

# Carbon Nanotube-Reinforced Polymer Filaments for Fused Deposition Modelling in Oil and Gas Applications: A Critical Review of Dispersion, Percolation, and Process-Structure-Property Relationships

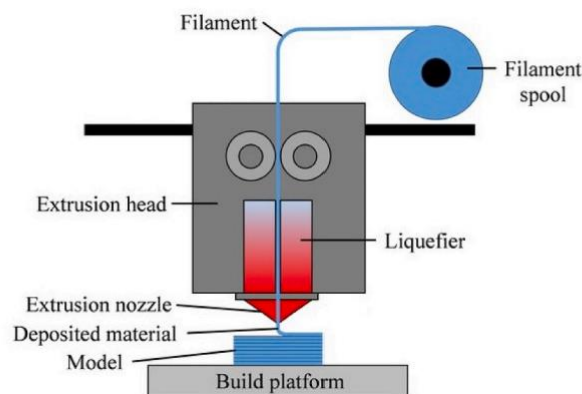
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**Abstract** - Carbon nanotube (CNT)-reinforced polymer filaments have attracted significant attention as multifunctional materials for fused deposition modeling (FDM), offering the potential to improve the mechanical, electrical, and thermal performance of printed components. Their lightweight nature and compatibility with additive manufacturing make them particularly attractive for demanding oil and gas applications. However, reported property enhancements are often inconsistent due to challenges associated with CNT dispersion, interfacial bonding, processing conditions, and FDM-induced anisotropy. This review critically examines the current state of CNT-reinforced FDM materials, focusing on the relationships between CNT characteristics, dispersion methods, processing parameters, and resulting properties. Key challenges, including printability limitations, electrical percolation variability, and mechanical performance trade-offs, are evaluated alongside conflicting interpretations of CNT reinforcement mechanisms. Particular attention is given to the suitability of these materials for oil and gas environments, where exposure to high temperatures, corrosive fluids, and cyclic loading demands exceptional durability. The review identifies a significant gap between laboratory-scale demonstrations and industrial deployment, highlighting the lack of standardized testing protocols and long-term environmental validation studies. A process–structure–property framework is proposed to guide future research, together with recommendations for durability assessment and application-driven testing. While CNT-reinforced FDM materials show considerable promise, their successful adoption in oil and gas applications will require improved dispersion control, process optimization, and rigorous qualification under service-relevant conditions.

**keywords:** Carbon nanotubes; Fused deposition modelling; Polymer nanocomposites; Additive manufacturing; Oil and gas materials; Electrical percolation; Dispersion; Multifunctional composites

## 1. INTRODUCTION

In the drive for lighter, corrosion-resistant materials, the oil and gas industry is exploring advanced composites. Additive manufacturing (AM) by Fused Deposition Modeling (FDM) as shown in Figure 1 offers design freedom and on-demand fabrication, but conventional FDM polymers such as ABS, PLA, Nylon) suffer from *limited mechanical strength, thermal stability, and chemical resistance* compared to metals (Danylenko & Lipovskyi, 2025) (Simunec et al., 2023). Carbon nanotubes (CNTs), with their exceptional mechanical stiffness (~1 TPa), tensile strength, and electrical/thermal conductivity, are natural candidates for reinforcement (Pratyush Behera et al., 2020) (Azeez, 2022; Meftahi et al., 2025). Figure 2 illustrates a high-aspect-ratio carbon-fiber fabric as an analog for CNT alignment. Incorporating small weight fractions of CNTs into polymers has been widely reported to increase modulus, strength, and enable conductivity (Fenta & Mebratie, 2024; Zeinedini et al., 2026)



**Figure 1:** Schematic illustration of typical FDM printer and its key components (Hosseinzadeh et al., 2025)

However, critical questions arise: Do CNTs truly deliver the transformative gains suggested, or are the reports overly optimistic? Are these enhancements reproducible in realistic FDM processes? This review scrutinizes such claims. We first outline the theoretical basis of CNT reinforcement and percolation (Section 2), then critically examine processing/dispersion issues (Section 3), mechanical and multifunctional properties (Sections 4–5), and FDM-specific anisotropy (Section 6). The core question: Can CNT–FDM filaments meet the demanding criteria of oil and gas applications, or do they remain mainly lab curiosities? We synthesize evidence to reveal contradictions and gaps, and propose directions to align research with industrial needs. All major statements are supported by recent references from 2021–2026.

## 2. THEORETICAL BASIS OF CNT REINFORCEMENT IN FDM SYSTEMS

### 2.1. Load Transfer and Mechanical Reinforcement

In polymer nanocomposites, CNTs are envisaged as nanoscale “fiber reinforcements” that can bear load and stiffen the matrix. For effective load transfer, several conditions must be met:

- (1) Strong interfacial bonding between CNTs and polymer
- (2) Uniform dispersion of individual CNTs (avoiding agglomerates), and
- (3) Alignment or network percolation that bridges the stress field.

In practice, pristine CNTs are chemically inert and poorly wet by polymers, leading to weak adhesion and limited stress transfer (Al-Zu'bi et al., 2023). This has led to two opposing interpretations in the literature:

- i. **Direct Reinforcement Theory:** CNTs contribute directly to stiffness and strength via a classic fiber-model scenario. When well-dispersed, they act as rigid rods that can carry load, provided the interface is engineered for example, via functionalization (Fulmali et al., 2022; Kohls et al., 2022). Under this view, even low CNT fractions (<2 wt%) can markedly raise modulus and yield strength.
- ii. **Constraint-Dominated Perspective:** Other studies argue that observed stiffening may largely come from restricted polymer mobility around CNT agglomerates, rather than true nanoscale reinforcement (Ali et al., 2025). Here, CNTs primarily act as “stiff inclusions” increasing modulus but not significantly enhancing toughness or strength, especially if agglomerates cause stress concentrations.

This debate is unresolved. Some modeling work suggests that load transfer efficiency in CNT nanocomposites often remains low unless interface chemistry is optimized (Tsai & Lu, 2009). The current literature lacks consensus on the dominant mechanism as to whether CNTs are acting as ideal nanoscale reinforcements or simply as immobile filler constraints. In either case, the FDM process adds complexity: melting, shear, and re-solidification affect CNT orientation and clustering, which we will examine.

### 2.2. Electrical Percolation Networks

CNTs promise to create electrically conductive polymer filaments, enabling anti-static parts or embedded sensors (Kanoun et al., 2021). Theoretical percolation predicts very low percolation thresholds for high-aspect-ratio fillers (often <0.1 vol%) (Martin et al., 2004) (Chen et al., 2015). Indeed, many experiments find percolation in the 0.1–3 wt% range, depending on CNT type either Single wall carbon nanotube (SWCNT) or multi wall carbon nanotube (MWCNT), dispersion, and alignment (Monajjemi et al., 2011). However, reported thresholds vary widely. For example, Doronin *et al.* (2024) obtained percolation in ABS at ~5 wt% (leading to ~10× conductivity improvement)[9], whereas other works report percolation near 1–2 wt% in PLA/CNT systems[3][10]. Such discrepancies indicate percolation is *process-sensitive*: poor dispersion or agglomeration can prevent network formation until much higher loading is used. Furthermore, anisotropic printing can align CNTs in-plane, raising percolation threshold in the out-of-plane direction.

### 2.3. Rheology and Printability

Adding CNTs increases polymer melt viscosity even at low loadings (Tsai & Lu, 2009). The formation of transient CNT networks in the melt (especially at high shear rates) can cause shear-thinning or even apparent yield stress (Hurin et al., 2025) While a modest viscosity increase can improve shape stability, too high viscosity leads to extrusion issues: nozzle clogging, inhomogeneous flow, and poor layer fusion (Zhang et al., 2025). Practically, most reports find an optimal CNT content (often 1–5 wt% depending on polymer) beyond which printability and surface quality degrade. This introduces an inherent trade-off: maximizing CNT concentration for properties versus maintaining smooth FDM printing.



Figure 2: a high-aspect-ratio carbon-fiber fabric as an analog for CNT alignment

### 3.CNT DISPERSION

CNT reinforcement benefits hinge critically on dispersion. Unfortunately, consistent dispersion of CNTs in polymer filaments remains an open problem.

#### 3.1. Overview of Dispersion Methods

Common strategies of CNT dispersion include:

- i. **Solution (solvent) dispersion:** CNTs are first ultrasonically or chemically dispersed in a solvent (often with surfactants), then mixed with polymer and evaporated (Yang et al., 2023). This can achieve good debundling, but residual solvent, low throughput, and environmental concerns limit scalability.
- ii. **Melt compounding:** Industrially viable twin-screw extrusion blends CNT powder with polymer pellets. While high shear in extruders can partially separate CNT bundles, severe shear can also shorten tubes[12]. Reports disagree on effectiveness; some claim enhanced dispersion[13], others note persistent micro-agglomerates.
- iii. **Dry blending / mechanofusion:** CNTs and polymer powder are dry-mixed, e.g. in a high-energy mixer. This method is simple but often yields only superficial coating of pellets and non-uniform distribution.
- iv. **Functionalization:** Chemical modifications (e.g. acid treatment, polymer grafting) improve CNT compatibility. This can yield better dispersion in the matrix but at the cost of disrupting CNT conductivity or causing defects[14].

Table 1 compares key features of these approaches.

**Table 1:** Dispersion Methods Comparison

Dispersion Method	Pros	Cons	Relevant Sources
<i>Solution (solvent) mixing</i>	High initial CNT debundling (especially with sonication)	Solvent removal, possible CNT re-agglomeration, not industrially scalable	(Dumée et al., 2013; Huang & Terentjev, 2012)
<i>Melt compounding</i>	Scalable, compatible with existing extrusion	Often insufficient CNT de-bundling; high shear can shorten CNTs	(Lee et al., 2023; Liu & Choi, 2012; Nayini & Ranjbar, 2022; Rodrigues et al., 2017)
<i>Dry high-shear blending</i>	Simple, no solvents	Typically leaves large CNT aggregates; poor uniformity	(Adu et al., 2024; Su et al., 2026)
<i>Chemical functionalization</i>	Improves polymer wettability	Can damage CNT structure/conductivity; added processing steps	(Nayak et al., 2019; Primc, 2022; Zambrzycki et al., 2024)
<i>Hybrid methods (e.g. surfactant + melt)</i>	Attempt combination of above	Cost, complexity; performance gains vary	(Ashwani Sharma et al., 2018; Yang et al., 2023)

### 3.2. Efficacy and Scalability

A major debate is whether any of these techniques can achieve truly homogeneous CNT dispersion at scale. Academic studies often employ solvent or lab-scale extrusion to claim “uniform dispersion” (typically validated by selective SEM images or melt rheology). However, SEM cross-sections capture only tiny regions and may miss unseen agglomerates; rheology shows network formation but not uniformity at the part scale. Notably, Ashwani (2018) emphasize that “precisely controlling CNT dispersion” is crucial yet still lacking (Ashwani Sharma et al., 2018). Similarly, (Choi et al., (2023) notes that extensive research on the best dispersion techniques is still lacking. Industry reports bluntly state “*Dispersions hold the key for CNT success*”(Conor, 2025), underscoring that inconsistent dispersion is the central bottleneck. In practice, many improvements in published studies reflect local areas of good dispersion, rather than a reproducible, homogeneous state throughout a filament or part.

### 3.3. Characterization Gaps

Adding to the problem, there is no standardized metric for CNT dispersion quality in filaments. Techniques like optical microscopy, SEM, or even Raman mapping are used inconsistently. As one review points out, better methods are needed to quantify dispersion and link it to performance (Shen et al., 2026). Without rigorous, standardized dispersion assessment, it is difficult to compare results across studies. As a result, claims of dispersion quality in many papers remain qualitative. We argue that future work should adopt statistical measures (e.g. image-based agglomerate counting, electrical noise analysis) to benchmark dispersion.

## 4. MECHANICAL PERFORMANCE: REINFORCEMENT OR ILLUSION?

Adding CNTs to FDM polymers often increases elastic modulus, but the impact on strength and toughness is variable.

### 4.1. Reported Trends

Numerous studies claim *stiffness improvements* of tens to hundreds of percent with low CNT loadings. For example, (Hosseinzadeh et al., ) reported a **17% increase** in ABS tensile strength (36→42 MPa) with just 1.5 wt% CNT [9], along with a large drop in electrical resistance. Other work (often in PLA or PETG matrices) reports similarly large modulus gains. Table 2 compiles representative results from recent literature, showing the wide range of reported enhancements.

**Table 2:** CNT Enhancement Results from Recent Literature

Polymer (Matrix)	CNT Type & Loading	Mechanical Outcome	Reference
	SWCNT, 1.5 wt%	Tensile ↑17% (36→42 MPa)[9]	(Hosseinzadeh et al., 2025)
ultrahigh molecular weight polyethylene (UHMWPE)	MWCNT, 2 wt%	Modulus ↑114%, Strength ↑62%	(Mahfuz et al., 2011)
Carbon fiber Reinforcement Polymers (CFRP)	SWCNT, 1 wt%	Flexural Strength ↑58%	(Praneeth et al., 2022)
Polystyrene (PS)	MWCNT, 0.3 wt%	No significant strength change in the degradation temperature	(Gündoğan & Karaağaç, 2025)
poly(vinyl alcohol) (PVA)	SWCNT, 0.2 wt%	Young’s modulus ↑20%	(Deng et al., 2011)

### 4.2. Inconsistencies and Trade-Offs

Crucially, not all studies find impressive effects. Some report only modest strength gains or even reductions at higher loadings. For example, (Gündoğan & Karaağaç, 2025) found that above 0.3 wt% CNT, PS composites plateau in strength and lose ductility. (Praneeth et al., 2022) noted that CNTs increased stiffness but made PLA more brittle. In practical terms, the addition of CNTs generally increases stiffness but often at the cost of toughness and elongation. This brittleness issue is critical for oil/gas parts which may face impact or cyclic stresses.

Moreover, the enhancement depends on print parameters. FDM parts are intrinsically anisotropic: strength is highest along the filament orientation and weakest across layers (Farashi & Vafae, 2022). CNTs do not eliminate this anisotropy. In fact, alignment of CNTs tends to follow the deposition direction, so “improvement” may only occur along certain directions. Comprehensive data on multi-axial properties is scarce, and many reports test only one build orientation.

### 4.3. Reinforcements

We revisit the earlier theoretical debate. The “Direct Reinforcement” camp points to cases like (Deng et al., 2011; Gündoğan & Karaağaç, 2025) where even small CNT additions raised strength appreciably, suggesting effective stress transfer. In contrast, the “Constraint Effect” camp observes that *apparent* stiffness increases could simply result from CNT networks restricting polymer flow. Without strong bonding, loads may bypass CNTs entirely. This ambiguity is evident in contradictory reports: studies using the same polymer/CNT system but different processing have reported both large and negligible gains.

Given the variability, this claims makes this obvious facts cast doubts in the reserch. The consensus however seems to be that interfacial engineering such as chemical functionalization or sizing is often needed to approach the theoretical reinforcement scenario. Absent that, most real-world FDM composites likely rely more on polymer chain immobilization, with CNTs acting as stiffness-imparting inclusions rather than load-carrying fibers. This means that while Young’s modulus can increase, actual strength and ductility often remain limited by polymer failure between CNT clusters.

## 5. ELECTRICAL AND THERMAL FUNCTIONALIZATION

CNT-filled filaments promise multifunctionality: conductivity for antistatic or sensing, and higher thermal conductivity for heat dissipation.

- i. **Electrical Properties:** Low CNT loadings can percolate, enabling conductivity (Earp et al., 2019). However, as noted, percolation threshold is highly variable. Spina *et al.* (2023) achieved a conductivity  $\sim 10$  S/m in ABS at 5 wt% MWCNT, but reported no mechanical strength loss (Beltrán et al., 2023). Yet, other groups report needing 10–15 wt% to approach semiconductive levels, at which point printing becomes very difficult. Importantly, stability of the conductive network under stress or environment is often not tested. Cracks or delamination in FDM parts can break the network.
- ii. **Thermal Properties:** CNTs have high intrinsic thermal conductivity, but gains in composites are modest unless networks are well-formed. Many studies note *small increases* in thermal conductivity (10–50%) that are of limited practical value. No study has yet demonstrated a CNT-FDM part serving as an effective thermal heat sink or barrier in oil/gas conditions.
- iii. **Sensor Integration:** The ability to embed strain or pressure sensing through piezoresistivity is an attractive idea. Some works have made rudimentary strain sensors in printed CNT composites. However, calibration, stability and repeatability of such sensors under field conditions remain unproven.

In sum, while multifunctionality is the selling point of CNT composites, most claims (especially for harsh-service benefits) are unvalidated. Long-term studies of conductivity under temperature/humidity cycling, and thermal aging, are essentially nonexistent to the best of our knowledge.

## 6. FDM-SPECIFIC CONSTRAINTS

CNT reinforcement cannot be considered outside the context of FDM’s unique challenges.

### 6.1. Anisotropy and Layer Bonding

FDM parts exhibit anisotropic behavior: properties along the filament (XY plane) differ from those across layers (Z direction) due to incomplete interlayer fusion (Somireddy & Czekanski, 2020). In practice, Z-direction strength can be 50% of XY-direction. CNTs do not magically homogenize this; if anything, they are carried with the filament so networks form mainly in-plane. Thus, out-of-plane properties often remain polymer-limited.

The review by (Bhushan et al., 2024) noted that optimizing parameters (temperature, raster, infill) can improve layer adhesion and reduce voids, but anisotropy and void formation remain critical challenges. Introducing CNTs adds another variable: if CNTs align along rasters, they might even exacerbate in-plane vs cross-plane differences. To date, few studies have measured 3D tensile surfaces or interlayer shear in CNT-FDM parts. Absent such data, claims of “improved FDM performance” are speculative at best.

### 6.2. Printability of CNT Filaments

A recurrent theme is the printability ceiling. Above certain CNT contents, filaments become brittle or highly viscous. Reports often stop at  $\sim 5$  wt% CNT. For instance, notes that 5 wt% greatly reduced electrical resistance, but did not discuss print quality at that loading (Lage-Rivera et al., 2023). Other authors report nozzle clogging or poor surface finish beyond  $\sim 3$ –4 wt%. Even at lower loadings, CNTs can cause *random extrusion glitches* (blobs or stutter) if shear is insufficient to break up agglomerates during printing.

Too little CNT yields minimal benefit, too much ruins processability. This trade-off is underreported in much of the literature. Standard rheometry (oscillatory flow curves) vs. extruder torque measurements are rarely provided, making it hard to correlate viscosity to printable CNT limits. This gap suggests reported property gains might often occur at an optimistic midrange of CNT that may be impractical for robust printing.

## 7. Oil & Gas Application

Given the above, the real question is: can CNT-FDM parts survive actual oilfield service conditions? Proposed applications in the literature include sensor housings, connectors, anti-static components, and even structural manifolds. But we identify serious shortcomings:

- v. **High Temperature:** Standard FDM polymers softens above ~100–120°C (PLA) or 80–90°C (PETG) (Shanmugam et al., 2024; Tisari et al., 2026). Nylon and ULTEM can go higher, but these are little studied with CNTs. Oilfield downhole tools often see 150°C. While CNTs marginally raise T<sub>g</sub> or thermal stability, no data has been found on CNT-FDM performance at 150–200°C for hundreds of hours. Without such data, claims of “high-temp viability” are unsubstantiated.
- vi. **Chemicals and Corrosion:** Oil/gas environments feature H<sub>2</sub>S, CO<sub>2</sub>, brines, hydrocarbons, and drilling fluids. Polymers can swell or become brittle in these. For CNT composites, the interface could be especially vulnerable to chemical attack. The only information comes from general polymer testing: ASTM D543 (chemical resistance) tests are advised, but virtually no CNT-FDM study has reported chemical soak tests. The Southwest Research Institute guidelines show polymers are routinely tested at high p/T with H<sub>2</sub>S (up to 20,000 psi and 650°F!). CNT composites have not been through such scrutiny.
- vii. **Mechanical Fatigue and Creep:** Oil/gas parts often see vibration, cyclic loads, and slow creep. FDM polymers already creep significantly, and CNT fillers reduce but do not eliminate creep. Under constant load at elevated temp, CNT networks may gradually reconfigure, altering properties. We found *no studies* of fatigue or long-term stress–strain for CNT-FDM composites.
- viii. **Standard Compliance:** Critical components must meet standards (API, NACE, ISO). There are no documented CNT-FDM materials in any oilfield material databases. This technology is essentially *out of spec* currently.

In sum, most claims of oil/gas readiness are **premature**. The review by Oladele *et al.* (2025) notes polymers’ roles in extreme environments but also highlights their “limitations” and need for overcoming hurdles[19]. We echo that: **CNT-FDM remains exploratory**. Any deployment plan must rigorously test parts under realistic H<sub>2</sub>S/CO<sub>2</sub>/brine exposures, as well as high-pressure steam/hydrocarbon immersion per industry protocols. Until then, use cases should be restricted to non-critical, internal components (e.g. sensor fixtures, anti-static covers) where risk is manageable.

## 8. METHODOLOGICAL LIMITATION

One of the major challenges reported in the literature has been the significant inter-study methodological differences and lack in rigor with regards to CNT-reinforced FDM composites. The lack of consistency in reporting is one of the problems. Comparisons are usually difficult because the researchers use various sample geometries, printing parameters and testing procedures. Mechanical performance tests according to literature include tensile, flexural, or shear tests, and many studies report just the average without sufficiently reporting variances or confidence intervals or tests of statistical significance. Often, these claims include no error bars, sample sizes or reproducible measures, which reduces the reliability of the conclusions. In addition, sample sizes are frequently small; many studies report on only three and five specimens. The limited number of samples does not give a sufficiently high statistical confidence for the inherent variability of FDM processes. Few recent studies have been able to use larger samples and use confidence interval analysis to increase the reliability of the results.

The other one is that highly idealized experimental conditions are used. Most investigations are made on pristine laboratory printed specimens under room temperature, quasi-static loading, whereas few investigate the effect of humidity, thermal cycling, dynamic loading or environmental degradation. These are not environments of demanding service as in oil and gas applications. In fact, there has been a recent emphasis on the importance of accelerated ageing procedures and realistic environmental testing to close this gap. Besides, the improvements reported could be driven by selective comparison – a neat polymer printed conventionally is compared to the CNT-filled material. In order to be meaningful, both reinforced and unreinforced materials need to be processed and tested under similar and optimized conditions. Additionally, there are limited opportunities for advanced characterization methods. Even though many modern tools for void analysis (e.g. X-ray computed tomography), in-situ microscopy and data-driven modeling techniques are available, they are largely underutilized and thus most knowledge is still based on empirical observations. As a result, there remains a substantial gap in validation with a vast number of isolated performance claims and only a handful of systematic and statistically robust studies that have been verified by other parties. Consequently, many reported benefits can be very context dependent and can be hard to replicate from one material, process and application to another.

## 10. FUTURE RESEARCH DIRECTIONS

Building on the identified research gaps, several priority areas should be pursued to advance the development and deployment of CNT-reinforced FDM materials. Greater attention should be given to CNT alignment control through the application of external electric or magnetic fields, as well as the optimization of printing parameters to orient nanotubes along desired directions. Recent studies suggest that field-assisted FDM can promote nanofiller alignment, potentially improving both electrical percolation and directional mechanical performance. Furthermore, researchers should explore novel CNT architectures that move beyond random dispersion, such as continuous CNT networks embedded within 3D-printed scaffolds or CNT-coated polymer fibers. Such architectures may provide more efficient load transfer and conductive pathways.

Another promising avenue involves hybrid reinforcement strategies that combine CNTs with complementary fillers such as graphene, carbon fibers, or other nanomaterials to achieve synergistic improvements in mechanical, thermal, and electrical properties while maintaining economic viability. In parallel, lifecycle assessments are needed to evaluate the recyclability of CNT-FDM materials and the potential release of nanotubes during service, wear, or disposal, which remains an important environmental and health consideration. Standardization efforts should also be prioritized through the development of consensus guidelines, similar to ASTM standards for polymers, to ensure consistent reporting of material composition, processing conditions, and performance metrics across studies.

Advances in high-throughput experimentation and digital manufacturing offer additional opportunities for accelerating material optimization. Robotic fabrication and automated testing platforms could rapidly evaluate a large number of material formulations and printing conditions, generating extensive datasets for analysis. Similarly, integrating in-situ monitoring systems, such as melt-pressure sensors and flow-imaging technologies, with post-processing characterization could support machine-learning-driven process optimization and closed-loop manufacturing systems, an emerging trend in additive manufacturing technologies [16]. Finally, future investigations should increasingly adopt application-driven approaches by targeting specific oil and gas use cases, including sensor housings, anti-static components, pipe fittings, and monitoring devices. Such studies should incorporate application-relevant performance assessments, including spark-discharge testing, electromagnetic interference (EMI) shielding evaluation, chemical resistance testing, and long-term environmental exposure. Through these efforts, CNT-FDM research can progress beyond proof-of-concept demonstrations toward robust, engineered solutions suitable for industrial deployment.

## 11. CONCLUSIONS

CNT-reinforced polymer filaments for fused deposition modeling (FDM) offer significant potential for the development of lightweight, multifunctional components with enhanced mechanical, electrical, and thermal properties. Numerous laboratory-scale investigations have demonstrated notable improvements in stiffness and conductivity at relatively low CNT loadings, indicating the feasibility of producing advanced functional parts [4,9]. However, these benefits remain highly dependent on achieving effective CNT dispersion, strong interfacial interactions, and precise process control, all of which continue to present substantial challenges. Moreover, the inherent anisotropy, void formation, and interlayer bonding limitations associated with FDM are not automatically resolved by CNT incorporation and often constrain overall performance [18].

A critical finding of this review is that, despite encouraging laboratory results, the suitability of CNT-FDM composites for oil and gas applications remains largely unverified. Very few studies have evaluated these materials under representative service conditions involving high temperatures, high pressures, corrosive H<sub>2</sub>S/CO<sub>2</sub> environments, brine exposure, cyclic loading, or long-term durability requirements. Consequently, many claims regarding oilfield readiness remain speculative and require rigorous validation through standardized testing protocols and accelerated environmental exposure studies.

Overall, while CNTs can substantially enhance the functionality of polymer-based FDM materials, their effectiveness is not guaranteed and depends strongly on processing quality and application-specific requirements. Realizing the full potential of CNT-enabled additive manufacturing will require systematic efforts to improve dispersion control, reproducibility, durability assessment, and industrial validation. By highlighting current limitations, identifying critical knowledge gaps, and proposing a structured research roadmap, this review aims to guide future investigations toward the development of reliable, field-ready CNT-FDM composites for demanding oil and gas applications.

### Conflict of Interest

The author declares no conflict of interest.

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