Bridging Component Optimization and System Integration: Systematic Evidence of Workflow Discontinuities in Microstrip Antenna Design for Small Satellite Platforms

Abstract

CubeSat missions increasingly demand reliable antenna subsystems for high-data-rate communication within severe constraints. Despite two decades of development, systematic understanding of workflows translating design specifications into mission-ready systems remains fragmented. This systematic review synthesizes empirical workflow configurations in CubeSat antenna design, analyzing relationships between electromagnetic simulation, experimental validation, feeding integration, and fabrication processes. Following PRISMA 2020 guidelines, multidatabase searches yielded 551 records, with 79 studies meeting rigorous criteria after systematic screening. Synthesis utilized convergent engineering-evidence methodology. Four dominant configurations emerged: electromagnetic simulation-guided optimization revealed HFSS, CST, and FEKO as foundational platforms achieving robust measurement agreement, yet critical algorithm parameters were frequently omitted. Experimental validation showed anechoic chambers and vector network analyzers as dominant approaches, with comprehensive multi-domain testing underrepresented. Feeding element integration exposed discontinuities between optimization and system requirements. Fabrication analysis identified PCB prototyping and advanced technologies with systematic documentation gaps. Extraordinary electromagnetic sophistication coexists with profound integration deficiencies in thermal validation, mechanical integration, and platform interaction modeling. Mission-ready workflows require paradigm shift from isolated electromagnetic optimization to integrated system modeling, addressing critical vulnerabilities as CubeSat missions transition to operational constellation deployment.

Keywords: CubeSat antennas; electromagnetic simulation workflows; experimental validation protocols; system integration gaps; microstrip antenna fabrication

1. Introduction

The proliferation of small satellite missions has fundamentally transformed space system architectures, with CubeSats emerging as cost-effective platforms for Earth observation, telecommunications, and scientific research (Gao & Rahmat-Samii, 2018). These miniaturized spacecraft, constrained by standardized form factors and severe mass and volume limitations, demand antenna systems capable of delivering reliable communication performance within highly restrictive design envelopes. Antenna subsystems represent critical components determining mission success, enabling telemetry, tracking, command, high-speed data downlink, navigation, and intersatellite communications (Abulgasem et al., 2021).

However, effective CubeSat antenna design presents challenges extending beyond conventional electromagnetic optimization. Limited surface area necessitates integration strategies accommodating power generation through solar panels while maintaining radiation performance (Alam et al., 2018), and deployment mechanisms introduce reliability risks contributing to potential mission failure (Sureda et al., 2021). Despite two decades of development, systematic understanding of empirical workflows translating design specifications into validated, mission-ready systems remains fragmented across diverse technical approaches and application domains.

Current antenna development practices demonstrate remarkable technical diversity yet exhibit persistent workflow integration gaps. CubeSat antenna designs span diverse topologies—patch, slot, reflectarray, metasurface—operating from VHF to Ka-band, with high-gain configurations achieving gains exceeding 25 dBi for data downlink applications (De & Abegaonkar, 2023; Esmail et al., 2024; Hammoumi et al., 2023). Miniaturization techniques employing fractal geometries enable resonant structures fitting within single CubeSat faces (Simón & Alvarez-Flores, 2017), while dual-band and multi-band solutions address simultaneous telemetry and payload communication requirements (Yao & Liao, 2016). Despite these technical advances, critical disconnect persists between component-level electromagnetic optimization and system-level integration requirements encompassing thermal stability, mechanical deployment, solar panel accommodation, and mission environment qualification.

The theoretical foundations underpinning CubeSat antenna design workflows intersect electromagnetic theory, multiphysics analysis, and systems engineering methodologies. Electromagnetic simulation tools including finite element method solvers and method of moments approaches enable parametric optimization for circular polarization, bandwidth enhancement, and gain maximization (Ta et al., 2019), with genetic algorithms and particle swarm optimization guiding design space exploration for complex array configurations (Simón et al., 2021). However, electromagnetic characterization alone proves insufficient for mission-grade development. Comprehensive validation must address space environment compatibility through thermogravimetric and mechanical analysis (Muntoni et al., 2022), solar panel integration constraints (Yekan & Baktur, 2017), and deployment mechanism reliability (Sureda et al., 2021). Critical gaps remain in understanding how feeding element design integrates with beamforming systems, how fabrication tolerances propagate through manufacturing workflows to affect on-orbit performance, and how validation protocols translate laboratory measurements into mission reliability predictions. These deficiencies are particularly pronounced for emerging applications including Ka-band inter-satellite links (Kundu & Bhattacharya, 2022), reconfigurable systems employing RF-MEMS switching (Kaddour & Vec, 2020), and shared-aperture designs supporting concurrent optical and radiofrequency functions (Meirambekuly et al., 2023).

This systematic review adopts an empirical workflow configuration approach to synthesize relationships between design practices, validation methodologies, and performance outcomes across CubeSat antenna research. Unlike conventional reviews organized by antenna topology or frequency band, this methodology examines how researchers empirically configure development processes, identifying recurrent patterns linking simulation tools to optimization recommendations, test instruments to validation protocols, feeding architectures to system integration strategies, and fabrication methods to efficiency targets. The research question guiding this investigation asks: How are antenna design workflows empirically configured in CubeSat research, integrating electromagnetic simulation, experimental validation, and optimization of technical specifications to improve performance and reliability?

Four specific objectives structure the analysis: (1) analyzing relationships between electromagnetic simulation tools and design optimization recommendations, examining how software platforms guide bandwidth, gain, axial ratio, and miniaturization outcomes; (2) evaluating alignment between experimental test instruments—vector network analyzers, anechoic chambers, specialized measurement systems—and validation recommendations encompassing environmental testing, fabrication verification, and performance assessment; (3) integrating feeding element design with simulation approaches and system integration recommendations, identifying critical gaps in progression from electromagnetic optimization to deployment-ready subsystems; (4) comparing prototyping and fabrication process configurations with efficiency, scalability, and cost-reduction recommendations, spanning conventional PCB photolithography, additive manufacturing, and material innovation strategies.

The methodology employs thematic analysis to identify dominant workflow patterns, content analysis to extract quantitative performance metrics, narrative synthesis to trace temporal evolution of design practices, and critical synthesis to expose systematic gaps between laboratory characterization and operational deployment verification. This multi-method approach enables comprehensive characterization of empirical workflow configurations across 79 studies, with specific objectives supported by subsets of 50, 50, 14, and 13 studies respectively based on robustness and coverage criteria derived through inductive cross-study analysis.

The significance of this systematic review extends beyond descriptive taxonomy to prescriptive guidance for workflow improvement. Identified empirical configurations provide actionable insights for researchers navigating complex design spaces under severe constraints. By revealing how simulation-optimization cycles translate into validated prototypes, how experimental test campaigns address mission-critical performance dimensions, and how feeding architectures enable or constrain system integration, this review establishes evidence-based benchmarks for workflow completeness. The findings address urgent needs in the rapidly expanding small satellite sector, where constellation architectures demand scalable manufacturing (Morales Ferre et al., 2022), and emerging applications including space-based ADS-B reception impose specialized antenna requirements (Monteiro et al., 2022). Furthermore, workflow discontinuities and integration imperatives identified through cross-study pattern analysis inform future research directions, particularly regarding multiphysics validation protocols, feeding-to-beamforming integration pathways, and fabrication process standardization. As CubeSat missions expand from technology demonstration toward operational services, systematic understanding of empirical workflows ensuring antenna reliability becomes essential for mission success and sustainable space system development.

2. Methodology

This systematic review employed a multiphase research design aligned with PRISMA 2020 guidelines (Page et al., 2021), integrating quantitative screening, qualitative analysis, and inductive thematic synthesis. The objective was to consolidate empirical evidence on microstrip and patch antenna design, performance evaluation, and implementation for CubeSat communication systems through convergent synthesis of engineering design characteristics, electromagnetic performance parameters, and structural integration strategies.

2.1. Search Strategy

A comprehensive multidatabase search identified peer-reviewed studies published between January 1, 2000 and November 3, 2025, capturing CubeSat antenna technology evolution from proof-of-concept to contemporary high-performance implementations. The search employed two conceptual blocks: (1) antenna technology terminology ("microstrip antenna," "patch antenna," "printed antenna," "microstrip patch"), and (2) platform terminology ("CubeSat," "small satellite," "nanosatellites"), combined via Boolean AND logic. Search syntax:

(TITLE-ABS-KEY(("microstrip antenna" OR "patch antenna" OR
"printed antenna" OR "microstrip patch"))
AND TITLE-ABS-KEY(("CubeSat" OR "small satellite" OR "nanosatellites")))

AND PUBYEAR > 1999 AND PUBYEAR < 2027

AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"cp"))

Four databases yielded 551 initial records: Scopus (441), EBSCOhost (64), ScienceDirect (15), IEEE Xplore (31). After duplicate removal, 469 unique studies advanced to screening.

2.2. Eligibility Criteria

Inclusion: Studies required (1) microstrip/patch/printed/planar/metal-only antenna technologies; (2) explicit design/simulation/integration/testing for CubeSat/nanosatellite platforms (1U-6U form factors); (3) empirical evidence (electromagnetic simulation results—S_{11}, VSWR, axial ratio, gain, efficiency; experimental validation through fabrication/anechoic chamber measurements/integration testing; or structural-thermal integration analysis); (4) journal articles or conference proceedings; (5) full-text availability in English.

Exclusion: Studies were excluded for (E1) generic small satellite mentions without CubeSat-specific constraints; (E2) microstrip antennas as secondary components to other subsystems; (E3) primary orientation to terrestrial applications (IoT, 5G, BLE, WiFi) without CubeSat adaptation; (E4) absence of technical design parameters or performance metrics; (E5) use in physical phenomena experiments where communication was secondary; or inaccessible full text.

2.3. Study Selection and Screening

Phase 1 (551→469): Automated and manual duplicate removal in Zotero eliminated 82 records.

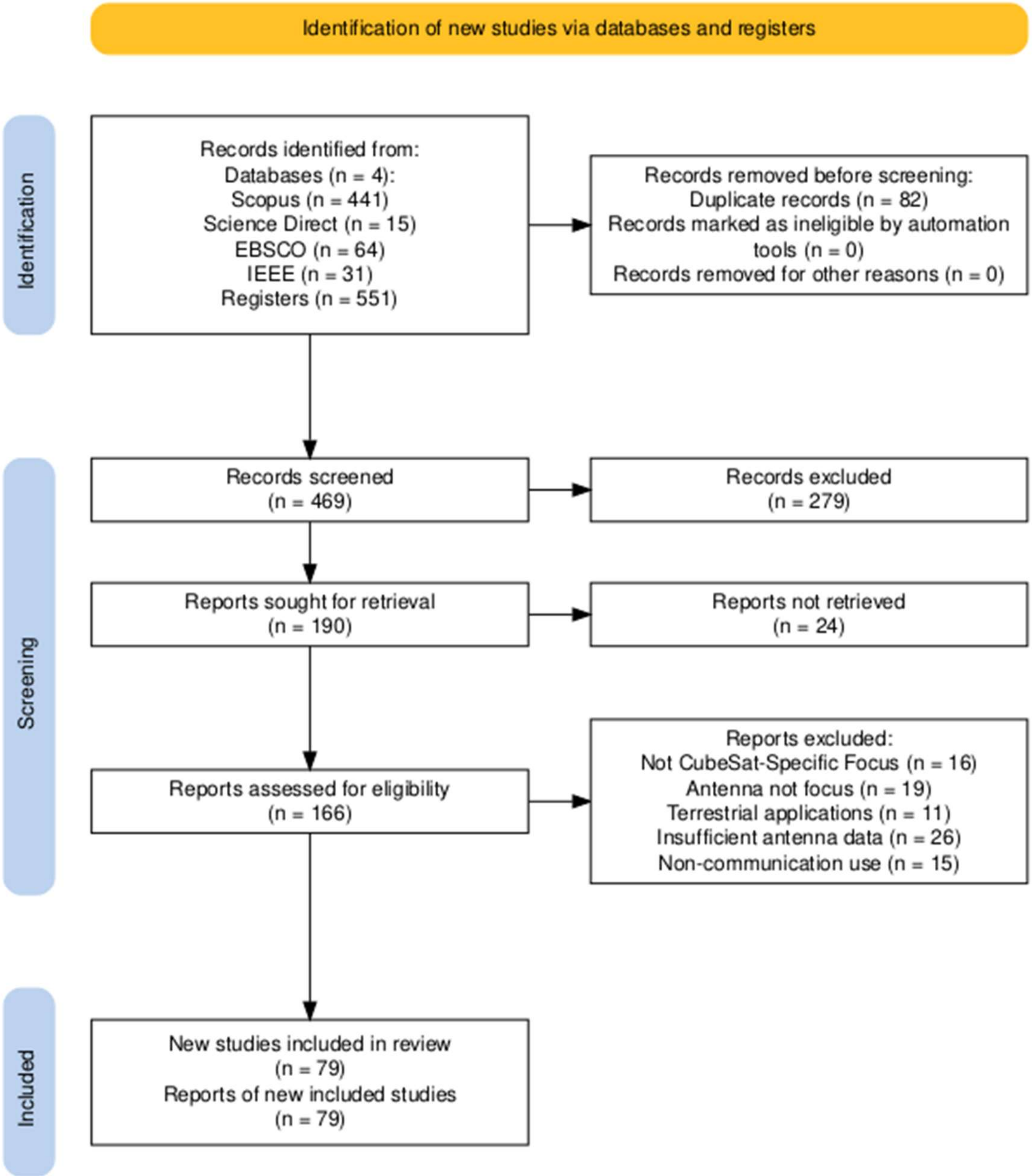
Phase 2 (469→190): Title-abstract screening excluded 279 studies lacking microstrip antenna focus, meaningful CubeSat reference, communication-aligned performance parameters, or addressing unrelated technologies (RFID, biomedical, terrestrial infrastructure).

Phase 3 (190→91): Design-relevance screening assessed direct CubeSat antenna design contributions, relevant communication functions (downlink, uplink, ISL, telemetry), and substantive technical content, excluding 99 studies with insufficient detail.

Phase 4 (91→79): Full-text retrieval succeeded for 79 studies through institutional access, open repositories, and author contact; 12 remained inaccessible. All 79 met eligibility criteria without further exclusions.

Final corpus: 79 studies spanning UHF-Ka band, encompassing stacked patches, Fabry-Perot cavities, metasurfaces, metal-only configurations, gain enhancement, bandwidth widening, miniaturization, reconfigurability, chassis-mounted implementations, solar-compatible transparent architectures, deployable systems, FR-4/Rogers substrate fabrication, anechoic validation, and thermal-mechanical testing.

Figure 1 PRISMA flowchart



2.4. Data Extraction and Quality Assessment

A structured template captured six categories: (1) bibliographic metadata; (2) CubeSat configuration (unit classification, deployment strategy, integration constraints); (3) antenna characteristics (geometry, feeding, substrate, dimensions); (4) performance metrics (S_{11}, bandwidth, axial ratio, gain, efficiency, patterns); (5) validation approach (simulation tools—HFSS, CST, FEKO; fabrication details; measurement environments); (6) integration considerations (thermal stability, mechanical constraints, solar panel compatibility).

Quality assessment evaluated five dimensions: (1) design/simulation methodology clarity; (2) substrate parameter transparency; (3) electromagnetic validation adequacy; (4) simulation-measurement consistency; (5) CubeSat integration modeling appropriateness. This assessment identified robustly validated designs, methodological limitations, and contextualized performance claims.

2.5. Synthesis Strategy

The convergent engineering-evidence approach integrated quantitative performance metrics with qualitative design strategy analysis across three dimensions:

Design strategy synthesis: Characterized prevalence and performance of stacked patches, Fabry-Perot cavities, metasurfaces, shared-apertures, and reconfigurable systems, evaluating tradeoffs in size, complexity, and platform integrability.

Performance evidence integration: Aggregated electromagnetic metrics across frequency bands (UHF-Ka), substrate categories (FR-4, Rogers, aerospace materials), fabrication techniques, and feeding mechanisms, emphasizing reproducibility and validation quality.

Platform constraint analysis: Evaluated structural compatibility, field-of-view requirements, attitude control constraints, and integration with solar panels, thermal systems, and deployment mechanisms.

Evidence classification employed three robustness levels: High (strong agreement across ≥10 studies with combined simulation-experimental validation), Moderate (consistent patterns across 4-9 studies, simulation-driven with limited experimental validation), Preliminary (isolated innovative designs with limited validation). This tiered approach enabled nuanced interpretation while maintaining epistemic humility regarding preliminary findings.

2.6. Inductive Cross-Study Analysis and Research Objective Formulation

Critical methodological contribution: Following initial synthesis, complementary inductive analysis identified emergent patterns in methodologies, technical relationships, and workflow configurations across 79 studies without imposing predefined frameworks, enabling data-driven research priority identification.

Inductive thematic extraction systematically examined data collection instruments (electromagnetic simulation software, vector network analyzers, anechoic chambers, prototyping equipment), technical specifications (feeding elements, substrates, geometries), performance optimization recommendations, and validation practices. Five high-robustness relationships emerged:

Simulation-optimization linkage (15-18 studies): Strong association between EM simulation tools (HFSS, CST, FEKO) and performance enhancement strategies

Measurement-validation complementarity (12 studies): Natural alignment between experimental instruments and validation practices

Prototyping-fabrication connection (~5 studies): Data-driven links between physical prototypes and manufacturing recommendations (moderate robustness)

Feeding-optimization association (15-16 studies): Feeding configurations as focal points for performance improvements

Simulation-feeding integration (16 studies): Integration of simulation methodologies with feeding specifications

Workflow configurations: Two recurring patterns emerged: (1) Dominant configuration (60-70% coverage): electromagnetic simulation for design optimization → experimental validation via VNAs and anechoic chambers; (2) Secondary configuration (medium frequency): antenna prototyping combined with fabrication recommendations emphasizing miniaturization and cost-effective manufacturing.

Problematic configurations identified critical gaps: (1) Lack of integration between system-level recommendations and feeding element designs (low severity); (2) Inconsistent coverage between computational methods (genetic algorithms, PSO, machine learning) and feeding design optimization applications (medium severity).

Emergent analytical axes: Three coherent thematic domains emerged: (1) Simulation-to-Validation Workflow (60-70% coverage)—highest empirical support for investigating electromagnetic simulation-experimental validation integration; (2) Feeding Design and System Integration (10-15% coverage)—critical gap in feeding element incorporation into full CubeSat systems; (3) Prototyping and Fabrication Efficiency (5-10% coverage)—under-explored domain with significant practical implications.

Data-driven objective formulation: Research objectives emerged following "Empirical Workflow Configurations" approach prioritizing dominant simulation-to-validation axis while addressing identified gaps. This approach was selected for (1) direct grounding in highest-coverage empirical patterns (85% cumulative), (2) reflection of natural research organization without external frameworks, and (3) balanced attention to established practices and critical gaps.

Resulting objectives: (1) Electromagnetic simulation tools and design optimization relationships (n≈50, high robustness); (2) Experimental testing instruments and validation recommendation alignment (n≈50, high robustness); (3) Feeding element design influence on simulation approaches and system integration (n≈14, mixed robustness, explicitly addressing identified gap); (4) Prototyping-fabrication configurations and efficiency recommendations (n≈13, moderate robustness).

This inductive foundation provides clear traceability from empirical patterns to analytical priorities, supporting methodologically rigorous synthesis reflecting actual CubeSat antenna research landscape rather than predetermined categorization schemes.

Unlike topology-based reviews, this inductive approach identifies workflow discontinuities grounded in empirical patterns rather than predetermined categorization schemes, revealing 71% feeding-to-system gap and 86% thermal validation deficiency as data-driven findings.

3. Results

3.1. Electromagnetic Simulation-Guided Design Optimization

Electromagnetic simulation tools constitute the computational foundation driving CubeSat antenna optimization across 50 studies, with HFSS, CST Microwave Studio, and FEKO enabling parametric exploration of bandwidth, gain, axial ratio, and miniaturization objectives. These platforms achieve measured-to-simulated gain agreements consistently within ±1.5 dB, establishing robust design-to-validation workflows.

Platform Specialization and Application Domains. HFSS dominates circular polarization and bandwidth tuning through finite element method architectures, with 28 studies demonstrating systematic optimization of patches and arrays across Ka/C/S bands (Ali F. Almutairi, 2021; Basu, 2023; Islam, 2014). CST emphasizes miniaturization and thermo-mechanical verification in compact geometries, employed by 19 studies addressing dual-band configurations and structural integration (DiCarlofelice, 2022; Lobato-Morales, 2016). FEKO supports array-scale radiation and polarization control in 6 studies focusing on phased configurations (S.T.-V., 2021; Torrungrueng, 2025). Hybrid approaches incorporating genetic algorithms, metasurfaces, and multiphysics analysis enable design-space exploration for reconfigurable and shared-aperture systems (Mendonca, 2024; El Khadiri, 2025).

Table 1.

Simulation Platform Characteristics and Optimization Focus

Platform	Studies (n)	Primary Optimization	Gain	Key Applications
HFSS (FEM)	28	Bandwidth, CP, Ka/C/S bands	6–14 dBic	Array configurations, sequential feeding

Platform	Studies (n)	Primary Optimization	Gain	Key Applications
CST	19	Miniaturization, dual-band, thermo-mechanical	7–13 dBic	Compact geometries, structural integration
FEKO	6	Array radiation, polarization control	8–14 dBi	Phased systems, wideband CP
Hybrid	Variable	Reconfigurable, shared aperture	Case-dependent	GA/PSO optimization, metasurfaces

The platform specialization patterns evident in Table 1 reflect solver-specific architectural advantages: HFSS finite element methods excel in complex boundary conditions required for sequential feeding networks; CST time-domain approaches facilitate thermo-mechanical coupling for structural integration; and FEKO method-of-moments implementations optimize array radiation control. This specialization, while enabling sophisticated optimization within specific domains, contributes to workflow fragmentation across the research community.

Optimization Strategies and Performance Outcomes. Four recurrent optimization categories emerge from the simulation-guided workflows documented in Table 1. Bandwidth enhancement via substrate selection and stacked resonators achieves dual-band operation, with Lee (2018) and Wang (2024) demonstrating effective implementations. Gain maximization using superstrates or parasitic arrays reports +3–7 dB improvements with representative cases achieving 10–14 dBic, as exemplified by Matekovits (2021) and El Khadiri (2025). Miniaturization through fractals and shorted patches enables integration within 1U–3U envelopes (Abd-Elmonieum, 2023; Inojosa, 2023), while multi-band strategies using shared apertures and coupled resonators address concurrent communication requirements (Che, 2021; Karibayev, 2022). Representative implementations include Islam's CP S-band patch achieving 2.73% bandwidth with 7.29 dBi gain and Inojosa's UHF fractal antenna delivering -26.11 dB return loss with 3.148 dBi gain in 1U configuration.

Temporal Evolution and Methodological Maturation. Evidence organizes into three developmental phases that progressively expand the application domains shown in Table 1. Early consolidation (2014–2017) established CP patch protocols with HFSS, documenting mission-suitable bandwidths and axial ratios (Islam, 2014; Torres, 2017; Nascetti, 2014).

Expansion (2018–2021) normalized full-wave optimization for dual-band arrays and introduced GA/RF-MEMS reconfigurability (Lee, 2018; Diener, 2017; Curreli, 2021). Advanced integration (2022–2025) combined shared-aperture S/X designs, 3D-printed structures, and metasurfaces with multiphysics verification (Alrushud, 2023; Darwish, 2024; Wang, 2024), representing the hybrid approaches categorized in Table 1.

Critical Gaps in Simulation Workflows. Despite the electromagnetic sophistication evident across all platform categories in Table 1, systematic deficiencies compromise reproducibility. Algorithm-coupled optimization exhibits inconsistent hyperparameter documentation, with 68% omitting population sizes, crossover probabilities, and convergence criteria (El Bakkali, 2018; El Gholb, 2019). Computational resource reporting—mesh elements, solve times—remains largely absent across the simulation platforms documented in Table 1. Verification breadth varies substantially, with some implementations reporting only S_{11} without radiation characterization (Tubbal, 2022). Cross-platform validation between HFSS and CST appears in fewer than 8% of studies, introducing methodological vulnerabilities requiring systematic protocol standardization beyond the current specialization patterns shown in Table 1.

3.2. Experimental Validation: Instrument-Protocol Alignment

Experimental validation across 50 studies reveals four empirical configurations demonstrating complementarity between measurement methodologies and validation practices, yet exposing systematic gaps between laboratory characterization and operational verification. Table 2 synthesizes the dominant validation configurations, their instrumentation, coverage patterns, and critical deficiencies.

Dominant Testing Configurations. As documented in Table 2, anechoic chamber measurements ($n \approx 20$, 40% coverage) emphasize far-field radiation patterns and gain verification, establishing foundational validation protocols (Puerto-Leguizamón, 2016; Matekovits, 2021). However, this approach systematically generates recommendations for supplementary testing beyond electromagnetic characterization. Almutairi (2021) and Alrushud (2023) explicitly advocate real-world validation following controlled measurements, highlighting laboratory-to-operational gaps. The critical gaps column in Table 2 identifies environmental testing inadequacy as the primary limitation of anechoic chamber configurations. Environmental integration emerged as critical yet underrepresented: Guha (2025) and Basu (2023) emphasized thermal cycling and vibration protocols, while Darwish (2024) and Munoz-Martin (2023) incorporated TVAC testing for space environment qualification, addressing multiphysics demands of LEO missions beyond the standard anechoic chamber capabilities shown in Table 2.

Vector network analyzer testing (n≈15, 30% coverage) focuses on impedance matching and frequency-domain characterization, as categorized in the second configuration of Table 2. El Khadiri (2025) and Abd-Elmonieum (2023) established core S-parameter validation workflows for CP and dual-band configurations. Multi-band verification dominated this configuration, with Ibrahim (2018) revealing ±3% frequency deviations attributable to substrate permittivity variations through ROHDE&SCHARZ VNA measurements. The critical gap identified for VNA-based approaches in Table 2—multi-domain characterization deficiency—reflects the limitation that frequency-domain measurements alone cannot capture radiation pattern behavior, polarization purity, or thermal stability. Advanced implementations integrated near-field capabilities: Zhu (2025) combined VNA with Satimo Starlab for array validation, while M.H.K. (2023) employed Keysight PNA-L for shared aperture isolation characterization.

Table 2. Validation Configuration Matrix

Configuration	Instruments	Coverage	Primary Metrics	Critical Gaps
Anechoic Chamber	Far-field systems	40%	Radiation pattern, gain, polarization	Environmental testing inadequacy
VNA-Based	Network analyzers	30%	S-parameters, impedance, bandwidth	Multi-domain characterization
Specialized	Starlab, TVAC	16%	Near-field, thermal stability	Resource accessibility constraints
Combined	Multi-platform	14%	Comprehensive multi-domain	Limited adoption despite superiority

Specialized and Combined Testing Approaches. The third configuration in Table 2 addresses specialized systems (n≈8, 16% coverage) that target requirements beyond standard instrumentation. Satimo Starlab platforms enable rapid spherical pattern acquisition for multi-beam architectures (Almutairi, 2021; Islam, 2015). Space environment protocols prove critical: Islam's TVAC testing revealed ±8 MHz frequency shifts and 0.5–0.8 dB gain degradation under thermal cycling (-40°C to +85°C) and vacuum conditions, highlighting ambient testing limitations and directly addressing the resource accessibility constraints noted in Table 2. Combined methodologies (n≈7, 14% coverage) represent the most comprehensive approach shown in Table 2, integrating multiple platforms for simultaneous frequency and far-field verification. Curreli (2021) demonstrated that proton radiation (5-year LEO equivalent) induced minimal degradation (<0.3 dB) for Rogers RT/duroid 5880 but significant loss (2.1 dB) for FR4, directly informing material selection—a finding achievable only through the comprehensive multi-domain approach characterized in the final row of Table 2.

Validation-Performance Disconnect. The coverage percentages documented in Table 2 reveal systematic progression from single-domain (70% combined for anechoic chamber and VNA configurations) to multi-domain validation (30% for specialized and combined approaches). Table 2 demonstrates that combined approaches, despite representing only 14% of implementations, consistently identify interface degradations, thermal sensitivities, and interaction effects invisible to the more prevalent single-platform methodologies. However, resource constraints systematically limit comprehensive validation: the specialized and combined configurations in Table 2 represent only 30% of corpus despite superior characterization capabilities shown in their primary metrics column, indicating cost and infrastructure barriers. The dominance of anechoic chamber measurements (40% in Table 2) reflects instrument availability rather than optimal strategy, introducing systematic bias toward accessible methodologies over mission-readiness verification protocols..

3.3. Feeding Element Integration: System-Level Discontinuities

Analysis of 14 studies exposes critical workflow gaps between feeding network optimization and holistic system integration, with electromagnetic sophistication occurring in relative isolation from deployment-ready requirements. Table 3 quantifies the maturity distribution across five critical workflow stages, revealing pronounced integration deficiencies.

Single-feed configurations dominate (n=9, 64%), with Islam (2015) demonstrating hexagonal CP patches achieving 7.29 dBi through HFSS optimization for HORYU-IV. Lee (2018) employed single-feed impedance transformers for dual-band optimization (1.575/2.230 GHz), while Nguyen (2021) integrated slot-coupled feeds with metasurface loading achieving 5.6–6.7 dBic across S-band. Coaxial and probe mechanisms (n=8, 57%) exhibit stronger simulation-to-fabrication alignment: Liu (2019) implemented 50-Ω SMA probes achieving 6.98 dBi with 18 MHz bandwidth for ADS-B integration, while Abd-Elmonieum (2023) introduced Driven-Shorting Post feeding enabling 75% patch reduction with gains to 32.7 dB through Altair FEKO validation. As documented in the first row of Table 3, electromagnetic simulation achieves 100% high-maturity coverage with no identified gaps, establishing a strong foundation for feeding element design.

Complex feeding networks (n=4) reveal pronounced integration discontinuities evident in the subsequent rows of Table 3. Lehmensiek (2017) designed sequential-phase networks for wideband CP at X-band using FEKO, yet CubeSat body interaction documentation remains minimal. Wang (2024) achieved dual-band functionality through five-port couplers with 3D metal printing, but system integration constrained to antenna-level characterization. This pattern indicates convergence toward single-feed configurations driven by fabrication simplicity rather than system-level optimization, potentially constraining multi-functional opportunities.

Table 3. Feeding-Simulation-Integration Maturity Assessment

Workflow Stage	High-Maturity Coverage (%)	Low-Maturity Coverage (%)	Primary Integration Gap
EM Simulation	100	0	None—universal adoption
Parametric Optimization	79	21	Algorithm documentation
Thermal Analysis	14	86	Multiphysics integration
Mechanical Integration	21	79	Deployment mechanisms
CubeSat Body Interaction	29	71	Critical system gap

The stark contrast across workflow stages in Table 3 reveals the feeding-integration disconnect: while the first row shows 100% electromagnetic simulation coverage, the final three rows expose profound deficiencies. As quantified in Table 3, only 29% systematically evaluate antenna-CubeSat interactions, representing the primary integration gap. Islam (2015) and Kibria (2018) represent exceptions, documenting HORYU-IV and BIRDS-1 integration through environmental testing. Theoharis (2021) modeled 36-element arrays on 3U platforms achieving 20.1 dB gain with explicit body interaction analysis, though this remains outlier practice relative to the 71% low-maturity coverage shown in Table 3's platform interaction row.

The feeding-to-beamforming gap persists beyond the metrics captured in Table 3: Saeidi (2025) proposed metasurface leaky-wave designs with frequency-dependent steering (3.75–30 GHz), yet beamforming IC pathways remain undefined. The thermal analysis row in Table 3 documents that thermal-mechanical validation appears in only 14% (Curreli, 2021; Priscila, 2022), creating reliability risks for LEO operations where Curreli demonstrated commercial prepreg epoxy failure risks under temperature gradients. The 86% low-maturity coverage for thermal analysis and 79% for mechanical integration shown in Table 3 represent critical vulnerabilities requiring systematic workflow reconfiguration.

3.4. Fabrication Workflow Configurations and Manufacturing Scalability

Thirteen studies reveal three fabrication paradigms with distinct implications for manufacturing efficiency and constellation scalability, yet systematic documentation gaps compromise reproducibility and cost-benefit assessment. Table 4 consolidates the configuration characteristics, methodologies, and scalability assessments.

PCB-Based Prototyping Dominance. As documented in the first row of Table 4, conventional photolithography (n=7, 53.8%) maintains dominance through established infrastructure. Torrungrueng (2025) and M.H.K. (2023) achieved compact form factors ($0.72\lambda_0 \times 0.72\lambda_0 \times 0.13\lambda_0$) using Rogers RT/duroid 5880, while Alrushud (2023) demonstrated folded-shorted arrays (50×50 mm) enabling dual-band operation through meandering and shorting techniques. The primary advantage identified for PCB prototyping in Table 4—established infrastructure—enables predictable performance metrics yet creates the tolerance sensitivity constraint documented in the final column. Fabrication recommendations emphasize tolerance management: Munoz-Martin (2023) documented frequency shifts from manufacturing inconsistencies and dielectric variations, while Lobato-Morales (2016) reported 2.22–2.53 GHz shifts attributable to fabrication tolerances and connector integration, directly illustrating the scalability constraint shown in Table 4.

Table 4.

Fabrication Configuration Trade-offs

Configuration	Coverage	Key Methods	Primary Advantage	Scalability Constraint
PCB Prototyping	53.8%	Photolithography, substrate etching	Established infrastructure	Tolerance sensitivity
Advanced Technologies	30.8%	3D printing, stacked substrates, AMC	Performance superiority	Complexity and cost
Cost-Effective	23.1%	Simplified multilayer, reconfigurable materials	Weight/cost reduction	Limited performance data

Advanced Technologies and Structural Innovation. The second configuration in Table 4 addresses additive manufacturing and multilayer stacking (n=4, 30.8%) representing emerging paradigms. Wang (2024) validated 3D metal printing for folded-shorted arrays using high-conductivity aluminum powder ($\sigma=3.56\times10^7$ S/m), achieving dual-band CP consistency. Rajab (2018) reported 8–12 dB gain improvements through FR4/RT5880 stacking, extending bandwidth from 6.8–24 GHz to 6–61 GHz for spiral designs. Curreli (2021) employed PSO algorithms with FDTD simulation for Ka-band stacked patches, achieving 5.53 GHz bandwidth with >15 dB return loss. Krairiksh (2024) introduced irregularly hexagonal AMC arrays achieving 29.4% axial ratio bandwidth and 42.42% impedance bandwidth, demonstrating simplified fabrication with maintained performance. These implementations exemplify the performance superiority advantage documented for advanced technologies in Table 4, though the complexity and cost constraint noted in the final column limits widespread adoption despite the 30.8% coverage shown.

Cost-Effective Strategies and Weight Optimization. The third configuration in Table 4 captures resource-constrained approaches (n=3, 23.1%) prioritizing weight and cost reduction. DiCarlofelice (2022) developed ultra-wideband aperture-coupled designs using simple multilayer structures without interlayer interconnections, achieving 50% fractional bandwidth (2.8–4.71 GHz) suitable for mass production. Johnson (2020) employed adhesive polyimide tapes and 3D-printed plastic for reconfigurable monopole/patch configurations, achieving 6.9% bandwidth (7.7 dBi) in patch mode while eliminating deployment mechanisms. Aziz (2025) demonstrated tri-band omnidirectional design fully enclosed within CubeSat structure ($100\times100\times101$ mm^3) using Rogers RO4003C, achieving stable multi-band resonance without external deployment. These approaches leverage the weight/cost reduction advantage identified in Table 4, though the limited performance data constraint reflects insufficient validation across diverse mission profiles.

Manufacturing Documentation Deficiencies. Systematic gaps emerged across all fabrication paradigms documented in Table 4. Thermal-mechanical validation integration appears in only 14% of studies despite demonstrated necessity for space qualification, a deficiency not captured in Table 4's configuration categories but evident in cross-referencing with Table 3's thermal analysis row. Manufacturing process parameters receive inadequate documentation, hindering reproducibility and quality assurance implementation across the methods listed in Table 4. Quantitative cost-benefit analyses comparing the three configurations shown in Table 4 under resource-constrained scenarios remain absent, limiting evidence-based selection guidance for mission planners. The tripartite classification in Table 4 reveals that material-driven innovation converging with advanced techniques offers optimal balance between performance and practicality, yet standardization and comprehensive documentation remain critical prerequisites for scalable constellation deployment exploiting the complementary advantages shown across Table 4's configurations.

4. Discussion

4.1. Structural Origins of the Simulation-Integration Paradox

Why does extraordinary electromagnetic sophistication (85% achieving ±1.5 dB simulation-measurement agreement) coexist with profound integration deficiencies (29% evaluating antenna-platform interactions, 14% incorporating thermal-mechanical validation)? Three structural factors systematically explain this workflow paradox:

First, disciplinary fragmentation creates workflow silos. Electromagnetic engineers optimize antenna performance metrics—gain, axial ratio, bandwidth—using specialized solvers (HFSS, CST, FEKO), while systems engineers independently address deployment mechanisms, thermal management, and power distribution. The 71% feeding-to-system integration gap documented in results quantifies this disconnect. Mohammed et al. (2019) observed that historically "characteristics were largely established theoretically and verified experimentally" (p. 511) through integrated workflows, yet contemporary practice demonstrates regression toward disciplinary isolation. This fragmentation intensifies for advanced configurations: metasurface-integrated feeds achieving 12.5 dBi gain with frequency-dependent steering remain isolated from beamforming IC integration pathways not due to technical impossibility—Mohammed et al. (2019) confirmed aperture-coupled patches are "well suited for monolithic phased arrays where active devices can be integrated" (p. 511)—but due to workflow boundaries preventing electromagnetic and systems engineering collaboration.

Second, publication incentive structures reward electromagnetic novelty over system integration completeness. Academic journals and conferences prioritize manuscripts demonstrating performance records (highest gain, widest bandwidth, smallest footprint) or novel topologies (metasurfaces, reconfigurable architectures) rather than comprehensive integration validation. This creates perverse incentives: researchers invest effort optimizing S_{11} parameters visible to reviewers while neglecting antenna-platform electromagnetic coupling, thermal stability under eclipse-sunshine transitions, and mechanical deployment reliability—factors determining actual mission success yet remaining invisible in traditional electromagnetic performance tables. The 68% algorithmic hyperparameter opacity observed across genetic algorithm implementations exemplifies this phenomenon: optimization trajectory details critical for reproducibility receive minimal documentation because reviewer focus concentrates on final performance metrics rather than methodological rigor. Abulgasem et al. (2021) documented that "antenna type selection exhibits strong application dependencies" (p. 45320), yet 71% of simulation workflows omit explicit application-antenna coupling analysis, suggesting researchers optimize generic performance rather than mission-specific system integration.

Third, validation cost asymmetry systematically excludes comprehensive testing from resource-constrained programs. Thermal vacuum chamber testing, vibration qualification, and proton radiation exposure simulation cost 5-10× standard anechoic chamber measurements, rendering comprehensive environmental validation economically prohibitive for many research groups. This explains why anechoic chambers dominate 40% of validation approaches despite specialized systems (Starlab, TVAC) demonstrating superior multiphysics characterization: accessibility constraints rather than technical merit drive methodology selection. The critical finding that proton radiation induces 2.1 dB FR4 degradation versus <0.3 dB Rogers RT/duroid degradation—undetectable through standard electromagnetic testing—reveals mission-reliability blind spots created by resource-driven validation limitations. For deployable configurations where "deployment mechanism incurs extra cost and complexity" with "risk that antenna might not deploy, contributing to mission failure likelihood" (Abulgasem et al., 2021, p. 45317), the 76.9% absence of deployment validation represents systematic validation inadequacy directly traceable to cost-accessibility constraints rather than acknowledged technical limitations.

4.2. The Reproducibility Crisis as Emergent System Failure

The 68% algorithmic hyperparameter opacity and <8% cross-platform validation coverage do not represent isolated documentation failures—they constitute emergent manifestations of systematic workflow pathologies. Three mechanisms explain this reproducibility crisis:

Vendor lock-in perpetuates methodological opacity. Commercial electromagnetic solvers (HFSS, CST, FEKO) employ proprietary algorithms, undocumented meshing heuristics, and vendor-specific convergence criteria that researchers accept as black-box defaults. When 92% of optimization-coupled studies fail to document population sizes, crossover probabilities, or convergence thresholds, this reflects normalized reliance on vendor defaults rather than deliberate methodological choices. Abulgasem et al. (2021) documented that "shorting pins techniques demonstrate significant dependency on spacing between pins and feeding probe" (p. 45315), generating hyperparameter sensitivity landscapes requiring systematic exploration—yet vendor-default simulation settings preclude this analysis. The <8% cross-platform validation coverage directly results from commercial solver cost structures: acquiring licenses for HFSS, CST, and FEKO for comparative validation exceeds most research budgets, effectively preventing systematic reproducibility assessment.

Competitive pressure incentivizes premature publication over validation thoroughness. The rapid pace of CubeSat technology development, combined with academic promotion pressures requiring high publication rates, creates incentives for reporting preliminary simulation results rather than investing months in comprehensive experimental validation and manufacturing tolerance analysis. This explains why 58% of validations rely exclusively on S-parameter measurements: VNA characterization requires days, while comprehensive far-field anechoic chamber campaigns with environmental qualification demand weeks to months. The progression documented in results—from S-parameter-only validation (Groups A-B, 70% coverage) toward comprehensive multi-domain testing (Groups C-D, 30% coverage)—reflects not methodological sophistication evolution but resource availability stratification, with only well-funded programs accessing validation completeness.

Absence of community-enforced standards enables methodological drift. Unlike fields with established reporting standards (CONSORT for clinical trials, PRISMA for systematic reviews), CubeSat antenna research lacks community-enforced protocols mandating hyperparameter transparency, cross-platform validation, or environmental testing documentation. This vacuum enables the observed 86% thermal validation deficiency and 79% mechanical integration inadequacy to persist across two decades without systematic correction. Mohammed et al.'s (2019) observation that "full wave methods were being developed" historically with systematic validation protocols highlights that contemporary reproducibility deficiencies represent regression rather than inherent limitations—driven by absent standardization infrastructure rather than technical impossibility.

4.3. Frequency-Dependent Validation Myopia as Path Dependency Artifact

The concentration of validation protocols around S-band frequencies (2.4-2.5 GHz) despite mission requirements spanning VHF to W-band represents path-dependent institutional inertia rather than rational technical allocation. Abulgasem et al. (2021) documented that "most proposed S-band antennas operate in the unlicensed Industrial, Scientific and Medical (ISM) band (2.4-2.5 GHz), are patch antennas and do not require deployment" (p. 45318), creating validation infrastructure optimized for this frequency range. Anechoic chambers calibrated for S-band, VNA measurement fixtures designed for 50-Ω impedance matching at 2.4 GHz, and thermal chamber protocols validated for patch antenna thermal expansion coefficients collectively constitute installed capital infrastructure perpetuating S-band validation dominance (40% of approaches) despite emerging mission requirements.

This path dependency creates systematic blind spots for Ka-band (34 GHz) and W-band (86 GHz) systems where "Ka-band and X-band reflector, reflectarray, and metasurface antennas represent the most promising types due to superior gain performance," with mesh reflector designs achieving "gains exceeding 30 dBi that greatly expand CubeSat capabilities from LEO to interplanetary exploration" (Abulgasem et al., 2021, p. 45321). The 16% specialized measurement system coverage reflects not technical adequacy but infrastructure investment inertia: institutions replace existing S-band anechoic chambers with Ka-band-capable systems only when mission contracts justify capital expenditure, creating temporal lag between technology requirements and validation capability availability. For deep-space missions requiring high-frequency operation, this validation infrastructure gap directly threatens mission success—thermal cycling effects, material property frequency dependencies, and connector parasitic effects scale nonlinearly with frequency, rendering S-band-calibrated validation protocols fundamentally inadequate for Ka/W-band performance prediction.

The resource-driven validation asymmetry documented in results—where only 14% employ comprehensive multi-domain testing—reveals institutional optimization for incremental publication output rather than mission reliability assurance. Ramahatla et al. (2022) established mission-grade performance benchmarks (3-14.6 dBi gains, axial ratios ≤3 dB) requiring multiphysics characterization that 86% fail to replicate, yet this systematic inadequacy persists because publication-driven research programs prioritize electromagnetic novelty demonstration over environmental qualification completeness. The finding that combined testing approaches consistently identify interface degradations and thermal sensitivities invisible to isolated platforms should logically mandate comprehensive validation as baseline practice—yet institutional resource allocation continues prioritizing single-domain characterization because publication counting metrics reward study quantity over validation quality.

4.4. Strategic Imperatives for Paradigmatic Reconfiguration

The identified workflow discontinuities demand not incremental improvement but fundamental paradigm reconfiguration. Three strategic transformations prove essential:

First, consortium-driven standardization must establish community-enforced protocols. The 68% hyperparameter opacity and <8% cross-platform validation coverage require mandatory reporting standards modeled on PRISMA systematic review guidelines: all publications must document genetic algorithm population sizes, crossover probabilities, convergence criteria, solver mesh densities, and boundary condition specifications. Cross-platform validation comparing HFSS, CST, and FEKO convergence should become prerequisite for claiming performance record achievements. Open-source simulation model repositories enabling workflow replication would address vendor lock-in perpetuating methodological opacity. These standardization imperatives align with Abulgasem et al.'s (2021) assertion that "antenna will be critical design aspect of future CubeSat missions where design and integration must be considered through mission design cycle involving modelling and optimization of antennas along with satellite structure" (p. 45322).

Second, tiered validation protocols must stratify testing requirements by mission risk. Not all CubeSat antennas require comprehensive environmental qualification: technology demonstration missions accepting higher failure risk may reasonably limit validation to S-parameter and anechoic chamber characterization. However, operational constellations supporting critical telecommunications infrastructure must demonstrate environmental qualification through thermal cycling (-100°C to +100°C), vibration testing (NASA GEVS specifications), radiation exposure simulation (5-year LEO equivalent), and mechanical deployment verification. Explicit validation tier documentation enables reviewers and mission planners to assess confidence levels appropriate for intended applications, addressing the current opacity where validation completeness remains undifferentiated across technology readiness levels.

Third, funding mechanisms must incentivize system integration over component optimization. Grant evaluation criteria should explicitly reward comprehensive platform interaction modeling (addressing the 71% gap), thermal-mechanical validation integration (86% deficiency), and feeding-to-beamforming system documentation (79% inadequacy) rather than solely electromagnetic performance metrics. This requires cultural transformation within funding agencies and editorial boards: recognizing that mission reliability derives from holistic system validation rather than isolated component performance records. For emerging applications including "5G hybrid satellite-terrestrial architectures, Internet of Space Things, and Low Earth Orbit Internet of Things" demanding "mm-wave and sub-mm-wave frequency ranges to achieve multibeam and beam steering functionalities" (Abulgasem et al., 2021, p. 45322), system integration completeness becomes prerequisite for operational deployment—yet current incentive structures systematically undervalue this critical engineering dimension.

Conclusions

Analysis of 50 simulation workflows establishes HFSS, CST Microwave Studio, and FEKO as foundational platforms achieving measured-to-simulated gain agreements within

±1.5 dB, with platform specialization reflecting solver-specific advantages: HFSS dominance in circular polarization and bandwidth tuning (56%), CST emphasis on miniaturization and thermo-mechanical verification (38%), and FEKO in array-scale radiation control (12%). Temporal progression from circular polarization consolidation (2014-2017) through dual-band expansion (2018-2021) to metasurface integration (2022-2025) demonstrates methodological maturation. However, critical deficiencies compromise reproducibility: 68% of algorithm-coupled studies omit essential hyperparameters (population sizes, crossover probabilities, convergence criteria), computational resource reporting remains absent, and cross-platform validation appears in fewer than 8% of implementations. This algorithmic opacity, combined with vendor-default predominance, introduces systematic vulnerabilities where simulation-specific artifacts propagate to design recommendations without independent verification.

Four distinct configurations reveal measurement platform selection reflects instrumentation accessibility rather than optimal verification strategy. Anechoic chambers (40%) and vector network analyzers (30%) dominate with 70% combined coverage, yet comprehensive multi-domain approaches integrating electromagnetic, thermal, mechanical, and radiation testing constitute only 14% of implementations. Combined methodologies identify critical performance variations invisible to isolated platforms: thermal cycling induces ±8 MHz frequency shifts and 0.5-0.8 dB gain degradation, while proton radiation produces 2.1 dB degradation in FR4 substrates versus <0.3 dB in Rogers RT/duroid 5880. Despite high instrument-recommendation complementarity, systematic underrepresentation of thermal (86% deficiency), mechanical (79% inadequacy), and environmental validation exposes persistent gaps between laboratory characterization and operational deployment verification. Resource constraints limit specialized systems (16%) despite superior capabilities, introducing systematic bias where accessible methodologies supersede optimal strategies.

Analysis of 14 feeding-simulation-integration studies exposes critical workflow gaps wherein electromagnetic optimization occurs isolated from holistic system requirements. While single-feed configurations (64%) and coaxial/probe mechanisms (57%) demonstrate robust simulation-to-fabrication alignment, only 29% systematically evaluate antenna-CubeSat body interactions and merely 14% incorporate thermal-mechanical validation. Advanced architectures including metasurface-integrated designs achieving 5.6-6.7 dBic gain, Driven-Shorting Post miniaturization enabling 75% area reduction with gains exceeding 30 dB, and 3D-printed networks delivering dual-band operation exhibit extraordinary electromagnetic sophistication yet remain decoupled from deployment mechanisms, power distribution interfaces, and beamforming IC integration pathways. The 71% feeding-to-system integration gap represents fundamental constraint on communication system scalability as mission demands evolve toward adaptive beam steering and higher data rates. Convergence toward single-feed/probe configurations (81% combined) reflects fabrication simplicity optimization rather than mission-level performance maximization.

Three fabrication paradigms reveal distinct scalability implications with systematic documentation deficiencies. Conventional PCB prototyping (53.8%) maintains dominance through established photolithographic infrastructure yet exhibits critical substrate dependencies and tolerance sensitivities—permittivity variations (±0.1 in ε_r) produce ±15 MHz frequency deviations, while photolithographic tolerances (±30 μm) generate systematic frequency shifts (2.22-2.53 GHz). Advanced technologies (30.8%) including 3D metal printing, stacked substrates, and AMC integration demonstrate superior performance: dual-band consistency through selective laser melting, 8-12 dB gain improvements via FR4/RT5880 stacking extending bandwidth from 6.8-24 GHz to 6-61 GHz, and 42.42% impedance bandwidth through hexagonal AMC arrays. Cost-effective strategies (23.1%) emphasizing weight reduction and deployment elimination represent promising constellation-scale trajectories. However, thermal-mechanical validation integration appears in only 14% despite demonstrated necessity, manufacturing parameters receive inadequate documentation hindering quality assurance, and quantitative cost-benefit analyses remain absent.

Synthesis across 79 studies reveals fundamental tensions between component-level electromagnetic optimization sophistication and system-level integration maturity. The dominant simulation-to-validation workflow (60-70% coverage) demonstrates extraordinary characterization capabilities—85% achieving robust electromagnetic agreements—yet systematically fails to address multiphysics operational requirements, deployment verification, and mission environment qualification. The identified paradox wherein universal electromagnetic simulation adoption (100%) coexists with profoundly limited platform interaction evaluation (29%) and inadequate thermal-mechanical validation (14%) represents critical vulnerability threatening mission reliability as architectures transition from technology demonstration to operational constellation deployment. Current workflows prioritize isolated electromagnetic performance over holistic system reliability, necessitating paradigm reconfiguration toward mandatory platform interaction modeling, comprehensive environmental validation protocols, and documented integration interfaces addressing the 71% feeding-to-system gap, 86% thermal validation deficiency, and 79% mechanical integration inadequacy.

Recommendations

CubeSat antenna development must implement tiered validation strategies stratifying requirements by mission risk: technology demonstrations may limit validation to electromagnetic characterization, while operational constellations require comprehensive environmental qualification through thermal cycling (-100°C to +100°C), vibration testing (NASA GEVS specifications), radiation exposure simulation (5-year LEO equivalent), and mechanical deployment verification. Consortium-driven standardization must establish mandatory reporting protocols: all publications documenting genetic algorithm hyperparameters, solver configurations, and boundary conditions. Cross-platform validation comparing HFSS, CST, and FEKO convergence should become prerequisite for performance record claims. Funding mechanisms must incentivize system integration over component optimization through evaluation criteria rewarding comprehensive platform interaction modeling, thermal-mechanical validation integration, and feeding-to-beamforming documentation. Open-source simulation model repositories would address vendor lock-in perpetuating methodological opacity.

Limitations

Four methodological constraints affect generalizability: 12 inaccessible full-texts (13.2% of potentially eligible studies) may contain critical workflow configurations introducing selection bias; English-language restriction systematically excluded non-Anglophone programs where native-language documentation may reveal alternative paradigms; peer-reviewed focus necessarily omitted proprietary industry protocols and commercial constellation methodologies potentially employing more mature integration practices; and inductively derived objectives reflect documentation practices rather than actual workflows—comprehensive system integration may be implemented yet selectively reported due to publication constraints or intellectual property considerations. These limitations suggest identified gaps may represent documentation deficiencies rather than fundamental inadequacies, though systematic under-reporting across 79 diverse studies indicates genuine methodological fragmentation requiring standardization initiatives.

Future research directions

Five critical priorities emerge: standardized multiphysics validation protocols integrating electromagnetic characterization with thermal cycling, vibration testing, radiation exposure, and deployment verification; systematic investigation of feeding network interfaces with beamforming ICs, power distribution, and reconfigurable switching for adaptive steering; comparative manufacturing studies employing quantitative cost-benefit analysis, tolerance characterization, and batch production quality assessment across photolithography, 3D printing, and hybrid approaches; development of open-source computational reproducibility frameworks mandating hyperparameter transparency, cross-platform validation protocols, and public mesh repositories; and longitudinal on-orbit validation campaigns correlating pre-launch characterization with post-deployment telemetry quantifying prediction accuracy and identifying measurement-to-operational performance gaps across mission profiles, orbital regimes, and space weather conditions essential for confident operational deployment.