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Review

Sustainable Composite Additive Manufacturing: From Recycling Pathways to Value-Retaining Circular Manufacturing

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Abstract: Additive manufacturing (AM) offers significant opportunities for resource-efficient composite manufacturing, yet its sustainability cannot be inferred solely from reduced material waste, design flexibility, or the incorporation of recycled feedstocks. The environmental performance of composite AM emerges from complex interactions among material architecture, manufacturing technology, energy and resource demand, recycling strategy, recovered-material quality, and subsequent functional use. This review critically examines these interactions through a structured analysis of 78 peer-reviewed studies published between 2012 and 2026, covering the principal AM technologies, polymer-, ceramic-, and metal-matrix composites, recycling pathways, environmental assessment, and circular manufacturing strategies. The evidence reveals a markedly heterogeneous sustainability landscape, with research concentrated in selected material–process combinations and substantially less evidence concerning economic assessment, industrial validation, and the behaviour of secondary feedstocks across multiple lifecycles. Mechanical, thermal, chemical, and metallurgical recycling routes exhibit distinct trade-offs between energy demand, process complexity, recovery efficiency, material degradation, scalability, and recovered-material quality, preventing the definition of a universally preferable recycling pathway. A central outcome of the review is that material recovery alone is an insufficient measure of circularity: sustainability depends increasingly on the functional and economic value retained after recovery and on the ability to redirect secondary materials towards technically appropriate applications. In this context, AM can act not only as a consumer of recycled feedstocks but as an enabling technology for circularity, using design freedom and application-specific adaptation to compensate for changes in secondary-material properties. Based on the synthesized evidence, an integrated decision framework is proposed linking material selection, AM process design, end-of-life strategy, recovered-material functionality, environmental and economic assessment, and industrial implementation. Future progress requires multi-cycle evaluation, harmonized lifecycle and techno-economic assessment, Design for Recycling integrated with Design for Additive Manufacturing, digital material traceability, and adaptive manufacturing strategies for variable secondary feedstocks. Overall, the review shifts the sustainability perspective from maximizing recycling efficiency towards value-retaining circular manufacturing, where materials, processes, products, and recovery pathways are co-designed to preserve engineering functionality and resource value across successive lifecycles.

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Keywords: additive manufacturing; 3D printing; composites; circular economy; sustainability; environmental impact; life cycle assessment

1. Introduction

Additive manufacturing (AM) has emerged as a key enabling technology for the transition toward more sustainable manufacturing systems and circular economy strategies. Its ability to produce complex geometries with minimal material waste, enable mass customization, and operate under near-net-shape manufacturing principles significantly reduces resource consumption compared with conventional manufacturing processes. Furthermore, AM facilitates the incorporation of recycled polymers, fibres, and industrial or biogenic waste streams into new products, promoting resource efficiency and localized production systems [1,2]. Across metals, polymers, ceramics, concrete, and hybrid material systems, AM technologies are currently classified into seven process categories according to the ISO/ASTM standards: Binder Jetting (BJT), Directed Energy Deposition (DED), Material Extrusion (MEX), Material Jetting (MJT), Powder Bed Fusion (PBF), Sheet Lamination (SHL), and Vat Photopolymerization (VPP). Although new manufacturing platforms continue to emerge for advanced materials, electronics, bio-based materials, and smart structures, they generally remain within this standardized classification framework [3].

Among these technologies, Material Extrusion has become the most extensively investigated process from a sustainability perspective. Techniques such as Fused Filament Fabrication (FFF/FDM) and Direct Ink Writing (DIW) are widely adopted because they can process thermoplastic filaments and paste-based feedstocks produced from post-consumer plastics, industrial residues, and inorganic or lignocellulosic fillers [4–6]. Nevertheless, despite the rapid expansion of research in this area, most published studies continue to emphasize mechanical performance, whereas environmental indicators, life cycle assessment (LCA), rheological behaviour, long-term durability, and economic sustainability receive considerably less attention [7].

Recent investigations have demonstrated that Material Extrusion can successfully manufacture both structural and functional composite components using recycled engineering polymers and reinforcing fibres without compromising their potential industrial applicability. Representative examples include recycled PET sandwich structures with optimized infill architectures, recycled PP-, PET-, and PS-based composites, recycled polypropylene reinforced with cocoa shell particles, and PLA or PPS composites reinforced with recycled carbon fibres for automotive and engineering applications [7–12]. However, these studies also identify several processing-related challenges that continue to limit broader industrial implementation. Warpage, weak interlayer adhesion, poor fibre dispersion, and changes in polymer crystallinity caused by repeated recycling and re-extrusion remain among the most significant technical limitations affecting component quality and long-term performance [13].

Beyond thermoplastic composites, sustainable additive manufacturing has progressively expanded toward mineral- and bio-based composite systems. Geopolymer composites incorporating construction and demolition waste (CDW) or recycled aerated concrete have demonstrated promising mechanical performance and durability when processed by extrusion-based additive manufacturing. Prospective life cycle assessments indicate that replacing conventional raw materials with recycled construction waste can significantly reduce global warming potential and toxicity impacts compared with traditional construction systems [14,15]. Similarly, extrusion- and powder-based AM processes have increasingly been employed to valorise biomass residues and food industry by-products. Agro-industrial wastes and fungi-based biocomposites have shown considerable potential for packaging and construction applications, with LCA studies reporting lower climate change impacts, particularly for customized and low-volume production. Nevertheless, these environmental benefits are often accompanied by trade-offs associated with land use, agricultural production, and biomass supply chains [16–18].

Comparative studies between conventionally manufactured composites and additively manufactured thermoplastic or thermoset composites further demonstrate that AM can substantially reduce material waste while simultaneously decreasing overall environmental impacts and production costs. These advantages become even more pronounced when recyclable polymer matrices and recycled reinforcements are combined with optimized design strategies, including geometry optimization and thickness adaptation, to satisfy structural requirements [5,19]. Despite these advances, sustainability performance remains highly dependent on the selected manufacturing technology, feedstock composition, recycling strategy, and process parameters. Although Material Extrusion currently presents the largest body of experimental evidence regarding sustainable composite manufacturing, other technologies, including Powder Bed Fusion, Vat Photopolymerization, Binder Jetting, and extrusion-based geopolymer systems, remain comparatively less explored from a life cycle perspective [20].

Although numerous studies have investigated individual aspects of additive manufacturing, composite materials, or recycling technologies, comprehensive analyses integrating additive manufacturing processes, composite systems, environmental assessment methodologies, and circular economy strategies remain relatively limited. Therefore, this review aims to provide a comprehensive and critical assessment of the sustainability of additive manufacturing technologies applied to composite materials, identifying current advances, existing limitations, and future research opportunities to support the development of more sustainable manufacturing systems.

2. Methodology

2.1. Review Design and Scope

This study adopted a structured literature review methodology to critically assess the sustainability of additive manufacturing (AM) technologies applied to composite materials, with particular emphasis on environmental performance, recycling pathways, resource efficiency, and circular manufacturing strategies. The review was designed not only to summarize existing research but also to identify relationships between AM processes, composite material systems, recycling technologies, sustainability assessment approaches, and the technological maturity of the solutions reported in the literature.

The scope was defined around four interconnected analytical dimensions: (i) additive manufacturing technology, (ii) composite material system, (iii) sustainability and recycling strategy, and (iv) environmental and industrial performance. This multidimensional structure was adopted to overcome the fragmentation commonly observed in literature, where AM processes, composite recycling, and environmental assessment are frequently investigated independently rather than as interconnected elements of the same manufacturing life cycle.

The systematic review considered 78 peer-reviewed journal articles published between 2012 and 2026 (Figure 1), a period covering the substantial expansion of research concerning sustainable additive manufacturing (AM), recycled feedstocks, composite valorisation, and circular manufacturing. Scopus and Web of Science were selected as the primary bibliographic databases because of their broad coverage of peer-reviewed engineering, materials science, manufacturing, and sustainability research. The eligibility criteria for the systematic review were restricted to peer-reviewed journal articles published within the specified period. Other sources cited throughout the manuscript, including Ph.D. theses, book chapters, technical standards, and publications preceding 2012, were used exclusively to provide theoretical background, establish fundamental concepts, or support technical discussions. These supplementary references were not included in the 78-study evidence base and were therefore excluded from the systematic screening, data extraction, and synthesis procedures.

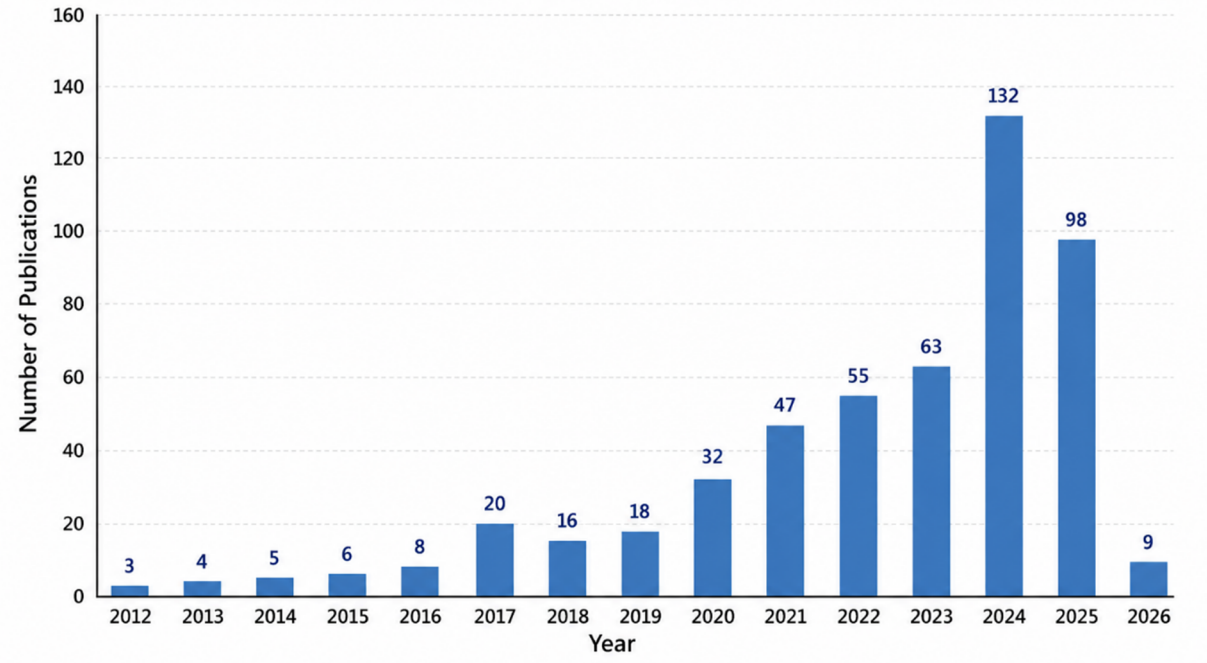

Figure 1. Annual distribution of the 78 studies included in the review according to publication year (2012–2026).

2.2. Literature Search Strategy

A structured literature search was performed in Scopus and Web of Science using combinations of search terms representing the seven core domains addressed by the review, as detailed in Table 1. These domains were selected to ensure comprehensive coverage of the research topics related to additive manufacturing, composite materials, sustainability, recycling, and circular manufacturing. Searches were conducted within titles, abstracts, and keywords to obtain broad coverage while retaining thematic relevance.

The search strategy combined terms associated with additive manufacturing, including "additive manufacturing", "3D printing", "material extrusion", "fused filament fabrication", "powder bed fusion", "vat photopolymerization", and related process terminology, with terms describing composite materials, such as "composite", "polymer composite", "fibre-reinforced composite", "metal matrix composite", and "biocomposite". Sustainability-related terms included "sustainability", "environmental impact", "life cycle assessment", "energy consumption", "resource efficiency", "recycling", "circular economy", "waste valorisation", and "recycled feedstock".

Database-specific search strings were adapted to the syntax and indexing structure of Scopus and Web of Science while preserving equivalent conceptual coverage. The final searches were performed on 21 January 2026. The complete search expressions and corresponding retrieval results are summarized in Table 1 to improve methodological transparency and reproducibility.

Table 1. Structured literature search protocol and methodological criteria adopted in the review.

Methodological Step	Description
Review objective	To critically assess the sustainability of additive manufacturing technologies applied to composite materials, integrating manufacturing processes, composite systems, recycling pathways, environmental performance, and circular manufacturing strategies.
Review design	Structured comprehensive literature review based on systematic identification, screening, classification, and comparative synthesis of relevant studies.
Databases	Scopus and Web of Science Core Collection.
Publication period	2012–2026.
Language	English.
Document type	Peer-reviewed journal articles.
Search fields	Title, Abstract, and Keywords (Scopus); Topic (Web of Science).
Core search domains	Additive Manufacturing; Composite Materials; Sustainability; Recycling; Circular Economy; Life Cycle Assessment; Resource Efficiency.
Generic Boolean search structure	("additive manufacturing" OR "3D printing" OR related AM process terms) AND (composite* OR "fibre-reinforced" OR biocomposite* OR related composite terms) AND (sustainab* OR recycl* OR "circular economy" OR "life cycle assessment" OR "environmental impact" OR "energy consumption" OR "resource efficiency").
Inclusion criteria	Studies addressing AM of composite materials or recycling routes relevant to composite AM feedstocks and reporting at least one sustainability-related dimension, including environmental impact, energy demand, material efficiency, waste generation or valorisation, recycling, resource recovery, carbon footprint, life-cycle performance, or circularity.
Exclusion criteria	Duplicate records; conference abstracts; editorials; non-peer-reviewed publications; studies focused exclusively on mechanical characterization or process optimization without sustainability relevance; studies without a meaningful connection to composite AM, recycled AM feedstocks, or circular manufacturing; publications providing insufficient information for scientific interpretation.
Screening procedure	Identification → Duplicate removal → Title and abstract screening → Full-text eligibility assessment → Final inclusion.
Final evidence base	78 peer-reviewed publications.
Data extraction dimensions	AM technology; composite material system; recycling strategy; environmental performance; circularity; industrial implementation.
Evidence synthesis	Descriptive mapping and critical comparative synthesis across technologies, materials, recycling routes, sustainability indicators, and industrial maturity.

Overall, this protocol establishes a transparent and reproducible basis for literature selection and analysis, ensuring that the final evidence base is systematically aligned with the technological, environmental, and circularity dimensions addressed in this review.

2.3. Eligibility Criteria and Study Selection

The retrieved records were screened according to predefined eligibility criteria established to ensure direct relevance to the objectives of the review. Studies were considered eligible when they: (i) were peer-reviewed journal publications; (ii) addressed an additive manufacturing process applied to a composite material or a recycling route relevant to composite AM feedstocks; (iii) investigated at least one sustainability-related

dimension, including environmental impact, energy demand, material efficiency, waste generation, recycling, resource recovery, carbon footprint, life cycle performance, or circularity; and (iv) provided sufficient methodological or quantitative information to support scientific interpretation.

Studies were excluded when they: (i) focused exclusively on mechanical characterization or process optimization without a sustainability or recycling dimension; (ii) addressed conventional composite manufacturing without a meaningful connection to additive manufacturing, recycled AM feedstocks, or circular manufacturing; (iii) consisted of conference abstracts, editorials, non-peer-reviewed documents, or other publications lacking sufficient scientific detail; (iv) were duplicates; or (v) did not provide sufficient information to support the analytical dimensions considered in this review.

The selection procedure comprised successive stages of identification, duplicate removal, title and abstract screening, full-text eligibility assessment, and final inclusion. Following database retrieval, duplicate records were removed before screening. Titles and abstracts were then evaluated against the predefined criteria, after which potentially relevant studies underwent full-text assessment. The final corpus comprised 78 publications, which formed the evidence base for the subsequent qualitative and comparative synthesis. The relevance of the final 78 studies was assessed through the application of predefined eligibility criteria at successive screening stages. During title and abstract screening, records were evaluated for their alignment with composite additive manufacturing and at least one sustainability-related dimension. Full-text assessment subsequently examined the methodological detail, scientific relevance, and availability of information required for the comparative synthesis. The selected studies were further classified according to AM technology, composite material system, recycling strategy, and sustainability assessment approach, allowing their contribution to the review objectives to be evaluated consistently. Regarding completeness, the search covered two major multidisciplinary databases and incorporated complementary terminology across the principal research domains. Nevertheless, the possibility of relevant studies being omitted due to database coverage, indexing differences, or search terminology cannot be entirely excluded. Therefore, the final selection should be interpreted as a structured and thematically representative evidence base rather than an exhaustive compilation of all available publications.

Figure 2 summarizes the workflow adopted for the literature search, screening, eligibility assessment, and final selection of the studies included in this review.

Although previous studies have investigated individual aspects of additive manufacturing, composite materials, recycling technologies, and environmental sustainability, the relationships between these dimensions remain insufficiently integrated within circular manufacturing frameworks. The main novelty of this review lies in adopting a value-retention-oriented perspective that connects additive manufacturing technologies, composite material systems, recycling pathways, environmental performance, and industrial feasibility. Based on the critical synthesis of 78 peer-reviewed studies, this review provides three principal contributions: (i) a multidimensional comparative analysis of recycling strategies and their associated environmental, technical, and industrial trade-offs; (ii) the proposal of an application-specific Functional Value Retention Index (FVRI) to conceptually assess whether recycled composites retain the performance required for subsequent engineering applications; and (iii) the development of an integrated decision framework linking material selection, additive manufacturing, recycling strategies, functional performance, sustainability assessment, and industrial implementation. Unlike approaches focused primarily on recycling efficiency or waste reduction, this review emphasizes the preservation of engineering functionality and resource value across successive material lifecycles. Therefore, the study aims not only to consolidate current knowledge but also to provide a structured basis for future research and decision-making towards value-retaining circular composite additive manufacturing.

2.4. Data Extraction and Classification Framework

A structured data extraction framework was applied to the 78 selected studies to enable systematic comparison across heterogeneous AM technologies, composite systems, recycling strategies, and sustainability indicators. For each publication, information was extracted and organised according to the eight data extraction dimensions presented in Table 2. This framework ensured a consistent and comprehensive assessment of the selected studies, facilitating cross-study comparisons and the identification of technological trends, research gaps, and sustainability-related challenges.

The first dimension characterized the manufacturing technology, including the AM process category, specific manufacturing technique, feedstock form, and relevant processing characteristics. The second dimension described the composite material system, including matrix family, reinforcement type, reinforcement origin, and the use of virgin, recycled, bio-based, or waste-derived constituents. The third dimension addressed recycling and circularity,

identifying the recycling route, recovered material, reuse strategy, closed- or open-loop pathway where reported, and compatibility of the recovered feedstock with subsequent AM processing.

Table 2. Data extraction and analytical classification framework.

Analytical Dimension	Variables Extracted	Analytical Purpose
AM Technology	Process category; specific AM technology; feedstock form; processing route; relevant process characteristics	Compare manufacturing pathways and identify technology-dependent sustainability patterns
Composite Material System	Matrix family; reinforcement type; reinforcement architecture; constituent origin; virgin, recycled, bio-based, or waste-derived content	Characterize material diversity and establish relationships between material configuration and sustainability performance
Recycling Strategy	Mechanical, thermal, chemical, or hybrid route; recovered fraction; recovery mechanism; reuse pathway; compatibility with subsequent AM processing	Compare recycling pathways and assess their suitability for circular composite manufacturing
Environmental Performance	LCA indicators; energy consumption; greenhouse gas emissions; carbon footprint; material efficiency; waste generation; resource consumption	Evaluate environmental benefits, burdens, and hotspots across material–process combinations
Circularity and Resource Valorisation	Recycled content; material recovery; reuse; waste valorisation; closed- or open-loop pathway; substitution of virgin resources	Assess material circulation and value-retention potential throughout the product life cycle
Technical Performance Retention	Fiber integrity; matrix degradation; mechanical property retention; feedstock quality; processability of recovered materials	Determine trade-offs between recycling intensity, recovered material quality, and functional reuse
Economic and Industrial Implementation	Processing complexity; scalability; technological maturity; infrastructure requirements; feedstock variability; reported economic constraints	Assess industrial feasibility and identify barriers to large-scale implementation
Application and End Use	Component/application type; structural requirements; secondary application; redesign or DfAM strategy	Relate recovered material performance to realistic engineering applications and value-retention opportunities

The fourth dimension characterized sustainability assessment, including Life Cycle Assessment (LCA), energy consumption, greenhouse gas emissions, material efficiency, waste reduction or valorisation, resource consumption, carbon footprint, economic assessment, and other circularity-related indicators reported by the original studies. Where available, information concerning industrial scale, technological maturity, feedstock variability, process limitations, and implementation barriers was also recorded.

This classification framework enabled the evidence to be analysed across multiple dimensions rather than solely according to publication chronology or AM technology. It also provided the basis for identifying areas of concentrated research activity, underrepresented technology–material combinations, and sustainability dimensions for which quantitative evidence remains limited.

To ensure a consistent and traceable synthesis of the selected literature, the 78 studies were analysed using a multidimensional data extraction and classification framework. As summarized in Table 2, the framework connects manufacturing technology and composite characteristics with recycling pathways, environmental performance, material value retention, and industrial applicability.

This structured classification enables the reviewed evidence to be interpreted beyond individual technologies or recycling routes, revealing relationships between material configuration, processing strategy, environmental performance, and functional value retention. It therefore provides the analytical basis for identifying cross-cutting trends, technological trade-offs, and research gaps across sustainable composite additive manufacturing.

This review was conducted through a structured literature survey focusing on the sustainability of additive manufacturing (AM) applied to composite materials. The primary objective was to identify, analyse, and critically discuss the current scientific knowledge regarding sustainable manufacturing strategies, recycling methodologies, environmental assessment, and circular economy approaches associated with composite additive manufacturing.

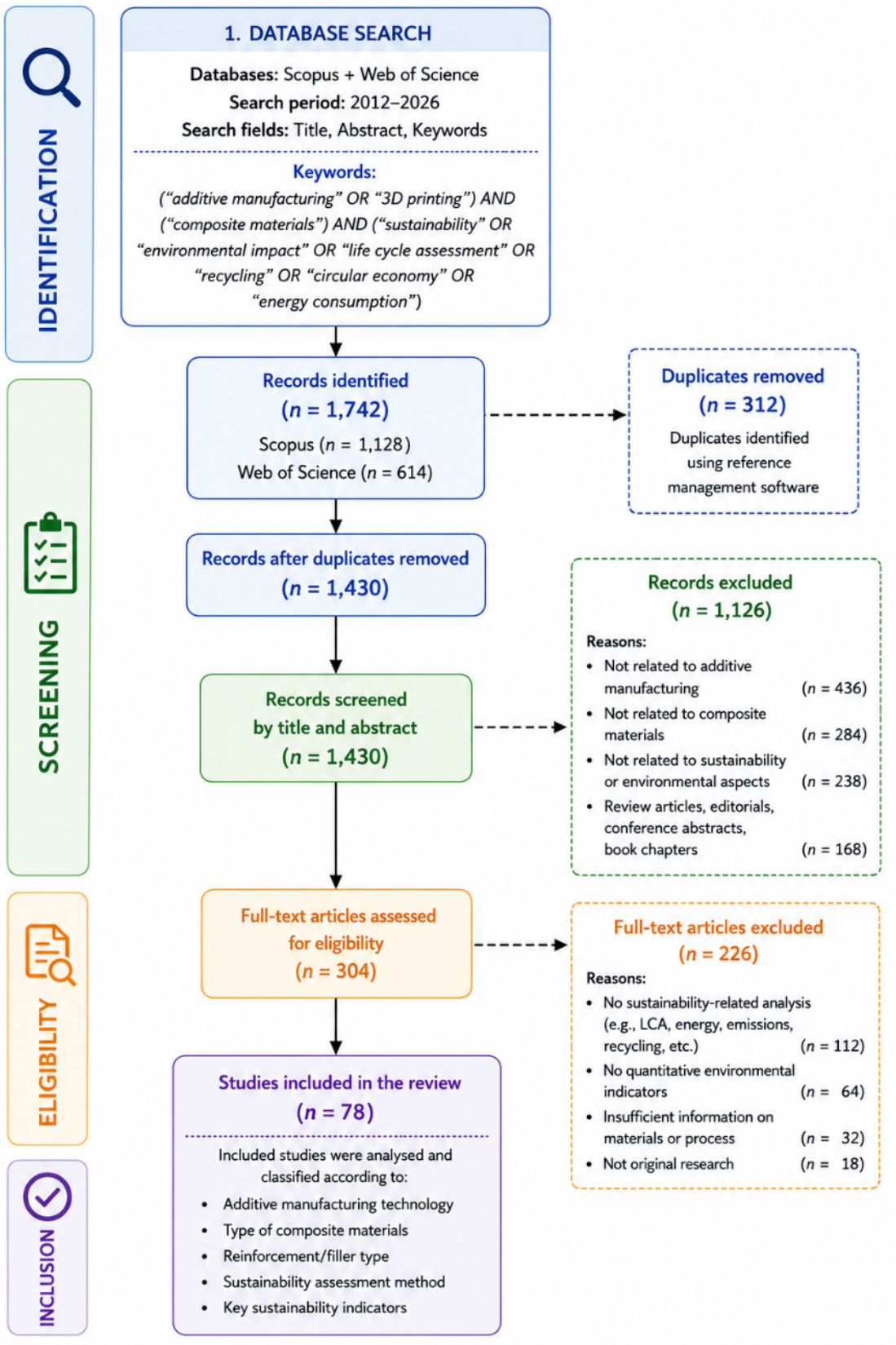

Figure 2. Flowchart of the literature search and study selection process adopted in this review.

2.5. Evidence Synthesis and Comparative Analysis

The extracted evidence was synthesized through a structured comparative approach combining descriptive mapping with critical qualitative interpretation. Studies were first grouped according to AM technology, composite family, recycling pathway, and sustainability assessment method. This organization enabled the relative concentration of research across different technological and material domains to be identified and provided the

basis for comparing reported sustainability benefits, environmental hotspots, technological limitations, and implementation barriers.

Particular attention was given to studies providing quantitative environmental evidence, including LCA results, energy demand, greenhouse gas emissions, material utilization, recycled content, and resource recovery. However, direct numerical comparison was performed only where the functional units, system boundaries, materials, and processing conditions were sufficiently compatible. Results obtained under substantially different methodological assumptions were interpreted comparatively rather than treated as directly equivalent, thereby avoiding unsupported ranking of technologies based on heterogeneous assessment conditions.

The synthesis subsequently examined the relationships between AM technology, composite architecture, recycling route, recovered material quality, environmental performance, and industrial maturity. This approach enabled the review to move beyond technology-by-technology description and identify broader patterns governing sustainable composite manufacturing. Particular emphasis was placed on trade-offs between energy demand and material recovery, recycling intensity and property retention, environmental performance and technological complexity, and recovery efficiency and functional value retention.

Finally, the integrated evidence was used to identify current research gaps and derive future research priorities concerning circular product design, recycling–AM integration, sustainability assessment, digital material traceability, and industrial scalability. The resulting synthesis therefore provides the analytical foundation for the comparative discussion and for the integrated decision framework proposed later in this review.

To complement the methodological classification of the selected literature, the evidence base was mapped across the principal AM technologies and sustainability assessment dimensions considered in this review. Figure 3 provides an integrated evidence landscape of the 78 included studies, enabling the concentration, fragmentation, and scarcity of research to be identified simultaneously across manufacturing technologies and sustainability domains. Since individual studies may address more than one analytical dimension, the resulting categories are non-mutually exclusive and should be interpreted as evidence density rather than as independent publication counts.

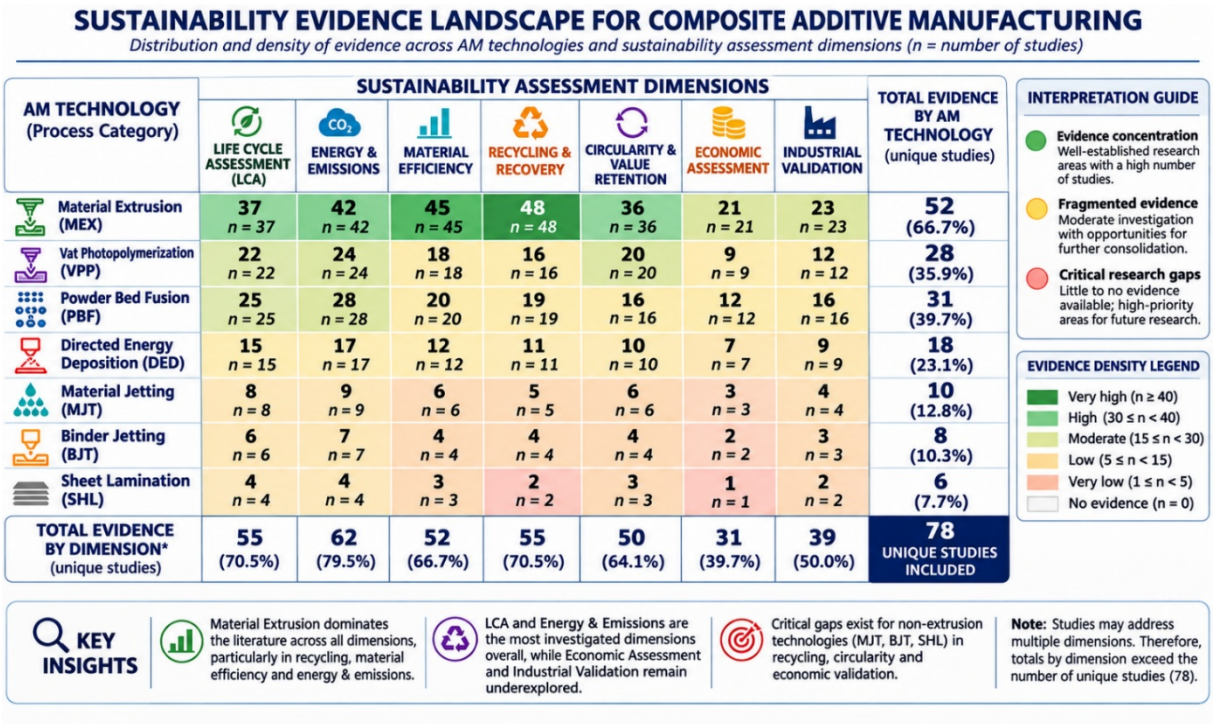

Figure 3. Sustainability evidence landscape for composite additive manufacturing, mapping the 78 included studies across AM technologies and sustainability assessment dimensions.

The evidence landscape reveals a markedly uneven distribution of sustainability research across both technologies and assessment dimensions. Material Extrusion concentrates the broadest evidence base, particularly in recycling and recovery, material efficiency, and energy-related assessment, whereas substantially less evidence is available for Material Jetting, Binder Jetting, and Sheet Lamination. Across the sustainability dimensions, environmental and resource-oriented assessments are more extensively represented than economic evaluation and industrial validation, indicating that the transition from laboratory-scale sustainability assessment towards integrated techno-economic and industrial evidence remains incomplete. These asymmetries provide a quantitative

basis for the subsequent critical analysis and identify where future research should move beyond demonstrating technical recyclability towards validating environmental, economic, and industrial viability.

3. Literature Review

According to the ISO/ASTM 52900 standard, Additive Manufacturing (AM) comprises seven process categories, each characterized by a distinct material deposition or consolidation mechanism [21,22]. These technologies differ considerably regarding feedstock compatibility, manufacturing principles, dimensional accuracy, production rate, energy consumption, and suitability for composite processing [23,24]. Such differences directly influence not only the mechanical performance of printed components but also their environmental impact and overall sustainability. Figure 4 presents the seven standardized AM process categories, while Table 3 summarizes their main representative technologies according to the ISO/ASTM classification.

Among the seven AM process categories, Material Extrusion is currently the most extensively employed for polymer composite manufacturing due to its low equipment cost, compatibility with recycled feedstocks, and processing flexibility. Conversely, technologies such as Powder Bed Fusion and Vat Photopolymerization provide superior dimensional accuracy and mechanical performance but generally involve higher equipment costs and energy consumption. Directed Energy Deposition and Binder Jetting are predominantly applied to metallic and ceramic composite systems, whereas Sheet Lamination and Material Jetting remain comparatively less explored for structural composite applications.

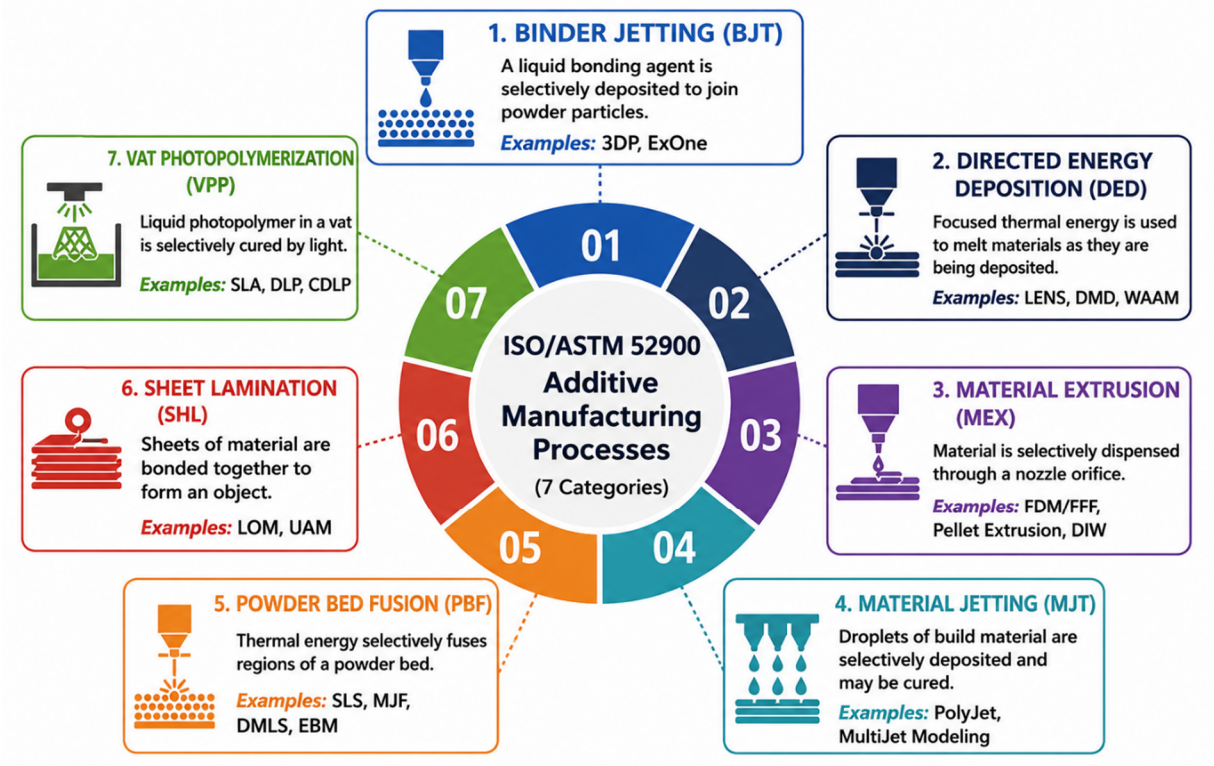

Figure 4. Standardized classification of additive manufacturing processes according to ISO/ASTM 52900, including the seven process categories, their operating principles, and representative technologies.

Table 3. Standardized classification of additive manufacturing technologies according to ISO/ASTM 52900.

AM Process Category	Process Principle	Representative Technologies	Typical Materials	Typical Composite Applications
Binder Jetting (BJT)	Selective deposition of a liquid binder onto a powder bed.	ExOne®, ColorJet Printing (CJP)	Metals, ceramics, sand	Metal and ceramic composite precursors, porous structures
Directed Energy Deposition (DED)	Focused thermal energy melts material during deposition.	LENS®, DMD, WAAM	Metals, metal powders, wires	Metal-matrix composites, repair, cladding, functionally graded materials
Material Extrusion (MEX)	Material is extruded through a heated nozzle layer by layer.	FDM/FFF, Pellet Extrusion, DIW	Thermoplastics, fibre-reinforced polymers, bio-composites	Polymer-matrix composites, structural and functional components

Table 3. *Cont.*

AM Process Category	Process Principle	Representative Technologies	Typical Materials	Typical Composite Applications
Material Jetting (MJT)	Selective deposition of droplets of liquid material followed by curing.	PolyJet®, MultiJet Modeling (MJM)	Photopolymers, waxes	Multi-material components, biomedical models, functional prototypes
Powder Bed Fusion (PBF)	Thermal energy selectively fuses powder particles.	SLS, SLM, DMLS, EBM, MJF	Polymers, metals, ceramics	High-performance polymer composites, complex geometries
Sheet Lamination (SHL)	Bonding and cutting of material sheets layer by layer.	Laminated Object Manufacturing (LOM), Ultrasonic Additive Manufacturing (UAM)	Paper, polymers, metals	Laminated structures, lightweight components
Vat Photopolymerization (VPP)	Selective curing of liquid photopolymer resin using light.	SLA, DLP, CLIP	Photopolymer resins, ceramic-filled resins	High-resolution composite parts, biomedical devices, lattice structures

3.1. Additive Manufacturing Technologies

3.1.1. Material Extrusion (ME)

Material extrusion is one of the most widely adopted AM techniques, particularly in polymer and composite processing. In this process, material is selectively dispensed through a nozzle, typically in the form of a molten thermoplastic filament or pellet feedstock. Fused Deposition Modeling (FDM), also referred to as Fused Filament Fabrication (FFF), is the most common implementation of this category [21–25].

This technique is especially attractive for polymer matrix composites due to its simplicity, low equipment cost, and ability to process fibre- and particle-reinforced thermoplastics. Studies have shown that short carbon fibre, glass fibre, and natural fibre reinforcements can significantly enhance mechanical performance, albeit at the expense of increased anisotropy and interlayer bonding challenges [26,27]. However, limitations remain regarding surface finish, dimensional accuracy, and void formation, which restrict its use in high-performance structural applications [28].

From a sustainability perspective, Material Extrusion has become the predominant AM technology for composite recycling due to its compatibility with recycled and bio-based feedstocks. Recycled thermoplastics, reclaimed carbon and glass fibres, natural fibres, and industrial by-products can be readily incorporated into filaments or pellet-based feedstocks, reducing raw material consumption and supporting circular manufacturing strategies. Furthermore, the relatively low processing temperatures and minimal material waste associated with ME contribute to lower environmental impacts compared with several conventional manufacturing processes. Nevertheless, repeated reprocessing may accelerate polymer degradation and reduce fibre length, making process optimization essential to preserve both material performance and environmental benefits [5,17].

3.1.2. Vat Photopolymerization (VPP)

Vat Photopolymerization (VPP) comprises a family of additive manufacturing processes in which liquid photopolymer resins are selectively cured by a light source, typically ultraviolet (UV) radiation. Stereolithography (SLA) and Digital Light Processing (DLP) are the two most established variants of this technology, offering high dimensional accuracy and excellent surface quality for complex geometries [29,30]. This process offers superior resolution, smooth surface finish, and excellent geometric accuracy compared to extrusion-based methods. It is particularly suitable for complex lattice structures, biomedical scaffolds, and high-precision components. Composite formulations, including ceramic- and fibre-filled photopolymers, have been developed to improve mechanical and functional properties [29]. Nonetheless, challenges related to limited material availability, photopolymer brittleness, and post-curing requirements remain significant barriers for large-scale industrial adoption [31].

From a sustainability perspective, Vat Photopolymerization presents both opportunities and challenges. The high dimensional accuracy of SLA and DLP enables the fabrication of lightweight structures with optimized geometries, reducing material consumption during service. However, most commercial photopolymer resins are petroleum-based, difficult to recycle, and require post-processing operations such as washing and UV post-curing, which increase energy consumption and generate chemical waste. Recent research has therefore focused on the development of bio-based photopolymers, recyclable resin systems, and composite formulations containing ceramic particles, natural fibres, or bio-derived fillers, aiming to improve both mechanical performance and environmental sustainability [29,31].

3.1.3. Powder Bed Fusion (PBF)

Powder Bed Fusion (PBF) comprises a family of additive manufacturing technologies in which thermal energy, typically generated by a laser or electron beam, selectively fuses regions of a powder bed to produce fully dense three-dimensional components. Selective Laser Sintering (SLS) is the most widely adopted polymer-based PBF process and has become one of the principal manufacturing routes for high-performance polymer and composite components [1]. This method enables the production of complex geometries without the need for support structures and offers relatively isotropic mechanical properties compared to material extrusion. PBF is well suited for processing polymer composites and composite-like systems, particularly those based on polyamides and filled powders [29]. However, high equipment costs, energy intensity, and limited powder recyclability continue to pose environmental and economic challenges [1].

From a sustainability perspective, Powder Bed Fusion presents a balanced combination of advantages and limitations. One of its main benefits is the efficient use of raw materials, as unfused powder can often be recovered and reused in subsequent manufacturing cycles, reducing material waste compared with subtractive manufacturing processes. This characteristic makes PBF particularly attractive for high-value polymer composites where feedstock costs are significant. However, repeated powder recycling may alter particle morphology, flowability, and thermal behaviour, ultimately affect part quality and require the periodic addition of virgin powder. Furthermore, the high energy demand associated with laser or electron beam operation remains a significant environmental challenge, highlighting the need for optimized process parameters and comprehensive life cycle assessments to fully evaluate the sustainability of PBF technologies [29].

3.1.4. Material Jetting (MJ)

Material Jetting (MJ) is an additive manufacturing process in which droplets of build material, typically photopolymers or waxes, are selectively deposited onto the build platform and immediately cured by ultraviolet (UV) light. This technology enables the fabrication of highly detailed components and supports the simultaneous deposition of multiple materials and colours within a single manufacturing process [29]. The ability to precisely control material placement makes material jetting attractive for functional grading and composite-like structures. However, the mechanical performance of printed parts is generally inferior to that of PBF or extrusion-based composites, limiting its application to prototyping, medical models, and visual components rather than load-bearing structures [5].

From a sustainability perspective, Material Jetting offers unique advantages due to its capability for highly precise material deposition, minimizing material waste and enabling the fabrication of complex multi-material components with localized functionality. This capability may contribute to lightweight designs and material-efficient structures, potentially reducing resource consumption during the product life cycle. However, its sustainability is limited by the reliance on photopolymer-based materials, which are generally difficult to recycle and often derived from non-renewable resources. In addition, the need for support materials, post-processing operations, and UV curing increases both material consumption and energy demand, highlighting the need for recyclable photopolymers and more sustainable resin formulations [29].

3.1.5. Binder Jetting (BJ)

Binder Jetting (BJ) is a powder-based additive manufacturing process in which a liquid binding agent is selectively deposited to join powder particles layer by layer. Unlike Powder Bed Fusion technologies, Binder Jetting does not employ thermal energy during the printing stage, thereby reducing residual stresses, thermal distortion, and energy consumption associated with part fabrication [3]. This technique is particularly suitable for ceramics and metal–matrix composite precursors, as well as porous structures. However, post-processing steps such as sintering or infiltration are mandatory to achieve adequate mechanical strength, which can introduce shrinkage and dimensional inaccuracies [29].

From a sustainability perspective, Binder Jetting presents several advantages due to the absence of high-energy heat sources during the printing stage, resulting in lower energy consumption and reduced thermal stresses compared with laser-based powder bed technologies. In addition, unused powder can often be recovered and reused, improving material utilization and reducing manufacturing waste. However, the mandatory post-processing steps, including debinding, sintering, or infiltration, substantially increase the overall energy demand and processing time while also influencing dimensional accuracy and final component properties. Consequently, the environmental performance of Binder Jetting should be assessed considering the complete manufacturing chain rather than the printing process alone, particularly for composite materials requiring complex post-processing routes [3,29].

3.1.6. Sheet Lamination (SHL)

Sheet Lamination (SHL) is an additive manufacturing process in which sheets of material, such as paper, polymer films, or metal foils, are successively bonded, cut to shape, and stacked to produce three-dimensional components. Laminated Object Manufacturing (LOM) is the most representative technology within this category and has been primarily applied to the fabrication of prototypes and large-scale components requiring relatively simple geometries [32].

Although Sheet Lamination enables rapid fabrication with relatively low material waste and reduced equipment complexity, its application in composite manufacturing remains limited. Weak interlayer bonding, restricted geometric flexibility, and comparatively lower mechanical performance reduce its suitability for demanding structural applications when compared with extrusion-, powder-, or photopolymer-based AM technologies [3]. Nevertheless, its ability to process laminated materials has attracted interest in certain fibre-reinforced systems and hybrid structures requiring tailored layer configurations.

From a sustainability perspective, Sheet Lamination offers several advantages, including efficient material utilization, relatively low energy consumption during fabrication, and the possibility of processing renewable or recyclable sheet materials such as cellulose-based laminates. However, the environmental performance of the process largely depends on the bonding agents employed, as adhesives may complicate material separation and reduce recyclability at the end of the product life cycle. Future developments should therefore focus on recyclable adhesive systems, bio-based bonding materials, and improved interlayer bonding strategies to expand the applicability of Sheet Lamination within sustainable composite manufacturing [32].

3.1.7. Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is an additive manufacturing process in which focused thermal energy, typically generated by a laser, electron beam, or plasma arc, is used to melt material as it is deposited in the form of powder or wire feedstock. Unlike powder bed technologies, DED enables simultaneous material deposition and melting, making it particularly suitable for manufacturing large-scale components, repairing damaged parts, and producing functionally graded materials [21]. DED is predominantly applied to metallic systems and has gained considerable attention in the aerospace, automotive, and energy sectors due to its capability for component repair, cladding, and feature addition. In composite manufacturing, the technology enables the fabrication of metal matrix composites (MMCs) and graded structures with locally tailored compositions and properties. However, challenges related to process stability, thermal management, surface finish, residual stresses, and dimensional accuracy continue to limit its broader industrial application, often requiring extensive post-processing to achieve the desired component quality [4,33].

From a sustainability perspective, Directed Energy Deposition represents one of the most promising additive manufacturing technologies because it extends component service life through repair and remanufacturing, thereby reducing raw material consumption and minimizing industrial waste. Instead of replacing damaged components, DED enables localized material deposition only where restoration is required, significantly improving resource efficiency and supporting circular manufacturing strategies. Nevertheless, the high energy consumption associated with concentrated heat sources, together with the need for precise process control and post-processing operations, remains an important environmental and economic challenge. Future developments should therefore focus on improving energy efficiency, process monitoring, and material utilization while integrating DED into digital manufacturing and life cycle assessment frameworks to maximize its sustainability potential [4,21].

3.2. Composite Materials

Composite materials are generally classified according to the type of matrix, as the matrix plays a fundamental role in determining the mechanical performance, thermal stability, processing behaviour, and suitability for additive manufacturing applications. Based on the matrix material, composites are commonly categorized into ceramic-matrix composites (CMCs), metal-matrix composites (MMCs), and organic-matrix composites (OMCs). While CMCs and MMCs are primarily employed in high-temperature and high-performance structural applications, their adoption in additive manufacturing remains relatively limited due to complex processing routes, high energy requirements, and extensive post-processing operations. Conversely, OMCs have become the dominant composite systems in additive manufacturing because of their compatibility with extrusion- and photopolymerization-based processes, lower processing temperatures, and broader material availability [34]. The classification of composite materials according to the matrix type is illustrated in Figure 5.

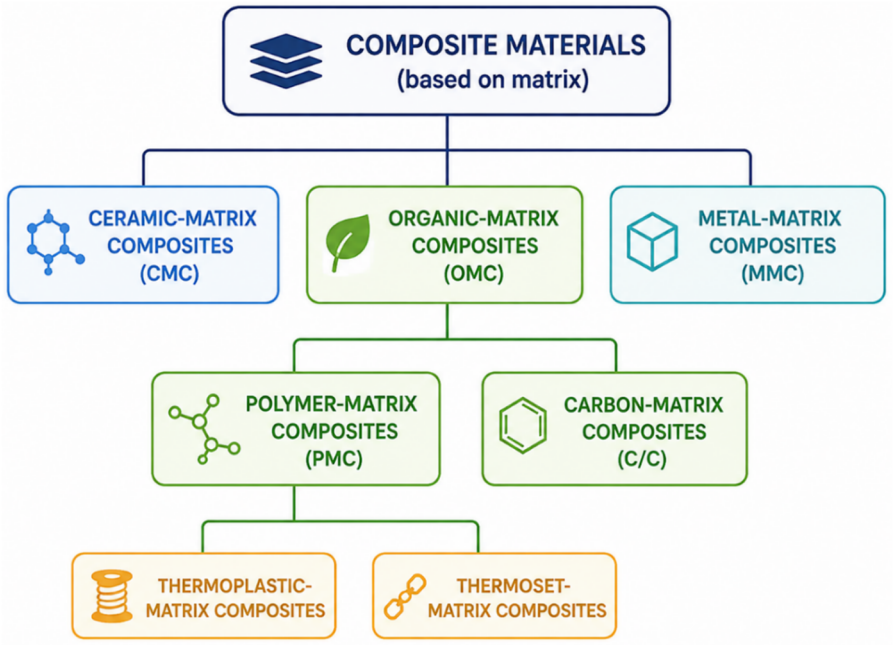

Figure 5. Classification of composite materials according to the matrix type, highlighting the main composite families and their subclasses commonly employed in additive manufacturing.

Among organic-matrix composites, polymer-matrix composites (PMCs) represent by far the largest class investigated in additive manufacturing. Their versatility allows the incorporation of fibres, particles, and waste-derived fillers while maintaining relatively simple processing conditions. PMCs are commonly divided into thermoplastic- and thermoset-matrix composites. Thermoplastic matrices are particularly attractive because they can be melted, reprocessed, and recycled, making them highly compatible with circular economy strategies and material extrusion technologies. In contrast, thermoset matrices exhibit superior thermal and chemical resistance but cannot be remelted after curing, restricting their application to indirect or hybrid additive manufacturing routes [29,35].

Carbon-matrix composites constitute a more specialized subgroup within organic-matrix composites. Owing to their exceptional thermal resistance and mechanical performance, these materials are attractive for demanding engineering applications. However, their application in additive manufacturing is still largely confined to research environments because of the challenges associated with material processing, manufacturing cost, and limited commercial feedstock availability [36].

Composite materials may also be classified according to the type of reinforcement employed, as this strongly influences load transfer mechanisms, mechanical anisotropy, and functional performance. Fibre-reinforced composites use discrete or continuous fibres to enhance stiffness and strength, making them particularly attractive for lightweight structural applications. Particulate composites incorporate dispersed particles to improve properties such as hardness, thermal stability, tribological behaviour, or sustainability, whereas structural composites, including laminated and sandwich architectures, derive their performance primarily from their structural configuration rather than from the constituent materials alone. Although these reinforcement strategies are well established in conventional manufacturing, their implementation in additive manufacturing continues to present challenges related to reinforcement orientation, interlayer bonding, and process scalability. Figure 6 illustrates the main categories of composite materials according to their reinforcement type [37–39].

In additive manufacturing, polymer-matrix composites (PMCs) are by far the most common composite systems. This is particularly true for material extrusion processes such as fused filament fabrication. Thermoplastic polymers like polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polypropylene (PP), polyamides (PA), thermoplastic polyurethane (TPU) and high-density polyethylene (HDPE) are widely used [38–42]. They are easy to melt, relatively cheap and can be recycled, which makes them attractive for both research and industrial use. These polymers usually print well and provide acceptable mechanical properties, while also allowing the use of recycled or bio-based feedstocks. Still, repeated thermal cycles during processing can damage polymer chains, reduce viscosity and slowly degrade mechanical performance, which can be a problem when material consistency is required [29,35].

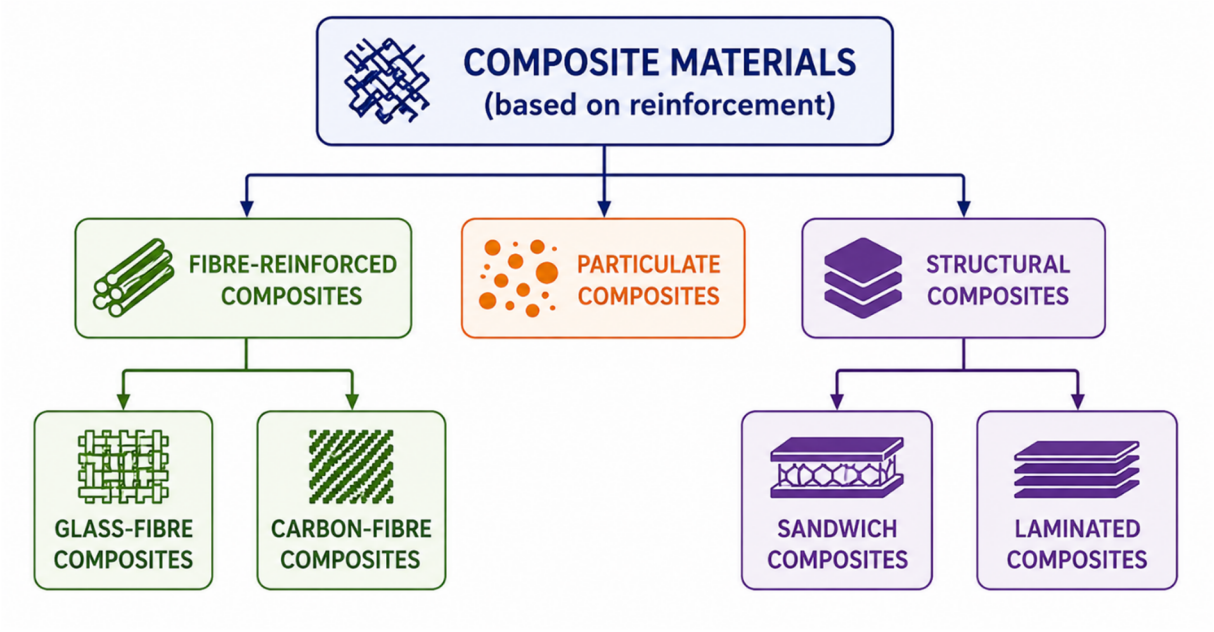

Figure 6. Classification of composite materials according to the reinforcement type, highlighting the principal reinforcement strategies employed in additive manufacturing.

Fibre-reinforced polymer composites are one of the most established PMC categories in additive manufacturing. Short glass and carbon fibres are commonly added to thermoplastic filaments to increase stiffness, strength and dimensional stability of printed parts. These fibres work well with extrusion-based processes and clearly improve mechanical performance. At the same time, several issues remain. Fibres can break during extrusion, interlayer bonding is often weak, and strong anisotropy appears because of the layer-by-layer deposition process. Continuous fibre and hybrid reinforcement concepts have also been studied, but their use in industry is still limited, mainly due to higher cost and process complexity [43–46].

The use of recycled fibres in polymer composites has grown in recent years, mostly because of sustainability and circular economy goals. Recycled carbon and glass fibres have been incorporated into matrices such as PLA and nylon with promising results. In some cases, thermo-mechanical properties close to those obtained with virgin fibres have been reported. These materials can reduce energy use, carbon footprint and raw material costs. However, variability in fibre length, surface condition and dispersion quality remains an issue, making reproducibility difficult and limiting large-scale adoption, especially for high-performance applications [36,38].

Natural fibre-reinforced composites are another important group of PMCs. Fibres coming from hemp, flax, jute, rice husk, walnut shell, cocoa shell, date palm residues and other agro-industrial by-products have been used in thermoplastic matrices for additive manufacturing. These biocomposites help reduce environmental impact and support waste valorisation. On the other hand, natural fibres are sensitive to moisture and temperature and their properties are not always consistent. Because of this, problems such as weak fibre–matrix adhesion, moisture absorption and unstable processing conditions are frequently reported, which can negatively affect print quality and mechanical behaviour [46–48].

Particle-filled polymer composites constitute another widely explored category, where inorganic or organic particles are added to polymer matrices to tailor mechanical, thermal, electrical, or tribological properties. Ceramic powders, biochar, graphite, mineral fillers, seashells, and food-industry by-products have been successfully used both as functional reinforcements and as sustainable fillers. These systems enable cost reduction and waste valorisation while enhancing specific properties such as stiffness or thermal stability. Nevertheless, high particle loadings often compromise filament flexibility, extrusion stability, and interlayer bonding, requiring careful optimization of particle size, shape, and concentration [49–51].

Metal- and ceramic-filled polymer composites are often seen as indirect routes for metal and ceramic additive manufacturing. These materials contain large amounts of metal or ceramic powders dispersed in a polymer binder, which is later removed through debinding and sintering. This approach allows complex parts to be produced using relatively simple extrusion-based printers. Even so, controlling shrinkage, porosity and dimensional accuracy remains difficult, and post-processing steps are energy intensive, which limits wider industrial use [4,5].

Biocomposites and bio-derived composite systems extend the use of composites beyond purely structural applications. Biodegradable polymers reinforced with bioactive fillers, nanocellulose, chitosan or food-industry

residues have shown multifunctional behaviour, such as biocompatibility, antibacterial effects and controlled degradation. Additive manufacturing makes it possible to control geometry and material distribution in detail, which is useful for application-specific designs. However, issues related to regulation, durability and long-term performance are still open [52].

Recycled polymer composites reinforced with waste-derived fillers have shown good potential for semi-structural and non-load-bearing applications, including furniture, interior components and construction elements. Systems based on recycled PET, ABS or PP combined with lignocellulosic or mineral fillers improve resource efficiency and reduce waste, while keeping acceptable mechanical performance. Even so, questions related to long-term durability, environmental resistance and standardisation of recycled feedstocks are still not fully resolved [53–55].

From a sustainability perspective, additive manufacturing of composite materials offers clear opportunities for better material efficiency, local recycling and circular economy integration. At the same time, the final sustainability outcome depends strongly on material choice, reinforcement type, processing conditions and end-of-life strategies. Life cycle assessment studies repeatedly point to the need for more consistent evaluation methods, improved recyclability of composite systems and a broader view of environmental trade-offs across the entire life cycle [56,57]. Error! Reference source not found.Figure 7 summarizes the principal composite material systems employed in additive manufacturing, highlighting their matrix types, reinforcement strategies, the most commonly used additive manufacturing processes, and their typical engineering applications.

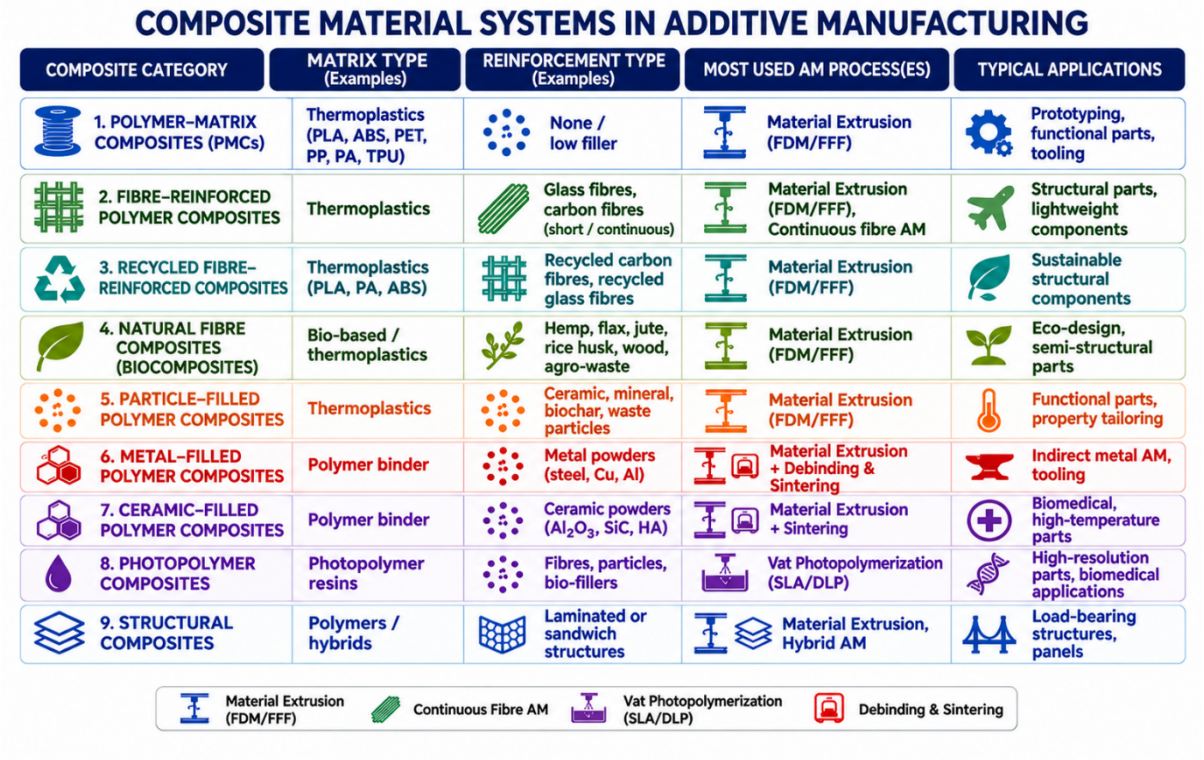

Figure 7. Overview of the principal composite material systems employed in additive manufacturing, highlighting their matrix types, reinforcement strategies, manufacturing processes, and typical engineering applications.

3.3. General Recycling System for Composite Materials

Recycling composite materials usually involves several interconnected stages that differ considerably from the recycling of single-material waste streams. Unlike conventional polymers or metals, composites combine matrices and reinforcements with distinct physical, chemical, and thermal properties, making their identification, separation, and recovery considerably more challenging. Consequently, recycling efficiency strongly depends on how waste is collected, sorted, conditioned, and processed, as well as on the possibility of reintroducing the recovered materials into manufacturing processes such as additive manufacturing [58]. Figure 8 illustrates the general recycling system for composite materials, highlighting the main processing stages from waste generation to material recovery and reintegration into manufacturing systems.

Composite waste can be generated throughout the entire product life cycle, including manufacturing scrap, rejected or failed parts, end-of-life components, and post-consumer products. In additive manufacturing, additional waste streams arise from failed prints, support structures, purging operations, and obsolete prototypes. Consequently,

effective collection systems require accurate knowledge of material composition to avoid contamination and maximize recycling efficiency. Once collected, composite waste must be sorted according to matrix type, reinforcement architecture, and filler content. Although manual sorting is still widely employed for high-value waste streams, automated identification techniques based on spectroscopy, density separation, and image analysis are increasingly being investigated to improve material traceability and reduce processing errors [59]. Following identification, composite waste undergoes pre-treatment operations such as cleaning, drying, shredding, and grinding to obtain flakes or granulates suitable for recycling. For fibre-reinforced composites, minimizing fibre damage during this stage is particularly important, as fibre integrity directly affects the mechanical performance of recycled materials. Depending on the matrix type and the intended application, recycling is subsequently performed using mechanical, thermal, or chemical routes. Thermoplastic composites can generally be recycled through re-melting and re-extrusion, allowing relatively direct reuse in filament- or pellet-based additive manufacturing. In contrast, thermoset composites require more complex thermal or chemical treatments to recover reinforcing fibres, often prioritizing functional material recovery rather than complete restoration of the original material properties [60,61].

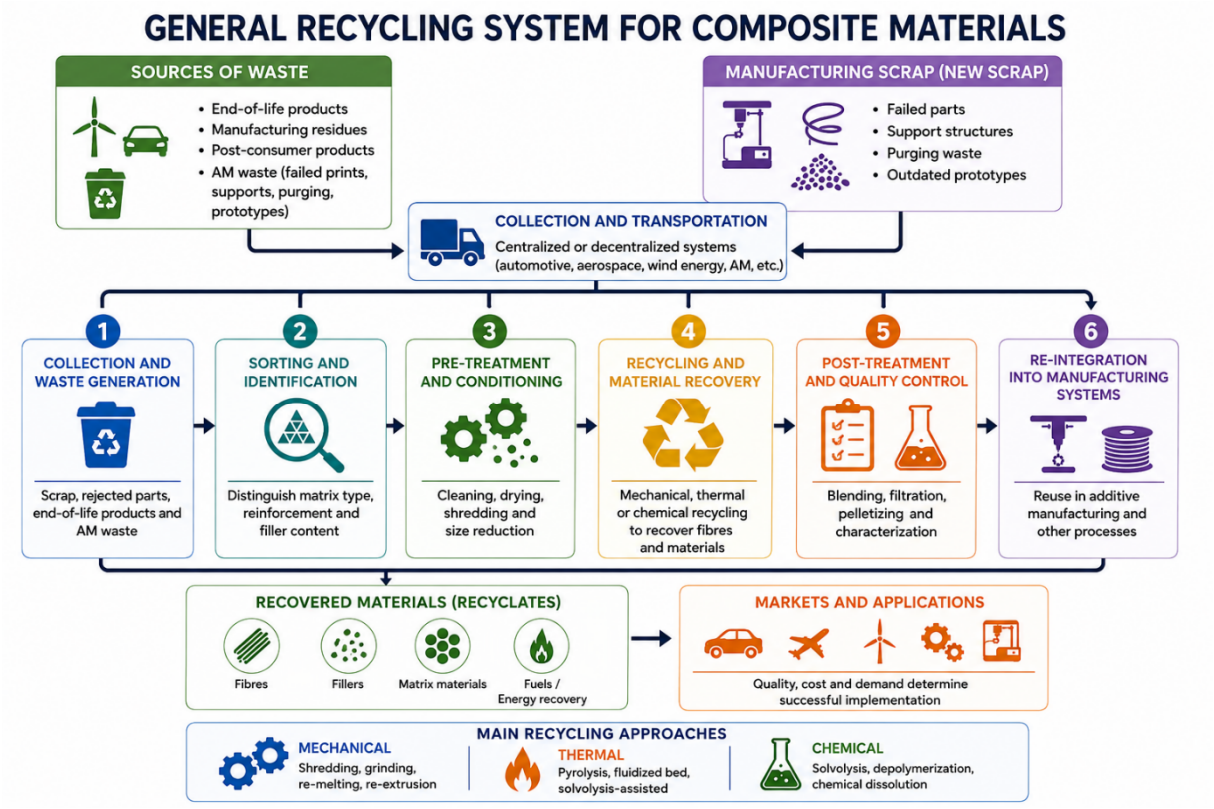

Figure 8. General recycling system for composite materials, illustrating the main stages from waste generation to material recovery and reintegration into manufacturing systems.

After recycling, recovered materials are subjected to post-treatment and quality control procedures before being reintroduced into manufacturing systems. Typical operations include blending with virgin polymers, compatibilization, filtration, pelletizing, and material characterization through rheological, thermal, and mechanical testing. For additive manufacturing applications, maintaining filament diameter consistency, melt flow behaviour, and homogeneous reinforcement dispersion is particularly important, as these factors directly influence print quality and component reliability. The recovered materials can then be reintegrated into manufacturing through design-for-recycling and design-for-additive-manufacturing strategies, allowing components to be redesigned according to the actual properties of recycled feedstocks rather than attempting to replicate the behaviour of virgin materials [62].

Although the recycling framework illustrated in Figure 8 provides a general overview of the recycling chain, practical implementation remains considerably more complex because of the heterogeneous nature of composite materials. Recent literature demonstrates that no universal recycling solution exists, and recycling strategies must be selected according to the matrix type, reinforcement architecture, and intended secondary application. Polymer-matrix composites continue to receive the greatest research attention, particularly thermoset composites, whose

crosslinked matrices make fibre recovery technically challenging. Conversely, thermoplastic composites have become increasingly attractive because they can be reprocessed through melt-based manufacturing routes, making them highly compatible with extrusion-based additive manufacturing. More recently, recycling studies have also expanded to metal-filled, ceramic-filled, and hybrid composite systems, where recycling performance must be evaluated not only in terms of material recovery but also regarding energy consumption, economic feasibility, and compatibility with existing manufacturing infrastructures [63].

Overall, composite recycling has evolved from isolated laboratory-scale studies toward increasingly integrated and application-oriented solutions. Nevertheless, no single recycling method is suitable for every composite system. Instead, mechanical, thermal, chemical, and hybrid recycling approaches should be selected according to the matrix material, reinforcement type, required component performance, and intended end use. Future developments are expected to combine advanced recycling technologies, digital material traceability, and additive manufacturing within circular economy frameworks, enabling more sustainable, resource-efficient, and application-specific composite manufacturing systems [2,11].

3.3.1. Mechanical Recycling

Mechanical recycling is the most established and industrially mature recycling route for polymer composite materials due to its relatively simple processing and compatibility with existing manufacturing infrastructure. The process generally begins with an initial size reduction stage, in which composite waste is fragmented using low-speed cutting or crushing equipment to produce coarse particles. These fragments are subsequently subjected to secondary grinding using hammer mills or other high-speed milling systems, reducing the particle size to the millimeter scale. The resulting material is then classified through techniques such as sieving and cyclonic separation, enabling the partial separation of fibre-rich and matrix-rich fractions according to particle size and density [64,65].

Several studies have investigated the reuse of mechanically recycled glass fibre composite waste as a partial substitute for virgin reinforcement in newly manufactured composites. Closed-loop recycling strategies for Sheet Moulding Compound (SMC) and Dough Moulding Compound (DMC), widely employed in the automotive industry, have demonstrated that innovative air classification methods can efficiently recover fibrous fractions suitable for secondary reinforcement applications. These recovered fibres have been extensively characterized through single-fibre tensile and pull-out tests, allowing direct comparison with virgin glass fibres [64,65].

The experimental results consistently indicate that mechanically recycled fibres exhibit lower tensile strength and reduced fibre–matrix interfacial adhesion than virgin reinforcements. Nevertheless, moderate incorporation levels generally produce only limited reductions in the overall mechanical performance of the resulting composites. As the recycled fibre content increases, however, more pronounced decreases in flexural strength, impact resistance, and structural integrity become evident due to fibre shortening and damage accumulated during crushing and grinding operations.

Although mechanical recycling offers advantages such as relatively low technological complexity, industrial scalability, and compatibility with thermoplastic composite processing, it also presents important limitations. The repeated comminution process progressively shortens reinforcing fibres, reducing their reinforcing efficiency and restricting their application mainly to filler materials or secondary reinforcement rather than primary load-bearing structural components. Consequently, mechanical recycling is currently considered the most economically viable recycling strategy for thermoplastic composites, although improvements in fibre preservation and material quality remain essential for expanding its application to high-performance engineering components [66].

3.3.2. Thermal Recycling

Thermal recycling of composite materials is based on high-temperature processing aimed at decomposing or removing the polymer matrix. In general, thermal treatment routes for composite waste can be divided into three main categories:

- Incineration or combustion solely for energy recovery
- Combustion processes that allow partial recovery of fibres and fillers alongside energy generation
- Pyrolysis processes designed to recover both reinforcing fibres and fuel products.

Incineration and combustion processes intended exclusively for energy generation are not strictly considered recycling technologies, as they do not enable material recovery, although the resulting inorganic residues may be valorised, for example, in cement production. Nevertheless, waste incineration plants with sufficient energy efficiency are classified as recovery facilities under several regulatory frameworks, including European directives,

which clearly distinguish between material recycling and energy recovery. Consequently, only combustion-based fibre recovery and pyrolysis are generally classified as true thermal recycling routes for composite materials [65].

Among thermal recycling approaches, fluidised-bed technologies have received significant attention due to their applicability to both combustion-based fibre recovery and pyrolysis-based material recycling. In combustion-based fluidised-bed processes, composite scrap is introduced into a reactor where the organic matrix is oxidised and used as an energy source, while reinforcing fibres are recovered. Parallel developments in fluidised-bed pyrolysis aim to depolymerise the resin under oxygen-free conditions, enabling recovery of both fibres and secondary fuels. In both cases, the polymer matrix contributes to energy generation, and excess heat can be recovered through integrated waste-heat recovery systems [67,68].

In a typical fluidised-bed combustion recycling process (Figure 9), composite waste is initially reduced in size to fragments of approximately 25 mm prior to feeding into the reactor. The fluidised bed consists of heated sand and air supplied at controlled temperatures, generally around 450 °C for polyester-based composites and up to 550 °C for epoxy-based systems. The recovered fibres are largely free of resin residues and typically exhibit average lengths in the range of 6–10 mm. Experimental investigations have shown that glass fibres recovered at lower temperatures can suffer tensile strength reductions of approximately 50%, whereas carbon fibres treated at higher temperatures tend to retain a greater proportion of their original properties, with stiffness losses on the order of 20%. Detailed characterisation of fibre morphology, length distribution, and mechanical performance indicates that fibres recovered through fluidised-bed processing are short, individual filaments with a fluffy appearance, in contrast to the continuous fibres produced by conventional manufacturing routes. Figure 9 shows the whole process [69].

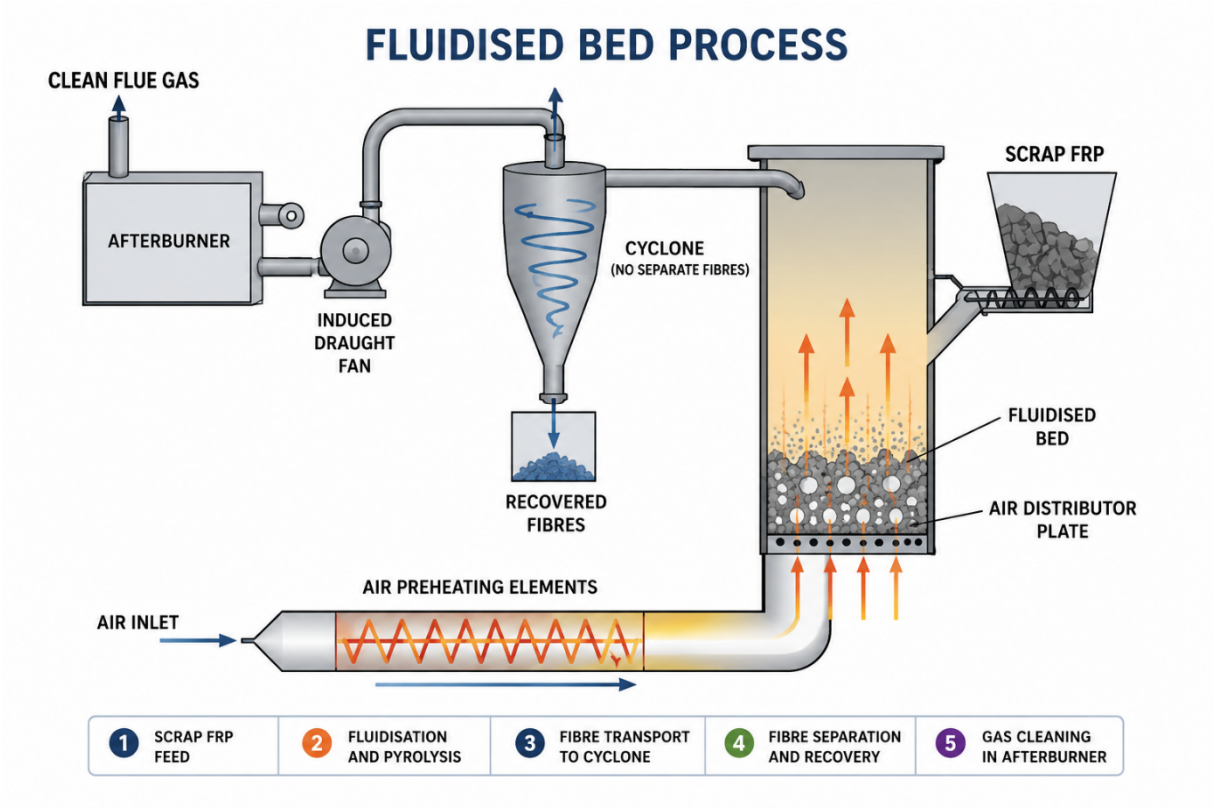

Figure 9. Schematic representation of the fluidised bed process for thermal recycling of fibre-reinforced polymer (FRP) composites, illustrating material feeding, fibre recovery, and gas cleaning.

Despite retaining a substantial fraction of their tensile strength, often up to 70–75%, the reduction in fibre length and mechanical performance restricts the reuse of fluidised-bed-recycled fibres to short-fibre applications such as moulding compounds. Economic assessments suggest that large-scale processing capacities, typically exceeding 10,000 tonnes per year, are required for glass fibre composite recycling to be commercially viable, whereas smaller-scale facilities may be feasible for carbon fibre composites due to their significantly higher market value. In this context, the quality and price of recycled fibres are critical factors governing the industrial implementation of fluidised-bed recycling technologies [65].

Pyrolysis represents an alternative thermal recycling route, involving the thermal decomposition of polymer matrices at temperatures typically between 300 and 800 °C in an oxygen-free environment. Under controlled

conditions, pyrolysis enables recovery of relatively long, high-modulus fibres while simultaneously converting the matrix into liquid, gaseous, and solid by-products. Operation at excessively high temperatures, approaching 1000 °C, can lead to severe degradation of fibre properties. Pyrolysis is applicable to a wide range of polymer-matrix composites, allowing both reinforcement recovery and partial valorisation of the matrix in the form of oils, gases, and char [67].

Compared with combustion processes, where polymer matrices are fully oxidised to carbon dioxide and water, pyrolysis breaks down crosslinked resins into lower-molecular-weight compounds that can be reused as chemical feedstocks or fuels. This feature represents a key advantage of pyrolysis, as it enables partial material recycling of the matrix rather than pure energy recovery. Both glass fibre and carbon fibre reinforced composites can be treated using pyrolysis, although the higher commercial value of carbon fibres makes pyrolysis-based recycling more economically attractive for carbon fibre systems. Various reactor configurations have been proposed for pyrolysis, including fixed-bed reactors, screw reactors, rotary kilns, and fluidised-bed reactors, with rotary kilns and fluidised beds generally considered the most suitable for large-scale operation.

One of the main challenges associated with pyrolysis lies in the handling and separation of the resulting products. The solid fraction typically consists of a mixture of reinforcing fibres, fillers, and carbonaceous residues, which must be further processed to isolate reusable fibres. The condensed liquid fraction comprises complex organic compounds with relatively high calorific values, often comparable to conventional fuel oils, while the gaseous fraction contains mixtures of carbon monoxide, carbon dioxide, and light hydrocarbons with lower heating values. These gaseous products can be combusted to supply the energy required for the endothermic pyrolysis process. The relative proportions of solid, liquid, and gaseous products depend strongly on composite composition and processing temperature, with solid residues generally accounting for the largest mass fraction [70].

In industrial practice, pyrolysis is frequently combined with a subsequent oxidation or gasification step to remove residual carbon and obtain cleaner fibres. This combined pyrolysis–gasification approach improves fibre purity but may further degrade mechanical properties due to high temperatures and oxidative conditions. An illustrative example is the ReFibre process developed in Denmark for recycling glass fibre composites from end-of-life wind turbine blades. In this system, turbine blades are initially segmented on-site into transportable sections and subsequently shredded before being fed into a rotating, oxygen-free furnace operating at approximately 500 °C. The resulting synthesis gas is used for electricity generation and to supply thermal energy to the process. A secondary oxidation step is employed to clean the recovered glass fibres, while metallic components are separated magnetically and dust is removed from the fibre fraction [70].

The glass fibres recovered through this combined pyrolysis–gasification route exhibit reduced mechanical performance and are therefore considered unsuitable for the manufacture of new turbine blades (Figure 10). Instead, they are more appropriately used in applications such as thermal insulation materials. Despite its technical feasibility, the ReFibre process has not yet achieved widespread commercial adoption, primarily due to economic constraints, as landfilling of decommissioned turbine blades remains a lower-cost option in regions where it is still permitted. Figure 10 represents the Pyrolysis process in composite materials.

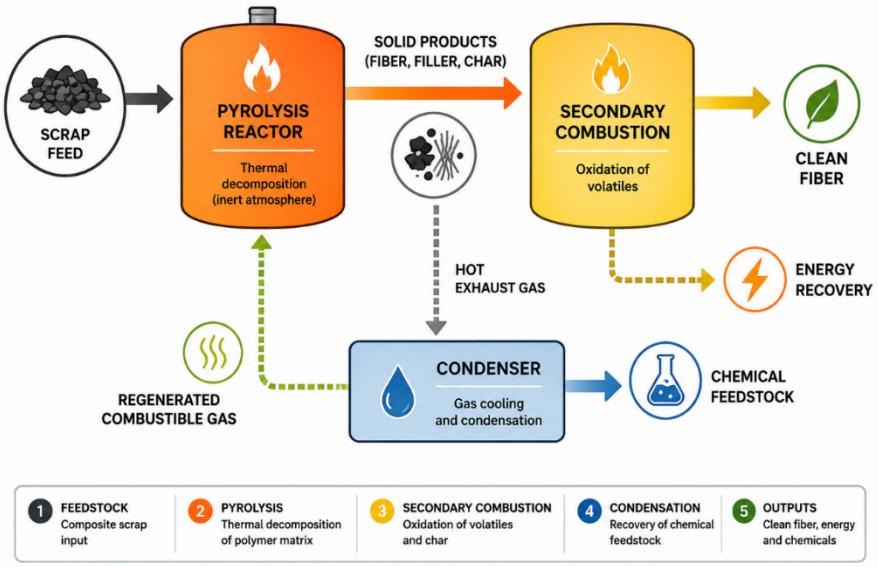

Figure 10. Schematic representation of the pyrolysis recycling process for composite materials, illustrating thermal decomposition, fibre recovery, energy recovery, and the production of chemical feedstocks.

3.3.3. Chemical Recycling

Chemical recycling includes several processes where the polymer matrix of a composite is removed or broken down using chemical solvents, so that the reinforcing fibres can be released. With this type of recycling, it is possible to recover relatively clean fibres and fillers, and at the same time transform the polymer matrix into smaller molecules, such as monomers or other petrochemical products. This dissolution-based approach is generally referred to as solvolysis. Depending on the solvent used, it can be classified into hydrolysis when water is applied, glycolysis when glycols are used, and acid digestion when acidic solutions are involved [71].

When water or alcohols are used as solvents, the process normally requires high temperatures and pressures. These conditions, often subcritical or supercritical, are needed to speed up the reactions and improve dissolution efficiency. Acid digestion works differently. It is usually carried out at atmospheric pressure, but the reactions tend to be much slower. Among the different solvolytic routes, glycolysis has shown good potential, particularly for breaking down epoxy resins into their original monomers, which can then be reused as chemical feedstocks. In this context, supercritical fluids, especially supercritical water and supercritical alcohols, have attracted attention as effective media for recovering both fibres and resin degradation products [72].

From an environmental point of view, the use of water and alcohol as solvents is often seen as relatively favourable. These solvents can be separated from the dissolved products using simple operations such as evaporation for water or distillation for alcohols. Solvolysis-based recycling has been applied to composites reinforced with different fibre types, including carbon and glass fibres, and many studies report that the recovered fibres keep most of their original mechanical properties. To make the process faster and more efficient, alkaline catalysts such as sodium hydroxide or potassium hydroxide are frequently added. Even so, important challenges remain. Removing catalyst residues from the recovered oils and purifying the resulting highly viscous depolymerized products is still difficult and limits wider industrial application.

Some of the first studies on chemical recycling were carried out several decades ago. Early work focused mainly on the hydrolysis of polyurethane foams, where high-pressure steam and elevated temperatures were used to break down the material. This process led to the formation of products such as diamine, polyols and carbon dioxide. In more recent years, attention has shifted toward the use of supercritical fluids, particularly for recycling carbon fibre reinforced composites. Experimental studies have investigated hydrothermal treatment using water under subcritical and supercritical conditions, with reported temperatures ranging approximately from 250 to 400 °C and pressures between 4 and 27 MPa. Supercritical water conditions are achieved only when both the temperature and pressure exceed the critical point of water (approximately 374 °C and 22.06 MPa). In addition, organic solvents, including alcohols such as methanol, ethanol, and propanol, as well as ketones such as acetone, have been investigated for their potential applications in solvent-assisted recycling processes. The main chemical recycling routes applied to composite materials are illustrated in Figure 11.

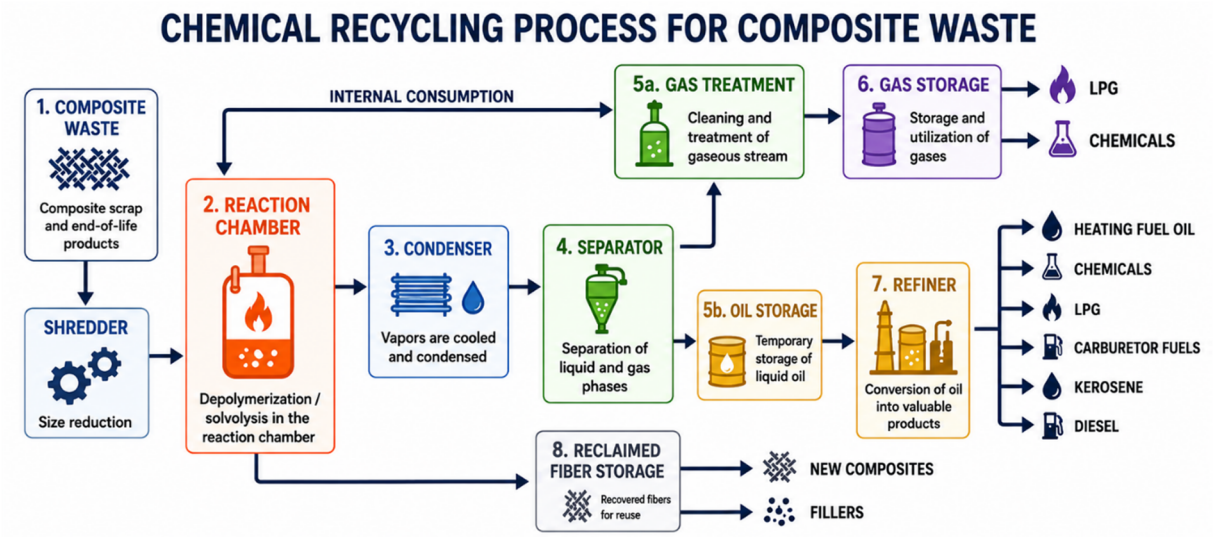

Figure 11. Schematic representation of the chemical recycling process for composite waste, illustrating pre-treatment, depolymerization, phase separation, product recovery, and the reintegration of recovered fibres into new manufacturing applications.

The results reported in the literature show that adding alkaline catalysts can greatly improve resin removal. In supercritical water systems, resin elimination efficiencies above 90% have been achieved. Under these

conditions, the recovered carbon fibres generally show only limited loss of mechanical performance, usually in the range of about 2% to 10%. Even higher efficiencies have been observed when supercritical alcohol is used. In some cases, resin removal close to 98% has been reported at temperatures around 350 °C, while the recovered fibres retained between 85% and 99% of the strength of virgin carbon fibres. Despite these encouraging outcomes, it is important to note that most of these experiments were performed at laboratory scale. Reactor volumes were very small, often limited to a few milliliters, typically using stainless steel autoclaves. As a result, there is still a clear need for further research and development before chemical recycling processes based on solvolysis and supercritical fluids can be applied at industrial scale. Scaling up these systems introduces additional challenges related to process control, safety and cost. Moreover, the efficiency of chemical dissolution depends strongly on the type of polymer matrix, which means that composite waste streams must be well identified and separated in advance. While these methods are suitable for processing production scrap with known composition, their use for post-consumer composite waste is much more difficult. Mixed material streams and the limited effectiveness of mechanical pre-sorting continue to be major obstacles for wider application [71,72].

3.3.4. Recycling of Thermoplastic Matrix Composites

Thermoplastic matrix composites are often seen as one of the most favourable composite systems when recycling is considered. This is mainly because thermoplastics can be melted and reshaped without undergoing permanent chemical crosslinking. In contrast to thermoset composites, thermoplastic systems can pass through several recycling cycles involving melting, extrusion and reprocessing. This characteristic makes them well suited for circular economy approaches and also fits naturally with additive manufacturing technologies. For these reasons, recent research has increasingly focused on both closed-loop and open-loop recycling strategies for thermoplastic composite waste coming from production processes as well as post-consumer sources [59].

One of the most common recycling routes for thermoplastic matrix composites combines mechanical size reduction with melt reprocessing. In practice, composite waste is first shredded into flakes or granules and then re-extruded to produce pellets or filaments that can be used in fused filament fabrication. Studies dealing with recycled ABS- and PET-based composites show that processing conditions play a key role at this stage. By controlling parameters such as extrusion temperature, shear rate and residence time, it is possible to maintain reasonable printability and reduce polymer degradation, leading to recycled filaments with stable diameter and acceptable mechanical behaviour [62,63].

Several case studies confirm that short fibre-reinforced thermoplastic composites can be successfully recycled for additive manufacturing applications. Work on recycled nylon systems reinforced with carbon and glass fibres indicates that blended recycled feedstocks can reach tensile strength and stiffness levels comparable to those obtained from single-source recycled materials. In particular, mixing different recycled composite streams has been shown to help balance stiffness and ductility, while also reducing variability linked to individual waste sources [38].

To further improve the performance of recycled thermoplastic composites, polymer blending and compatibilization strategies are often applied. During reprocessing (Figure 12), compatibilizers such as maleic-anhydride-grafted polymers can be added to enhance fibre–matrix adhesion and partially compensate for degradation effects. Case studies on recycled polypropylene composites filled with agricultural waste materials demonstrate that adjusting the compatibilizer content can lead to noticeable improvements in tensile strength and impact resistance, allowing recycled composites to be reused in semi-structural applications [48].

Thermoplastic elastomer composites have also attracted attention in the shows context of recycling and additive manufacturing. In particular, thermoplastic polyurethane (TPU)-based systems have been studied, since they combine flexibility with good mechanical resilience. Results reported in the literature show that recycled TPU composites reinforced with particulate fillers can retain high elasticity and abrasion resistance even after several processing cycles. This makes them suitable for applications such as flexible parts or damping elements, extending recycling concepts beyond rigid structural components [39].

Another recycling-oriented approach involves the use of waste-derived reinforcements in thermoplastic composites. Instead of aiming for full property recovery, recycled polymer matrices can be combined with bio-based or industrial residues. Case studies using recycled PET reinforced with date palm frond nanoparticles or food-industry by-products report improvements in stiffness and thermal stability, together with a reduction in environmental impact. These strategies focus on functional reuse and are well aligned with design-for-additive-manufacturing principles, as illustrated in Figure 12 [17,53].

From an additive manufacturing perspective, recycled thermoplastic composites benefit from the flexibility of extrusion-based processes, which tolerate higher material variability compared to conventional manufacturing. Distributed recycling models, where thermoplastic composite waste is locally processed into new feedstocks, have

been proposed as viable solutions to reduce transportation emissions and material losses. Such systems support decentralized production and promote the integration of recycling directly into manufacturing environments [55].

Overall, recycling of thermoplastic matrix composites offers a technically viable and economically attractive pathway toward sustainable composite manufacturing. While challenges related to polymer degradation, fibre damage, and material variability persist, recent case studies demonstrate that optimized reprocessing, blending, and additive manufacturing integration can enable high-value reuse of recycled thermoplastic composites across a wide range of applications [62].

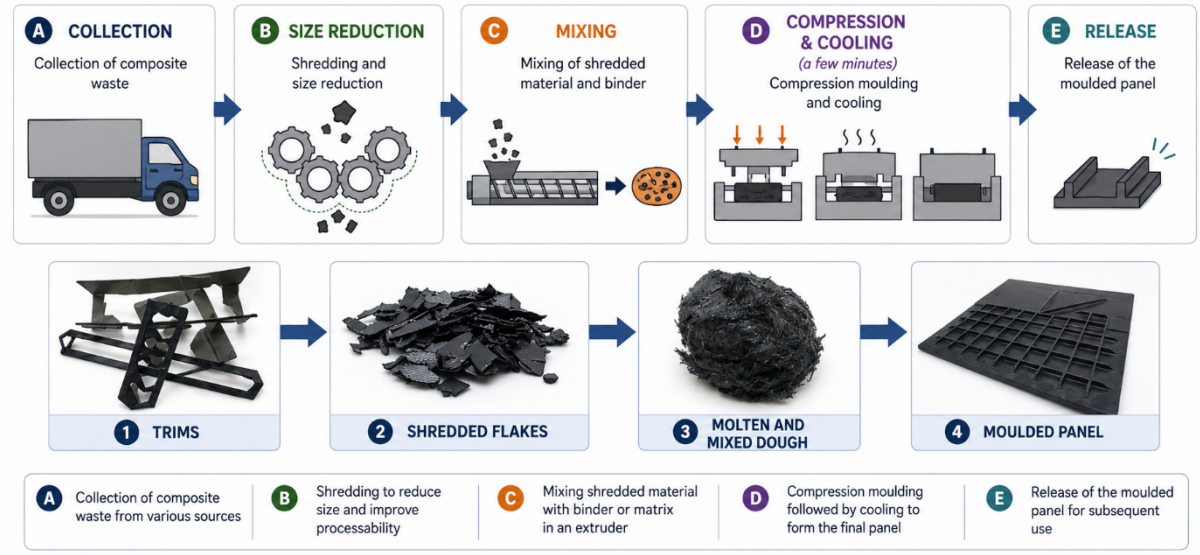

Figure 12. Schematic representation of the recycling and remanufacturing process for thermoplastic matrix composites, illustrating waste collection, size reduction, material reprocessing, compression moulding, and the production of new composite components.

3.3.5. Recycling of Thermoset Matrix Composites

Thermoset matrix composites are extensively employed in high-performance engineering applications because of their excellent mechanical properties, thermal stability, and chemical resistance. However, the irreversible crosslinked network formed during the curing process prevents these materials from being remelted or reshaped, making their recycling considerably more challenging than that of thermoplastic composites. As a result, large quantities of thermoset composite waste are generated by industries such as aerospace, automotive, wind energy, and construction, driving the development of alternative recycling strategies capable of recovering value from end-of-life components [73].

Among the available recycling routes, mechanical recycling remains the simplest and most industrially accessible approach. In this process, cured thermoset composites are crushed or milled into powders and short fibrous fragments, which are subsequently reused as fillers or secondary reinforcements rather than as primary structural fibres. Several studies have demonstrated that incorporating ground thermoset composite waste into thermoplastic matrices can improve stiffness and dimensional stability, particularly in extrusion-based additive manufacturing applications. Nevertheless, reductions in tensile strength and impact resistance are commonly observed owing to fibre shortening and the loss of reinforcement continuity during the comminution process [49].

Mechanical recycling has also enabled the development of hybrid composite systems in which thermoset-derived fillers are incorporated into recyclable thermoplastic matrices such as ABS and polypropylene. These hybrid feedstocks can be processed into filaments for Fused Filament Fabrication (FFF), providing an effective route for the valorisation of thermoset waste in situations where direct fibre recovery is either technically difficult or economically unattractive. Although the recycled thermoset phase no longer acts as a primary reinforcement, its incorporation contributes to waste reduction while maintaining acceptable performance for non-critical engineering applications.

Besides mechanical processing, thermal recycling technologies have been investigated as promising alternatives for recovering reinforcing fibres from thermoset composites, particularly those reinforced with glass fibres. Controlled thermal degradation of the polymer matrix enables partial fibre recovery while eliminating most of the organic matrix. Although exposure to elevated temperatures generally reduces fibre strength because of

thermal damage, recovered fibres remain suitable for secondary applications, including non-structural composite components, insulation products, and construction materials.

More recently, chemical-assisted recycling methods have attracted considerable attention as selective alternatives capable of preserving reinforcement quality. Instead of completely degrading the polymer matrix, solvent-assisted processes partially depolymerize or soften the thermoset network, facilitating fibre separation while minimizing surface damage. Experimental studies on epoxy-based composites have shown that these approaches preserve fibre integrity more effectively than conventional thermal treatments, improving compatibility with secondary polymer matrices used in additive manufacturing and other composite manufacturing processes [74,75]. The general workflow of a chemical recycling route is illustrated in Figure 11.

From a sustainability perspective, recent studies emphasize that thermoset composite recycling should not be evaluated exclusively according to material recovery efficiency. Functional reuse, application requirements, energy consumption, and environmental benefits must also be considered when selecting an appropriate recycling strategy. Several circular design approaches demonstrate that incorporating thermoset-derived recyclates into lower-performance but higher-volume products can provide significant environmental advantages, particularly when combined with additive manufacturing technologies that enable geometry optimization and performance compensation through design [54,56].

Overall, recycling thermoset matrix composites remains considerably more complex than recycling thermoplastic systems because of the permanent crosslinked nature of the polymer matrix. Nevertheless, recent research demonstrates that combining mechanical recycling, hybrid material development, thermal treatment, and selective chemical recycling offers promising opportunities for extending the service life of thermoset composite materials. Rather than relying solely on disposal, these complementary approaches enable the recovery of valuable materials and support more circular manufacturing strategies, particularly when integrated with additive manufacturing technologies and component designs specifically adapted to the properties of recycled materials [73].

3.3.6. Recycling of Metal Matrix Composites

Metal matrix composites (MMCs) are increasingly employed in applications requiring high specific strength, wear resistance, and thermal stability, including aerospace components, automotive parts, and tooling systems. However, their recycling remains technically challenging because of the strong interfacial bonding between the metallic matrix and ceramic- or carbon-based reinforcements. High melting temperatures, complex reactions between constituent phases, and low tolerance to contamination further complicate material recovery and reuse [76]. Consequently, MMC recycling generally requires more energy-intensive and tightly controlled processing than the recycling of polymer-based composites [34].

Mechanical recycling is commonly employed as an initial treatment route for MMC waste. Components are crushed, milled, or ground into powders and particulate fractions that can subsequently be used as secondary raw materials. Although this approach largely preserves the chemical composition of the waste, it destroys the original reinforcement architecture and frequently produces non-uniform particle size and reinforcement distributions. Mechanically recycled MMCs are therefore seldom reused directly in high-performance structural applications and are more commonly employed in non-critical components, fillers, or secondary material formulations [77].

Thermal recycling routes are mainly based on remelting and alloy reprocessing, particularly for aluminium- and magnesium-matrix composites. During remelting, the metallic matrix becomes liquid while the reinforcing phase remains solid, which may permit partial separation through sedimentation, filtration, or other physical methods. Nevertheless, reinforcement agglomeration, oxidation, and undesirable interfacial reactions can significantly reduce material quality. Repeated remelting cycles may also decrease ductility and increase brittleness, limiting the number of times an MMC can be effectively recycled through this route [75,78].

The reuse of MMC waste as feedstock for powder-based additive manufacturing has attracted increasing attention. Mechanically processed scrap can be converted into powders suitable for technologies such as Binder Jetting or Laser Powder Bed Fusion. Studies involving recycled aluminium–ceramic composite powders have reported acceptable densification and mechanical performance when Binder Jetting is followed by sintering. However, successful processing depends strongly on controlling powder morphology, particle size distribution, flowability, and binder content [59].

Indirect recycling strategies have also been investigated. In these approaches, metallic powders recovered from MMC waste are blended with polymer binders to produce composite filaments or pellets. These feedstocks can be processed by Material Extrusion and subsequently converted into dense metallic components through debinding and sintering. This route enables the reuse of MMC-derived metallic fractions in comparatively low-

cost additive manufacturing systems and may avoid some of the processing difficulties associated with direct remelting or powder-bed processing [45].

Recent research has further highlighted the potential of hybrid recycling strategies that combine mechanical pre-processing with additive manufacturing-based reshaping. Rather than requiring recycled materials to reproduce the properties of virgin MMCs, these approaches use geometry optimization and adapted load paths to compensate for reduced or more variable material performance. Such design-driven reuse strategies align with sustainability-oriented manufacturing because they prioritize functional suitability and material valorisation over strict equivalence with virgin feedstocks.

From a broader perspective, the viability of MMC recycling also depends on economic and logistical factors, including scrap availability, collection and separation efficiency, processing costs, and demand for recycled materials. Although MMC recycling can require substantial energy input, life cycle assessment studies indicate that environmental benefits may still be achieved when recycled feedstocks replace primary metal production. This advantage is particularly relevant for aluminium-based systems because of the high environmental burden associated with primary aluminium production.

Overall, the recycling of MMCs remains less mature than the recycling of conventional metallic alloys because of the difficulty of preserving reinforcement distribution and interfacial integrity. Nevertheless, the combination of mechanical processing, controlled remelting, powder-based additive manufacturing, and indirect extrusion–sintering routes offers promising opportunities for material recovery and functional reuse. Future progress will depend on improved feedstock characterization, contamination control, process standardization, and design strategies adapted to the properties of recycled MMCs.

3.3.7. Comparative Analysis of Recycling Technologies

The wide variety of recycling technologies currently available reflects the complexity and diversity of composite material systems. As discussed throughout the previous sections, no single recycling route is suitable for every type of composite. Instead, the selection of an appropriate recycling strategy depends on several factors, including the matrix material, reinforcement type, required material performance, environmental impact, processing cost, and the intended end use of the recovered products.

Mechanical recycling remains the most mature and economically attractive option, particularly for thermoplastic composites, owing to its relatively simple processing and compatibility with conventional manufacturing and additive manufacturing technologies. However, the comminution process generally shortens reinforcing fibres and reduces mechanical performance, limiting the recovered material to secondary or semi-structural applications. Thermal recycling techniques, including fluidised-bed processing and pyrolysis, enable the recovery of reinforcing fibres from thermoset composites, although fibre degradation and relatively high energy consumption remain important limitations. Chemical recycling offers the highest potential for preserving fibre quality and recovering valuable matrix constituents but is currently constrained by process complexity, solvent management, and higher operational costs.

For metal matrix composites, recycling strategies are primarily based on remelting, alloy reprocessing, and indirect powder reuse through additive manufacturing. Although these approaches can substantially reduce the environmental burden associated with primary metal production, they generally require strict control of contamination, reinforcement distribution, and interfacial stability to ensure acceptable material performance.

Figure 13 summarizes the principal recycling technologies currently reported for thermoplastic-, thermoset-, and metal-matrix composites, comparing their main technological characteristics, typical applications, and current levels of technological maturity. The comparison clearly demonstrates that the maturity of recycling technologies varies considerably among composite systems, with thermoplastic composites currently offering the most established recycling routes, while thermoset and metal matrix composites still require significant technological development to enable large-scale circular manufacturing. Table 4 provides a comparative synthesis of the principal composite recycling pathways, considering recovery efficiency, energy requirements, material degradation, process complexity, scalability, economic feasibility, and typical applications. The comparison highlights the distinct advantages and limitations of mechanical, thermal, chemical, and metallurgical recycling. Since the available studies differ considerably in material systems, processing conditions, and assessment methodologies, the comparison is presented qualitatively rather than through directly normalized numerical indicators. This approach reinforces the importance of selecting recycling strategies according to the characteristics of the composite material and the intended application of the recovered feedstock.

Table 4. Qualitative comparison of composite recycling pathways in terms of recovery performance, energy requirements, material degradation, process complexity, scalability, economic feasibility, and typical applications.

Criterion	Mechanical Recycling	Thermal Recycling	Chemical Recycling	Metallurgical Recycling
Recovery efficiency	Good mass recovery; limited fibre quality retention	Effective fibre recovery; matrix generally decomposed	Potentially high-quality fibre recovery; possible matrix constituent recovery	High metal recovery potential; composition-dependent
Energy requirements	Generally low to moderate	Generally high	Variable; potentially high	Generally high due to melting and refining
Material degradation	Fibre shortening and matrix degradation	Possible fibre surface damage and strength loss	Generally better fibre preservation; chemistry-dependent	Oxidation, contamination, and interfacial changes
Process complexity	Low	Moderate to high	High	Moderate to high
Scalability	Relatively established	Industrial applications exist; process-dependent	More limited industrial validation	Established metal recycling; composite-specific challenges
Economic feasibility	Relatively favourable	Dependent on recovered fibre value and energy costs	Limited by reagent, solvent, and processing costs	Dependent on metal value, separation, and refining costs
Typical applications	Recycled filaments, pellets, and non-structural components	Recovered fibres for secondary composites	Higher-value recovered fibres and chemical constituents	Reprocessed alloys, powders, and MMC feedstocks

Overall, future advances in composite recycling are expected to arise from the integration of multiple recycling strategies rather than from the adoption of a single universal solution. Combining mechanical, thermal, and chemical recycling with additive manufacturing, digital material traceability, and circular design principles will be essential for maximizing resource efficiency, extending material life cycles, and improving the environmental sustainability of composite manufacturing.

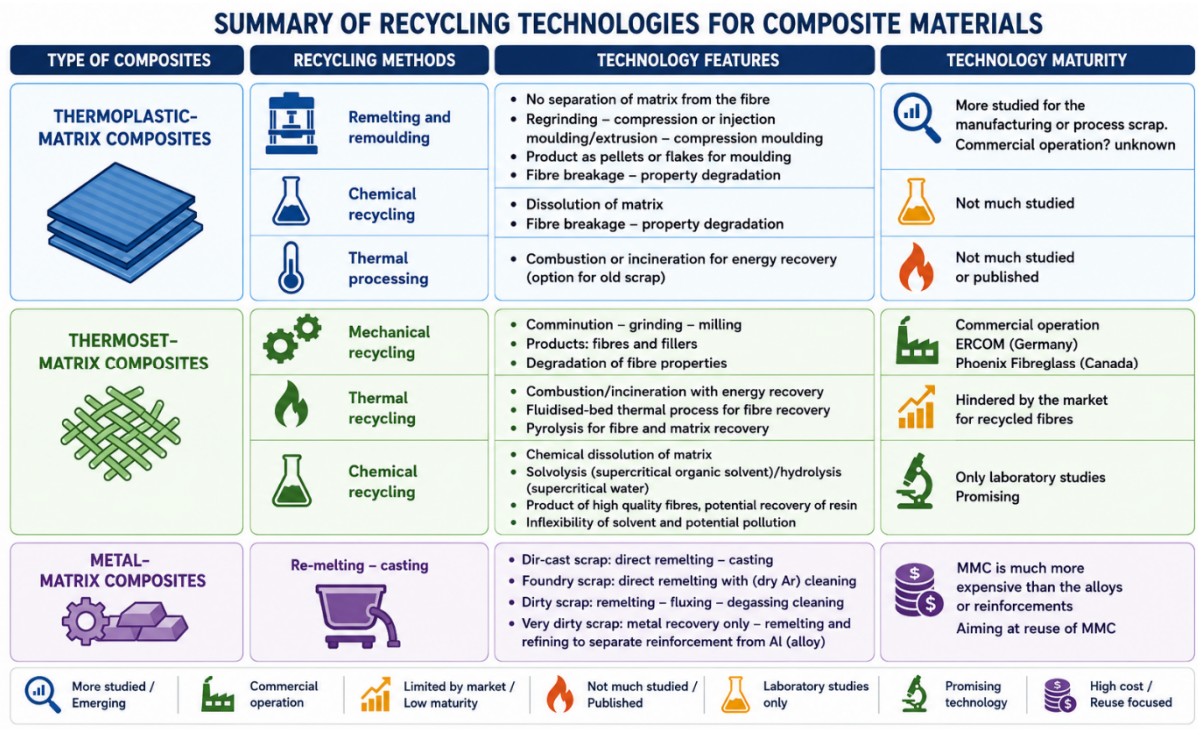

Figure 13. Comparative overview of the principal recycling technologies for thermoplastic-, thermoset-, and metal-matrix composites, highlighting their main technological characteristics and current levels of maturity.

4. Discussion

4.1. Sustainability Is a Material–Process–End-of-Life Problem

The evidence reviewed in this study demonstrates that the sustainability of composite additive manufacturing cannot be attributed to a manufacturing technology or recycling route in isolation. Instead, environmental

performance emerges from the interaction between material composition, reinforcement architecture, processing conditions, energy requirements, product functionality, and end-of-life strategy. This systems perspective is particularly important for composite materials because improvements achieved during one life-cycle stage may generate additional burdens elsewhere. For example, material-efficient AM processes may still exhibit significant energy demand, while highly recyclable thermoplastic systems may experience progressive property degradation after repeated processing cycles [29,35,56,57].

The reviewed evidence therefore challenges technology-centred interpretations in which sustainability is inferred directly from reduced material waste or the incorporation of recycled feedstocks. Material Extrusion illustrates this duality particularly well: its compatibility with recycled polymers, recovered fibres, and waste-derived fillers provides substantial circularity opportunities [5,17], yet repeated extrusion can modify polymer rheology, shorten reinforcing fibres, and progressively reduce mechanical performance [29,35]. Similarly, PBF enables substantial powder recovery, but repeated reuse affects powder morphology, flowability, and thermal behaviour, while the energy intensity of the process remains an important environmental burden [29]. Sustainability should consequently be evaluated at the level of the complete material–process–product system rather than through isolated process indicators.

4.2. Recycling Efficiency versus Functional Value Retention

A central finding emerging from the reviewed literature is that material recovery efficiency and sustainability are not equivalent objectives. The environmental and engineering value of recycling depends not only on the quantity of material recovered but also on the functionality retained after recovery, the energy and resources required by the recycling process, and the suitability of the recovered material for subsequent applications. This distinction is particularly relevant for composites, where recycling frequently modifies fibre length, interface quality, matrix properties, reinforcement distribution, or material architecture [64,65].

Mechanical recycling provides the clearest example. Its technological simplicity, comparatively low processing requirements, and industrial maturity make it attractive for thermoplastic and several fibre-reinforced composite systems. However, successive comminution and reprocessing progressively reduce reinforcement effectiveness and restrict the achievable secondary applications [64,65]. Such routes should therefore not automatically be interpreted as closed-loop recycling merely because the material is physically recovered. When functional performance decreases substantially, the process may represent value cascade or downcycling rather than genuine functional circularity.

Conversely, the inability to reproduce virgin-material properties does not necessarily eliminate the sustainability value of a recycled composite. Several studies indicate that recovered materials can remain environmentally and technically valuable when redirected towards applications with requirements compatible with their residual properties [54,56]. Additive manufacturing is particularly relevant in this context because geometry, material distribution, wall thickness, infill architecture, and load paths can be adapted to compensate partially for changes in feedstock performance. Similar design-driven reuse strategies have been proposed for recycled MMCs, where functional suitability rather than strict equivalence with virgin feedstocks becomes the principal criterion for material valorisation [55,56].

Accordingly, functional value retention provides a more meaningful circularity criterion than recovery rate alone. A recycling pathway that recovers a smaller fraction of material while preserving high-value functionality may, under appropriate system boundaries, provide greater sustainability benefits than a high-yield route producing material with limited secondary utility.

4.3. Comparative Sustainability of Recycling Pathways

The comparison of recycling pathways further demonstrates that each technology occupies a different position within the trade-off between process complexity, energy demand, recovered-material quality, and industrial maturity. Mechanical recycling remains the most accessible route because it relies on established size-reduction and separation technologies and can be readily integrated with thermoplastic processing [64,65]. Its principal limitation is progressive loss of reinforcement quality, making its sustainability increasingly dependent on whether viable secondary applications exist for the resulting recyclate.

Thermal routes address a fundamentally different problem by enabling reinforcement recovery from crosslinked thermoset matrices that cannot be remelted. Pyrolysis and related thermal treatments can recover valuable fibres and secondary products, but their environmental performance depends strongly on operating temperature, energy source, process efficiency, and the sensitivity of the reinforcement to thermal degradation [11,16]. Fibre recovery alone is

therefore insufficient to establish environmental superiority; the avoided production of virgin reinforcement must compensate for the burdens generated during recovery.

Chemical and solvent-assisted routes provide a different balance. Their principal advantage is the potential to preserve reinforcement integrity more effectively and, in some cases, recover valuable matrix-derived constituents [74,75]. However, solvent demand, reaction conditions, separation requirements, process complexity, and current industrial maturity can offset these material-quality advantages. Chemical recycling should therefore be regarded as a high-value recovery pathway whose sustainability depends on achieving sufficient process efficiency and scale rather than as an inherently preferable alternative to mechanical or thermal recycling.

The situation is further differentiated for MMCs. Remelting can avoid part of the substantial environmental burden associated with primary metal production, particularly for aluminium-based systems [38], but contamination, reinforcement redistribution, oxidation, and interfacial reactions may compromise subsequent material performance [34,75–78]. Powder recovery and AM-based reprocessing provide alternative pathways [45,59], particularly when recovered feedstocks can be redirected towards applications specifically designed around their resulting properties.

Taken together, these findings confirm that no recycling hierarchy can be defined independently of material system and application. Mechanical, thermal, chemical, and metallurgical routes should instead be regarded as complementary technological options whose relative sustainability depends on the balance between environmental burden, recovered-material quality, scalability, and functional destination.

4.4. Additive Manufacturing as a Circularity Enabler

Within this broader circularity perspective, additive manufacturing should not be interpreted merely as a destination for recycled feedstocks. Its more significant contribution lies in enabling recovered materials to be reintroduced into engineering applications under design conditions adapted to their actual properties. The combination of material-efficient fabrication, geometry optimization, local production, and compatibility with heterogeneous feedstocks creates opportunities to retain material value even when recycling modifies the original material performance [1,2,5,19].

This capability is particularly evident in Material Extrusion, where recycled polymers, recovered fibres, natural reinforcements, and waste-derived fillers can be incorporated into filament- or pellet-based feedstocks [5,17]. However, the same principle extends beyond polymer extrusion. Recycled MMC fractions can be converted into powders for Binder Jetting or PBF [59], while indirect routes combining recovered metallic powders with polymer binders enable extrusion followed by debinding and sintering [45]. These examples demonstrate that AM can function as a technological bridge between material recovery and functional reincorporation.

More importantly, AM introduces the possibility of design compensation. Rather than requiring recycled materials to reproduce the properties of virgin feedstocks, components can be redesigned through geometry optimization, adapted load paths, local reinforcement, wall-thickness modification, or other DfAM strategies to satisfy functional requirements using materials with altered or more variable properties [54–56]. This changes the role of AM within circular manufacturing: from a manufacturing process consuming recycled material to an enabling technology capable of preserving engineering value after material degradation.

Nevertheless, this potential should not be interpreted as evidence that AM automatically improves sustainability. Energy demand, support generation, post-processing, feedstock conditioning, failed builds, and material-specific recycling constraints remain relevant environmental burdens [29,56,57]. The environmental advantage of AM must therefore be demonstrated through life-cycle assessment rather than inferred from geometric efficiency or recycled content alone.

4.5. From Environmental Assessment to Industrial Circularity

A further finding of this review is the persistent imbalance between technical demonstration and comprehensive sustainability validation. Many studies successfully demonstrate the processing of recycled or bio-derived composite feedstocks, whereas fewer evaluate whether the proposed solutions remain environmentally advantageous when energy consumption, feedstock preparation, transportation, post-processing, recycling yield, and replacement of virgin materials are considered across the complete life cycle [56,57]. This distinction is critical because technical recyclability does not necessarily imply environmental sustainability.

LCA therefore remains essential for comparing alternative material–process–recycling configurations, but methodological consistency is equally important. Differences in functional units, system boundaries, electricity mixes, allocation procedures, assumed recycling credits, and component lifetimes can substantially influence reported environmental benefits. Direct comparison between studies should consequently be undertaken only where assessment

conditions are sufficiently compatible. Future work would benefit from greater methodological harmonization and from combining environmental indicators with technical performance and material quality retention.

Economic and industrial dimensions remain similarly important. Recycling technologies that demonstrate high recovery quality at laboratory scale may remain unsuitable for industrial implementation because of processing cost, solvent management, energy demand, feedstock variability, collection logistics, contamination, or insufficient demand for recovered materials. This challenge is particularly evident for MMC recycling, where scrap availability, separation efficiency, processing costs, and market demand influence the viability of material recovery even when environmental advantages over primary production are possible [38].

To support a more quantitative interpretation of functional value retention, an application-specific Functional Value Retention Index (FVRI) can be proposed as the ratio between the functional performance of a recycled composite and the minimum performance required for its intended application. This relationship can be expressed as $FVRI = P_r/P_{req}$, where P_r represents the measured performance of the recycled material or component and P_{req} corresponds to the minimum acceptable performance for the target application. An $FVRI \geq 1$ indicates that the recycled material satisfies the selected functional requirement, whereas an $FVRI < 1$ indicates that the requirement is not fulfilled. The relevant performance indicator may include tensile strength, elastic modulus, fatigue resistance, thermal stability, or another application-dependent property. When multiple requirements must be satisfied simultaneously, each should be evaluated separately to avoid masking critical performance limitations. This proposed index provides an initial quantitative interpretation of functional value retention, although its broader applicability requires experimental validation across different composite systems and recycling cycles.

Consequently, the transition towards circular composite AM requires the simultaneous evaluation of environmental performance, technical functionality, economic viability, circularity potential, and industrial readiness. Sustainability assessment should therefore evolve from isolated environmental indicators towards multicriteria decision frameworks capable of identifying solutions that remain advantageous across the complete manufacturing and recovery system. Based on these interdependencies and the principal trade-offs identified across the reviewed literature, an integrated decision framework is proposed in Figure 14 to support the systematic selection and evaluation of sustainable composite AM and recycling pathways.

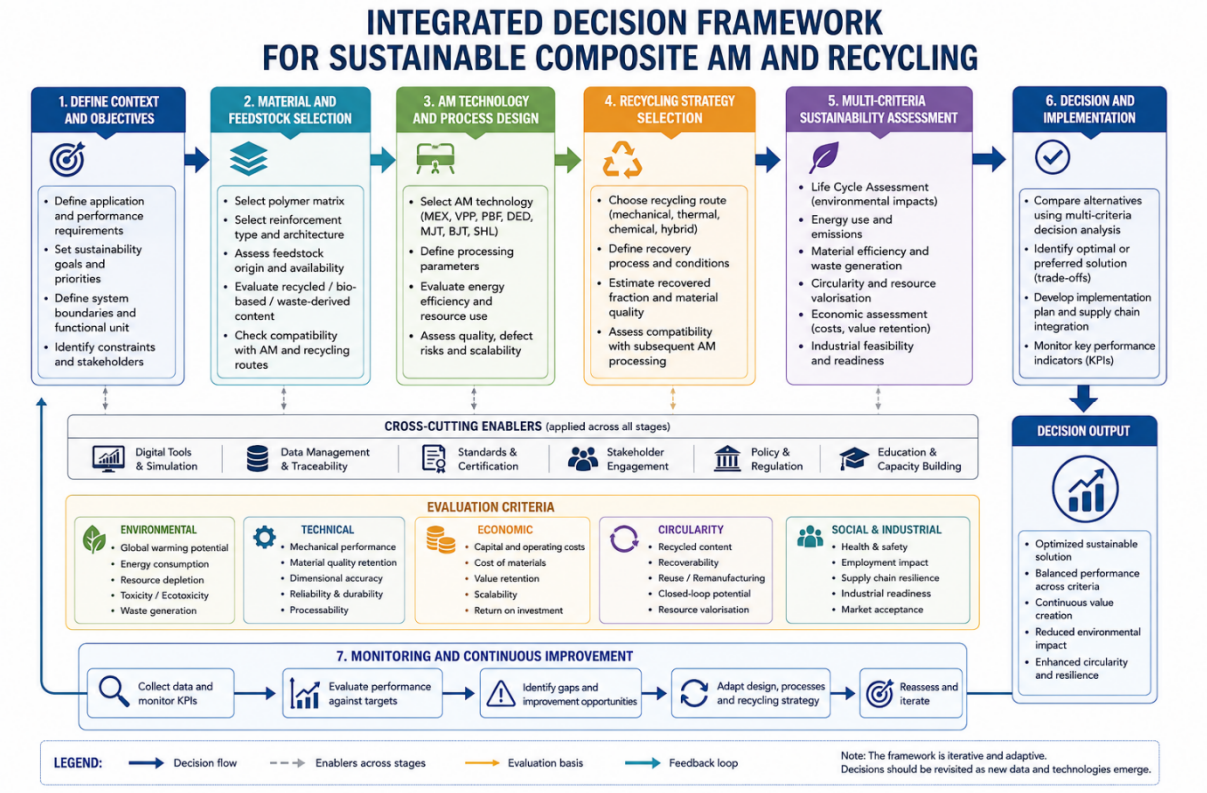

Figure 14. Integrated decision framework for sustainable composite additive manufacturing and recycling, linking material and process selection, end-of-life strategy, multidimensional sustainability assessment, implementation, and continuous improvement.

The proposed framework shifts the sustainability decision from the selection of an isolated manufacturing or recycling technology towards the optimization of the complete material–process–recovery system. Importantly, the most sustainable pathway is not necessarily the route achieving the highest material recovery rate, but rather the configuration that retains the greatest functional and economic value while minimizing environmental burdens and remaining technically and industrially feasible. By incorporating feedback and continuous reassessment, the framework also recognizes that sustainability decisions are dynamic and should evolve with material degradation, technological maturity, energy conditions, regulatory requirements, and the availability of new recovery technologies. This integrated perspective provides a basis for moving from fragmented sustainability improvements towards lifecycle-oriented decision-making in circular composite additive manufacturing.

Accordingly, value retention rather than material recovery alone emerges as the central decision criterion connecting composite design, additive manufacturing, recycling, and circularity.

5. Future Perspectives

5.1. From Recycling Efficiency to Multi-Cycle Value Retention

Future research should move beyond evaluating recycling pathways primarily through recovery yield or the properties obtained after a single recycling event. For composite materials, the more relevant scientific question concerns how functional value evolves across successive manufacturing–use–recovery cycles. Repeated thermal exposure, mechanical comminution, fibre shortening, matrix degradation, interfacial deterioration, and contamination can progressively modify the performance and processability of secondary feedstocks, particularly in thermoplastic composite systems [29,35,64,65].

Longitudinal studies involving multiple recycling cycles are therefore required to quantify the evolution of mechanical, thermal, rheological, and processing properties and determine when materials should remain within equivalent applications, be redirected towards less demanding functions, or leave the technical material cycle. Such evidence would enable circularity to be assessed in terms of cumulative functional value retained over time, rather than solely through the mass fraction recovered after each cycle.

Current research already provides evidence of the technical feasibility of reintegrating recycled composite materials into additive manufacturing processes. For instance, studies involving recycled ABS- and PET-based composites have demonstrated that mechanically processed waste can be re-extruded into filaments suitable for producing new components, provided that processing conditions are adequately controlled [62,63]. Similarly, recycled carbon- and glass-fibre-reinforced thermoplastic composites have shown promising mechanical performance when incorporated into secondary manufacturing applications [38]. These findings indicate that material recovery and subsequent remanufacturing are technically achievable, particularly through Material Extrusion. However, most reported applications remain focused on individual recycling events or laboratory-scale demonstrations. Evidence concerning repeated recycling of additively manufactured composite components, long-term property retention, and industrial-scale environmental and economic benefits remains limited. Therefore, future research should prioritize the experimental validation of complete circular manufacturing chains, including component production, use, recovery, reprocessing, and remanufacturing into new functional products.

5.2. Design for Recycling and Design for Additive Manufacturing

A second priority is the integration of Design for Recycling (DfR) with Design for Additive Manufacturing (DfAM). Current recycling strategies frequently address end-of-life recovery after material systems and component architectures have already been defined. A more effective circular approach would incorporate recoverability, disassembly, material separation, secondary processability, and anticipated property evolution during the initial design stage.

AM offers particular opportunities in this context because component geometry, internal architecture, material distribution, reinforcement placement, and functional requirements can be tailored to the characteristics of secondary feedstocks [5,19,54–56]. Future research should therefore investigate design compensation strategies capable of maintaining component functionality despite reductions or variability in recycled-material properties. This would shift the objective from reproducing virgin material performance towards designing products specifically for the capabilities of circular feedstocks.

5.3. Harmonized Life-Cycle and Techno-Economic Assessment

The evidence landscape also indicates a need for more consistent sustainability assessment. Comparisons between studies remain difficult when different functional units, system boundaries, electricity mixes, recycling

credits, transport assumptions, product lifetimes, or avoided virgin-material scenarios are employed. Future research should develop harmonized assessment protocols tailored to composite AM systems, enabling more robust comparison between manufacturing and recovery pathways.

Environmental assessment should additionally be integrated with Life Cycle Costing (LCC) and techno-economic analysis. A recycling technology may demonstrate favourable material recovery or environmental performance while remaining industrially impractical because of energy demand, chemical consumption, feedstock preparation, separation requirements, capital expenditure, or insufficient market value of recovered materials. Multicriteria assessment combining environmental impact, technical performance, retained value, cost, circularity, and scalability is therefore essential for translating laboratory results into industrial decisions.

5.4. Digital Traceability and Material Passports

Circular composite manufacturing will increasingly depend on knowing not only what a material is, but also what has happened to it throughout its lifecycle. Secondary feedstocks may differ substantially in composition, reinforcement content, processing history, degradation state, contamination, and number of previous recycling cycles. Without this information, recovered materials become heterogeneous inputs whose variability can compromise AM process stability and final component quality.

Future circular manufacturing systems should therefore integrate digital traceability, material passports, and lifecycle data management capable of recording material origin, composition, manufacturing conditions, use history, recovery route, and relevant property evolution. Such information could provide the data infrastructure required to qualify secondary feedstocks and support decisions concerning their most appropriate subsequent application.

5.5. Towards Intelligent and Adaptive Circular Manufacturing

The longer-term research direction is the convergence of recycling, AM, lifecycle assessment, and intelligent manufacturing into adaptive circular production systems. Digital twins, Artificial Intelligence, advanced sensing, and data-driven process control could enable manufacturing parameters to be adjusted according to the characteristics and history of each recycled feedstock rather than assuming constant virgin-material behaviour.

In such systems, material characterization and traceability data could inform predictive models of processability and component performance, while environmental and economic information could support real-time selection between alternative manufacturing, reuse, remanufacturing, and recycling pathways. The ultimate objective would be a closed-loop architecture in which material history → feedstock condition → process adaptation → product performance → recovery decision become continuously connected.

Achieving this vision will require substantial progress in standardized data architectures, interoperability, sensor-based material characterization, predictive modelling, certification of recycled feedstocks, and industrial-scale validation. Nevertheless, it represents a logical evolution from current isolated recycling demonstrations towards manufacturing ecosystems capable of preserving material functionality and economic value across multiple lifecycles.

Collectively, these research directions indicate that the next stage of sustainable composite AM should move beyond demonstrating whether recycled materials can be processed. The central scientific challenge is to determine how materials, products, manufacturing processes, digital information, and recovery technologies can be co-designed to preserve functionality and value across successive lifecycles. Future progress will therefore depend on the transition from recyclable materials to intelligent value-retaining circular manufacturing systems.

6. Conclusions

This review critically examined the sustainability of additive manufacturing technologies for composite materials by integrating evidence concerning manufacturing processes, material systems, recycling pathways, environmental performance, circularity, and industrial implementation. The resulting synthesis demonstrates that sustainability in composite AM cannot be determined from manufacturing efficiency, recycled content, or material recovery in isolation. Instead, it emerges from the interaction between material architecture, process requirements, energy and resource consumption, recovered-material quality, functional performance, and the end-of-life pathway adopted.

A central conclusion is that material recovery and sustainability are not equivalent objectives. Mechanical recycling offers technological simplicity and relatively straightforward integration with thermoplastic processing, but repeated size reduction and reprocessing may progressively reduce reinforcement effectiveness and restrict subsequent applications. Thermal routes enable valuable reinforcement recovery from thermoset composites but introduce energy demand and potential material degradation, whereas chemical approaches can provide higher-quality recovery at the expense of greater process complexity and demanding operating conditions. For metal matrix composites, remelting and powder-based recovery offer additional circularity pathways, although

contamination, reinforcement redistribution, and processing requirements remain important constraints. Consequently, no recycling technology can be considered universally preferable; its sustainability depends on the material system, recovery burden, retained functionality, and intended secondary application.

This leads to one of the principal conceptual outcomes of the review: functional value retention should complement material recovery rate as a central criterion for circular composite manufacturing. Recycled materials do not necessarily need to reproduce the properties of their virgin counterparts to retain engineering and environmental value. When recovered feedstocks are matched with applications compatible with their residual performance, or when component design is adapted to compensate for altered material properties, useful functionality can be preserved across successive material cycles. This perspective shifts circularity from the objective of recovering the maximum quantity of material towards retaining the maximum feasible engineering value.

Additive manufacturing has a distinctive role within this transition. Beyond reducing material waste or accepting recycled feedstocks, AM provides design freedom that can facilitate the functional reincorporation of recovered materials through geometry adaptation, material distribution, tailored architectures, and application-specific redesign. AM can therefore operate as a technological bridge between material recovery and functional reuse, extending circularity beyond recycling itself. However, such benefits should not be assumed intrinsically: energy consumption, feedstock preparation, post-processing, failed production, and recycling requirements must remain within the sustainability assessment boundary.

The evidence synthesized in this review also reveals that technological feasibility currently advances faster than comprehensive sustainability validation. Environmental assessment remains uneven across technologies and material systems, while economic performance, industrial scalability, feedstock variability, traceability, and real production validation require substantially greater attention. Future assessments should therefore integrate environmental, technical, economic, circularity, and industrial-readiness dimensions rather than relying on isolated indicators or laboratory-scale recyclability demonstrations.

The integrated decision framework proposed in this review translates these findings into a lifecycle-oriented approach connecting material and feedstock selection, AM process design, recycling strategy, multicriteria sustainability assessment, industrial implementation, and continuous improvement. Its principal implication is that sustainable composite AM should be approached as an interconnected material–process–product–recovery system, in which decisions made at one stage influence both the environmental burden and the value retained at subsequent stages.

Future research should consequently prioritize experimentally validated closed-loop material pathways, standardized life-cycle assessment methodologies, quantitative evaluation of property retention over multiple recycling cycles, techno-economic assessment at industrial scale, and digital material traceability. Particular attention should also be given to Design for Recycling and Design for Additive Manufacturing strategies capable of accommodating the variability and performance evolution of secondary feedstocks. Integrating these approaches with digital twins, AI-assisted process control, and lifecycle data management may further enable adaptive manufacturing systems capable of responding to material history and changing feedstock characteristics.

Ultimately, the transition towards sustainable composite additive manufacturing will depend less on identifying a single optimal manufacturing or recycling technology than on co-designing materials, processes, products, and recovery pathways around retained value throughout the lifecycle. By connecting fragmented evidence on composite AM and recycling within a unified sustainability perspective, this review provides a foundation for moving from isolated demonstrations of recyclability towards value-retaining, lifecycle-oriented, and industrially viable circular manufacturing systems.

Author Contributions

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References

1. Ngo, T.D.; Kashani, A.; Imbalzano, G.; et al. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Compos. Part B Eng.* **2018**, *143*, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012.
2. Habiba, R.D.; Malça, C.; Branco, R. Exploring the Potential of Recycled Polymers for 3D Printing Applications: A Review. *Materials* **2024**, *17*, 2915. https://doi.org/10.3390/ma17122915.
3. Lee, J.Y.; An, J.; Chua, C.K. Fundamentals and applications of 3D printing for novel materials. *Appl. Mater. Today* **2017**, *7*, 120–133. https://doi.org/10.1016/j.apmt.2017.02.004.
4. Saadi, M.A.S.R.; Maguire, A.; Pottackal, N.T.; et al. Direct Ink Writing: A 3D Printing Technology for Diverse Materials. *Adv. Mater.* **2022**, *34*, 2108855. https://doi.org/10.1002/adma.202108855.
5. Tadi, S.P.; Maddula, S.S.; Mamilla, R.S. Sustainability aspects of composite filament fabrication for 3D printing applications. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113961. https://doi.org/10.1016/j.rser.2023.113961.
6. Ror, C.K.; Negi, S.; Mishra, V. Development and characterization of sustainable 3D printing filaments using post-consumer recycled PET: Processing and characterization. *J. Polym. Res.* **2023**, *30*, 350. https://doi.org/10.1007/s10965-023-03742-2.
7. Ibrahim, I.; Ashour, A.G.; Zeiada, W.; et al. A Systematic Review on the Technical Performance and Sustainability of 3D Printing Filaments Using Recycled Plastic. *Sustainability* **2024**, *16*, 8247. https://doi.org/10.3390/su16188247.
8. Al Rashid, A.; Koç, M. 3D-Printed recycled polyethylene terephthalate (PET) sandwich structures—Influence of infill design and density on tensile, dynamic mechanical, and creep response. *Int. J. Lightweight Mater. Manuf.* **2025**, *8*, 442–452. https://doi.org/10.1016/j.ijlmm.2025.03.001.
9. Zander, N.E.; Gillan, M.; Burckhard, Z.; et al. Recycled polypropylene blends as novel 3D printing materials. *Addit. Manuf.* **2019**, *25*, 122–130. https://doi.org/10.1016/j.addma.2018.11.009.
10. Giani, N.; Mazzocchetti, L.; Benelli, T.; et al. Towards sustainability in 3D printing of thermoplastic composites: Evaluation of recycled carbon fibers as reinforcing agent for FDM filament production and 3D printing. *Compos. Part A Appl. Sci. Manuf.* **2022**, *159*, 107002. https://doi.org/10.1016/j.compositesa.2022.107002.
11. Garmabi, M.M.; Jalali, A.; Manzoor, A.; et al. Driving sustainability and performance: 3D-printing of lightweight functional components using recycled carbon fiber reinforced polyphenylene sulfide composites for automotive industry. *Prog. Addit. Manuf.* **2025**, *10*, 2397–2409. https://doi.org/10.1007/s40964-024-00757-z.
12. Morales, M.A.; Maranon, A.; Hernandez, C.; et al. Development and Characterization of a 3D Printed Cocoa Bean Shell Filled Recycled Polypropylene for Sustainable Composites. *Polymers* **2021**, *13*, 3162. https://doi.org/10.3390/polym13183162.
13. Ghabezi, P.; Sam-Daliri, O.; Flanagan, T.; et al. Circular economy innovation: A deep investigation on 3D printing of industrial waste polypropylene and carbon fiber composites. *Resour. Conserv. Recycl.* **2024**, *206*, 107667. https://doi.org/10.1016/j.resconrec.2024.107667.
14. Mahmoodi, O.; Siad, H.; Lachemi, M.; et al. Recent advances in CDW-based geopolymers: A review of mechanical performance, structural application, 3D printing, durability and sustainability. *J. Environ. Manag.* **2025**, *391*, 126358. https://doi.org/10.1016/j.jenvman.2025.126358.
15. Balina, K.; Gailitis, R.; Sinka, M.; et al. Prospective LCA for 3D-Printed Foamed Geopolymer Composites Using Construction Waste as Additives. *Sustainability* **2025**, *17*, 6459. https://doi.org/10.3390/su17146459.
16. Rahman, A.M.; Tan, E.C.D.; Pei, Z. 3D printing of packaging inserts from biomass-fungi composites: Environmental sustainability analysis. *Discov. Appl. Sci.* **2025**, *7*, 739. https://doi.org/10.1007/s42452-025-07264-y.

17. Bareen, M.A.; Derossi, A.; Corradini, M.G.; et al. Enhancing 3D Printing Performance and Product Quality Through the Valorization of Food By-Products and Waste. *Compr. Rev. Food Sci. Food Saf.* **2025**, *24*, e70267. https://doi.org/10.1111/1541-4337.70267.
18. Laoutid, F.; Lafqir, S.; Toncheva, A.; et al. Valorization of Recycled Tire Rubber for 3D Printing of ABS- and TPO-Based Composites. *Materials* **2021**, *14*, 5889. https://doi.org/10.3390/ma14195889.
19. Andreozzi, M.; Bianchi, I.; Di Pompeo, V.; et al. Sustainability assessment of autoclave and 3D printed composites with thermosetting and thermoplastic matrices. *Int. J. Adv. Manuf. Technol.* **2025**, *138*, 3221–3237. https://doi.org/10.1007/s00170-025-15689-3.
20. Pezzana, L.; Wolff, R.; Stampfl, J.; et al. High temperature vat photopolymerization 3D printing of fully bio-based composites: Green vegetable oil epoxy matrix & bio-derived filler powder. *Addit. Manuf.* **2024**, *79*, 103929. https://doi.org/10.1016/j.addma.2023.103929.
21. British Standards Institution. *BS EN ISO/ASTM 52900:2021*; Additive Manufacturing—General Principles—Fundamentals and Vocabulary. BSI British Standards: London, UK, 2022. https://doi.org/10.3403/30448424.
22. Singh, G.; Brar, G.S.; Singh, R. On Mechanical Properties of 3D-Printed Secondary Recycled Acrylonitrile Butadiene Styrene Composite for Silencer Application in Short-Range Gun. *J. Mater. Eng. Perform.* **2024**, *33*, 10295–10309. https://doi.org/10.1007/s11665-023-08684-w.
23. Coronado, D.R.R.; Chen, W.H.; Ubando, A.T. Advancements in biochar-reinforced 3D printing filaments for material extrusion: A review on material performance, sustainability, and circular economy. *Compos. Part C Open Access* **2026**, *19*, 100687. https://doi.org/10.1016/j.jcomc.2025.100687.
24. Ramesh, M.; Niranjana, K.; Bhoopathi, R.; et al. Additive manufacturing (3D printing) technologies for fiber-reinforced polymer composite materials: A review on fabrication methods and process parameters. *e-Polym.* **2024**, *24*, 20230114. https://doi.org/10.1515/epoly-2023-0114.
25. Saini, P.; Chatterjee, H.; Choudhari, A.; et al. Circular economy and sustainability innovation: A deep investigation to use recycled propylene with zeolites in 3D printing and injection molding. *Prog. Addit. Manuf.* **2025**, *10*, 9475–9490. https://doi.org/10.1007/s40964-025-01176-4.
26. Wang, X.; Jiang, M.; Zhou, Z.; et al. 3D printing of polymer matrix composites: A review and prospective. *Compos. Part B Eng.* **2017**, *110*, 442–458. https://doi.org/10.1016/j.compositesb.2016.11.034.
27. Chawla, K.; Singh, R.; Singh, J.; et al. Investigations on mechanical properties of secondary recycled ABS reinforced with Fe powder for 3D printing applications. *Mater. Today Proc.* **2022**, *50*, 2450–2454. https://doi.org/10.1016/j.matpr.2021.10.291.
28. Blanzeanu, E.; Marin, M.; Verziu, M.N.; et al. Chitosan-polylactic acid composites: From seafood waste to advanced functional materials for 3D printing. *Adv. Compos. Hybrid Mater.* **2025**, *8*, 66. https://doi.org/10.1007/s42114-024-01131-x.
29. Ligon, S.C.; Liska, R.; Stampfl, J.; et al. Polymers for 3D Printing and Customized Additive Manufacturing. *Chem. Rev.* **2017**, *117*, 10212–10290. https://doi.org/10.1021/acs.chemrev.7b00074.
30. Ateeq, M.; Akbar, A.; Shafique, M. Advancing circular economy: Comparative analysis of recycled and virgin carbon fiber 3D printed composites on performance and eco-efficiency. *Polymer* **2025**, *317*, 127865. https://doi.org/10.1016/j.polymer.2024.127865.
31. Chia, H.N.; Wu, B.M. Recent advances in 3D printing of biomaterials. *J. Biol. Eng.* **2015**, *9*, 4. https://doi.org/10.1186/s13036-015-0001-4.
32. Galib, G.; Silva, F.J.G.; Pedroso, A.F.V.; et al. A Comprehensive Review of Additive Manufacturing Technologies for Composite Materials. *J. Mech. Eng. Manuf.* **2025**, *1*, 2. https://doi.org/10.53941/jmem.2025.100002.
33. Shahrubudin, N.; Lee, T.C.; Ramlan, R. An Overview on 3D Printing Technology: Technological, Materials, and Applications. *Procedia Manuf.* **2019**, *35*, 1286–1296. https://doi.org/10.1016/j.promfg.2019.06.089.
34. Yang, Y.; Boom, R.; Irion, B.; et al. Recycling of composite materials. *Chem. Eng. Process. Process Intensif.* **2012**, *51*, 53–68. https://doi.org/10.1016/j.cep.2011.09.007.
35. Cruz Sanchez, F.A.; Boudaoud, H.; Hoppe, S.; et al. Polymer recycling in an open-source additive manufacturing context: Mechanical issues. *Addit. Manuf.* **2017**, *17*, 87–105. https://doi.org/10.1016/j.addma.2017.05.013.
36. Bledzki, A.K.; Seidlitz, H.; Goracy, K.; et al. Recycling of Carbon Fiber Reinforced Composite Polymers—Review—Part 1: Volume of Production, Recycling Technologies, Legislative Aspects. *Polymers* **2021**, *13*, 300. https://doi.org/10.3390/polym13020300.
37. Mushtaq, R.T.; Wang, Y.; Bao, C.; et al. Multi-objective optimization of laser polishing parameters for enhanced mechanical properties, sustainability, and surface finish of 3D-Printed industrial ABS polymers using response surface methodology (RSM). *J. Mater. Res. Technol.* **2024**, *29*, 3168–3184. https://doi.org/10.1016/j.jmrt.2024.02.023.
38. Al-Mazrouei, N.; Al-Marzouqi, A.H.; Ahmed, W. Characterization and Sustainability Potential of Recycling 3D-Printed Nylon Composite Wastes. *Sustainability* **2022**, *14*, 10458. https://doi.org/10.3390/su141710458.

39. Mohamed, T.S.; Nassef, E.; Morsy, A.; et al. Enhancing 3D printing sustainability: Reinforcing thermoplastic polyurethane with recycled polyurethane foam for durable applications in orthopedic footwear. *J. Vinyl Addit. Technol.* **2024**, *30*, 1153–1163. https://doi.org/10.1002/vnl.22109.
40. Castanon-Jano, L.; Palomera-Obregon, P.; Lázaro, M.; et al. Enhancing sustainability in polymer 3D printing via fusion filament fabrication through integration of by-products in powder form: Mechanical and thermal characterization. *Int. J. Adv. Manuf. Technol.* **2024**, *133*, 1251–1269. https://doi.org/10.1007/s00170-024-13635-3.
41. Kennedy, S.M.; Wilson, L.A.; M, J.A.; et al. Natural fiber filaments transforming the future of sustainable 3D printing. *MethodsX* **2025**, *14*, 103385. https://doi.org/10.1016/j.mex.2025.103385.
42. Ki, D.; Kang, S.Y.; Park, K.M. Upcycling of Wastewater Sludge Incineration Ash as a 3D Printing Technology Resource. *Front. Sustain.* **2021**, *2*, 697265. https://doi.org/10.3389/frsus.2021.697265.
43. Nguyen, H.T.; Crittenden, K.; Weiss, L.; et al. Recycle of waste tire rubber in a 3D printed composite with enhanced damping properties. *J. Clean. Prod.* **2022**, *368*, 133085. https://doi.org/10.1016/j.jclepro.2022.133085.
44. Garg, M.; Rani, R.; Meena, V.K.; et al. Significance of 3D printing for a sustainable environment. *Mater. Today Sustain.* **2023**, *23*, 100419. https://doi.org/10.1016/j.mtsust.2023.100419.
45. Nekin Joshua, R.; Sakthivel, A.R. Reinforced Polymer Composite Filaments in Fused Deposition Modeling of 3D Printing Technology: A Review. *Adv. Eng. Mater.* **2025**, *27*, 2402509. https://doi.org/10.1002/adem.202402509.
46. Agrawal, P.; Lima, P.D.A.; da Cunha, R.B.; et al. Development of acrylonitrile–butadiene–styrene (ABS)/natural fiber composite filaments for innovative 3D and 4D printing. *Polym. Eng. Sci.* **2024**, *64*, 6037–6053. https://doi.org/10.1002/pen.26967.
47. Beg, M.D.H.; Pickering, K.L.; Akindoyo, J.O.; et al. Recyclable hemp Hurd fiber-reinforced PLA composites for 3D printing. *J. Mater. Res. Technol.* **2024**, *33*, 4439–4447. https://doi.org/10.1016/j.jmrt.2024.10.082.
48. Morales, M.A.; Porras, J.; Maranon, A.; et al. Effect of Polypropylene-Grafted-Maleic Anhydride and Rice Husk Particle Size on 3D -Printing Filament Composites from Recycled Polypropylene. *Polym. Compos.* **2025**, *46*, 15125–15141. https://doi.org/10.1002/pc.30118.
49. Fico, D.; Rizzo, D.; De Carolis, V.; et al. Sustainable Polymer Composites Manufacturing through 3D Printing Technologies by Using Recycled Polymer and Filler. *Polymers* **2022**, *14*, 3756. https://doi.org/10.3390/polym14183756.
50. Romani, A.; Tralli, P.; Levi, M.; et al. Metallization of Recycled Glass Fiber-Reinforced Polymers Processed by UV-Assisted 3D Printing. *Materials* **2022**, *15*, 6242. https://doi.org/10.3390/ma15186242.
51. Mantelli, A.; Romani, A.; Suriano, R.; et al. UV-Assisted 3D Printing of Polymer Composites from Thermally and Mechanically Recycled Carbon Fibers. *Polymers* **2021**, *13*, 726. https://doi.org/10.3390/polym13050726.
52. Zhao, P.; Rao, C.; Gu, F.; et al. Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment. *J. Clean. Prod.* **2018**, *197*, 1046–1055. https://doi.org/10.1016/j.jclepro.2018.06.275.
53. Elessawy, N.A.; El Shakhs, A.; Fahmy El-Saka, M.; et al. Sustainable and eco-friendly 3D printing filament fabricated from different recycled solid wastes and evaluate its impact on interior and furniture design. *Results Eng.* **2024**, *23*, 102428. https://doi.org/10.1016/j.rineng.2024.102428.
54. Yadav, K.; Sharma, A.; Siraj, N.; et al. Advanced 3D-Printed Nanocellulose Composites from Cow Dung for UV Shielding and Antibacterial Applications in the Biomedical Sector. *BioNanoScience* **2025**, *15*, 564. https://doi.org/10.1007/s12668-025-02181-1.
55. Sonigara, K.K.; Vaghasiya, J.V.; Mayorga-Martinez, C.C.; et al. Point-of-use upcycling of 3D printing waste for developing 3D-printed Zn–I2 batteries. *J. Mater. Chem. A* **2025**, *13*, 11804–11816. https://doi.org/10.1039/d5ta00919g.
56. Dananjaya, S.A.V.; Chevali, V.S.; Dear, J.P.; et al. 3D printing of biodegradable polymers and their composites—Current state-of-the-art, properties, applications, and machine learning for potential future applications. *Prog. Mater. Sci.* **2024**, *146*, 101336. https://doi.org/10.1016/j.pmatsci.2024.101336.
57. Ashima, R.; Haleem, A.; Bahl, S.; et al. Automation and manufacturing of smart materials in additive manufacturing technologies using Internet of Things towards the adoption of industry 4.0. *Mater. Today Proc.* **2021**, *45*, 5081–5088. https://doi.org/10.1016/j.matpr.2021.01.583.
58. Shahpasand, R.; Talebian, A.; Mishra, S.S. Investigating environmental and economic impacts of the 3D printing technology on supply chains: The case of tire production. *J. Clean. Prod.* **2023**, *390*, 135917. https://doi.org/10.1016/j.jclepro.2023.135917.
59. Stoof, D.; Pickering, K. Sustainable composite fused deposition modelling filament using recycled pre-consumer polypropylene. *Compos. Part B Eng.* **2018**, *135*, 110–118. https://doi.org/10.1016/j.compositesb.2017.10.005.
60. Mishra, V.; Ror, C.K.; Negi, S.; et al. Development of sustainable 3D printing filaments using recycled/virgin ABS blends: Processing and characterization. *Polym. Eng. Sci.* **2023**, *63*, 1890–1899. https://doi.org/10.1002/pen.26330.
61. Mantelli, A.; Levi, M.; Turri, S.; et al. Remanufacturing of end-of-life glass-fiber reinforced composites via UV-assisted 3D printing. *Rapid Prototyp. J.* **2019**, *26*, 981–992. https://doi.org/10.1108/rpj-01-2019-0011.
62. Pemas, S.; Gkiliopoulos, D.; Samiotaki, C.; et al. Valorization of Tomato Agricultural Waste for 3D-Printed Polymer Composites Based on Poly(lactic acid). *Polymers* **2024**, *16*, 1536. https://doi.org/10.3390/polym16111536.

63. Mishra, V.; Negi, S.; Kar, S. FDM-based additive manufacturing of recycled thermoplastics and associated composites. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 758–784. https://doi.org/10.1007/s10163-022-01588-2.
64. Palmer, J.; Ghita, O.R.; Savage, L.; et al. Successful closed-loop recycling of thermoset composites. *Compos. Part A Appl. Sci. Manuf.* **2009**, *40*, 490–498. https://doi.org/10.1016/j.compositesa.2009.02.002.
65. Pickering, S.J. Recycling technologies for thermoset composite materials—Current status. *Compos. Part A Appl. Sci. Manuf.* **2006**, *37*, 1206–1215. https://doi.org/10.1016/j.compositesa.2005.05.030.
66. Palmer, J.A.T. Mechanical Recycling of Automotive Composites for Use as Reinforcement in Thermoset Composites. Ph.D. Thesis, University of Exeter, Exeter, UK, 2009.
67. Pickering, S.J. Thermal methods for recycling waste composites. In *Management, Recycling and Reuse of Waste Composites*; Elsevier: Amsterdam, The Netherlands, 2010; pp. 65–101. https://doi.org/10.1533/9781845697662.2.65.
68. Kaminsky, W. Fluidized bed pyrolysis of waste polymer composites for oil and gas recovery. In *Management, Recycling and Reuse of Waste Composites*; Elsevier: Amsterdam, The Netherlands, 2010; pp. 192–213. https://doi.org/10.1533/9781845697662.2.192.
69. Yip, H.L.H.; Pickering, S.J.; Rudd, C.D. Characterization of carbon fibers recycled from scrap composites using fluidized bed process. *Plast. Rubber Compos.* **2002**, *31*, 278–282. https://doi.org/10.1179/146580102225003047.
70. Blazsó, M. Pyrolysis for recycling waste composites. In *Management, Recycling and Reuse of Waste Composites*; Elsevier: Amsterdam, The Netherlands, 2010; pp. 102–121. https://doi.org/10.1533/9781845697662.2.102.
71. Piñero-Hernanz, R.; García-Serna, J.; Dodds, C.; et al. Chemical recycling of carbon fibre composites using alcohols under subcritical and supercritical conditions. *J. Supercrit. Fluids* **2008**, *46*, 83–92. https://doi.org/10.1016/j.supflu.2008.02.008.
72. Dang, W.; Kubouchi, M.; Sembokuya, H.; et al. Chemical recycling of glass fiber reinforced epoxy resin cured with amine using nitric acid. *Polymer* **2005**, *46*, 1905–1912. https://doi.org/10.1016/j.polymer.2004.12.035.
73. Morici, E.; Dintcheva, N.T. Recycling of Thermoset Materials and Thermoset-Based Composites: Challenge and Opportunity. *Polymers* **2022**, *14*, 4153. https://doi.org/10.3390/polym14194153.
74. Kladovasilakis, N.; Pemas, S.; Pechlivani, E.M. Computer-Aided Design of 3D-Printed Clay-Based Composite Mortars Reinforced with Bioinspired Lattice Structures. *Biomimetics* **2024**, *9*, 424. https://doi.org/10.3390/biomimetics9070424.
75. Cortés, A.; Bañón-Veracruz, M.; Jiménez-Suárez, A.; et al. Enhancing efficiency and sustainability of digital light processing 3D-Printing by novel two-stage processing of carbon nanotube reinforced nanocomposites. *J. Mater. Res. Technol.* **2024**, *29*, 3237–3248. https://doi.org/10.1016/j.jmrt.2024.02.018.
76. Kyriakidis, I.F.; Kladovasilakis, N.; Pechlivani, E.M.; et al. Mechanical Performance of Recycled 3D Printed Sustainable Polymer-Based Composites: A Literature Review. *J. Compos. Sci.* **2024**, *8*, 215. https://doi.org/10.3390/jcs8060215.
77. Gauss, C.; Pickering, K.L.; Graupner, N.; et al. 3D-printed polylactide composites reinforced with short lyocell fibers—Enhanced mechanical properties based on bio-inspired fiber fibrillation and post-print annealing. *Addit. Manuf.* **2023**, *77*, 103806. https://doi.org/10.1016/j.addma.2023.103806.
78. Hassan, M.; Mohanty, A.K.; Misra, M. 3D printing in upcycling plastic and biomass waste to sustainable polymer blends and composites: A review. *Mater. Des.* **2024**, *237*, 112558. https://doi.org/10.1016/j.matdes.2023.112558.