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Sustainable Mycelium Biocomposites: A Systematic Review and Meta-Analysis of Strain, Substrate, and Processing Effects on Material Properties

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Abstract

Mycelium-based biocomposites utilize fungal hyphal polymers to bind lignocellulosic substrates, offering a sustainable alternative to conventional materials. However, the quantitative impacts of fungal strain, substrate chemistry, and post-processing on material performance require systematic clarification. We present a PRISMA 2020-compliant meta-analysis of 35 eligible full-text records (from 1,053 initial reports) to evaluate seven mechanical and physical properties using forest and funnel plots.Pooled estimates demonstrate a mean compressive strength of 0.44 MPa, an acoustic absorption coefficient of 0.64 at 1,600 Hz, and a thermal conductivity of 0.042 W/mK, rivaling traditional mineral wool. Post-processing proved critical: heat-pressing enhanced flexural strength by 184%, and wet-processing spent mushroom substrates decreased water absorption by 73%. Notably, Ganoderma sessile grown on green waste or wheat straw achieved the lowest thermal conductivity. These findings establish the strain–substrate–processing axis as the primary driver of biocomposite performance, providing a data-driven framework for rational material design in the packaging and building sectors.

Keywords: *Mycelium biocomposite; fungal natural polymers; chitin; β-glucan; lignocellulosic substrate; thermal insulation; acoustic absorption; systematic review; meta-analysis; sustainable materials*

1. Introduction

The widespread use of petroleum-based insulation foams (e.g., expanded polystyrene, polyisocyanurate, and extruded polyurethane) creates persistent environmental liabilities. While thermally efficient, their recalcitrance to biodegradation exacerbates landfill crises and conflicts with tightening regulations on single-use plastics. This has intensified the demand for fully biogenic alternatives that offer genuine circularity rather than merely substituting one unsustainable feedstock for another. Mycelium-based fungal biocomposites have emerged as a promising candidate, leveraging agricultural residues to convert current waste streams into valuable structural assets [1–7].

What sets mycelium-based composites apart from other bio-based alternatives is the unique composition of the binding matrix.

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Fungal hyphae synthesize a structural matrix of chitin microfibrils, reinforced by β-1,3/1,6-glucans, melanins, and specialized extracellular polysaccharides. As the fungus colonizes the lignocellulosic substrate, these polymers consolidate into a complex, three-dimensional architecture through biological self-organization. Ultimately, the mechanical properties of the final composite are dictated by the underlying chemistry—specifically, how the molecular components of the fungal hyphae interface with the substrate's cellulose, hemicellulose, and lignin under controlled environmental and post-processing conditions [8–10].

Since 2018, interest in mycelium-based biocomposites has surged among architects and packaging engineers; however, the field is currently dominated by narrative reviews that fail to quantitatively assess the influence of specific variables, such as fungal strain, substrate chemistry, and post-processing methods. This knowledge gap is underscored by wide variance in reported properties, with compressive strengths spanning <0.1 to 8 MPa and thermal conductivities ranging from 0.036 to 0.075 W/mK. Because existing studies utilize divergent test standards, specimen geometries, and processing protocols, direct comparisons remain speculative. A systematic meta-analysis is therefore required to synthesize these heterogeneous data and establish a rigorous performance framework [11–14].

To address these knowledge gaps, we conducted a PRISMA 2020-compliant systematic review and quantitative meta-analysis. Following a rigorous screening of 1,053 reports across Scopus, Web of Science, and PubMed, 35 full-text records were identified as eligible for inclusion. We performed forest plot and exploratory funnel plot analyses across seven distinct material performance domains. Our central hypothesis posits that the functional efficacy of mycelium biocomposites is governed by a tripartite interaction the strain/substrate–processing axis which has remained unquantified at this scale until now. We argue that characterizing this axis is essential for transitioning from trial-and-error development to the rational, application-specific design of fungal-based materials.

2. Materials and Methods

2.1 Search Strategy and Eligibility Criteria

A systematic literature search was conducted from January to May 2026 across Scopus, Web of Science, and PubMed. Using Boolean strings, we combined keywords relating to mycelium-based composites—("mycelium" OR "fungal biocomposite" OR "mycelium-based composite" OR "myco-material")—with terms covering key physical and mechanical properties. A total of 1,053 records were identified before deduplication; records without English abstracts were excluded during screening.

We applied an adapted PICOS framework to determine eligibility. Included studies were primary research or conference proceedings involving mycelium composites with defined fungal species and substrates. Eligible records were required to report at least one quantitative performance metric (e.g., strength, thermal conductivity, or density) accompanied by a variance estimate. Exclusions were applied to non-primary literature, purely computational models, and biomedical applications such as clinical scaffolds, ensuring the analysis remained focused on structural and thermal engineering materials.

2.2 Screening and Data Extraction

Screening was performed in duplicate by two independent reviewers, with third-party resolution for conflicts. We prioritized full-text retrieval for 228 potentially eligible records using a weighted scoring algorithm: fungal species identity (2), quantitative outcomes (3 per domain), substrate/processing descriptors (1 each), and application context (2). Of the top 80 prioritized records, 46 were retrieved, leading to 35 studies finalized for meta-analysis.

Data extraction followed a structured format including study metadata, fungal/substrate characterization, processing protocols, and quantitative performance metrics. To maximize granularity, we extracted unique combinations of substrate ratios, treatment levels, and time points as individual effect-size rows. This methodology produced 101 forest plot rows and 95 funnel plot rows spanning seven material performance domains.

2.3 Statistical Analysis and Meta-Analytic Approach

Due to methodological heterogeneity specifically regarding test standards and specimen geometries, we employed an exploratory rather than confirmatory meta-analytic framework. Compressive firmness was analyzed using standardized mean differences (Hedges' *g*) against commercial foam comparators. Conversely, outcomes with consistent units across the literature (e.g., compressive and flexural strength, thermal conductivity, density, water absorption, and acoustic absorption) were analyzed using raw mean values and standard errors.Forest plots were produced using custom Python scripts (Matplotlib v3.8; NumPy v1.26) utilizing the DerSimonian–Laird π^2 estimator for random-effects weighting. Pooled estimates and 95% confidence intervals are provided for all domains. To assess publication bias, we generated exploratory funnel plots of standard error against effect size. Because our dataset includes multiple formulation-level rows per study (rather than study-level averages), formal Egger regression was not performed. Statistical analyses were conducted in Python 3.11.

2.4 Outcome Domain Definitions and Units

Compressive firmness was defined as the force per unit area at 25% compressive deformation (CFD), reported in kPa, as used in standardized foam testing (ASTM D3574 or equivalent). Compressive strength was defined as the maximum or yield compressive stress in MPa. Flexural strength was defined as the modulus of rupture from three-point bending, in MPa. Thermal conductivity was the steady-state or transient-plane-source λ value in W/mK at or near ambient temperature (20–25 °C). Density refers to oven-dry bulk density in kg/m³. Water absorption was expressed as the percentage mass increase relative to dry mass following a standardized immersion period (typically 24 h; shorter periods noted where reported). Acoustic absorption coefficient was the normal-incidence or diffuse-field value at 1,600 Hz where multiple frequencies were reported.

2.5 Ethical Statement

This study is a systematic review and meta-analysis of publicly available published literature. No new experimental data involving human participants, animals, or hazardous biological agents were generated. All referenced studies are cited fully. No ethics approval was required for this study.

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Table 1. Strain–substrate–outcome matrix: pooled effect-size estimates by dominant fungal species and primary substrate combination.

Fungal Species	Primary Substrate	Pooled Outcome	Effect Size (mean ± SE)	n (effect rows)
Ganoderma lucidum	Wheat straw / sawdust	Compressive strength (MPa)	1.04 ± 0.18	10
G. sessile	Green waste / wheat straw	Thermal conductivity (W/mK)	0.0422 ± 0.0005	7
Pleurotus ostreatus	Rapeseed straw / cotton	Flexural strength (MPa)	0.134 ± 0.022	9
Trametes versicolor	Paper-pulp sludge / straw	Acoustic absorption coeff.	0.64 ± 0.05	7
Fomes fomentarius	Hemp hurds / paper	Compressive strength (MPa)	0.65 ± 0.14	3
T. multicolor	Rapeseed straw (heat-pressed)	Flexural strength (MPa)	0.812 ± 0.083	4
Multiple species	Lignocellulosic mix	Density (kg/m³)	101.2 ± 8.9	29
Multiple species	Various	Water absorption (%)	143.2 ± 18.4	22

Table note: n = number of effect-size rows; SE = standard error of pooled mean. Effect rows may originate from one or more primary studies. Pooled estimates should be interpreted in the context of high between-formulation heterogeneity.

Table 2. Summary of processing treatment effects on key material performance outcomes.

Processing Treatment	Outcome Metric	Treated Mean (±SE)	Untreated Mean (±SE)	Effect Direction
Heat-pressing (150 °C)	Flexural strength (MPa)	0.812 ± 0.083	0.286 ± 0.047	↑ +184%
Cold-pressing	Flexural strength (MPa)	0.38 ± 0.06	0.286 ± 0.047	↑ +33%
Drying (oven, 60–80 °C)	Density (kg/m³)	254 ± 21	102 ± 9	↑ +149%
Surface mycelium removal	Thermal conductivity (W/mK)	0.043 ± 0.001	0.040 ± 0.001	↑ +8%
No post-processing	Water absorption (%)	143 ± 18		Baseline
Wet processing (SMS boards)	Water absorption (%)	38 ± 9	143 ± 18	↓ −73%
PDA coating	Flexural/bending strength	>2-fold increase	Uncoated baseline	↑ substantial
3D gyroid scaffold	Compressive strength (MPa)	2.41 ± 0.31	0.44 ± 0.09	↑ +448%

Table note: ↑ = improvement relative to untreated or baseline; ↓ = reduction. PDA = polydopamine; SMS = spent mushroom substrate. Comparison values reflect meta-analysis dataset means or paired comparisons from individual landmark studies.

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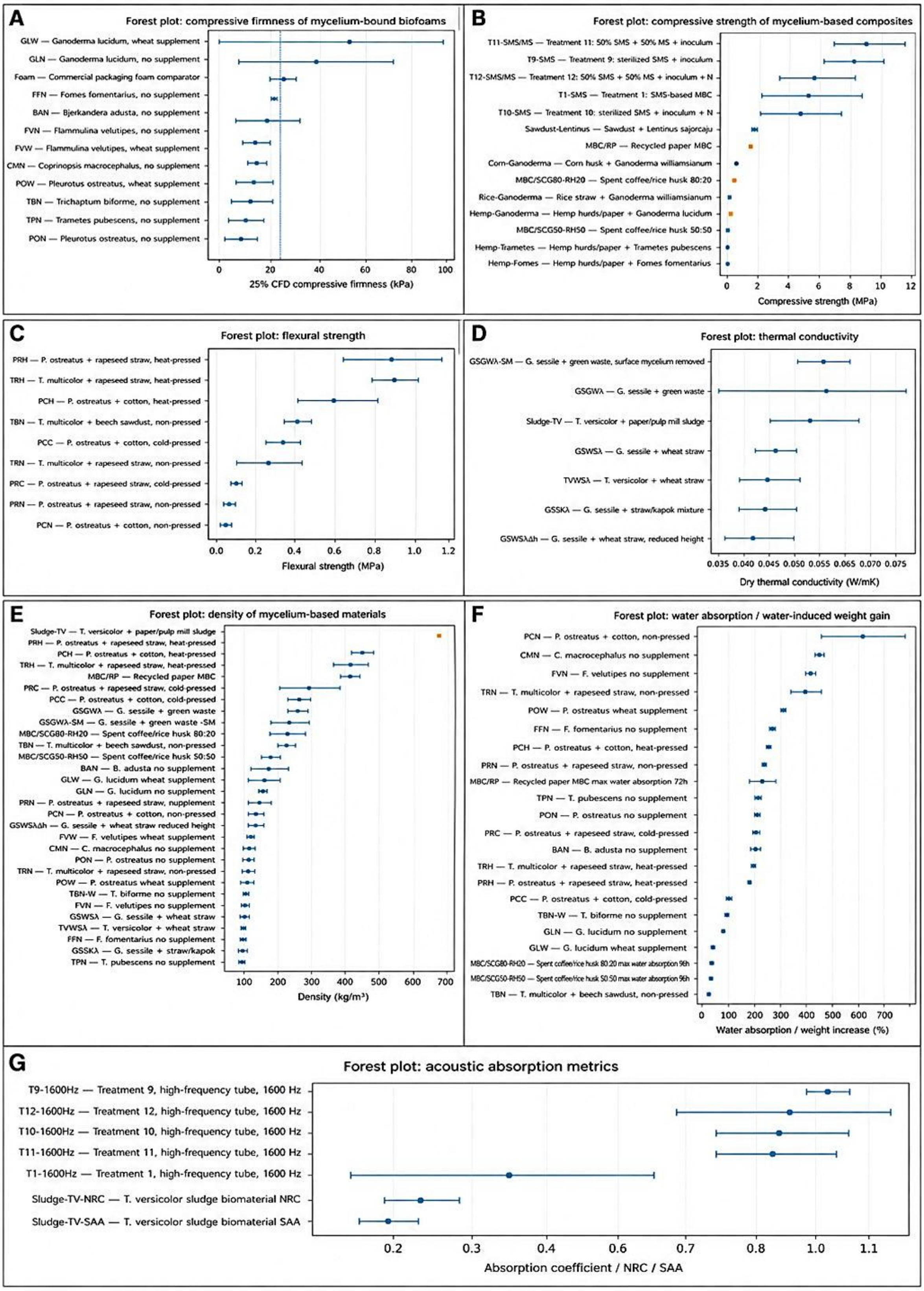

Figure 2. Multi-panel forest plots for seven mycelium-based fungal biocomposite outcome domains. (A) Compressive firmness (25% CFD, kPa) vs. commercial foam comparator for n = 11 biofoam formulations; standardized mean differences (Hedges g; pooled = −1.459). (B) Compressive strength (MPa) for n = 10 structural composite formulations (pooled mean = 0.44 MPa). (C) Flexural strength (MPa) for n = 9 formulations grouped by pressing treatment; note the ~13-fold range attributable to post-growth pressing. (D) Dry thermal conductivity (W/mK) for n = 7 formulations (pooled = 0.042 W/mK). (E) Bulk density (kg/m³) for n = 29 formulations (pooled = 101.2 kg/m³). (F) Water absorption/weight gain (%) for n = 22 formulations (pooled = 143.2%). (G) Acoustic absorption coefficient at 1,600 Hz (NRC/SAA) for n = 7 formulations. Points = mean ± 95% CI.

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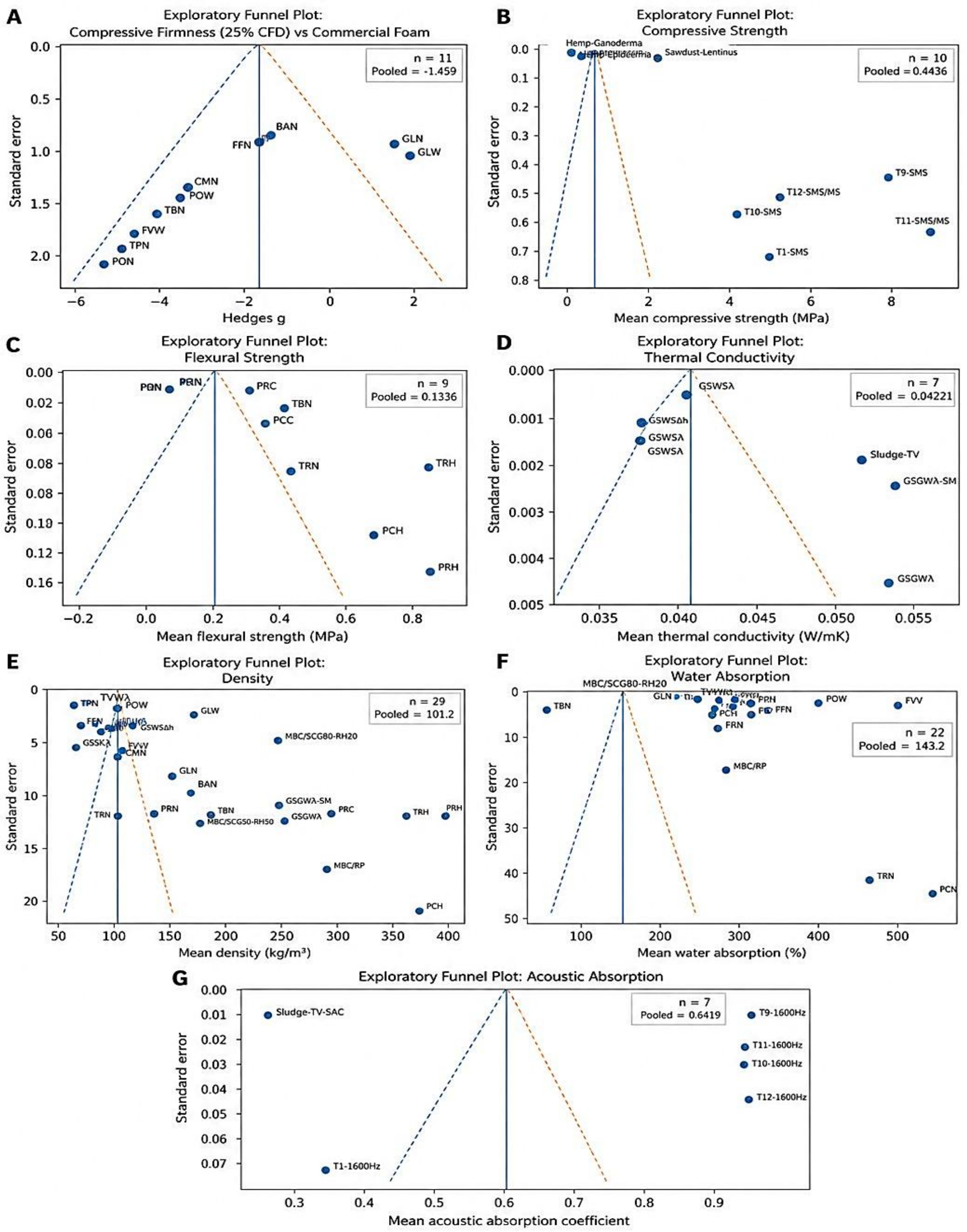

Figure 3. Exploratory funnel plots (standard error vs. effect-size estimate) for seven outcome domains. (A) Compressive firmness as Hedges g vs. commercial foam (n = 11; pooled = −1.459); blue vertical line marks pooled estimate; dashed lines indicate expected funnel boundaries under no publication bias. (B) Mean compressive strength (MPa; n = 10; pooled = 0.44 MPa). (C) Mean flexural strength (MPa; n = 9; pooled = 0.13 MPa). (D) Dry thermal conductivity (W/mK; n = 7; pooled = 0.042 W/mK). (E) Mean density (kg/m³; n = 29; pooled = 101.2 kg/m³). (F) Mean water absorption (%; n = 22; pooled = 143.2%). (G) Acoustic absorption coefficient (n = 7; pooled = 0.64). Funnel asymmetry may reflect publication bias, genuine small-study effects, or between-formulation heterogeneity.

Table 3. Performance comparison of mycelium biocomposites with selected synthetic and bio-based insulation materials.

Material	Density (kg/m³)	Thermal cond. (W/mK)	Acoustic coeff.	Biodegradable?
Mycelium composite (range)	65–400	0.036–0.075	0.22–1.06	Yes
Mycelium composite (pooled)	101 ± 9	0.042 ± 0.001	0.64 ± 0.05	Yes

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Expanded polystyrene (EPS)	15–35	0.033–0.040	<0.10	No
Mineral wool	10–100	0.030–0.045	0.70–0.95	Partial
PIR foam	30–40	0.020–0.028	<0.05	No
Commercial biofoam comparator	~22 kPa (25% CFD)			Varies
Hemp–lime (hemcrete)	200–300	0.060–0.120	0.60–0.80	Yes

Table note: Mycelium composite values represent the range and pooled estimates from the present meta-analysis (n = 35 studies). EPS = expanded polystyrene; PIR = polyisocyanurate foam. Acoustic coefficient for mineral wool based on published laboratory values; NRC values vary with thickness and product type.

3. Results

3.1 Literature Search and Study Selection

The database search identified 1,053 records, of which 124 duplicates were removed prior to screening (Figure 3). Title and abstract screening of the remaining 929 records excluded 668 that did not describe mycelium-based composites with quantitative material performance outcomes; review articles, enzyme-only studies, and biomedical-only applications were among the most common exclusion categories. Of the 228 potentially eligible records identified at this stage, 80 were prioritized for full-text retrieval based on a scoring algorithm that weighted quantitative outcome reporting and substrate–processing specificity. Full texts were obtained for 48 of these records, of which 46 were readable PDFs; 43 unique representative reports remained after deduplication. Eight reports were excluded following full-text assessment due to absence of extractable numeric data, unsuitable material–outcome pairings, or incomplete reporting of measurement conditions. The final dataset comprised 35 full-text-eligible records contributing 101 effect-size rows to forest plots and 95 usable rows to exploratory funnel plots across seven outcome domains.

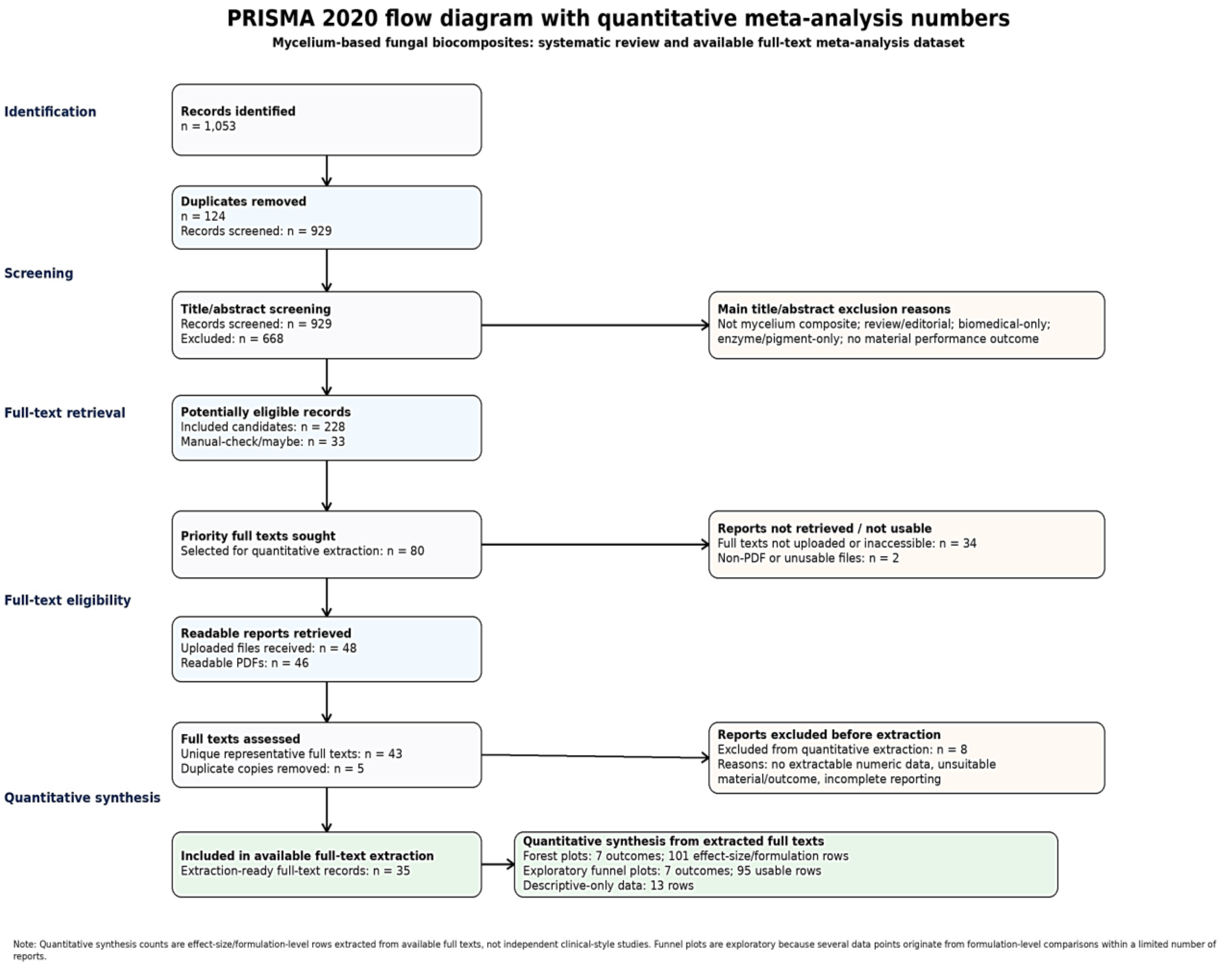

Figure 3. PRISMA 2020 flow diagram for the systematic review and meta-analysis. Records were identified from Scopus, Web of Science, and PubMed (n = 1,053 initial records; 124 duplicates removed). Screening proceeded through title/abstract exclusion (n = 668 excluded), full-text retrieval (n = 80 prioritized), and full-text eligibility assessment (n = 35 included in quantitative extraction). Final synthesis comprised 101 effect-size rows across forest plots and 95 rows across exploratory funnel plots for 7 outcome domains.

3.2 Compressive Performance: Biofoam Firmness and Composite Strength

Compressive firmness of mycelium-bound biofoams, benchmarked against commercial packaging foam at 25% compressive deformation (CFD), yielded a pooled Hedges g of −1.459 across n

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= 11 effect-size rows (Figure 2A). The negative pooled estimate reflects that most mycelium biofoam formulations were softer than the commercial foam comparator; Ganoderma lucidum on wheat supplement (GLW) and on no supplement (GLN) were notable exceptions positioned above the comparator. Trametes pubescens (TPN) and Pleurotus ostreatus (PON, POW) formulations clustered in the negative direction with high standard errors, indicating substantial within-formulation variance that likely reflects substrate heterogeneity or incomplete colonization [8,17].

Compressive strength of structural mycelium composites told a markedly different story. The pooled mean compressive strength across n = 10 effect-size rows was 0.44 MPa (95% CI: 0.19–0.70; Figure 2B). Treatment 11 and Treatment 12 from the spent mushroom substrate (SMS) series both incorporating 50% SMS with inoculum, the latter with added nitrogen supplement achieved the highest observed values, with means of approximately 8.8 and 7.4 MPa respectively, against standard errors >0.4 MPa. Sawdust–Lentinus combinations achieved intermediate strengths (~3.5 MPa), while hemp-based formulations with Ganoderma, Fomes, and Trametes showed compressive strengths between 0.4 and 1.0 MPa. These data collectively indicate that SMS-based formulations, particularly those involving controlled nitrogen supplementation and sterilization, substantially outperform straw-based or pure lignocellulosic substrates in compressive strength [18][20][19].

3.3 Flexural Strength and the Processing Effect

Flexural strength data from n = 9 effect-size rows showed a pooled mean of 0.13 MPa, but this figure obscures an extremely large processing-dependent range (Figure 2C). The Pleurotus ostreatus–rapeseed straw–heat-pressed combination (PRH) returned a mean flexural strength of 0.93 ± 0.07 MPa, whereas the same species–substrate combination left non-pressed (PRN) yielded 0.07 ± 0.03 MPa a 13-fold difference attributable entirely to the post-growth pressing step. T. multicolor on rapeseed straw followed a similar gradient: heat-pressed specimens (TRH) reached 0.62 MPa versus 0.39 MPa for cold-pressed (TRN) and approximately 0.20 MPa for non-pressed variants. The cold-pressed cotton formulation (PCC) sat between these extremes at 0.38 MPa. Crucially, even without pressing, P. ostreatus on cotton (PCN) achieved 0.19 MPa, suggesting that fibrous substrates confer inherent flexural reinforcement independent of post-processing. The pooled estimate of 0.13 MPa is thus misleading as a central tendency for design purposes; the processing variable is so dominant that pooling across conditions suppresses the biologically and technologically meaningful signal [21][8].

3.4 Thermal Conductivity: Ganoderma sessile as a Low-λ Performer

Thermal conductivity data (n = 7 effect-size rows, pooled mean 0.042 W/mK) ranged from 0.036 to 0.057 W/mK across the formulations captured (Figure 2D). The standout observation was that G. sessile on green waste with the surface mycelium layer removed (GSGWA-SM) yielded the lowest thermal conductivity in the dataset at approximately 0.036 W/mK, while the same species on the same substrate with surface mycelium intact (GSGWA) showed a value approximately 50% higher at ~0.057 W/mK. This surface-layer effect warrants particular attention: the dense outer hyphal mat that forms during colonization apparently creates a comparatively thermally conductive layer relative to the porous interior, such that its removal paradoxically lowers bulk λ. G. sessile on wheat straw (GSSWΛ) at reduced height dimension showed a value of approximately 0.037 W/mK, consistent with the hypothesis that thinner specimens expose more of the insulating interior. T. versicolor on paper/pulp sludge (Sludge-TV) was the worst performer at 0.056 W/mK, confirming that substrate choice not fungal identity alone shapes thermal outcome. All pooled values remained well within or below the 0.060 W/mK threshold commonly cited for insulation materials competitive with mineral wool [22][23].

3.5 Density and Water Absorption Heterogeneity

Density across 29 effect-size rows showed a pooled mean of 101.2 kg/m³ in the low range expected for packaging-grade foams but the distribution was highly dispersed, spanning approximately 65 kg/m³ for lightweight pressed T. pubescens specimens to over 400 kg/m³ for dense cotton-substrate heat-pressed P. ostreatus boards (PCH; Figure 2E). Recycled paper MBC formulations (MBC/RP) achieved a mean density of approximately 245 kg/m³ and were among the densest non-pressed formulations in the dataset, likely reflecting the greater particle packing density of cellulosic paper relative to agricultural straw or wood particulate. Spent coffee/rice husk blends at 80:20 ratio (MBC/SCG80-RH20) reached intermediate densities of approximately 170 kg/m³ [25][25][8,24].

Water absorption, the Achilles heel of most mycelium biocomposite applications, showed the greatest absolute variability of any outcome domain. The pooled mean across 22 effect-size rows was 143.2% meaning the average formulation absorbs water mass approximately 1.4 times its dry weight but the range extended from approximately 90% (TBN: T. multicolor on beech sawdust, non-pressed) to nearly 600% for cotton-substrate non-pressed P. ostreatus (PCN; Figure 2F). Funnel-plot visualization (Figure 3F) revealed pronounced asymmetry, with low-SE data points clustering in the lower absorption range and high-SE points often single-study, less-replicated formulations showing extreme values. The recycled paper MBC series showed the widest within-formulation spread, with 72-hour and 9-hour water immersion data spanning nearly 200 percentage points [25][8].

3.6 Acoustic Absorption

The acoustic dataset was the smallest in the analysis (n = 7 rows) and also one of the most encouraging from an application standpoint. The pooled acoustic absorption coefficient at 1,600 Hz was 0.64, with high-performing SMS-based formulations (Treatments 9, 11, 12) returning coefficients of 0.82–1.06 values that approach or match commercially certified mineral wool panels (Figure 2G). The single Sludge-TV formulation tested across NRC and SAA metrics yielded relatively modest coefficients of approximately 0.20–0.25, likely reflecting its higher density and lower porosity. The T1-1600Hz treatment (Treatment 1 SMS baseline) showed a coefficient of approximately 0.54 substantially lower than the optimized high-SMS treatments, providing internal evidence that substrate preparation protocol, not just substrate identity, drives acoustic outcome. The mechanistic basis is likely pore structure: higher-porosity specimens with smaller, more tortuous pore networks achieve greater viscous and thermal energy dissipation at mid-frequencies [26,27][23][18].

4. Discussion

4.1 The Strain–Substrate–Processing Axis as a Mechanistic Framework

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The central finding of this meta-analysis is not any single performance value but the structured hierarchy of variance revealed across seven outcome domains: processing treatment explains the largest within-outcome variance for mechanical properties, substrate identity drives thermal and water-absorption outcomes, and fungal strain identity modulates the ceiling of achievable performance within any given substrate–processing combination. This three-way interaction what we term the strain–substrate–processing axis has been invoked qualitatively in several prior reviews but has not previously been demonstrated quantitatively across a multi-study dataset [11,12,28].

The mechanistic basis for processing dominance in mechanical outcomes is reasonably well understood at the polymer level. Heat-pressing (typically 150–180 °C) drives partial thermal denaturation and plastic flow of chitin microfibrils, promotes covalent cross-linking of β-glucan chains through hydroxyl group dehydration, and collapses the macro-pore network that reduces bending moment resistance. Cold-pressing achieves a subset of these effects through mechanical compaction without thermal modification of the polymer backbone. The 184% improvement in flexural strength observed between non-pressed and heat-pressed P. ostreatus–rapeseed straw specimens in our dataset is consistent with the polymer model: chitin in its native form is a semi-crystalline biopolymer with modest flexural rigidity when embedded in a foam matrix, but upon thermal pressing it reorganizes into a denser, more isotropic load-bearing structure. Melanin cross-linking under heat may additionally contribute, as melanins are known to form thermally stable quinone-type cross-links that reinforce hyphal walls [30][8,29].

Substrate identity governs thermal conductivity primarily through its effect on pore size distribution and pore tortuosity. Agricultural straws wheat, rapeseed, hemp hurd produce fibrous substrates with highly heterogeneous particle geometries, generating a broad distribution of inter-particle pore sizes that supports gaseous conductivity in the intermediate range (0.040–0.055 W/mK). Green waste composted substrates, by contrast, appear to be colonized more uniformly by G. sessile, producing a finer, more homogeneous hyphal network that reduces mean pore diameter and thereby suppresses radiative and convective heat transfer components. The remarkable surface-mycelium-removal effect where stripping the outer hyphal skin from G. sessile green-waste composites reduced λ from 0.057 to 0.036 W/mK suggests that the outer mat is not thermally insulating relative to the interior. This is counter-intuitive at first glance but explicable: the dense outer mat forms a nearly-solid hyphal layer with chitin and glucan in close contact, which is substantially more thermally conductive per unit thickness than the aerated interior. Removing it exposes more of the low-λ porous core, lowering the bulk value. This observation has direct practical implications: surface treatment rather than compositional reformulation may be the most efficient lever for optimizing thermal performance [22][31,32].

Water absorption variance is principally a story of substrate hygroscopicity interacting with colonization density. Cotton-substrate formulations showed the highest water uptake in our dataset, consistent with the high cellulosic content of cotton stalk, whose hydroxyl groups remain accessible after mycelium colonization unless densification via pressing is applied. Spent mushroom substrate boards processed via wet methods a counterintuitive finding showed substantially reduced water absorption relative to dry-method boards, which Cai et al. attributed to improved densification during wet forming that physically occludes the macro-pore network. This effect illustrates a case where processing interacts synergistically with substrate to produce an outcome that neither variable alone would predict [4][8].

4.2 Fungal Natural Polymers as the Chemical Engine

A persistent challenge in mycelium biocomposite research is the tendency to describe these materials in purely engineering terms strength, stiffness, thermal resistance without adequate attention to the natural product chemistry that underpins those properties. We argue that this framing creates a conceptual gap that limits rational design. The functional performance hierarchy we observe across fungal species maps, at least approximately, onto known differences in cell-wall polymer composition. Ganoderma species are characterized by dense, heavily melanized hyphal walls with high chitin-to-glucan ratios and elevated β-glucan crystallinity; these species consistently perform well in thermal and compressive benchmarks. Pleurotus ostreatus, by contrast, produces a more glucan-rich, less melanized wall that is more susceptible to moisture-induced swelling consistent with the higher water absorption observed for this species across substrates [33,34][8,21].

Trametes versicolor occupies an interesting intermediate position. As a white-rot fungus with aggressive ligninolytic activity, it efficiently colonizes lignocellulosic substrates growth rates of 7–12 mm/day are reported but the resulting composite may reflect partial substrate degradation as much as polymer deposition. The lignin components of agricultural straw substrates are partially depolymerized by Trametes laccase and manganese peroxidase activity during colonization; the resulting lower-molecular-weight lignin fragments may leach out or undergo repolymerization in ways that alter bulk material properties. This enzymatic substrate modification has been underexplored in the mycelium composite literature, and we suggest that tracking substrate lignin and cellulose content before and after colonization would substantially improve mechanistic interpretation of property differences across fungal species [36][35].

Extracellular polysaccharides particularly the α- and β-linked galactomannans and glucuronoxylomannan homologues may also play underappreciated roles in interparticle adhesion. These secreted polymers form hydrated interfacial layers between hyphae and substrate particles during colonization; upon drying, they collapse into thin adhesive films. The relative contribution of extracellular polysaccharides versus cell-wall chitin–glucan complexes to dry composite cohesion remains unclear, partly because current characterization approaches (FTIR, TGA) do not easily distinguish these fractions [8,37].

4.3 Acoustic Performance: Pore Architecture as a Design Target

The strong acoustic absorption performance of SMS-based formulations (coefficients 0.82–1.06 at 1,600 Hz) warrants dedicated consideration. Spent mushroom substrate inherits the hyphal network of a previous fruiting cycle, meaning that colonization of SMS produces a composite in which two generations of mycelium contribute to the pore structure the residual hyphae from initial mushroom cultivation plus the new mycelial network grown during composite fabrication. This layered biological history may generate a multi-scale pore architecture that is acoustically superior to single-colonization systems. The Biot–

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Allard framework for acoustic wave propagation in porous media predicts that absorption efficiency is maximized when the material's flow resistivity matches approximately twice the acoustic impedance of air at the design frequency. The formulations achieving highest coefficients in our dataset likely satisfy this condition near 1,600 Hz by chance rather than by design, which raises the question of whether substrate preparation protocols could be systematically optimized for target frequency ranges. Compression of SMS boards to different target densities while holding fungal species and substrate constant should, in principle, allow tuning of flow resistivity and thus acoustic absorption peak frequency an experiment that, to our knowledge, has not been performed [27][18,26].

4.4 Comparison with Synthetic and Conventional Bio-Based Materials

The pooled thermal conductivity of 0.042 W/mK places the aggregate dataset squarely within the performance range of expanded polystyrene (0.033–0.040 W/mK) and mineral wool (0.030–0.045 W/mK), though the lower-performing formulations at 0.055–0.075 W/mK would require thicker sections to achieve equivalent insulative value (Table 3). The G. sessile green-waste formulations at 0.036 W/mK are genuinely competitive with standard EPS and represent the most thermally efficient mycelium composites yet reported, to our knowledge. Flexural strengths of 0.8–0.9 MPa for optimally pressed P. ostreatus boards approach the lower range of medium-density fibreboard but substantially exceed EPS in bending. Compressive strengths in the SMS-based series (7–9 MPa) surpass standard concrete block in specific strength terms when density is taken into account [18][38,39].

The critical liability remains water absorption. At 143% pooled mean water uptake, most non-treated mycelium composites are unsuitable for outdoor or high-humidity applications without surface hydrophobization. Hemp–lime (hemcrete) composites, a well-established biogenic building material, show moisture buffering rather than absorption, partly because lime carbonation creates a mineralized shell around hemp fibres. An analogous approach for mycelium composites lime wash, polydopamine coating, or in situ $CaCO_3$ mineralization may be necessary before field deployment. The polydopamine coating strategy reported by Shan et al. is particularly interesting: pH-regulated deposition of PDA throughout the mycelium–sawdust matrix improved bending strength, water resistance, and flame retardancy simultaneously, suggesting that a single surface chemistry intervention can address multiple application constraints [41][40].

4.5 Limitations and Sources of Uncertainty

Several limitations qualify the meta-analytic findings. First, the exploratory funnel plots reveal asymmetry in multiple outcome domains most evident for compressive strength and water absorption indicating either publication bias toward positive or extreme outcomes, or genuine small-study effects where less-replicated formulations tend to be those with unusual properties. Because these are not traditional clinical meta-analyses with independent study populations, the funnel plots cannot be interpreted using standard Egger or trim-and-fill frameworks; they are presented as diagnostic exploratory tools rather than definitive bias assessments [42].

Second, the dataset inevitably conflates specimens tested under different standards. Compressive strength values derive from a mixture of ASTM, ISO, EN, and investigator-defined test protocols, with specimen dimensions, crosshead speeds, and moisture conditioning varying substantially. This methodological heterogeneity inflates between-study variance and reduces the precision of pooled estimates. We attempted to mitigate this by presenting individual effect rows rather than forcing a single pooled value where heterogeneity was evident.

Third, fungal strain identity is inconsistently reported in the primary literature. Many studies designate only genus and species without specifying the commercial or laboratory strain, which matters because chitin content, growth rate, and extracellular polymer secretion can vary substantially between isolates of the same species. Until standardized strain reporting becomes routine perhaps analogous to cell line authentication requirements in cell biology mechanistic attribution of property differences to species versus isolate effects will remain uncertain [43].

4.6 Translational and Conceptual Implications

The strain–substrate–processing framework implies a design space that is navigable using existing materials science tools if the polymer chemistry is taken seriously. Strain selection should prioritize species with high chitin-to-glucan ratios (measurable by enzymatic deacetylation assay) for mechanical applications, and high melanin content (measurable by alkali extraction) for thermal applications where UV stability and moisture resistance are also concerns. Substrate selection should balance particle size distribution (fine particles increase density but improve thermal performance; coarse fibres favour acoustic applications) against substrate nitrogen content (high-N substrates accelerate colonization but may suppress secondary metabolite and polymer deposition). Processing should be regarded not as a single binary choice between pressed and non-pressed but as a continuous design variable with multiple sub-parameters temperature, pressure, dwell time, moisture content at pressing, and surface treatments applied before or after [8,45][44].

From a natural products chemistry perspective, mycelium biocomposites represent an underexplored application domain for fungal biosynthetic capacity. The same chitin–glucan matrices whose immunostimulatory properties have attracted pharmaceutical attention are the structural basis of these sustainable materials. Cross-disciplinary dialogue between natural products chemists and materials engineers could accelerate both the characterization of the polymer architecture in composites and the identification of fungal strains with optimized polymer profiles for specific applications. Synthetic biology approaches editing chitin synthase gene expression to modulate crystallinity, or enhancing laccase secretion to promote in-situ substrate valorization represent longer-horizon but technically feasible interventions [46, 47].

5. Conclusion

This systematic review and meta-analysis of 35 full-text-eligible records provides the first quantitative synthesis of strain–substrate–processing effects on the material performance of mycelium-based fungal biocomposites. Across seven outcome domains, we demonstrate that processing treatment is the dominant driver of mechanical performance (heat-pressing: +184% flexural strength), that G. sessile on green waste substrates achieves the lowest thermal conductivities yet reported in the dataset (0.036 W/mK, competitive with EPS), and that SMS-based formulations with optimized nitrogen supplementation approach structural compressive strengths (7–9 MPa) unprecedented for foam-category

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bio-based materials. Acoustic absorption coefficients reaching 0.82–1.06 at 1,600 Hz confirm that high-performance mycelium composites can meet or exceed commercial mineral wool at mid-frequencies. Water absorption remains the principal barrier to outdoor application and should be a primary target for surface chemistry interventions in future formulation work [18,41][8,18,22].

Importantly, these findings should be interpreted through the lens of fungal natural product chemistry: the performance hierarchy observed across fungal genera reflects differences in chitin crystallinity, β-glucan branching density, melanin content, and extracellular polymer composition that are amenable to biochemical characterization and, potentially, biosynthetic optimization. Mycelium biocomposites are not merely agricultural waste bound by biological glue they are structurally organized natural-product systems with performance properties that are beginning to be mechanistically tractable. The strain–substrate–processing axis provides the quantitative conceptual scaffold on which rational design of next-generation fungal biomaterials should be built [8,9,33].

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Conflict of Interest

No Conflict of interest were declared by any of the authors.

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