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Alkali-Treated Pineapple Leaf and Water Hyacinth Fibers for PLA Biocomposites: A Review

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Abstract. *Sustainable polymer composites require renewable reinforcements whose mechanical performance, processing feasibility, durability, and end-of-life behavior are supported by evidence. This review maps alkali-treated pineapple leaf fiber (PALF) and water-hyacinth-related materials for polylactic acid (PLA) and related biopolymer composites, focusing on interface modification, mechanical and flexural behavior, durability limitations, and application gaps. A PRISMA-style systematic mapping approach was applied using a corrected modular evidence-mapping strategy rather than one all-concept Boolean string. From a precompiled reference-summary dataset of 1,218 records, 50 studies were retained after residual duplicate checking, title-and-abstract screening, full-text eligibility assessment, and quality appraisal. Evidence was classified into direct PLA/PALF studies, WHF fiber-reinforcement studies, WHF filler or functional-additive studies, water-hyacinth biomass-to-PLA feedstock studies, alkali-treatment/interface studies, broader PLA/natural-fiber evidence, and methodological sources. PALF has stronger direct evidence in PLA matrices, including continuous-fiber 3D printing, layer-to-layer additive manufacturing, molding routes, and hybrid systems. WHF remains underexplored in PLA; current evidence mainly comes from WHF/HDPE, WHF/PBS, WHF/thermoplastic starch, WHF/epoxy, and feedstock-conversion studies. The quantitative extraction reports treatment conditions, fiber fractions, processing routes, tensile and flexural values, moduli, impact data, and percentage changes where available. Examples include flexural strength of 35.81 MPa and modulus of 5.28 GPa for alkali-treated coir/PALF/PLA, 132.75 MPa flexural strength for NaOH-treated jute-PALF/PLA, and flexural-strength gains of 15.86-98% across relevant systems. The proposed PLA/PALF/WHF hybrid is framed as a testable PALF-primary/WHF-secondary hypothesis requiring direct validation, standardized treatment, durability testing, LCA, and application-specific assessment.*
Keywords: *PLA; pineapple leaf fiber; water hyacinth fiber; alkali treatment; flexural testing.*

Type of the Paper: Review Article.

1. Introduction

The transition from petroleum-based materials toward renewable, biodegradable, and lower-impact alternatives is a major focus in polymer engineering. Natural-fiber-reinforced composites can reduce material density, valorize agricultural and aquatic residues, and support applications in automotive interiors, panels, packaging, furniture, acoustic structures, casings, and lightweight semi-structural products [1–7]. However, sustainability claims must also consider processing feasibility, durability, recycling or degradation, and end-of-life performance [8].

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Polylactic acid (PLA) is widely used as a bio-based thermoplastic matrix because it can be processed by extrusion, injection molding, compression molding, hot pressing, and fused deposition modeling. Nevertheless, neat PLA is brittle and moisture-sensitive, while its performance is strongly affected by thermal history and processing conditions. Lignocellulosic reinforcement can improve stiffness and reduce dependence on petroleum-based materials, but the resulting properties depend on fiber–matrix adhesion, fiber orientation, loading, void content, treatment, and processing route [9–12].

Pineapple leaf fiber (PALF) and water hyacinth fiber (WHF) are complementary biomass resources. PALF is an agricultural residue with relatively high cellulose content and stronger direct evidence as a mechanical reinforcement in PLA. In contrast, WHF evidence is mainly derived from HDPE, PBS, thermoplastic starch, and epoxy systems. Water-hyacinth conversion into lactic acid or PLA-like polymers represents a separate biomass-to-polymer pathway and is therefore not treated as fiber-reinforcement evidence [13,14].

The relevance of PALF valorization is supported by the scale of pineapple cultivation. Indonesia produced approximately 3.16 million tons of pineapple in 2023, with Lampung contributing 722,847 tons [15]. Although these data do not directly quantify leaf waste, they indicate a substantial source of post-harvest biomass that could support PALF-based biocomposite development.

Water-hyacinth valorization should be interpreted cautiously because biomass accumulation is site-specific. In Rawapening Lake, Prasetyo et al. [16] reported relative growth rates of 6.40–7.26% per day and doubling times of 9.6–10.8 days. These results demonstrate rapid growth under the studied conditions but should not be generalized to all water bodies because growth depends on nutrient availability, season, water quality, and management. WHF is therefore positioned as a potential fiber, filler, or feedstock rather than as an established PLA reinforcement.

Alkali treatment is commonly used to remove waxes, hemicellulose, pectin, lignin, oils, and weak surface layers from lignocellulosic fibers. This treatment can increase surface roughness, improve wetting, and strengthen mechanical interlocking at the fiber–matrix interface. However, its effectiveness is condition-dependent; excessive NaOH concentration, prolonged immersion, inadequate washing, or poor drying may damage cellulose microfibrils and reduce composite performance [17,18].

Flexural testing is particularly relevant because many potential PLA-based products experience bending loads. Flexural behavior is influenced by fiber orientation, length, loading, stacking sequence, interlayer bonding, voids, matrix cracking, delamination, moisture uptake, and interfacial failure. Accordingly, flexural strength and modulus should be interpreted together with tensile, impact, water-absorption, morphological, thermal, and durability data [3].

The novelty of this review lies in mapping the different levels of evidence for PLA/PALF systems, WHF-related polymer composites, and alkali-treated natural fibers rather than claiming that WHF is already established in PLA. The review distinguishes direct and indirect evidence, identifies the limitations of transferring WHF results from non-PLA matrices, and proposes a short-, medium-, and long-term research roadmap for PLA/PALF/WHF hybrids [19].

The proposed hybrid design is based on a mechanistic hypothesis. PALF is expected to act as the primary load-bearing reinforcement because direct PLA/PALF and PALF-hybrid studies report tensile and flexural benefits when fiber placement, treatment, and interfacial bonding are controlled [20–24]. WHF is proposed as a lower-fraction secondary fiber or filler that may reduce matrix-rich regions, occupy interstitial spaces, lower density, and promote crack deflection or damping, provided that its size, loading, treatment, drying, and dispersion are controlled [25–28]. A true hybrid effect should only be claimed if PLA/PALF/WHF outperforms neat PLA and the corresponding single-fiber composites, or exceeds a rule-of-mixtures prediction under identical processing and testing conditions.

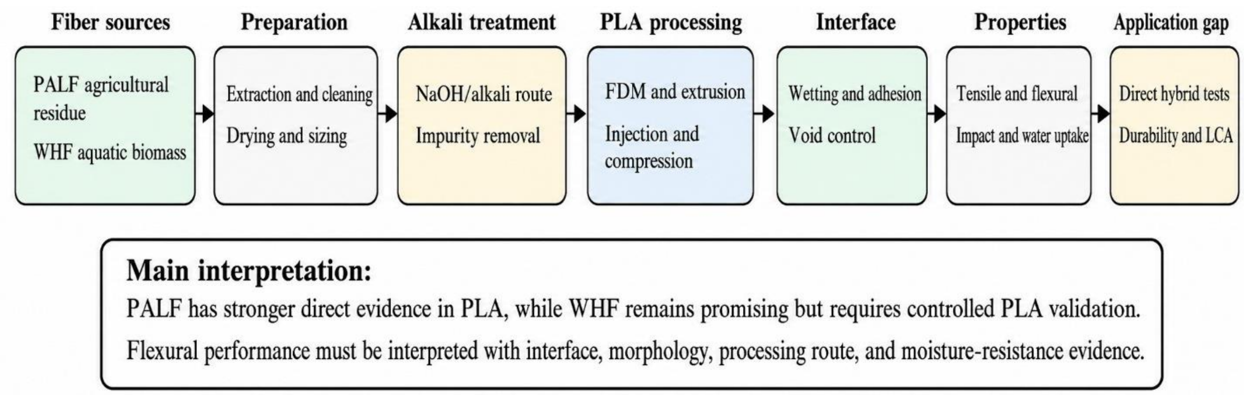

Fig. 1. Conceptual framework linking PALF and WHF sources, alkali treatment, PLA processing, interface formation, mechanical and flexural properties, and application gaps.

2. Materials and methods

2.1. Review design and research questions

This systematic mapping review followed PRISMA-style identification, screening, eligibility, inclusion, and reporting [29]. It addressed evidence maturity, alkali-treatment effects, determinants of tensile, flexural, impact, and water-absorption behavior, and validation needs for a direct PLA/PALF/WHF hybrid.

Meta-analysis was not performed because matrices, fiber forms and fractions, treatment conditions, processing routes, specimen geometries, test standards, and control denominators were too heterogeneous for defensible pooling. Numerical findings are therefore presented as comparative extraction rather than pooled effect estimates.

2.2. Search strategy, Boolean logic, source dataset, and eligibility criteria

The identification stage was revised to accurately reflect the source of the evidence corpus. The review began with a precompiled reference-summary dataset containing 1,218 records related to PLA, PALF, WHF, alkali treatment, natural-fiber composites, and mechanical or flexural performance. This figure represents one aggregated dataset and should not be interpreted as the combined total of independent searches in Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, MDPI, or other publisher platforms.

The dataset was initially searched on 25 May 2026 and finalized on 30 May 2026. DOI verification, bibliographic checking, and full-text confirmation were completed within the same period. The review included English-language research and review articles published from 2020 onward that provided sufficient methodological and property-related information. Non-English records, inaccessible full texts, conference abstracts with limited methods, and studies lacking relevant treatment, interface, mechanical, or flexural evidence were excluded. Because the original database-specific search logs were unavailable, separate raw hit counts could not be reconstructed. Database and publisher names therefore indicate indexing, retrieval, and verification functions rather than independent PRISMA identification sources.

Official production statistics and site-specific water-hyacinth growth studies cited in the Introduction were used only as contextual background. They were not included in the PRISMA corpus, quality appraisal, or quantitative synthesis because they did not report material-performance evidence for PLA, PALF, WHF composites, alkali treatment, or mechanical properties.

The original all-concept Boolean expression was replaced with a modular evidence-mapping strategy. The corpus was not generated using a compulsory query requiring PLA, PALF, WHF, alkali treatment, and mechanical or flexural terms to appear together. Instead, separate search blocks covered direct PLA/PALF studies, WHF reinforcement evidence, WHF filler or functional-additive studies, water-hyacinth biomass-to-PLA conversion, alkali-treatment and interface mechanisms, and broader PLA/natural-fiber mechanical evidence. The combined PALF–WHF query was used only to check for direct hybrid studies.

A record advanced to eligibility assessment when it matched at least one search block and reported relevant information on formulation, treatment, interface behavior, mechanical or flexural performance, morphology, thermal properties, water absorption, durability, or application readiness. Studies were included when they addressed PLA, PLA blends, PALF, WHF, natural-fiber composites, or hybrid biocomposites and reported relevant material properties or surface modification. Studies were excluded when they were outside the PLA or natural-fiber scope, lacked mechanical or flexural evidence, provided no treatment or interface relevance, focused on unrelated metal or ceramic systems, or contained insufficient methodological detail.

Table 1. Identification source, count, and verification role

Source or role	Count used in PRISMA identification	Use and reporting clarification
Precompiled reference summary dataset	1,218 records	Primary identification source. This is a single consolidated dataset, not a cumulative total of independent raw hits from seven databases.
Internal duplicate check	1 residual duplicate removed	Duplicate checking was applied to the consolidated dataset before title and abstract screening.
Scopus field/source label in the reference summary	Recorded where available; not counted separately	Used as an indexing label in the reference summary and as a bibliographic verification aid.
Web of Science and publisher platforms: ScienceDirect, SpringerLink, Wiley Online Library, Taylor and Francis Online, MDPI, and other publisher pages	0 additional records added to the PRISMA count	Used for cross-checking, DOI confirmation, full-text retrieval, and data verification; not treated as independent identification sources in the corrected PRISMA flow.
Records available for screening after duplicate removal	1,217 records	Records screened by title and abstract for relevance to PLA, PALF, WHF, alkali treatment, mechanical properties, and flexural testing.

2.3. Data extraction, quality appraisal, and risk of bias

The extraction framework recorded bibliographic details, material system, fiber type and form, loading, treatment, processing method, test procedures, characterization techniques, principal findings, limitations, and relevance to future PLA/PALF/WHF hybrids. It was expanded to capture numerical data where available, including treatment conditions, fiber fraction, tensile and flexural properties, impact strength, hardness, water absorption, durability, and percentage change relative to the stated control. The intended role of each biomass component was also classified as PALF primary reinforcement, WHF secondary reinforcement or filler, or water hyacinth feedstock. Proposed comparisons for testing hybrid effects included neat PLA, PLA/PALF, PLA/WHF, untreated PLA/PALF/WHF, and treated PLA/PALF/WHF.

Study quality was evaluated using a 12-point framework covering six domains: material formulation, treatment reproducibility, processing route, mechanical testing, characterization support, and reporting transparency. Each domain received 0, 1, or 2 points for inadequate, partial, or adequate reporting. Total scores of 9–12 indicated high quality, 6–8 moderate quality, and 0–5 low or background evidence. The appraisal included treatment and interface studies [30], background reviews [31,32], PLA/natural-fiber systems [33,34], direct PALF evidence [35], WHF-related evidence [25], and methodological sources [36].

Risk of bias was assessed qualitatively for study selection, treatment and processing reproducibility, measurement quality, selective reporting, and comparability. Lower risk was assigned to studies with clear formulations, complete treatment and processing details, recognized test standards, replication or statistical analysis, and supporting SEM, FTIR, XRD, DSC/TGA, or water-absorption data. Higher risk was assigned when formulation, treatment, statistical analysis, or supporting evidence was incomplete.

Quality-appraisal and qualitative risk-of-bias results are presented in Table 2. Of the 50 retained sources, 31 were rated as high-quality, 16 as moderate-quality, and 3 as low or background/methodological evidence using the six-domain, 12-point framework. Higher ratings reflected clear material formulation, reproducible treatment and processing, appropriate mechanical testing, supporting characterization, and transparent reporting. Moderate ratings indicated incomplete reporting in one or more domains, while low ratings were mainly assigned to methodological or background sources rather than direct materials-performance studies.

Risk of bias was classified as low, moderate, or high based on study selection, treatment and processing reproducibility, measurement quality, selective reporting, and comparability. Studies with moderate risk were retained but interpreted cautiously, particularly when the evidence was indirect or less certain than direct PLA/PALF or PLA/WHF findings.

The protocol was not prospectively registered in PROSPERO or OSF. This is acknowledged as a limitation because the study was designed as a materials-engineering systematic mapping review based on a precompiled reference-summary dataset.

Table 2. Quality-appraisal scores and qualitative risk-of-bias ratings for the 50 retained sources

Ref.	Study/source	MF	TR	PR	MT	CS	RT	Total	Quality	RoB
[1]	Vinod et al. 2021	2	2	2	2	2	2	12	High	Low
[2]	Abdel Kader et al. 2025	2	1	1	1	1	2	8	Moderate	Moderate
[3]	Abdel-Hakim et al. 2021	2	1	2	2	2	2	11	High	Low
[4]	Abdel-Hakim et al. 2024	2	2	2	2	2	2	12	High	Low
[5]	Abdelkawy et al. 2023	2	2	2	0	2	2	10	High	Moderate
[6]	Abdelkawy et al. 2025	2	2	2	0	2	2	10	High	Moderate
[7]	Abdur Rahman et al. 2023	2	1	1	0	1	2	7	Moderate	Moderate
[8]	Jaiswal et al. 2022	2	2	1	0	1	2	8	Moderate	Moderate
[9]	Abraha et al. 2023	2	2	2	2	2	2	12	High	Low
[10]	Abu Hassan et al. 2022	2	0	2	2	2	2	10	High	Moderate
[11]	Abu Hassan et al. 2023	2	0	2	2	2	2	10	High	Moderate
[12]	Abul Hasan 2026	2	0	2	2	2	2	10	High	Moderate
[13]	Abesho et al. 2025	2	0	2	2	2	2	10	High	Moderate
[14]	Abo et al. 2026	2	2	2	1	2	2	11	High	Moderate
[17]	Abisha et al. 2025	2	2	2	2	2	2	12	High	Low
[18]	Adeniyi et al. 2021	2	0	2	0	2	2	8	Moderate	Moderate

Ref.	Study/source	MF	TR	PR	MT	CS	RT	Total	Quality	RoB
[19]	Santos et al. 2024	1	0	0	0	2	2	5	Low (background)	Moderate
[20]	Hasan et al. 2026	2	2	2	2	2	2	12	High	Low
[21]	Raja et al. 2026	2	1	2	2	2	2	11	High	Low
[22]	Siakeng et al. 2021	2	2	2	2	2	2	12	High	Low
[23]	Suteja et al. 2022	2	0	2	2	1	2	9	High	Moderate
[24]	Suvanjumrat et al. 2026	2	0	2	2	2	2	10	High	Moderate
[25]	Arivendan et al. 2022	2	0	2	2	2	2	10	High	Moderate
[26]	Behera et al. 2025	2	2	2	2	2	2	12	High	Low
[27]	Raharjo et al. 2026	2	2	2	2	2	2	12	High	Low
[28]	Suwanniroj and Suppakarn 2022	2	2	2	2	2	2	12	High	Low
[29]	Page et al. 2021a	0	0	0	0	2	2	4	Low (method)	Low
[30]	Adediran et al. 2021	2	2	2	2	2	2	12	High	Low
[31]	Rajeshkumar et al. 2021	2	1	1	1	1	2	8	Moderate	Moderate
[32]	Rajeshkumar et al. 2023	2	1	1	1	1	2	8	Moderate	Moderate
[33]	Bhagia et al. 2021	2	1	2	0	1	2	8	Moderate	Moderate
[34]	Rao et al. 2024	2	2	2	2	2	2	12	High	Low
[35]	Anand et al. 2022	2	2	2	2	2	2	12	High	Low
[36]	Page et al. 2021b	0	0	0	0	2	2	4	Low (method)	Low
[37]	Acharya et al. 2024	2	1	1	1	1	2	8	Moderate	Moderate
[38]	Adam and Bekele 2026	2	1	1	1	1	2	8	Moderate	Moderate
[39]	Adjei-Yeboah and Jahan 2026	2	1	2	0	1	2	8	Moderate	Moderate
[40]	Afkari et al. 2022	2	1	2	2	2	2	11	High	Low
[41]	Agarwal et al. 2021	2	1	2	2	2	2	11	High	Low
[42]	Aguiar et al. 2026	2	1	2	2	2	2	11	High	Low
[43]	Ahmad et al. 2025	2	1	2	0	1	2	8	Moderate	Moderate
[44]	Ahmad et al. 2023a	2	1	2	0	1	2	8	Moderate	Moderate
[45]	Ahmad et al. 2023b	2	0	2	2	2	2	10	High	Low
[46]	Ahmad et al. 2022	2	0	2	2	2	2	10	High	Low
[47]	Aisyah et al. 2021	2	1	1	1	1	2	8	Moderate	Moderate
[48]	Ajayi et al. 2025	2	1	1	1	1	2	8	Moderate	Moderate
[49]	De et al. 2024	2	1	1	1	1	2	8	Moderate	Moderate
[50]	Raja et al. 2025	2	0	2	2	1	2	9	High	Moderate
[51]	Rao et al. 2024	2	1	2	2	2	2	11	High	Low
[52]	Wudu et al. 2025	2	1	2	0	1	2	8	Moderate	Moderate

MF = material formulation; TR = treatment reproducibility; PR = processing route; MT = mechanical testing; CS = characterization support; RT = reporting transparency; RoB = risk of bias. Domain scores were 0-2; totals of 9-12, 6-8, and 0-5 indicate high, moderate, and low/background evidence, respectively.

2.4. Literature selection

The corrected PRISMA process began with a precompiled reference-summary dataset of 1,218 records. Because the dataset had already been consolidated, only one residual duplicate was removed, leaving 1,217 records for title and abstract screening. Of these, 922 were excluded as irrelevant to PLA-based biocomposites, PALF, WHF, alkali treatment, natural-fiber composites, or mechanical and flexural performance. The remaining 295 full-text articles were assessed, and 245 were excluded because of insufficient material relevance, treatment or interface information, mechanical data, or methodological detail. Ultimately, 50 studies were included in the qualitative synthesis.

The synthesis included both direct and indirect evidence. Direct PLA/PALF studies provided the main basis for evaluating PALF, whereas WHF evidence from HDPE, PBS, thermoplastic starch, epoxy, and biomass-to-PLA pathways was used only to assess potential relevance. These findings were not treated as proof of WHF performance in PLA because differences in matrix polarity, stiffness, crystallinity, processing temperature, and interfacial chemistry may limit cross-matrix comparisons.

Table 3. Corrected PRISMA based literature selection process

Stage	Selection process and description	Records	Clarification
Identification	Records identified from the precompiled reference summary dataset	1,218	Single aggregated dataset count; not a cumulative seven-database hit total.
Duplicate removal	One residual duplicate record removed within the aggregated dataset	1	The low duplicate count reflects prior consolidation before screening.
Screening	Records screened by title and abstract	1,217	Screened for PLA, PALF, WHF, alkali treatment, mechanical properties, and flexural testing.
Screening exclusion	Records excluded as irrelevant	922	Excluded for material, treatment, or testing irrelevance.
Eligibility	Full text articles assessed for eligibility	295	Assessed for material system, method detail, and mechanical relevance.
Full text exclusion	Full text articles excluded	245	Excluded for lack of PLA/biopolymer relevance, PALF/WHF relevance, treatment relevance, mechanical/flexural data, or sufficient methodological detail.
Included	Studies included in qualitative synthesis	50	Used for thematic synthesis and evidence classification.

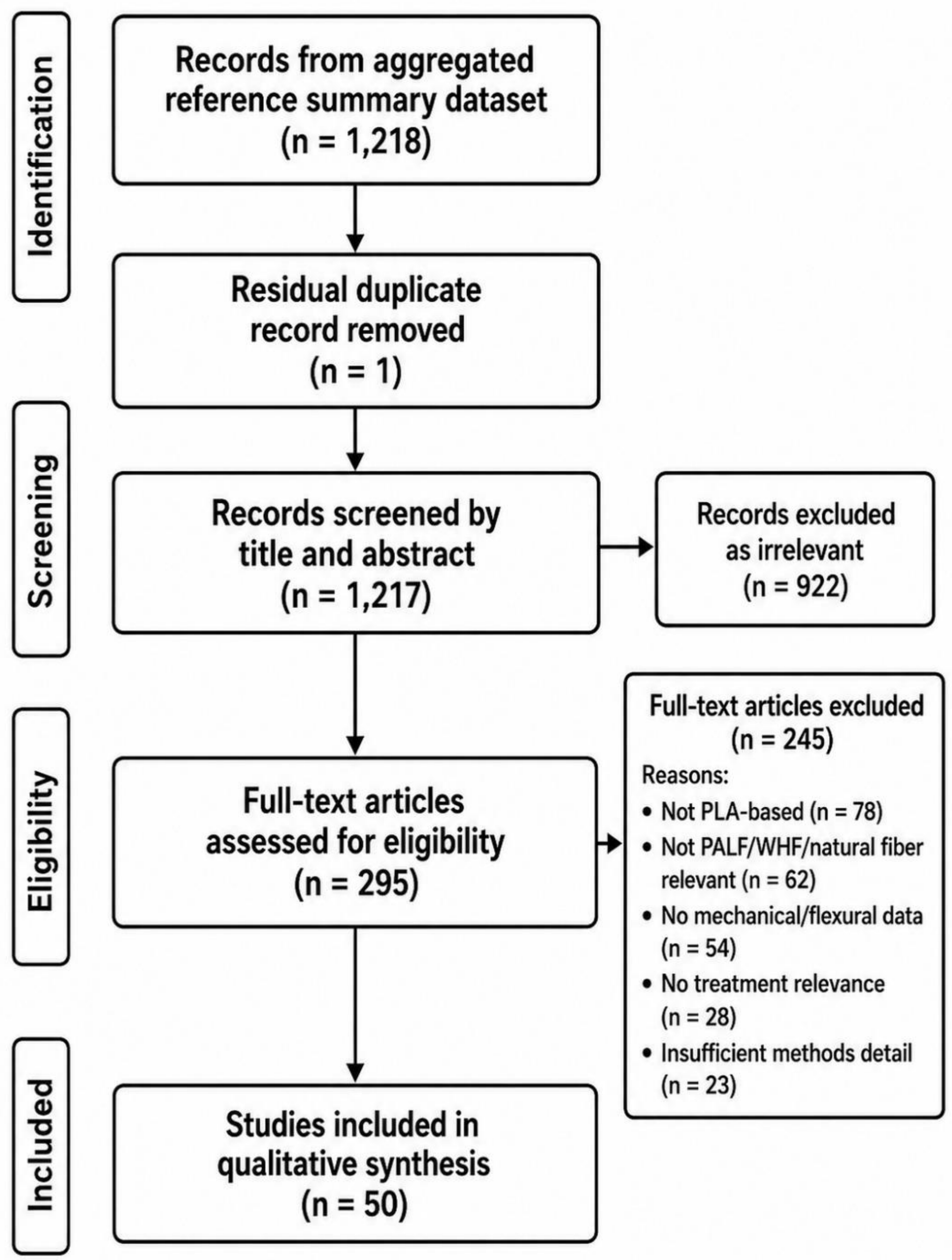

Fig. 2. Corrected PRISMA-style flow diagram showing residual duplicate checking, screening, eligibility assessment, and inclusion from one aggregated reference-summary dataset.

3. Results and Discussion

3.1. Evidence mapping and thematic classification

The evidence base is broad but uneven. PALF appears in direct PLA and PLA-related reinforcement studies, whereas WHF fiber/filler evidence is dominated by non-PLA matrices. Biomass-to-PLA conversion is a distinct feedstock pathway. Accordingly, PALF is the stronger primary-reinforcement candidate, while WHF remains a promising but unverified secondary phase requiring direct PLA validation [13].

Performance is governed jointly by treatment severity, fiber size and loading, orientation, wetting, voids, and processing temperature. Broader studies on thermomechanical behavior, interface modification, additive manufacturing, stacking, LCA, filament processing, woven composites, applications, recycling, PALF particles, environmental degradation, and alternative PALF biomaterials provide supporting context [37–42].

3.2. PLA matrix, processing route, and biocomposite performance

PLA accommodates extrusion, molding, hot pressing, and FDM, but reinforcement can raise stiffness while reducing ductility or impact resistance when dispersion or bonding is poor. Route-specific variables-drying, fiber size, thermal stability, raster and layer geometry, stacking pressure, and void removal-limit transfer of results between systems.

3.3. PALF as direct and related reinforcement evidence

PALF currently provides the strongest direct evidence for PLA-based biocomposites. Continuous PALF/PLA produced by 3D printing improved tensile strength over neat PLA, although elongation decreased as stiffness increased [23]. Layer-to-layer PLA/PALF manufacturing also showed that optimized fiber placement and interlayer bonding can enhance tensile and flexural performance [24].

Hybrid studies support this trend. Alkali-treated coir/PALF/PLA improved flexural and dynamic mechanical behavior [22], while jute/PALF/PLA and PALF/hemp/PLA systems showed that treatment, fiber ratio, and processing optimization strongly influence tensile, flexural, impact, durability, and environmental performance [20,21].

Evidence from silane-treated PALF, PALF-based polymers, particle-filled 3D-printed composites, and PALF-derived biomaterials further confirms the importance of fiber length, surface treatment, morphology, and binder selection [35]. These indirect studies help explain transferable mechanisms, but conclusions for PLA should still rely primarily on direct PLA/PALF evidence [22–24].

Table 4. Key PALF and PALF/PLA-related evidence retained in the synthesis

Study	Material system	Processing/treatment	Extracted quantitative mechanical/flexural data
Hasan et al. [20]	Jute-PALF/PLA hybrid	NaOH, KOH, and SLS treatments; compression molding; 20-30 wt% fiber loading	NaOH treatment improved tensile strength and modulus by 71.49% and 67.98% over untreated composites at 20 wt%; maximum tensile strength 110.96 MPa at 30 wt%; flexural strength 132.75 MPa; impact strength 577.25 J/m; hardness 106.8 Shore D; water absorption 15-20% lower; soil weight loss 1.2% at 30 wt%.

Study	Material system	Processing/treatment	Extracted quantitative mechanical/flexural data
Raja et al. [21]	PALF-hemp/PLA hybrid	Compression molding and Taguchi optimization	PALHF-re-PLA composite increased tensile strength by 73.50%, flexural strength by 60.00%, and impact resistance by 58.40%.
Siakeng et al. [22]	Coir/PALF/PLA hybrid	Alkali-treated hybrid fibers	Treated C1P1 hybrid composite (C1P1A) achieved the highest flexural strength of 35.81 MPa and flexural modulus of 5.28 GPa among the hybrid biocomposites; C1P1A also showed the highest Tg and storage modulus trend.
Suteja et al. [23]	Continuous PALF/PLA	3D printing; extrusion temperature and feed-rate variation; ASTM D638 tensile test with factorial design	Tensile strength increased relative to pure PLA and elongation decreased; dimensional error did not exceed the usual FDM range; exact tensile/flexural values were NR in the reference summary.
Suvanjumrat et al. [24]	PLA/PALF green composite	Layer-to-layer additive manufacturing; optimized 5.0 mm3/s extrusion rate, 0.3 mm PLA layer, 0.8 mm line spacing, three PALF sheets	Optimized PLA/PALF achieved modulus of elasticity 235 MPa and tangent modulus 1130 MPa; tensile strength increased by 37.6% and flexural strength by 15.86% compared with additively manufactured pure PLA.
Anand et al. [35]	Silane-treated PALF composite	Fiber-length and surface-treatment study	SEM-supported fracture toughness was 15-32 MPa for 5-10 mm fibers and 42-55 MPa for 15-20 mm fibers; 20 mm PALF gave the best flexural, tensile, impact, and wear-resistance trend.
Raja et al. [50]	PLA with banana and pineapple particles	FDM with fiber-particle fraction variation	Increasing banana fiber volume fraction up to 2% increased compressive strength by 27.97% and flexural strength by 3.95%, while tensile strength decreased by 5.6% relative to plain PLA.
Wudu et al. [52]	PALF-based biomaterial	Bio-binder and dyeing route	Supports PALF valorization beyond load-bearing PLA composites; not used as direct PLA mechanical evidence.

NR = not reported in the reference-summary source. Values are study-specific and were not pooled across different matrices, loadings, treatments, or processes.

3.4. Separated WHF reinforcement, filler, and biomass-to-PLA feedstock evidence

Water-hyacinth evidence was divided into three distinct pathways: WHF as lignocellulosic reinforcement, WHF as a short fiber, filler, carbon source, or functional additive, and water-hyacinth biomass as a feedstock for lactic acid or PLA-like polymer production. These categories were interpreted separately as reinforcement, filler/functional-composite, and biomass-conversion evidence.

WHF/HDPE studies indicate that alkali treatment and dispersing agents can improve tensile, flexural, and impact performance [27], while WHF/epoxy research provides information on morphology, cellulose content, crystallinity, thermal behavior, and lightweight-composite potential [25]. WHF/thermoplastic-starch and WHF/APP/PBS systems also show potential for biodegradable or flame-retardant composites when loading, compatibilization, and processing are controlled [26,28]. However, these findings remain indirect for PLA because the matrix properties and processing conditions differ.

Abo et al. [14] converted water-hyacinth biomass into lactic acid and PLA-like material through hydrolysis, fermentation, and polymer conversion. This study supports feedstock valorization but does not demonstrate WHF reinforcement in PLA. Therefore, it was used only as biomass-conversion evidence and not to support claims about WHF mechanical reinforcement.

Table 5. Separated water-hyacinth evidence streams: reinforcement, filler/functional-additive, and feedstock conversion

Evidence category	Study/material system	Water-hyacinth role and processing	Extracted quantitative mechanical/flexural data
Water hyacinth as feedstock/conversion route	Abo et al. [14]; water-hyacinth-derived PLA	Water-hyacinth biomass converted to fermentable sugars, lactic acid, and PLA-like material through acid hydrolysis, fermentation, and polymer conversion.	Lactic acid yield: 15.04 wt% experimentally and 15.19 wt% predicted; synthesized PLA: tensile strength 29.4 MPa, elongation at break 35.6%, Young modulus 82.6 MPa, Tg 62.9 °C, Tc 106.5 °C, Tm 183.15 °C; soil-burial degradation 12.5% after 30 days; water absorption 4.7% after 16 h.
WHF as fiber reinforcement	Arivendan et al. [25]; WHF/epoxy composite	Mechanically extracted WHF used as a natural fiber reinforcement; compression molding; morphology, thermal, and mechanical characterization.	WHF contained 62.15% cellulose and 14.82% hemicellulose; crystallinity index was 54.82%; exact tensile/flexural/impact values were NR in the reference summary.
WHF as filler or short-fiber component	Behera et al. [26]; WHF/thermoplastic starch	Alkali-treated water-hyacinth short fibers incorporated into a biodegradable thermoplastic-starch matrix by hot pressing.	At 2 wt% WHF, tensile strength increased by 113% and flexural strength by 98% relative to virgin thermoplastic starch; impact strength 8.3 kJ/m2; hardness 9.8; thermal stability up to 320 °C; soil-burial mass loss 65% after 60 days.

Evidence category	Study/material system	Water-hyacinth role and processing	Extracted quantitative mechanical/flexural data
WHF as fiber reinforcement	Raharjo et al. [27]; WHF/HDPE biocomposite	WHF used as reinforcement in HDPE; NaOH alkali treatment and dispersing-agent immersion were applied to improve interface quality.	Compared with untreated WHF/HDPE, tensile strength increased by 32.48%, flexural strength by 27.7%, and impact strength by 23.9%.
WHF as functional filler/carbon source	Suwanniroj and Suppakarn [28]; WHF/APP/PBS composite	WHF used with ammonium polyphosphate and PBS-g-GMA compatibilizer as part of a flame-retardant PBS composite system.	PBS-g-GMA improved tensile strength, flexural strength, and crystallization rate; the 15 wt% WHF/30 wt% APP/15 wt% PBS-g-GMA/PBS composite reached UL-94 V-0 and maximum LOI of 29.2%; exact tensile/flexural values were NR in the reference summary.

Feedstock conversion in Ref. [14] is not used to support WHF reinforcement claims.

3.5. Alkali treatment and interface formation

Alkali treatment can improve adhesion by removing weak surface constituents and exposing a rougher fibrillar surface [1,4,6]. Benefits depend on concentration, time, neutralization, washing, and drying; excessive treatment can damage cellulose and lower fiber strength [5,6,38]. Moisture control remains essential because swelling and interfacial debonding can erode long-term performance [10,11].

3.6. Mechanical properties, flexural testing, and failure mechanisms

Tensile, flexural, impact, hardness, and water-absorption tests address complementary performance domains. Flexural response is particularly application-relevant because bending can trigger matrix cracking, debonding, pull-out, fiber breakage, delamination, and void-assisted propagation; numerical results should therefore be interpreted with process and fracture-morphology evidence [40,41,43–46].

Tables 4–6 replace qualitative labels with reported values, treatment conditions, fiber fractions, and control-based changes. Examples include 35.81 MPa flexural strength and 5.28 GPa flexural modulus for alkali-treated coir/PALF/PLA [22], 132.75 MPa for NaOH-treated jute-PALF/PLA [20], and a 15.86% flexural gain for layer-to-layer PLA/PALF [24]. WHF-related systems reported 27.7% and 98% flexural gains in HDPE and thermoplastic-starch matrices, respectively [26,27].

These outcomes support mechanistic cross-study comparison, but not direct ranking or meta-analysis, because the studies differ in matrix type, fiber loading, treatment conditions, processing routes, specimen geometries, testing standards, and control materials. Accordingly, Table 6 reports NR for unavailable values and retains the original control or reference condition used in each study.

Table 6. Comparative tensile, flexural, and water-absorption evidence from retained studies

Study/ref.	Material system and treatment	Tensile evidence	Flexural evidence	Water absorption/durability evidence
Abo et al. [14]	Water-hyacinth biomass converted to PLA-like material; feedstock/conversion route	Synthesized PLA tensile strength 29.4 MPa; elongation at break 35.6%; Young modulus 82.6 MPa.	NR; this is feedstock-conversion evidence, not WHF reinforcement evidence.	Water absorption 4.7% after 16 h; soil-burial degradation 12.5% after 30 days.
Hasan et al. [20]	Jute-PALF/PLA; NaOH, KOH, and SLS treatments; compression molding; 20-30 wt% fiber loading	Maximum tensile strength 110.96 MPa; NaOH treatment increased tensile strength and modulus by 71.49% and 67.98% over untreated composites at 20 wt%.	Flexural strength 132.75 MPa.	Water absorption was 15-20% lower; soil weight loss 1.2% at 30 wt%.
Raja et al. [21]	PALF-hemp/PLA hybrid; compression molding and optimization	Tensile strength increased by 73.50%.	Flexural strength increased by 60.00%.	NR in the reference-summary source.
Siakeng et al. [22]	Alkali-treated coir/PALF/PLA hybrid	NR in the reference-summary source.	Highest flexural strength 35.81 MPa and flexural modulus 5.28 GPa for treated C1P1A.	NR in the reference-summary source.
Suvanjumrat et al. [24]	Layer-to-layer PLA/PALF green composite; optimized additive-manufacturing parameters	Tensile strength increased by 37.6% compared with additively manufactured pure PLA.	Flexural strength increased by 15.86%; modulus of elasticity 235 MPa and tangent modulus 1130 MPa were reported.	NR in the reference-summary source.

Study/ref.	Material system and treatment	Tensile evidence	Flexural evidence	Water absorption/durability evidence
Behera et al. [26]	Alkali-treated WHF/thermoplastic starch; 2 wt% WHF	Tensile strength increased by 113% relative to virgin thermoplastic starch.	Flexural strength increased by 98% relative to virgin thermoplastic starch.	Soil-burial mass loss reached 65% after 60 days; direct water-absorption value was NR in the reference-summary source.
Raharjo et al. [27]	WHF/HDPE; NaOH treatment and dispersing-agent immersion	Tensile strength increased by 32.48% relative to untreated WHF/HDPE.	Flexural strength increased by 27.7% relative to untreated WHF/HDPE.	NR in the reference-summary source; indirect for PLA.
Raja et al. [50]	FDM PLA with banana and pineapple particles	Tensile strength decreased by 5.6% relative to plain PLA.	Flexural strength increased by 3.95%; compressive strength increased by 27.97% at 2% banana-fiber volume fraction.	NR in the reference-summary source.

NR = not reported in the reference-summary source. The comparison is not meta-analytic because matrices, loadings, treatments, processing routes, and controls differ.

3.7. Morphological, thermal, and durability evidence

SEM, FTIR, XRD, DSC, and TGA help link treatment and processing to pull-out, voids, debonding, crystallinity, transitions, and degradation. Durability evidence remains limited: hydrophilic fibers can swell and weaken interfaces, while PLA is vulnerable to hydrolytic and environmental ageing. Future claims require water uptake, thickness swelling, cyclic humidity, thermal ageing, UV exposure, soil burial, and retained-property measurements.

3.8. Critical comparison of PALF and WHF

PALF has stronger direct support in PLA; WHF remains supported mainly by non-PLA reinforcement or filler systems, while water-hyacinth-to-PLA conversion is a separate valorization route. The hybrid should therefore be role-differentiated rather than an equal blend: PALF provides the principal load path and WHF is tested at lower fractions for packing, crack deflection, damping, or cost reduction.

3.9. Mechanistic rationale for the proposed PALF/WHF hybrid design

The PALF–WHF combination is framed as a testable mechanistic design. PALF is assigned as the primary reinforcement because it has stronger direct evidence in PLA systems, while WHF is proposed more cautiously as a secondary short fiber or filler based mainly on indirect evidence from non-PLA matrices. The hybrid therefore examines whether a PALF-dominant load-bearing network can be supplemented with a controlled WHF phase without reducing interfacial bonding, moisture resistance, or flexural reliability.

This approach makes the novelty falsifiable rather than merely identifying a research gap. The proposed system is not an equal PALF–WHF blend. PALF is expected to provide the main load transfer and bending stiffness, whereas WHF is introduced at lower loading to improve stress distribution, fill matrix-rich regions, deflect cracks, or enhance damping. If WHF increases agglomeration, moisture uptake, or interfacial weakness, its role should be limited to filler, functional additive, or biomass-valorization applications.

The PLA/PALF/WHF hybrid should therefore be evaluated in terms of mechanical performance, interface quality, synergy, sustainability, techno-economic feasibility, and industrial readiness.

Table 7. Mechanistic and application-readiness hypothesis for future PLA/PALF/WHF hybrid biocomposites

Design element	Mechanistic assumption	Evidence-based rationale	Validation requirement
PALF-dominant network	PALF carries the principal tensile and flexural load.	Direct PLA/PALF and PALF-hybrid studies support load transfer when placement, treatment, and bonding are controlled [20–24].	Compare neat PLA, PLA/PALF, and the hybrid under identical processing; measure tensile/flexural properties, voids, interlayer bonding, and SEM pull-out.
WHF secondary phase	WHF is introduced at a lower fraction as short fiber or filler for packing, crack deflection, damping, or cost reduction.	WHF improves selected properties in HDPE, PBS, thermoplastic starch, and epoxy, but evidence remains indirect for PLA [25–28].	Use matched PLA/WHF and PLA/PALF/WHF controls with fixed size, loading, treatment, and drying; determine whether WHF adds value or dilutes PALF.
Interface control	Moderate alkali treatment should improve roughness and wetting without weakening the fibers.	Impurity removal can improve adhesion, whereas excessive treatment can damage cellulose [1,5,6,38].	Report concentration, time, washing, neutralization, drying, FTIR/SEM, water uptake, and failure morphology for both fibers and the hybrid.
Synergy criterion	Coexistence is not synergy; the hybrid must exceed single-fiber controls or a weighted rule-of-mixtures response.	PALF and WHF differ in evidence maturity and expected mechanical role.	Use the same PLA grade, total loading, process, and test standard for neat PLA, PLA/PALF, PLA/WHF, and PLA/PALF/WHF.
Sustainability and scale-up	Circularity and application readiness require environmental, economic, and	Feedstock valorization does not prove reinforcement, and laboratory gains may	Assess density, durability, LCA/end-of-life, collection and treatment cost,

Design element	Mechanistic assumption	Evidence-based rationale	Validation requirement
	manufacturing validation in addition to mechanical performance.	not survive scale-up [14].	wastewater, energy, feedstock consistency, pilot-scale repeatability, and application standards.
Techno-economic feasibility	The hybrid is practical only if PALF/WHF collection, drying, treatment, compounding, and processing can be achieved at acceptable cost and resource use.	Mechanical improvement alone is insufficient for application readiness because alkali treatment, drying, wastewater handling, processing energy, and quality control may increase cost.	Perform techno-economic analysis covering feedstock supply, drying, NaOH use, washing/neutralization, wastewater treatment, processing energy, labor, equipment, yield loss, and cost comparison with neat PLA and petroleum-based alternatives.
Industrialization readiness	The hybrid can be translated to industry only if performance is reproducible under scaled processing with consistent fiber quality, moisture control, and particle-size distribution.	Laboratory improvements may not translate into stable products because natural fibers vary in moisture, size, dispersion, thermal stability, and interfacial behavior.	Conduct pilot-scale trials, batch-to-batch repeatability tests, moisture-control validation, fiber-size standardization, processing-window evaluation, durability testing, and application-specific standard testing.

3.10. Research gaps and future directions

The review identifies several barriers to application-ready PLA/PALF/WHF biocomposites. Direct hybrid studies remain limited, alkali-treatment conditions are not standardized, WHF evidence in PLA is still weak, flexural failure is insufficiently reported, and durability under moisture, UV exposure, soil burial, thermal ageing, and cyclic loading requires further study. Many sustainability claims also lack life-cycle and end-of-life validation [42].

A staged roadmap is therefore proposed. Short-term research should standardize PALF and WHF treatment conditions. Medium-term work should develop direct PLA/PALF/WHF hybrids with controlled fiber ratio, length, orientation, and processing. Long-term studies should validate products through application-specific standards, durability testing, biodegradation analysis, life-cycle assessment, and scale-up trials.

Industrial readiness further requires techno-economic and manufacturing evaluation. Cost analysis should cover biomass collection, drying, sizing, chemicals, wastewater treatment, compounding, energy, labor, equipment, and quality control. Life-cycle assessment should compare the hybrid with neat PLA, other PLA/natural-fiber composites, and petroleum-based alternatives under consistent system boundaries. Scale-up should also assess feedstock stability, moisture control, particle-size uniformity, treatment reproducibility, processing compatibility, product consistency, and application-specific performance.

4. Conclusions

This systematic mapping review evaluates alkali-treated PALF and water-hyacinth-related pathways in PLA and related biopolymer composites, focusing on interface behavior, mechanical and flexural performance, morphology, durability, and application readiness. Water-hyacinth evidence is separated into three pathways: WHF as reinforcement, WHF as filler or functional additive, and water-hyacinth biomass as feedstock for lactic-acid or PLA-like polymer production. Feedstock conversion supports biomass valorization but does not demonstrate WHF reinforcement in PLA.

The review contributes by clarifying these evidence pathways, reporting quality appraisal and risk of bias, summarizing quantitative mechanical and durability data, and proposing a testable PALF-primary/WHF-secondary hybrid concept linked to techno-economic analysis, life-cycle assessment, and industrial validation.

PALF currently has stronger direct support as a PLA reinforcement. Studies on continuous PALF/PLA, layer-to-layer PLA/PALF, coir/PALF/PLA, and PALF-hybrid systems show that controlled fiber placement, treatment, and interfacial bonding can improve tensile and flexural performance. In contrast, WHF evidence is derived mainly from HDPE, PBS, thermoplastic starch, and epoxy systems. WHF should therefore be considered a potential secondary fiber, filler, or functional additive rather than an established PLA reinforcement.

Alkali treatment can improve surface roughness, wetting, mechanical interlocking, and load transfer, but excessive treatment may damage fibers. Flexural testing remains essential because bending behavior is strongly affected by interface quality, voids, fiber alignment, interlayer bonding, cracking, and delamination. Numerical results should be interpreted with treatment conditions, fiber fractions, processing routes, and control materials, since direct comparison is unreliable when experimental conditions differ.

The proposed PLA/PALF/WHF system is formulated as a testable, PALF-dominant hybrid. PALF provides the main load-bearing structure, while controlled amounts of WHF may improve packing, crack deflection, damping, density, cost, or biomass utilization. This hypothesis should be tested through comparable PLA/PALF, PLA/WHF, and PLA/PALF/WHF formulations, standardized treatment, mechanical and morphological evaluation, durability testing, life-cycle assessment, techno-economic analysis, scale-up, and product-level validation before claims of synergy or industrial readiness are made.

Data availability statement

Data supporting this systematic mapping review are derived from the published studies cited in the reference list. The review matrix, classification table, and quality appraisal scoring sheet can be made available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Achmad Zakki Ardiansyah: Conceptualization, methodology, data curation, analysis, investigation, visualization, and original draft. **Tri Hartutuk Ningsih** and **Vivi Aisah Fardilah**: Validation, analysis, and review/editing. **Anggra Fiveriati**: Supervision, project administration, validation, and review/editing.

Declaration of Competing Interest

The authors declare no competing interests.

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Declaration of Generative AI and AI-assisted Technologies in the Writing Process

Generative AI was used only for language and readability refinement. All content was reviewed and approved by the authors, who accept responsibility for the manuscript.

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