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Review on Comparison of Composite Material Preparation: Traditional vs. Modern Methods and the Future Paradigm Shift

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Abstract: Composite materials have emerged as essential solutions across industries due to their high strength-to-weight ratio, enhanced durability, and tailored functionality. This review presents a comprehensive comparison of traditional and modern composite material preparation techniques, highlighting their process mechanisms, advantages, and limitations. Traditional methods such as hand lay-up, vacuum bagging, and filament winding are evaluated alongside advanced techniques like solution mixing, in-situ polymerization, and additive manufacturing. Particular focus is given to the integration of nanotechnology, natural fiber reinforcements, and digital advancements such as 3D printing and digital twins. Furthermore, the paper identifies current challenges in processing, fiber-matrix compatibility, and sustainability. The study concludes by discussing future directions in smart composite systems, emphasizing eco-friendly materials, machine learning integration, and real-time process monitoring. This paradigm shift redefines composite fabrication for next-generation applications in aerospace, automotive, biomedical, and construction sectors.
Keywords: Composite materials, traditional techniques, modern fabrication methods, 3D printing, natural fiber composites, nanocomposites, additive manufacturing, digital twin, sustainable materials, polymer matrix composites

I. INTRODUCTION

Composite materials have special qualities because they include two or more different components that stay apart in the finished product (Dawoud & Saleh, 2018). Beyond materials science, this idea encompasses natural structures like wood and shells as well as composite images. Composites, as used in materials science, usually comprise a matrix material reinforced with fibers or particles, such as polymers with nanoparticles or concrete with steel bars. Fiber distribution, orientation, and length are only a few of the many variables that affect composite construction, making certification difficult for crucial applications. Nonetheless, the capacity to forecast composite properties is being improved by better models and simulations. The synergistic blending of pre-existing components into composites is an alluring fabrication technique as material development grows more intricate.

Authors composite materials are engineered combinations of two or more constituent materials with distinct features that result in a new material with enhanced qualities. They usually comprise two phases: the matrix phase is made up of metals, polymers, or ceramics, while the reinforcing phase is usually fibers, flakes, or particles Mohamed et al. (2018), and Egbo (2020). In contrast to conventional materials, these materials provide benefits such increased strength, reduced weight, and affordability (Nagavally, 2016). Applications for composites can be found in a number of industries, such as biomedical engineering, automotive, aerospace, and naval. Composites are showing promise as materials for tissue replacement and repair in the biomedical industry, enhancing the use of current ceramic, polymeric, and metallic biomaterials (Egbo, 2020).

Composite material gradually prepared as traditional and modern method. Composite materials have progressed from conventional to novel uses in a variety of industries by combining different ingredients to produce greater qualities (Laeth Hussain et al., 2024). These materials have better wear resistance, a longer lifespan, and are lighter than traditional metals and alloys (Jeevan R et al., 2024). Advanced methods like additive manufacturing, neural networks, and finite element analysis are used in contemporary composite development processes (Valigun Margarita, 2024). Composite performance has been further improved by the incorporation of hybrid fiber reinforcements and nanotechnologies (Laeth Hussain et al., 2024). Combining natural fibers like banana with synthetic fibers like carbon and e-glass creates environmentally beneficial substitutes (Jeevan R et al., 2024). Damage-free machining and uniform nanoparticle dispersion are two issues that still plague production processes (Laeth Hussain et al., 2024).

(A. Bosacka& M. Zienkiewicz-Strzałka, 2020) Composite materials continue to meet market demands and environmental concerns as technology develops, offering prospects for better industrial uses.

II. MATERIAL AND METHOD

Table 2.1 provides a comparative overview of traditional, modern, and advanced methods used in composite material preparation. It outlines each method's key features, advantages, and limitations. Traditional techniques such as hand lay-up and pultrusion offer simplicity and low cost but suffer from inconsistent quality. Modern methods like solution mixing and in-situ polymerization enhance performance and process control but often involve higher complexity or safety concerns. Advanced approaches, including additive manufacturing, digital twins, and machine learning, introduce customization, real-time monitoring, and predictive modeling, though they require sophisticated tools and data infrastructure.

Preparation Method	Category	Key Features	Advantages	Limitations
Hand Lay-Up	Traditional	Manual fiber placement and resin application	Low cost, simple	Inconsistent quality, labor-intensive
Vacuum Bagging	Traditional	Uses vacuum pressure for resin compaction	Better fiber wetting, improved strength	Requires vacuum tools and expertise
Pultrusion	Traditional	Continuous fibers pulled through resin	Uniform profiles, high volume	Limited to constant cross-sections
Spray-Up	Traditional	Simultaneous spraying of resin and fibers	Faster than hand lay-up	Lower finish quality, operator-dependent
Solution Mixing	Modern	Polymer and fillers mixed in solution	Good filler dispersion	Solvent hazards, limited to low loadings
Melt Mixing	Modern	High-temperature extrusion and blending	Scalable, thermoplastic compatibility	Poor dispersion at high filler content
In-Situ Polymerization	Modern	Polymerization occurs with reinforcement	Strong bonding, better properties	Sensitive to reaction conditions
Resin Transfer Molding	Modern	Resin injected into fiber-filled mold	High quality, low void content	High tooling cost, complex control
Electrospinning	Modern	Nanofiber spinning from polymer solution	High porosity, biomedical use	Slow throughput, requires solvent recovery
Additive Manufacturing	Advanced	3D printing from digital model	Custom designs, minimal waste	Limited materials, poor interlayer bonding
Digital Twin Integration	Advanced	Real-time virtual modeling	Process optimization, defect prediction	Requires IoT sensors and simulation models
Machine Learning	Advanced	Data-driven modeling and prediction	Optimizes materials and processes	Needs large datasets, model validation

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A. Methods of Preparing Traditional Polymer Composites

1) The Hand Lay-Up Technique

The earliest and most basic approach. Glass or carbon fibers are examples of reinforcing fibers that are manually inserted into a mold. Over the fibers, polymer resin (such as polyester or epoxy) is brushed or poured. The composite is either mildly heated or let to cure at room temperature. utilized for automobile parts, aircraft parts, and boat hulls. The traditional method for preparing a polymer composite is called hand lay-up. One popular approach for creating polymer composites, especially glass fiber reinforced epoxy composites, is the hand lay-up method. Fillers like TiO2 can be added to improve mechanical qualities using this straightforward and affordable process (Mahmood et al., 2017). However, hand lay-up might produce somewhat less tensile strength .Spray, press molding, transfer molding, vacuum molding, cold molding, autoclave molding, filament winding, and matrix injection are further techniques used in the production of fiber-reinforced polymer composites (Ismayilova et al., 2024). Cost-effective, automated fabrication with better control over defects is the main emphasis of recent developments in composite manufacturing (Uzay & Geren, 2020).

2) Open mold casting:

Similar to hand lay-up, but the mold is open on one side, allowing for easier access to the fiber placement. A flexible technique for creating polymer composites, open mold casting is especially well-suited for generating intricate pieces on a small scale (Tuzhilin et al., 2020). The procedure uses spray-up or hand lay-up methods with thermoset resins such as epoxy vinyl esters and unsaturated polyesters (Andresen, 2001). Aluminum, isocyanate foam, and 3D-printed PLA are among the materials that have been investigated for molds; aluminum works well for materials such as PDCPD (Grabowski et al., 2017). Although automation is still difficult, advanced methods like centrifugal casting can improve mechanical qualities (Talapov& Melnikov, 2020). A new technique that blends polymer synthesis and processing, vacuum-assisted free casting works well with thermosets and some thermoplastics (Tuzhilin et al., 2020). For small quantities, open molding provides cost-effectiveness and design freedom; nevertheless, to get the appropriate short- and long-term qualities in the finished composite, it necessitates careful material selection and professional workmanship (Andresen, 2001).

3) Vacuum bagging:

Applying vacuum pressure to the mold during curing to remove air bubbles and improve fiber consolidation. An improved technique over conventional hand lay-up methods for creating polymer composites is vacuum bagging. Higher fiber volume fractions and improved mechanical qualities are the results of this technique, which uses vacuum pressure to eliminate air and extra resin (Hall &Javanbakht, 2021). Tensile strength can be increased by 2-6%, tensile/flexural modulus by 11-15%, interlaminar shear strength by 5-6%, impact strength by 15-20%, and hardness by 1-3% when vacuum bagging is used instead of manual lay-up (Muralidhara et al., 2020). By lowering the void content, a double-vacuum-bag method can enhance composite quality even further (Ren et al.,). In contrast to vacuum bagging and hand lay-up techniques, one study found that vacuum infusion produced the highest ultimate tensile strength of 346.15 MPa and average modulus elasticity of 10673.4 MPa (Abdurohman et al., 2018). This suggests that vacuum infusion may produce even better results. Vacuum bagging overcomes many of the drawbacks of wet layup procedures, although it does require additional tools and expertise (Hall &Javanbakht, 2021).

4) Pultrusion

Continuously pulling a reinforced fiber strand through a resin bath, resulting in a consistent profile. A continuous manufacturing method for creating polymer composite profiles with consistent cross-sections is pultrusion (Joshi, 2012). Because thermoplastic pultrusion can be recycled and reprocessed, it is becoming more popular than thermoset pultrusion (Minchenkov et al., 2021). Pre-impregnated thermoplastic tapes that can be manufactured via pultrusion and compression molding are one example of recent developments (Esfandiari et al., 2022). Despite its benefits, thermoplastic pultrusion is still less widely used than thermoset pultrusion (Minchenkov et al., 2021).Pultruded composites' increasing applications, material qualities, and process efficiency are the main areas of ongoing study (Joshi, 2012).

5) The Spray-Up Technique

Spraying chopped fibers and resin onto a mold is comparable to hand lay-up; it uses a spray pistol to distribute fibers and resin simultaneously; it is quicker than hand lay-up, but the composites are of worse quality. Used in the building of large items such as tanks and bathtubs.

Both short and long fiber reinforced polymers (FRP) can be manufactured using the flexible spray-up technique.

According to (Zegeye et al.2023), it has benefits including shorter impregnation times and fewer product flaws. The method is effective and flexible enough to accommodate design modifications since it concurrently sprays matrix resin and cut reinforcements onto a mold (Kikuchi et al., 2013).

Although it has historically been applied to glass fibers, more recently, research has looked at its usage with carbon fiber reinforced polymers (CFRP) (Kikuchi et al., 2013). To enhance manufacturing processes, motion capture techniques can be used to examine operator skill, which determines the quality of spray-up composites (Kikuchi et al., 2013).

An advanced spray multiple layup approach has been presented to address quality control restrictions such inconsistent thickness and fiber loading. This process incorporates updated gun-calibration procedures and spray skills that are advocated by industry groups (Ha et al., 2015). Spray-up can be utilized in open molding procedures and is especially well-suited for producing a variety of shapes (Andresen, 2001).

6) Compression Molding

A conventional technique for preparing composites is compression molding, which uses molds and pressure to shape resin and fiber mixtures into the required geometries (Warden, 2018). Although steel or aluminum are commonly used to make traditional compression molds, newer studies have looked into other materials and methods.

The use of thermoplastic materials in additive manufacturing has been studied as an affordable and accessible way to create compression molds, generating parts with strengths that are on par with those produced using aluminum molds (Warden, 2018). An optimized process called compression resin transfer molding (CRTM) has been developed, combining traditional resin transfer molding and compression molding to produce high-performance carbon fiber-reinforced epoxy composites with superior mechanical properties and reduced porosity (Sun et al., 2018).

Furthermore, using bulk molding compounds and specialized tooling ideas for precise temperature control, compression molding of long chopped fiber thermoplastic composites has demonstrated potential for producing complicated, high-performance parts at greater production rates

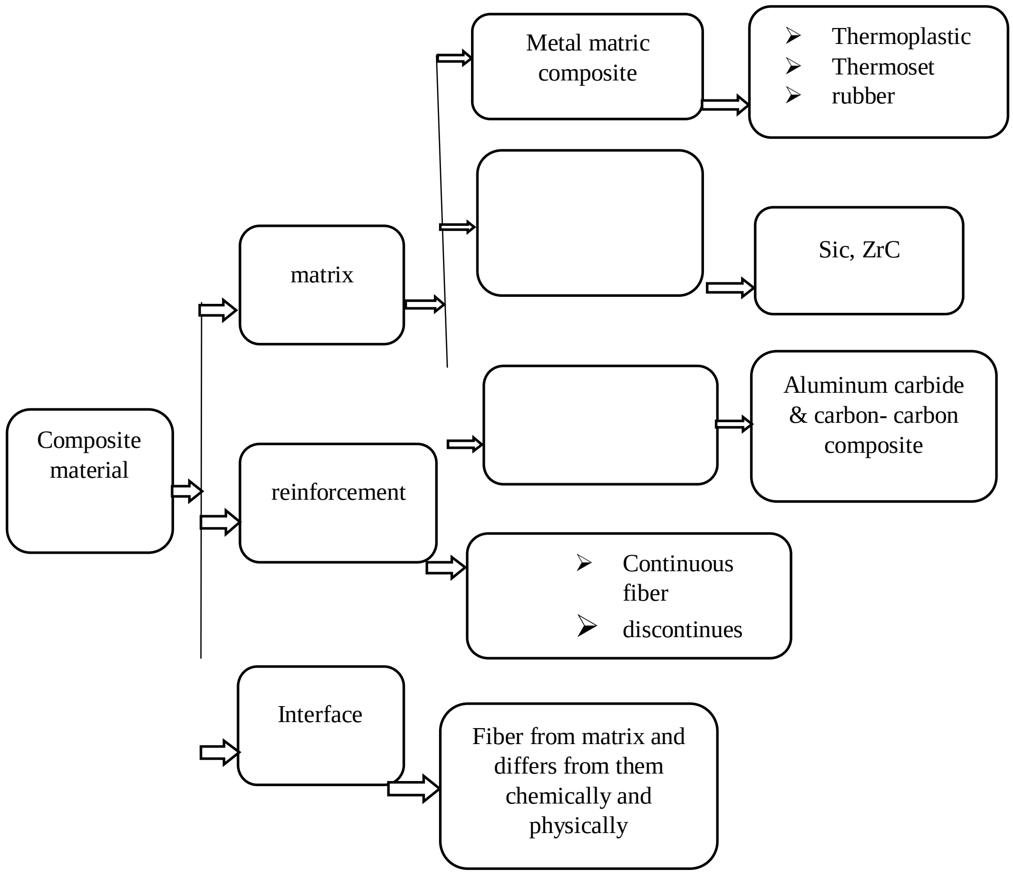
7) Winding Filament

Resin is applied to continuous fibers that have been coiled around a revolving mandrel.

creates spherical or cylindrical structures with exceptional strength. Usedto make rocket casings, tanks, and pipes. A manufacturing process called filament winding is used to create polymer composite structures, especially pipes and tubes (Andrianov et al., 2022; Metodieva et al., 2016). Continuous fibers impregnated with a polymer matrix are wound around a mandrel in this procedure (Misri et al., 2015; Özbay et al., 2020). Fiber orientation, tension, and winding velocity are important considerations in filament winding design (Pop Metodieva et al., 2016). Although thermoplastics may provide difficulties because of their high melt viscosity, the method can be applied to both thermosetting and thermoplastic matrices (Özbay et al., 2020). The use of hybrid yarn thermoplastic composites to solve problems with fiber dispersion and wetting (Özbay et al., 2020) and the development of low-cost filament winding technology for academic and startup environments (Andrianov et al., 2022) are examples of recent developments. The successful incorporation of natural fibers, like kenaf, into filament-wound composites has also increased the range of materials available (Misri et al., 2015).

Figure 2.1: Types of Fibers in Composites

Figure 2.1 illustrates the two primary types of fibers used in composite materials: continuous fibers and discontinuous (short) fibers. Continuous fibers provide high strength and stiffness along the length of the fiber, making them suitable for structural applications, while discontinuous fibers are easier to process and are commonly used in molded composite parts. The selection between these types depends on the desired mechanical properties and fabrication method.



B. Modern methods for preparing polymer composites

1) Mixing

Dispersing filler materials (such as fibers or nanoparticles) and dissolving polymers in solvents. With benefits over other processes including melt mixing and ball milling, solution mixing is a popular methodology for creating polymer-carbon nanocomposites (Rahaman et al., 2019). Although melt mixing might work better at greater loadings, it can improve the dispersion of carbon nanotubes (CNTs) in polymer matrices at low filler concentrations (Sui et al., 2019). In contrast to ball milling, solution mixing has been demonstrated to evenly distribute CNTs in metal matrix composites without resulting in structural damage (Kumar et al., 2023). Additionally, this process improves the final composites' thermal stability. A solution casting technique enhances nanofiller dispersion in fused filament fabrication (FFF) 3D printing, resulting in a greater Young's modulus, less fluctuation from part to part, and the capacity to employ higher nanofiller loadings (Ledford et al., 2021).

2) Melt Mixing (Extrusion & Injection Molding)

Melt mixing, which involves the distributive and dispersive mixing of high-viscosity fluids, is an essential step in the creation of composites (Kajiwara & Nakayama, 2011). Several polymer composites, such as polycarbonate/multi-wall carbon nanotube (MWNT) composites, poly(lactic acid)/layered silicate nanocomposites (Mohapatra et al., 2012), and polypropylene/MWNT composites, have been successfully made using this technique. Improved mechanical and thermal stability result from the process's ability to disperse and align nanofillers inside the polymer matrix. For example, at only 0.25 weight percent loading, MWNT inclusion in polypropylene produced a 138% increase in modulus and a 32% improvement in toughness. Additionally, melt mixing can change the polymer matrix's glass transition temperature and crystalline shape.

3) In-Situ Polymerization

Strong interfacial bonding is produced when monomers are polymerized in the presence of reinforcing materials. High-performance composites, such as carbon-fiber-reinforced polymers (CFRP), use these materials.

The procedure has been used in a number of systems, such as fiber-reinforced composites and nanocomposites. For example, as compared to traditional melt-mixed composites, kaolin/Nylon-6 composites made by in-situ polymerization demonstrated superior filler dispersion, a higher glass transition temperature, and enhanced mechanical characteristics. Likewise, nylon 3 and poly (phenylene terephthalamide) all-polyamide molecular composites demonstrated improved strength and modulus without compromising flexibility. In comparison to thermoset-based composites, recent developments have included the creation of quick manufacturing procedures for multifunctional nanocomposite components, which offer benefits including shorter cycle times, increased production efficiency, and simpler recycling (Gupta et al., 2019).

4) Resin Transfer Molding (RTM)

A mold filled with reinforcing fibers is filled with liquid resin, creating precisely controlled high-strength composites. Common in aerospace and automotive applications. In the process of creating composites, low-viscosity thermoset resins are injected into a mold that has fiber reinforcement. This process is known as resin transfer molding, or RTM. Low volatile emissions, lower tooling costs, and high-quality products are some benefits of RTM (Hedley, 1994). Race tracking, fiber deformation, and void creation are some of the process's difficulties, nevertheless (Sozer et al., 2012). In order to comprehend and optimize RTM, process modeling is essential, and academics have created a number of models to solve these problems. Mold deflection, capillary action, flow rate, and processing parameters are some of the variables that impact part quality. Local pressure has been identified as a critical element in the investigation of macrovoid development and migration using a two-phase flow model. When correctly designed and managed, RTM may produce high-quality parts despite its complexity.

5) Electrospinning

Compared to traditional preparation techniques, this method improves the thermal and mechanical properties of composites by increasing filler dispersion and interfacial bonding. Polymer solution is electrically spun into nanofiber composites. Used in biomedical and filtration applications. The use of conductive nanoparticles increases jet flow velocity and decreases fiber diameter, according to numerical analysis of the electrospinning process (Ahmed & Xu, 2020). Because of their high surface area, high aspect ratio, and porosity, electrospun nanofiber composites are appealing for a range of energy, environmental, and medical applications (Toriello et al., 2020). The limitations of neat nanofibers, such as their poor mechanical strength and thermal instability, have been addressed by the development of composite and modified nanofibers with improved properties, which are the result of recent advances in materials science and modification techniques (Toriello et al., 2020).

6) Additive Manufacturing(3D Printing)

Additive manufacturing, another name for 3D printing, is a game-changing technique that creates things from digital models' layer by layer (Chen et al., 2020). It has developed quickly, reaching a wide range of industrial applications in many industries in addition to rapid prototyping (Bogue, 2013). 3D printing improves workflow and precision in orthodontics by enabling the production of customized dental appliances (Slaymaker et al., 2023). The technology's increasing influence on manufacturing and healthcare is demonstrated by its adaptability in creating prosthetics and medical implants. Significant changes in the development and production of items are anticipated as the possibility for personal manufacturing and creative applications grows with the accessibility of 3D printers (Bogue, 2013). Composite material 3D printing has become a cutting-edge manufacturing method that provides design flexibility and the ability to fabricate complicated structures with little waste (Nugroho et al., 2021). This technology includes a number of techniques, such as vat photopolymerization, powder bed fusion, and material extrusion (Nugroho et al., 2021; Somireddy, 2021). High-performance composites with improved mechanical, electrical, thermal, and optical properties have been created as a result of the addition of fillers and material mixing (Kalsoom et al., 2016). Authors concentrating on creating in-house materials utilizing different reinforcements and matrices, and polymer matrix composites (PMCs) have drawn special attention (Singh et al., 2020). Applications for 3D printed composites' adaptability can be found in a variety of industries, including the jewelry, automobile, aerospace, and biomedical sectors (Singh et al., 2020). To fully utilize the promise of this disruptive technology, there are still obstacles to overcome in terms of increasing the variety of printable materials and enhancing their qualities (Kalsoom et al., 2016).

In order to improve the properties of polymer matrices, different fillers and nanoparticles are incorporated into them during the modern polymer composites preparation process. Small amounts of nanosized particles are added to create nanocomposites, which have amazing improvements in mechanical, structural, and physical properties (Pandey, 2020).

Recent trends focus on developing biodegradable and biocompatible composites employing natural fibers and matrices as eco-friendly alternatives to petrochemical-based products (Haina et al., 2020). Electrophysical qualities can be modified by selecting appropriate fillers, adjusting their number and particle sizes, to generate antistatic products and electromagnetic protective coatings (Kakhramanov et al., 2019). Filler materials have a key role in increasing mechanical properties, decreasing costs, and enhancing surface finish and thermal properties of polymer composites (Kumar et al., 2018). Extrusion, sol-gel processes, sputtering, and physical evaporation deposition are some of the preparation techniques (Pandey, 2020). High-strength, heat-resistant, and electroconductive composites can be made in novel ways thanks to the development of hybrid polymer nanocomposites and mechanical-chemical synthesis techniques (Kakhramanov et al., 2019)

C. Nano-Enhanced Polymer Composites

These composites increase mechanical, thermal, and barrier properties by incorporating inorganic nanoparticles or nanomaterials into polymer matrices (Diez-Pascual, 2022). These nanocomposites are made using a variety of synthetic processes, including melt-intercalation, monomer intercalation, and standard solvent approaches. When added to polymers, graphene and its functionalized derivatives show promise as nanofillers, providing better mechanical, electrical, and physical. The performance of the composite can be further enhanced by surface modifications of graphene nanostructures (GNS), which can improve their dispersion inside the polymer matrix (Saravanan et al., 2014). New opportunities for polymer modification have been made possible by the advent of nanoscale composite technology, which has advanced polymers' functionality and potency.

D. Natural challenge of preparing composite

Natural fiber reinforced polymer composites (NFRP) have drawn interest because of its affordability and environmental advantages. However, there are still issues with their preparation, such as hydrophilicity, poor fiber-matrix interaction, and variations in fiber (Shah et al., 2019). Chemical pre-treatments to improve adhesion are frequently used to overcome these problems. For the fabrication of bio-composite materials, processing methods like extrusion, injection molding, and compression molding are frequently employed. Creating sustainable composites from bio-based household and industrial waste, including as cellulose, chitin, and keratin sources, has been the subject of recent study. Although these materials have special qualities and advantages for the environment, more study is required to resolve issues and maximize their effectiveness (Rehman et al., 2024).

E. Non-natural challenge

Because they are environmentally beneficial and have the potential to replace synthetic materials, natural fiber-reinforced composites are becoming more and more popular. However, there are several difficulties in their machining, processing, and preparation. Carefully choosing procedures and parameters is necessary for the synthesis and creation of these composites. Fiber properties can be enhanced by a variety of retting procedures, chemical treatments, and surface alterations. Additional difficulties arise from machining processes, which are frequently required as secondary processing. One of the biggest barriers to possible applications is still the lack of basic understanding in raw material processing for composite manufacturing. Natural fiber-reinforced composites have potential qualities such non-toxicity, environmental friendliness, and good specific loading applications, despite these difficulties (Seal et al., 2022).

F. 3D paradigm shifts issues

With its ability to provide personalization, on-demand production, and decreased waste, 3D printing is a paradigm change in both manufacturing and healthcare (Wijk & Wijk, 2015). For better surgical planning and treatments, this technology makes it possible to create intricate, patient-specific designs (Ryan et al., 2017). A sustainable and circular economy that moves away from plastics derived from fossil fuels is promised by the combination of 3D printing and biomaterials (Wijk & Wijk, 2015). 3D printing is revolutionizing individualized healthcare in the medical field by bridging several fields to provide patient-centered care (Thomas & Singh, 2021). Although the technology has a lot of promise, there are procedural issues with its clinical integration, and more quantitative research of the results and financial effects is needed (Ryan et al., 2017). Notwithstanding these obstacles, 3D printing is developing quickly and is anticipated to transform healthcare delivery, international commerce dynamics, and manufacturing processes (Thomas & Singh, 2021).

G. Challenge in 3D printing

There are many obstacles that 3D printing must overcome in a variety of applications. Material restrictions, robot system limits, design complexity, and regulatory considerations are important difficulties in the construction industry (Romdhane et al., 2020). Mechanical strength, form complexity, pore optimization, and vascularization are major challenges for bone substitutes (Masaeli et al., 2019). Technical issues in manufacturing include laborious design procedures, a lack of material possibilities, poor precision, and low efficiency; managerial issues include database administration, intellectual property rights, and corporate innovation (Chen & Lin, 2017). Resolution and accuracy are the main issues for electrochemical and microfluidic applications, which are categorized into process, material, size, and application categories (Kumar et al., 2019). Notwithstanding these difficulties, 3D printing has advantages including quicker building, lower costs, more geometric freedom, sustainability, and enhanced safety (Romdhane, 2020). Despite significant advancements, several challenges remain in the 3D printing of polymer composites. Among the many benefits of additive manufacturing (AM) of polymer composites include rapid prototyping, waste minimization, and adjustable geometries (Shelare et al., 2023; Gajbhiye et al., 2024). However, a number of obstacles prevent its broad use. These include the requirement for better mechanical qualities, limited material availability, and subpar product quality (Park et al., 2022). Material jetting, fused deposition modeling, stereolithography, and selective laser sintering are important AM techniques for polymer composites (Krawczak, 2015). Researchers stress the need to increase the number of appropriate polymer and composite materials, lower costs, improve surface polish, increase dimensional stability, and provide better process modeling and simulation tools in order to overcome the limits that now exist (Krawczak, 2015). Electronics, automotive, medical, and aerospace are just a few of the industries that use 3D-printed polymer composites (Gajbhiye et al., 2024). To fully utilize AM for polymer composites in high-performance applications, future research should concentrate on resolving these issues (Shelare et al., 2023).

H. Main challenges

- Restricted Choice of Materials
- Issues with Printability
- Poor Interlayer Bonding Nozzle Clogging
- Mechanical and Thermal Restrictions Exorbitant Manufacturing Costs
- Post-processing treatment

I. Defects in 3D printed PLA composite

The mechanical characteristics and manufacturing flaws of PLA composites provide difficulties for 3D printing. Carbon fiber-reinforced PLA composites flaws are greatly influenced by processing factors, according to micro-CT research; porosity increases with lower feed rates (Wu et al., 2023). When compared to compression-molded samples, FFF-printed PLA has a lower modulus and tensile strength; however, adding cellulose nanofibers can improve mechanical qualities and minimize voids (Ambone et al., 2020). According to (Kuentz et al.,2016), metal-reinforced PLA composites have higher porosity, which could result in worse mechanical characteristics. Researchers have created a variety of PLA composites with enhanced qualities for certain uses, like electrical conductivity, tissue engineering, and biomedicine, in order to overcome these problems (Tumer et al., 2021).

J. 3D Printing Making the Digital Real

1) 3D printing in Digital twin

Digital twins (DT) are showing promise as a way to overcome 3D printing's problems, especially in additive manufacturing and concrete printing. DTs facilitate real-time data transmission and analysis by offering virtual representations of real-world objects (Sundara et al., 2020). By eliminating trial-and-error methods, they can optimize 3D printing procedures, save expenses, and enhance quality (Kantaros et al., 2021; Wang et al., 2023). From design to production and maintenance, DT applications in 3D printing cover a range of lifecycle stages (Wang et al., 2023). Real-time 3D printer monitoring and control can be made easier with augmented reality-enabled DTs (Sundara et al., 2020). However, due to a lack of knowledge about their idea and development techniques, the full potential of DTs in 3D printing has not yet been achieved (Kantaros et al., 2021. These knowledge gaps must be filled in order to improve DT deployment in 3D printing technologies across industries (Bhattarai et al., 2022). Digital twin (DT) technology is increasingly being utilized to 3D printing of PLA composites, allowing real-time monitoring and control of the manufacturing process. DT coupled with ultrasonic assessment can evaluate material qualities and alter printing parameters to obtain desired outcomes (Pozhanka&Zagrai, 2024).

DT can be combined with machine learning techniques, like random forest classifiers, to forecast printed component performance using simulations and experimental data (Butt &Mohaghegh, 2022). IoT-based sensors for digital twinning and heritage building monitoring could be made from PLA composites like ABS-PLA-Al (Kumar et al., 2023). By improving mechanical qualities and broadening applications in domains including biomedical, tissue engineering, and smart textiles, PLA composites overcome the drawbacks of pure PLA in 3D printing (Tumer & Erbil, 2021).

2) Virtual 3D printing

For evaluating and refining additive manufacturing processes, virtual 3D printing simulation has become a useful tool. Before physical manufacturing, users can evaluate print quality and identify possible problems using voxel-based simulators that mimic the layer-by-layer manufacture of 3D objects (Ueng et al., 2018; Ueng et al., 2017). These simulators provide more in-depth insights than traditional line-based methods by revealing the internal and external architecture of virtual models (Ueng et al., 2017). With the development of 3D printing technology, its uses are becoming more varied and include medical implants, replacement parts, and prototyping. Additionally, designers are now able to produce items with customized material properties because to recent advancements in micro-level multi-material printing (Carver, 2015). Innovative applications in areas like free-form solar cells, lighting products, and lightweight mechatronics are being made possible by the advancements in virtual material design, which are being bolstered by multi-physics simulation and multiscale modeling (Carver, 2015).

3) 3D printing in machine learning of PLA composite

The creation of polylactic acid (PLA) composites has been greatly influenced by recent developments in 3D printing and machine learning (ML). In their investigation into the creation of PLA composites reinforced with carbon fiber, Hu et al. (2020) showed that a higher carbon fiber content improves mechanical and thermal properties, with ML forecasting peak performance at 6.7 weight percent carbon fiber. The electro-mechanical study of nanostructured polymer matrix composites was the main emphasis of Hossain et al. (2022, 2024), who emphasized the use of machine learning (ML) to optimize processing parameters and enhance mechanical properties by including titanium dioxide nanoparticles. According to their results, machine learning is capable of accurately forecasting extrusion temperatures and establishing a correlation with the materials' microstructural properties. In their thorough analysis of biodegradable polymers in 3D printing, Dananjaya et al. (2024) addressed issues with mechanical qualities and recycling while highlighting the use of machine learning (ML) for material preparation and design adaption. When taken as a whole, these researches highlight how 3D printing and machine learning may revolutionize sustainable production.

K. Tax credit for research in 3D printing

With current developments in sustainable materials reducing environmental consequences, 3D printing in ecology offers time and cost advantages for producing unique equipment and experimental objects (Behm et al., 2018). 3D printing speeds up the drug discovery and development process in cancer research, allowing for the production of personalized medical devices, bioprinted cancer cell models, and anticancer medications (Li et al., 2021). The growing number of papers shows how popular the technology is, with universities in Europe, Asia, and the Americas conducting the majority of the research (Ruggeri Pereira et al., 2019). Recent developments include composite printing for piezoelectric devices, volumetric 3D printing for faster production, and the capacity to print a variety of materials, such as metals suitable for spaceships and living cells (Karakurt & Lin, 2020).

III. RESULTS AND DISCUSSION

This review provides a comparative synthesis of the evolution of composite material preparation from traditional to advanced methods. Traditional techniques such as hand lay-up, vacuum bagging, filament winding, and pultrusion continue to be widely used in industrial sectors due to their low cost, ease of implementation, and suitability for large structural components. These processes, although robust, are often labor-intensive and present challenges in achieving consistent fiber distribution, void-free matrices, and high-performance mechanical properties.

In contrast, modern fabrication methods like melt mixing, in-situ polymerization, solution mixing, and resin transfer molding (RTM) offer superior control over microstructure, fiber-matrix interaction, and filler dispersion. Melt mixing and solution casting enable scalable manufacturing of nanocomposites by facilitating uniform distribution of nano-fillers such as carbon nanotubes (CNTs), graphene, and metal oxides, which significantly enhance thermal, electrical, and mechanical properties of polymer matrices. For instance, in-situ polymerization has shown to improve interfacial bonding and glass transition temperatures, resulting in composites with higher durability and resistance to environmental degradation.

Moreover, the integration of advanced digital manufacturing tools such as additive manufacturing (3D printing) has revolutionized the composite fabrication landscape. Additive manufacturing enables layer-by-layer construction of components with complex geometries, customized structures, and reduced material wastage. When combined with nanotechnology, such as PLA reinforced with carbon or cellulose nanofibers, 3D printed composites can achieve high specific strength and tailored functionalities. However, common issues include interlayer adhesion defects, nozzle clogging, and material anisotropy.

Recent developments in Digital Twin (DT) technology and Machine Learning (ML) applications present a paradigm shift. Digital twins enable real-time simulation and monitoring of composite fabrication processes, optimizing parameters such as temperature, pressure, and feed rate. ML models, trained on large datasets, are being used to predict mechanical behavior, failure modes, and microstructural features, improving consistency and reducing trial-and-error in composite design.

Despite these advancements, several limitations persist. Printability of hybrid composites is often restricted by rheological incompatibilities. Natural fiber-based composites face inconsistencies in fiber properties, leading to variability in mechanical strength and thermal stability. Additionally, eco-friendly bio-composites often suffer from high moisture absorption and poor compatibility with polymer matrices, limiting their applicability in high-stress environments.

IV. RESEARCH GAP

Although the field of composite materials has witnessed significant innovation, critical research gaps remain. Many fabrication techniques are still evaluated at laboratory scale, with limited demonstration of scalability and industrial reproducibility. This gap is particularly evident in 3D printed composites, where performance inconsistencies and lack of standardized testing under dynamic conditions hinder broader adoption.

Furthermore, the integration of Machine Learning with Digital Twin ecosystems in real-time composite manufacturing remains underexplored. While promising, current studies mostly simulate ideal conditions, and the lack of robust datasets for training models limits predictive accuracy. Another critical issue is the performance predictability of natural fiber-reinforced composites, which varies due to inconsistent fiber morphology, environmental degradation, and poor fiber-matrix adhesion.

Sustainability remains a pressing concern. Although biodegradable composites from agricultural or industrial waste show potential, their lifecycle assessments, end-of-life recyclability, and economic viability are not well-studied. The challenge of simultaneously achieving environmental sustainability, high mechanical performance, and cost-effectiveness continues to constrain mainstream adoption.

V. FUTURE SCOPE

Looking forward, future research should prioritize the standardization of composite fabrication protocols to bridge the gap between laboratory-scale experimentation and industrial-scale production. This includes developing universal metrics for evaluating printability, fiber dispersion quality, and interlayer adhesion in additive manufacturing of composites.

Research should also focus on enhancing interfacial adhesion mechanisms, particularly for natural fiber and hybrid composites, through advanced surface modifications such as plasma treatments, coupling agents, or nanocoatings. These approaches can significantly improve durability, moisture resistance, and load transfer efficiency.

Furthermore, the integration of AI/ML and Digital Twin frameworks should be scaled from simulation environments to real-time feedback systems in manufacturing. This would enable predictive process control, defect detection, and optimization of resource consumption, thereby transforming composite manufacturing into a fully intelligent, self-correcting process.

Sustainability-driven innovations, including the development of biodegradable, self-healing, and recyclable nanocomposites, are also expected to dominate future research. Hybrid composites that combine renewable fibers with nanomaterials like graphene, MXenes, and cellulose nanocrystals can unlock multifunctional properties essential for next-generation applications in aerospace, defense, and biomedical engineering.

VI. CONCLUSION

The comparative review of traditional and modern composite preparation techniques highlights a transformative shift in material engineering. While traditional methods like hand lay-up and pultrusion continue to provide value in large-scale and cost-sensitive applications, modern and digital approaches offer precision, functional enhancement, and customization capabilities.

The convergence of nanotechnology, additive manufacturing, machine learning, and digital twins has created a new frontier in smart and sustainable composite manufacturing. However, unresolved issues such as variability in natural fibers, interfacial bonding deficiencies, and lack of industrial-scale validation call for sustained research efforts.

Ultimately, the future of composite materials lies in developing eco-compatible, intelligent, and high-performance systems that align with Industry 4.0 principles and circular economy goals. Collaborative research across materials science, data science, and manufacturing domains is key to unlocking the full potential of composites in global industries.

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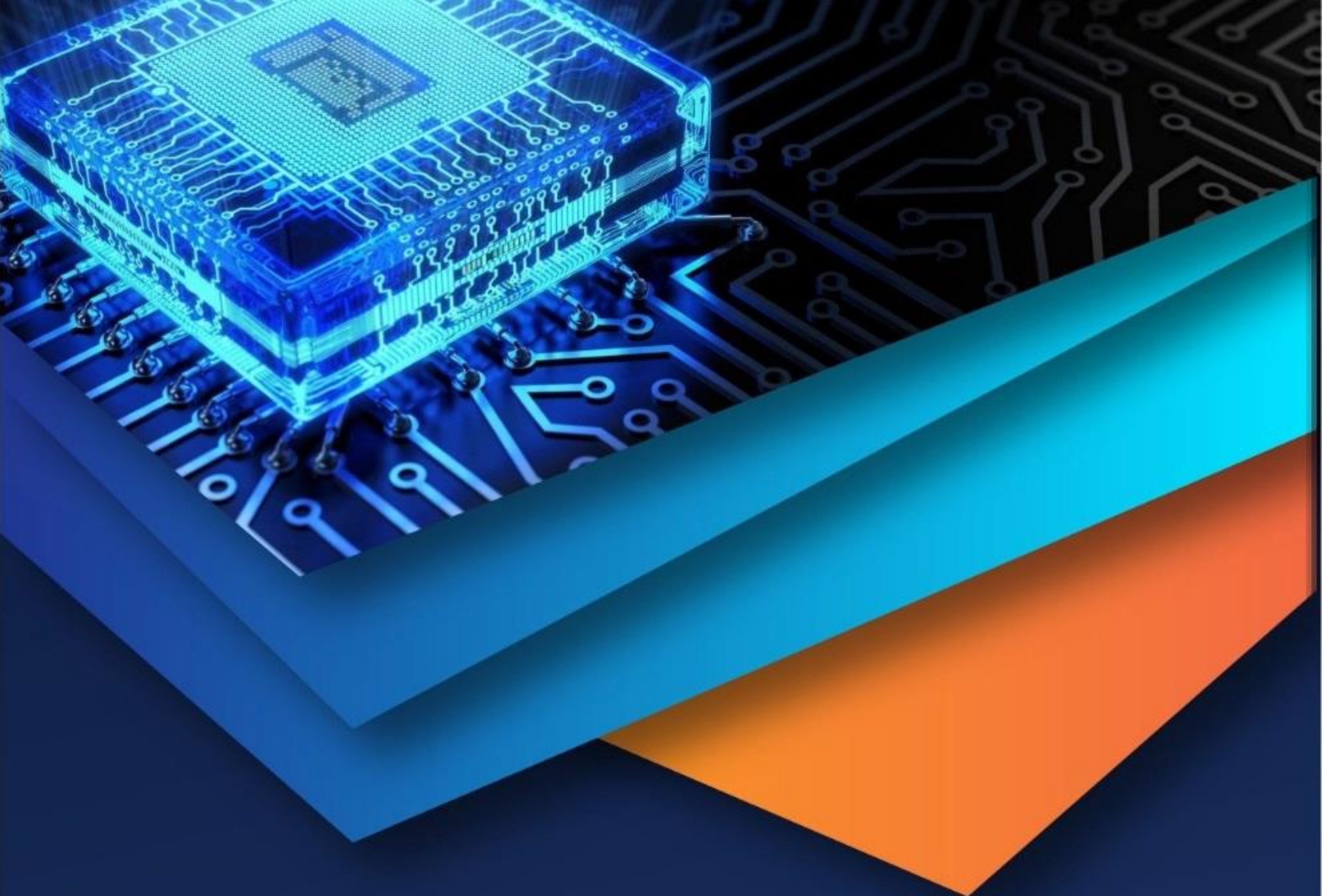

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