation

Flax fibres provide the selected reinforcement because their availability, stiffness and compatibility with thermoplastic processing support evaluation of lightweight components. Supplier documentation records origin, extraction method, previous treatment and storage history. Fibre lots remain identifiable throughout preparation because growing and extraction conditions influence morphology and mechanical behaviour [14]. Drying precedes compounding, with temperature and duration established through moisture checks without unnecessarily increasing thermal exposure. Size reduction and sieving produce defined length classes; representative

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measurements describe length, diameter and aspect ratio distributions rather than relying exclusively on nominal supplier dimensions. Moisture content is measured before processing, and prepared fibres remain in sealed containers. Initial microscopy records bundles, surface debris and visible damage. Replicate sampling across each lot assesses variability. Preparation reduces avoidable differences while recognising that biological reinforcement remains heterogeneous, even after classification, drying and controlled storage within the same experimental programme.

3.3 Treatment Conditions, Compatibilisation and Comparison Groups

The design compares unreinforced recycled polypropylene, untreated flax composites, treated flax composites and formulations containing a polypropylene-compatible coupling agent. A matrix-plus-compatibiliser control identifies additive effects unrelated to fibre bonding. An additional treated-fibre-plus-compatibiliser group permits assessment of combined modification where resources support the interaction comparison. Alkali treatment represents the selected surface modification, while maleated polypropylene provides the compatibilisation route [15]. Preliminary trials establish suitable treatment concentrations, exposure periods and compatibiliser levels before the main comparison. The protocol records solution concentration, liquor ratio, temperature, washing endpoint and subsequent drying conditions. Treatment residues require control because surface modification and inadequate washing can produce different material responses [16]. Reinforcement contents are defined by dry mass fraction, and all additive proportions use an explicitly stated denominator. A factorial design separates fibre loading, treatment and compatibilisation effects [17]. Independent compounding batches provide replication. Multiple specimens from each batch improve measurement precision but do not replace manufacturing replication. Randomised batch preparation reduces systematic associations between formulation, processing day and equipment condition during the planned series of controlled experimental comparisons.

3.4 Compounding, Moulding and Processing Controls

A twin-screw extruder compounds the formulations, followed by injection moulding of test specimens. Equipment configuration, barrel temperature profile, screw speed, throughput and feeding sequence remain documented for every run. Processing temperatures accommodate polypropylene melting while limiting unnecessary fibre exposure, with preliminary trials informing the operating window [14]. Dried matrix and fibres enter through a controlled sequence that supports dispersion without excessive residence time. Torque, pressure and observable instability provide process records rather than substitutes for material characterisation. Pellet cooling, storage and redrying follow consistent procedures. Mould temperature, injection settings, holding pressure and cooling time remain controlled because specimen structure depends on manufacturing history. Fibre length measurements after processing assess shortening where feasible [18]. Deviations receive recorded dispositions, including acceptance, investigation or rejection. Rejected batches remain in the traceability log, with reasons documented before comparative testing begins or formulation outcomes are examined.

3.5 Specimen Allocation, Conditioning and Traceability

Specimens receive identifiers linking formulation, feedstock, fibre lot and manufacturing batch. Allocation covers mechanical testing, thermal analysis, microscopy and moisture assessment, with randomised testing order where practical. Conditioning temperature, relative humidity, exposure duration and specimen dimensions accompany each record [19]. Dry and moisture-conditioned groups remain distinguishable throughout analysis. Specimen orientation and mould position are retained where they influence interpretation. Independent batches constitute manufacturing replicates, while specimens remain nested within their respective batches. Exclusion rules address dimensional nonconformity, preparation damage and invalid test failures before comparisons. This traceability supports evaluation of mechanical performance and the structural evidence explaining differences between formulations.

Table 1. Material formulations, processing controls and experimental comparisons.

Formulation/group	Matrix and fibre specification	Fibre content	Interfacial modification	Controlled processing conditions	Purpose of comparison
Unreinforced matrix	Characterised recycled polypropylene	0%	None	Documented extrusion, moulding and conditioning	Establish baseline matrix response
Matrix plus compatibiliser	Same recycled polypropylene	0%	Maleated polypropylene at selected levels	Equivalent processing history; additive content recorded	Isolate changes caused by the compatibiliser

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Formulation/group	Matrix and fibre specification	Fibre content	Interfacial modification	Controlled processing conditions	Purpose of comparison
Untreated reinforced composites	Recycled polypropylene and prepared flax	Prespecified dry mass fractions	None	Controlled moisture, feeding, residence time and moulding	Measure reinforcement effects
Treated-fibre composites	Same matrix and alkali-treated flax	Matched reinforcement fractions	Documented alkali treatment and washing	Equivalent compounding and moulding conditions	Assess surface-treatment effects
Compatibilised composites	Same matrix and untreated flax	Matched reinforcement fractions	Maleated polypropylene	Controlled additive denominator and processing	Assess compatibilisation effects
Combined modification	Same matrix and treated flax	Matched reinforcement fractions	Alkali treatment plus maleated polypropylene	Equivalent processing and conditioning	Examine combined effects and interactions

4. MECHANICAL TESTING AND INTERFACE CHARACTERISATION

4.1 Tensile and Flexural Performance

Tensile testing follows ISO 527-1 and ISO 527-2 for moulded specimens, with geometry selected to suit the fibre-reinforced polypropylene system [18]. The laboratory protocol records overall dimensions, gauge length, thickness, width and specimen orientation before testing. Extensometer measurements support modulus and strain determination, while loading speeds follow the selected method and remain consistent across formulations. Tensile strength, elastic modulus and strain at failure are reported separately because increased stiffness does not necessarily indicate greater strength or ductility. Flexural testing follows ISO 178 using a documented three-point configuration [19]. Specimen thickness determines the appropriate support span and test settings; the actual span, loading rate and calculation procedure accompany the results. Flexural strength and modulus are interpreted within the method's deformation limits. All groups receive equivalent conditioning, and calibrated equipment provides traceable force and displacement measurements. Failure location, grip slippage, abnormal fracture and invalid runs are recorded before replacement decisions. Comparisons use independently manufactured batches with specimens distributed across testing sessions. This arrangement separates formulation differences from changes associated with equipment setup, conditioning or test order under the same documented environmental conditions.

4.2 Impact Response and Fracture Behaviour

Notched Charpy testing follows ISO 179-1 using identical specimen geometry and orientation across formulations [20]. The procedure specifies notch type, depth, root geometry, machining method and inspection criteria. Specimens receive consistent conditioning, and the pendulum capacity suits the expected energy range. Absorbed energy is 116rganize116t by the cross-sectional area remaining beneath the notch, with results expressed in the method's prescribed units. Break classifications and specimens that do not separate completely remain documented. Reinforcement can increase stiffness while reducing impact resistance, particularly where restricted matrix deformation or processing defects promote brittle failure. Fracture inspection therefore considers fibre pull-out, debonding, matrix yielding and fibre fracture [21]. Results describe the selected configuration rather than an intrinsic toughness independent of geometry. Charpy and Izod values, and notched and unnotched measurements, are not treated as interchangeable. Temperature, orientation and notch sensitivity inform interpretation of experimental comparisons.

4.3 Microscopy, Dispersion and Interfacial Evidence

Microscopy examines both mechanically fractured specimens and representative untested sections to distinguish failure features from pre-existing manufacturing defects. A prespecified sampling plan selects batches, specimen positions and magnifications without relying on visually favourable examples. Images document fibre distribution, bundles, agglomeration, voids, interfacial gaps and matrix coverage. Preparation procedures 116rganize cutting damage and fibre displacement. Where image analysis quantifies void area or dispersion, segmentation rules, field selection and analyst checks remain consistent. Fracture surfaces can reveal pull-out cavities, fibre breakage and matrix deformation associated with different failure mechanisms [21]. However,

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apparent matrix coverage or fewer gaps only supports an interpretation consistent with adhesion; it does not directly quantify interfacial strength. Infrared spectroscopy examines treatment-related surface chemistry, using untreated references and cautious interpretation of overlapping bands. Explicit quantitative adhesion claims require an additional pull-out or microbond test with documented geometry, embedded length and assumptions. Such measurements distinguish apparent interfacial shear strength from a universal material constant. Triangulation across these methods limits conclusions based on a single representative image or isolated chemical signature.

4.4 Moisture Response and Thermal Processing Compatibility

Water absorption follows ISO 62 under specified immersion or humidity conditions [22]. Initial dry mass, exposure temperature, weighing intervals and surface-drying procedures remain documented. Uptake is expressed relative to initial mass, while thickness changes provide complementary evidence of swelling. Matched conditioned specimens undergo mechanical testing to estimate property retention against appropriately stored controls. Thermogravimetric analysis examines decomposition under a recorded atmosphere and heating programme. Differential scanning calorimetry 117rganize117tion melting and 117rganize117tion117n, with thermal history and mass 117rganize117tion stated [23]. Results identify whether treatments or additives introduce processing constraints alongside mechanical gains. Moisture can change fibre dimensions, matrix response and interfacial integrity, complicating attribution to adhesion alone. Exposure duration therefore accompanies every comparison. Accelerated conditioning identifies susceptibility under laboratory conditions; it does not establish service life without justified relationships between the test environment and actual operating conditions for the intended application.

4.5 Statistical Comparisons and Measurement Reliability

Primary outcomes and comparisons are specified before examining results. Analysis reports independent batch counts, specimen numbers, means, standard deviations and confidence intervals. Hierarchical models or batch-level comparisons account for specimens nested within manufacturing batches, avoiding pseudoreplication [24]. Treatment-by-loading interactions are examined only where the design supports their estimation. Residual behaviour, variance patterns and influential observations inform assumption checks. Transformations or robust alternatives receive explicit justification rather than automatic application. Absolute properties accompany percentage changes, with denominators identified. Invalid tests remain traceable, and exclusions follow documented rules. Engineering interpretation considers uncertainty, effect magnitude and application requirements rather than significance alone. These integrated measurements 117rganize subsequent results around performance changes and the structural evidence supporting their interpretation across all evaluated material formulations.

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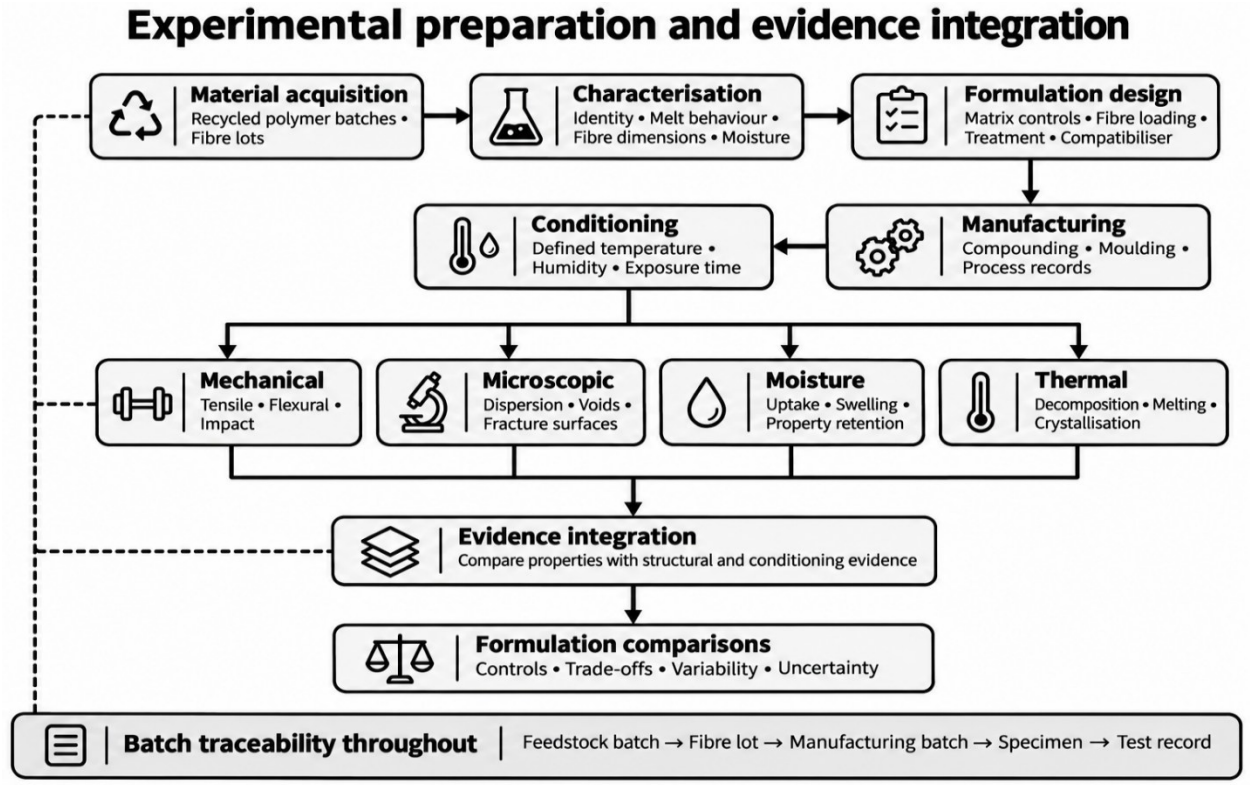


Figure 2. Experimental preparation and evidence-integration workflow.

5. RESULTS AND COMPARATIVE PERFORMANCE ASSESSMENT

Illustrative results using data. The values below demonstrate reporting and are not experimental findings. No statistical significance or validated application suitability is claimed.

5. Results and Comparative Performance Assessment

5.1 Feedstock Consistency and Achieved Composite Quality

The dataset comprised three recycled polypropylene feedstock batches and six formulations, each represented by three manufacturing batches. Five specimens per manufacturing batch provided 15 observations per formulation for each mechanical test and conditioning state [24].

Feedstock melt flow rates ranged from 11.8 to 13.2 g/10 min under the assumed test conditions of 230°C and 2.16 kg. Prepared flax fibres had a mean initial length of 4.2 mm and moisture content of 0.8%. Mean fibre length after compounding was 1.6 mm, illustrating processing-related shortening [25].

Measured fibre contents ranged from 19.6% to 20.4% for nominal 20% formulations and averaged 29.5% for the nominal 30% formulation. Specimen thickness ranged from 3.92 to 4.08 mm. Untreated composites showed more fibre bundles and interfacial gaps than modified formulations. No batches were excluded in this example, and comparisons retained equivalent processing and conditioning assumptions.

5.2 Mechanical Effects of Reinforcement and Interfacial Modification

Untreated flax reinforcement at 20% increased mean tensile strength from 24.0 to 27.0 MPa, representing a 12.5% improvement over the recycled matrix. Tensile modulus increased from 1.10 to 2.20 GPa. However, strain at failure decreased from 18.0% to 5.2%, and notched impact strength declined from 5.0 to 3.5 kJ/m² [26]. These differences illustrated increased stiffness accompanied by reduced deformation capacity and impact resistance.

Alkali treatment increased tensile strength to 30.5 MPa, while compatibilisation increased it to 34.0 MPa. The matrix-plus-compatibiliser control reached 24.8 MPa, showing that the additive also changed the unreinforced matrix response [27].

The combined modification at 30% fibre content produced the highest tensile strength, 38.0 MPa, and modulus, 3.50 GPa. Its impact strength remained below that of the compatibilised 20% composite. Because both fibre content and modification differed, this comparison did not isolate their separate contributions [28].

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Table 2. Comparative mechanical performance, durability and engineering trade-offs: example.

Formulation	Tensile strength/modulus	Flexural strength/modulus	Notched Charpy impact strength	Conditioned tensile strength retention	Variability/uncertainty	Main trade-off
Recycled polypropylene	24.0 ± 1.2 MPa / 1.10 ± 0.06 GPa	34.0 ± 1.6 MPa / 1.25 ± 0.07 GPa	5.0 ± 0.4 kJ/m²	97.9%	3 batches; 15 specimens per test/state	Lowest stiffness; greatest elongation
Matrix + 2% compatibiliser	24.8 ± 1.1 MPa / 1.12 ± 0.05 GPa	35.0 ± 1.5 MPa / 1.28 ± 0.06 GPa	4.9 ± 0.4 kJ/m²	98.0%	3 batches; 15 specimens per test/state	Small property changes; additive requirement
Untreated flax, 20%	27.0 ± 1.8 MPa / 2.20 ± 0.12 GPa	43.0 ± 2.5 MPa / 2.50 ± 0.14 GPa	3.5 ± 0.4 kJ/m²	78.1%	3 batches; 15 specimens per test/state	Higher stiffness; lower impact response and retention
Alkali-treated flax, 20%	30.5 ± 1.5 MPa / 2.35 ± 0.11 GPa	48.0 ± 2.2 MPa / 2.70 ± 0.13 GPa	3.9 ± 0.3 kJ/m²	85.9%	3 batches; 15 specimens per test/state	Improved strength; treatment and washing burden
Untreated flax, 20% + 2% compatibiliser	34.0 ± 1.4 MPa / 2.55 ± 0.10 GPa	54.0 ± 2.0 MPa / 2.95 ± 0.12 GPa	4.4 ± 0.3 kJ/m²	91.2%	3 batches; 15 specimens per test/state	Balanced response; added material cost
Treated flax, 30% + 2% compatibiliser	38.0 ± 1.9 MPa / 3.50 ± 0.16 GPa	62.0 ± 2.8 MPa / 4.05 ± 0.18 GPa	4.0 ± 0.4 kJ/m²	88.9%	3 batches; 15 specimens per test/state	Highest stiffness; greater processing demand and lower ductility

5.3 Linking Mechanical Response with Structural Evidence

Image analysis assigned void area fractions of 3.8% to untreated 20% flax composites, 2.7% to treated composites and 1.8% to compatibilised composites. The combined 30% formulation showed a slightly higher value of 2.3%, illustrating how increased reinforcement could complicate impregnation despite modification.

The illustrative fracture descriptions associated untreated fibres with pull-out cavities and modified formulations with greater matrix coverage and more fibre fracture. These patterns were consistent with improved load transfer but did not constitute direct measurements of interfacial strength [29].

The combined formulation's highest stiffness did not coincide with the lowest void fraction or greatest impact resistance. This distinction demonstrated why fibre loading, orientation, residual length and matrix deformation must accompany adhesion-based interpretations.

5.4 Durability, Benchmarking and Formulation Trade-Offs

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Conditioned tensile strengths were 23.5, 24.3, 21.1, 26.2, 31.0 and 33.8 MPa, respectively, producing the retention percentages in Table 2. Untreated reinforcement showed the greatest proportional deterioration. Compatibilised 20% flax retained a larger proportion of its dry strength than the combined 30% formulation [30].

Against the recycled matrix control, the latter achieved a 58.3% increase in dry tensile strength and a 218.2% increase in tensile modulus. Nevertheless, the compatibilised 20% formulation provided a more balanced combination of impact response and moisture retention.

No virgin-polymer or commercial benchmark was assumed. Test-method alignment did not establish component acceptance [31]. Without cost, fatigue, creep or service-exposure evidence, neither formulation qualified as universally preferable.

5.5 Robustness and Sensitivity of the Main Findings

The summaries illustrated property trade-offs, but they did not establish reproducibility across batches. Specimen-level standard deviations could not determine whether manufacturing-batch effects changed formulation rankings [32]. Likewise, one fibre loading for each treatment combination prevented complete separation of loading and modification effects.

The strongest descriptive pattern was increased stiffness alongside reduced ductility and variable moisture retention. Further analysis required batch-level observations and matched treatment–loading combinations. These limitations framed interpretation of reinforcement mechanisms, manufacturing feasibility and application requirements.

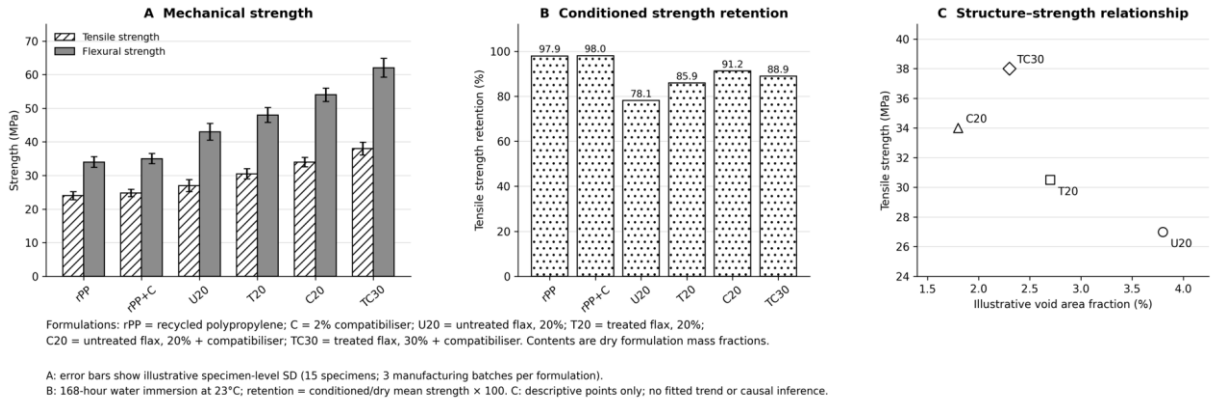


Figure 3. Integrated formulation-performance assessment using data.

Panel A compares mechanical properties, Panel B presents conditioned tensile strength retention, and Panel C relates illustrative void area fractions to tensile strength.

6. DISCUSSION AND ENGINEERING IMPLICATIONS

6.1 What the Findings Establish About Reinforcement and Adhesion

The example illustrates how interfacial modification could add value beyond untreated reinforcement, rather than establishing an experimentally demonstrated effect under the conditions illustrated. At 20% flax, tensile strength increased from 27.0 MPa without modification to 30.5 MPa after treatment and 34.0 MPa with compatibilisation. Accompanying reductions in illustrative void fractions and pull-out features were consistent with improved load transfer. However, microscopy cannot independently quantify adhesion, and these constructed patterns do not validate a mechanism. Published research supports examining interface quality alongside fibre geometry and dispersion [30]. Increased stiffness also differed from improved toughness: untreated reinforcement doubled tensile modulus but reduced impact strength. This trade-off is compatible with restricted matrix deformation and altered fracture processes [31]. The combined 30% formulation provided the highest stiffness, but its comparison with 20% formulations confounded loading and modification. Fibre shortening, orientation, crystallinity and recycled matrix variability remained alternative explanations. Stronger adhesion therefore represented a plausible interpretation requiring direct interfacial measurements and matched comparisons. The example demonstrated a reporting approach that balanced mechanical gains against competing properties; it did not establish an optimal treatment, a reproducible manufacturing benefit or statistically supported superiority across independent batches.

6.2 Manufacturing Feasibility and Application Selection

Manufacturing feasibility depends on whether material preparation and processing remain controllable at production scale. Alkali treatment introduces chemical handling, washing, drying and wastewater requirements,

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while compatibilisation adds material cost and dosing responsibilities [32]. Neither route is automatically preferable because processing simplicity, supply consistency and required performance differ between applications. Moisture control is important during fibre storage, feeding and compounding. Extrusion and moulding equipment may accommodate the materials, but feeder reliability, torque, residence time and tooling behaviour require verification. Fibre variability also creates quality assurance demands beyond checking nominal reinforcement content [33]. The property profiles suggest candidates for screening, such as rigid housings or interior panels, rather than confirmed component applications. Higher stiffness could support dimensional requirements, while reduced impact response could exclude demanding impact environments. Maintenance implications include moisture exposure, inspectability and replacement requirements. Component geometry, joints, stress concentrations and service temperatures remain untested. Consequently, laboratory specimen comparisons guide material development but do not establish nonstructural or semi-structural suitability without application-specific qualification and documented acceptance requirements for each component.

6.3 Limitations, Environmental Claims and Transferability

The principal limitation is that all findings are valid. Their apparent consistency cannot substitute for measured batch variation, uncertainty estimates or independent replication. Even an equivalent experimental study would face restrictions from selected feedstock sources, fibre lots and specimen geometries. Unmeasured orientation, manufacturing variation and incomplete interfacial testing would constrain attribution. Recycled polymers can vary with contamination and processing history, limiting transfer between recovery streams [34]. Results from polypropylene and flax would not automatically apply to other matrices or fibres. Fatigue, creep, weathering, thermal cycling and repeated recycling were not assessed. The short conditioning scenario also cannot establish long-term durability. Environmental interpretation requires separate evidence: renewable reinforcement and recycled content do not independently prove lower lifecycle impacts. Treatment chemicals, washing water, drying energy, processing losses and component lifetime affect comparative performance [35]. Additives and fibre damage can influence subsequent recovery options. Environmental superiority therefore requires a defined functional comparison, transparent system boundaries and credible end-of-life assumptions, rather than inference from composition or laboratory strength alone under selected conditions of assessment.

6.4 Research and Development Priorities

Development priorities begin with measured validation across additional recycled feedstocks, fibre lots and independently manufactured batches. Matched factorial comparisons should separate reinforcement loading, treatment and compatibiliser concentration before selecting formulations. Longer moisture exposure, fatigue and creep testing should examine whether initial gains persist under relevant service conditions [30]. Scalable treatment routes require assessment of chemical consumption, washing demand and process consistency [32]. Repeated processing should quantify fibre shortening, matrix changes and retained properties. Component trials should assess geometry, joints, impact locations and realistic environmental exposure against documented acceptance criteria. Together, reproducibility, durability, production capability and lifecycle evidence determine whether a promising formulation becomes a qualified engineering material. These requirements frame the concluding assessment of contribution and responsible selection in practice.

7. CONCLUSION

7.1 Principal Findings and Material Contribution

Improving recycled polymer performance requires attention to feedstock variability, reinforcement characteristics and interface quality. The synthetic example illustrated higher tensile strength and stiffness following flax reinforcement and interfacial modification, alongside reduced ductility and formulation-dependent impact resistance. At matched fibre content, 121ompatibilization provided greater illustrative strength than untreated reinforcement, while the combined higher-loading formulation achieved the highest stiffness. These comparisons demonstrated reporting trade-offs rather than experimentally verified superiority. Moisture retention further differentiated formulations, showing why dry strength alone cannot determine material selection. Structural patterns suggested improved load transfer but did not prove adhesion mechanisms. No formulation therefore qualified as universally optimal, and actual experimental measurements remain necessary to establish reproducible material contributions.

7.2 Conditions for Engineering Adoption

Engineering adoption requires reproducible manufacturing, documented feedstock quality and conditioning representative of intended exposure. Application-specific testing must establish whether components satisfy defined mechanical, dimensional and environmental requirements. Durability, processing capability and lifecycle evidence remain essential, particularly where treatment chemicals, moisture sensitivity or repeated recycling affect performance. Uncertainties concerning batch variation, interfacial strength, fatigue and creep require

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resolution before qualification. The synthetic comparisons support experimental planning rather than deployment decisions. With measured validation and appropriate quality assurance, controlled reinforcement and interfacial engineering offer potential to expand reliable uses of recycled polymers.

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