Designing framework for standardization and testing requirements of rain radar in Indonesia

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Article Info	ABSTRACT
	Indonesia's tropical environment requires advanced rainfall monitoring systems to strengthen disaster early warning capabilities. However, the absence of a dedicated national standard for rain radar has limited domestic technology growth and interoperability. This study develops a framework for the Indonesian National Standard (SNI) for rain radar by integrating the framework for analysis, comparison, and testing of standards (FACTS) with structural equation modeling (SEM). Stakeholder requirements were systematically analyzed and translated into technical specifications, benchmarked against International Organization for Standardization (ISO) and World Meteorological Organization (WMO) standards, and statistically validated. SEM results indicate that performance parameters (β =0.70) and testing methods (β =0.76) are the most influential components of the framework. The validated model establishes five essential domains—system specifications, testing procedures, calibration and maintenance, installation criteria, and system control. The resulting FACTS-SEM framework provides a robust, evidence-based foundation for developing and validating meteorological instrumentation standards suited to Indonesia's tropical context.

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1. INTRODUCTION

Indonesia's tropical climate is characterized by high rainfall, averaging 200-300 mm/day with extremes exceeding 380 mm/day, making the country highly vulnerable to hydro-meteorological disasters such as floods and landslides [1], [2]. According to the National Disaster Management Agency (BNPB), more than 12,800 events were recorded by 2019 [3], underscoring the urgent need for advanced early warning systems. Real-time rainfall monitoring is a cornerstone of disaster mitigation, and weather radar technology, especially those using Doppler systems, has proven highly effective in detecting rain particles, ice particles, and wind shear, providing essential data for weather surveillance and nowcasting [4], [5].

Historically, Indonesia's market for radar technology has been dominated by imported products. Strengthening domestic capability in rain radar manufacturing is therefore crucial for achieving technological sovereignty and national resilience, as shown in Figure 1. The X-band rain radar, initially developed by the Center for Atmospheric Science and Technology (National Aeronautics and Space Agency (LAPAN)), now National Research and Innovation Agency (BRIN), represents a promising local innovation tailored for tropical meteorological monitoring [6]–[9]. Its compact design and cost efficiency make it suitable for

regional hydrometeorological networks and early warning applications. However, to ensure product quality, safety, and interoperability, a robust regulatory framework is essential. The Indonesian National Standard (SNI), established under Law No. 20 of 2014 on standardization and conformity assessment, provides this foundation by ensuring reliability, consumer protection, and global competitiveness [10]. According to the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) guide 2, standardization involves developing consensus-based technical specifications that balance safety, environmental, and technological considerations in response to societal needs [11].

Figure 1. Rain radar

Developing a new standard for complex technologies such as weather radar presents challenges in harmonizing diverse stakeholder interests, government agencies, manufacturers, researchers, and operational users while maintaining alignment with international best practices [11], [12]. International references such as ISO 19926-1 [13] and the World Meteorological Organization (WMO) Commission for Instruments and Methods of Observation (CIMO) guide no. 8 [14]–[16] define comprehensive performance, calibration, and operational parameters. However, these guidelines are primarily designed for temperate environments and do not fully address tropical requirements such as high humidity (>90% RH), elevated ambient temperatures, and intense convective precipitation, which impose unique durability and calibration challenges [17]–[19]. Consequently, a clear gap exists between international benchmarks and Indonesia's environmental and industrial needs.

A methodological gap also persists in standard development processes. While frameworks exist for organizing and comparing standards, few incorporate quantitative validation of the resulting structures. The framework for analysis, comparison, and testing of standards (FACTS), developed by the U.S. National Institute of Standards and Technology (NIST), offers a structured approach to standard lifecycle management and stakeholder organization through analytical tools like the Zachman framework [20], [21]. In parallel, structural equation modeling (SEM) enables the quantitative assessment of relationships among latent variables such as performance, reliability, and stakeholder influence. Yet, the integration of these two methodologies using FACTS to design and SEM to validate standard frameworks remains unexplored, particularly in meteorological instrumentation [22], [23].

This study proposes an integrated FACTS-SEM approach to develop a comprehensive and empirically validated framework for the SNI on rain radar systems. The research aims to i) identify and prioritize key technical requirements through stakeholder analysis, ii) benchmark these requirements against international standards, and iii) statistically validate their interrelationships using SEM. This integration ensures that the proposed standard is both stakeholder-driven and data-verified, bridging qualitative consensus with quantitative rigor. Ultimately, the framework provides a scientific basis for enhancing the accuracy, reliability, and interoperability of domestically developed rain radar systems, thereby strengthening Indonesia's capacity for hydro-meteorological disaster preparedness.

The remainder of this paper is structured as follows: section 2 details the integrated FACTS-SEM methodology. Section 3 presents the results of the stakeholder analysis, gap analysis, and SEM validation, followed by a critical discussion of the findings. Finally, section 4 concludes with the study's implications and recommendations.

2.   METHOD

This study was designed to develop and validate a framework for the SNI for rain radar. To achieve this, an integrated methodological approach was employed, combining the qualitative, structured framework of the FACTS with the quantitative, validating power of SEM. The rationale for this integration is twofold: the FACTS method provides a systematic process to capture and organize complex stakeholder needs into technical requirements [20], while SEM offers a robust statistical tool to empirically validate the structural relationships between these requirements and the overarching goals of standardization [24], [25]. The research was conducted in four primary phases, as illustrated in Figure 2.
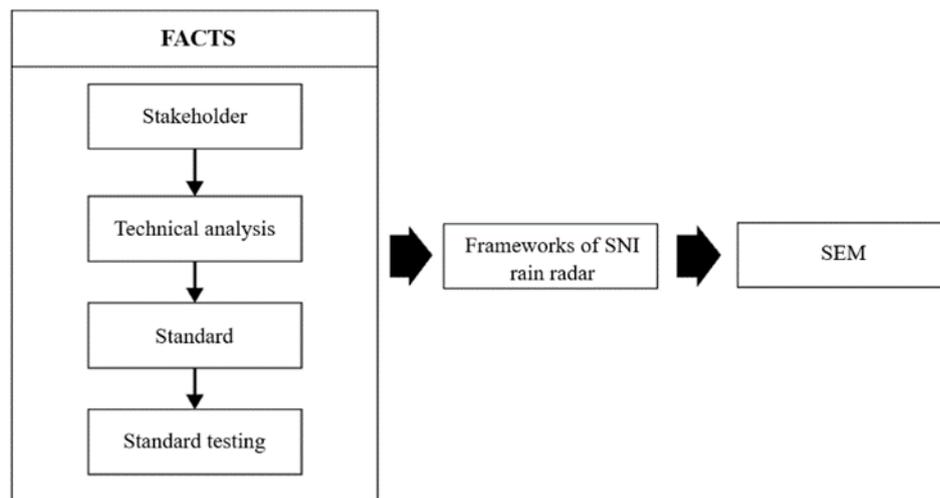

Figure 2. Research workflow integrating the FACTS approach and SEM validation

2.1. Phase 1: stakeholder analysis and requirement elicitation

The first phase systematically identified relevant stakeholders and elicited their requirements to ensure consensus and broad acceptance of key principles in standardization [11]. Five primary stakeholder groups were classified through expert consultation and literature references: i) government regulators (e.g., Ministry of Communication and Information, The National Standardization Agency of Indonesia (BSN)); ii) end-users (Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG), and BNPB); iii) domestic manufacturers; iv) R&D institutions (BRIN); and v) testing laboratories. This classification ensured balanced representation from policy to implementation.

Stakeholder requirements were gathered using two complementary methods for data triangulation. A systematic literature review of journals, technical reports, and international standards (ISO, WMO) [13]–[16] established the baseline and informed interview design. Semi-structured interviews with representatives from each group captured context-specific needs on system performance, operations, and testing beyond the scope of existing documents. The outcome was a consolidated stakeholder requirement matrix, as in Table 1, serving as the empirical foundation for translating expectations into technical specifications in the subsequent phase.

2.2. Phase 2: technical translation using the Zachman framework

The second phase focused on translating stakeholder requirements, often articulated in qualitative or functional terms, into clear and measurable technical specifications. This translation process was essential to ensure that the stakeholder-driven needs identified in phase 1 could be accurately reflected in a formalized standard. The Zachman framework was adopted as the organizing structure for this task, as it systematically addresses the six fundamental dimensions of information (what, who, where, when, why, and how), thereby ensuring a holistic and traceable linkage between functional needs and technical requirements [20]–[23].

The translation process began with a detailed analysis of each stakeholder requirement to determine its corresponding technical expression. For example, a user requirement such as "system durability in outdoor environments" was mapped to measurable specifications, including enclosure protection ratings (IP code), environmental sealing, and operating temperature range. This structured mapping process ensured that every stakeholder expectation was transformed into a quantifiable parameter that could be tested and verified during standard implementation. The iterative review with technical experts further enhanced precision, ensuring that no requirement was left ambiguous or redundant.

The output of this phase was a comprehensive technical requirements table, as later presented in Table 2 of the results. This table served as a foundational document for the draft standard, consolidating stakeholder expectations into engineering terminology aligned with measurement, testing, and certification criteria. The systematic application of the Zachman framework thus ensured clarity, completeness, and internal consistency, providing a robust foundation for the subsequent benchmarking and validation phases.

Table 1. Requirements based on stakeholder needs

Stakeholder	Requirements
Government	– There are working frequency requirements that have been set according to the Ministry of Communication and Information. – Minimum power limits.
Consumer/user	– Passing security, safety, and quality testing from system and sub-system levels. – Equipment calibration and product maintenance. – Instructions for use/installation procedures. – Durability is required because the radar is installed outdoors.
R&D rain radar	– The resolution and accuracy of the radar are determined to see the performance of the radar. – Various types of radars need limitations. – The range must be at least. – Clutter. – Connectivity has a minimum limit to achieve good quality. – The system can be monitored remotely.
Manufacturer	– Different types of radars need limitations. – The range must be at least. – The operational temperature of the radar is determined. – Passing security, safety, and quality testing at the system and sub-system levels.
Testing laboratory	– Product testing, if possible, using existing testing standards. – Passing security, safety, and quality testing from the system and sub-system levels.
International journal	– Sensitivity, resolution, and accuracy of radar [5], [9]. – Radar rotation speed [6], [17]. – Antenna and transceiver type [15], [26]. – System loss [16], [26]. – Pulse repetition frequency [16], [26]. – Duty cycle [27], [28]. – Beam width [26], [29]. – Pulse length [16]. – Clutter [30]. – Calibration [30].

Table 2. Translation of requirements into technical parameters

Requirement	Technical analysis	Category
There are work frequency requirements that have been regulated according to the Ministry of Communication and Information	Limitations of working frequencies used	Radar system specification
Minimum power limit	Radar power output requirements	Radar system specification
Sensitivity, resolution, and accuracy of the radar	Sensitivity, resolution, accuracy	Performance metrics
Range distance	Wide coverage area	Performance metrics
Connectivity	Data transfer speed	Performance metrics
Antenna type, beam width, system loss	Antenna specifications	Radar system specification
Radar rotation speed	Radar rotation speed	Radar system specification
Transceiver	Transmitter type	Radar system specification
Pulse repetition frequency	Pulse repetition frequency	Radar system specification
Duty cycle	Duty cycle	Radar system specification
Pulse length	Pulse length	Radar system specification
Operating temperature	Operating temperature	Radar system specification
Durability	Enclosure type	Environmental specs
Product testing, if possible, using existing testing standards. Passing security, safety, and quality testing at both system and sub-system levels.	-	Verification
Equipment calibration and product maintenance clutter	-	Support procedures
Instructions for use/installation procedures	-	Support procedures
Remote system control	-	Support procedures

2.3. Phase 3: gap analysis against international standards

In the third phase, the technically defined parameters derived from the previous step were benchmarked against internationally recognized standards to ensure global alignment and contextual relevance. The main objective of this phase was to identify areas of conformity, divergence, and enhancement opportunities relative to established international practices. Two major reference documents

were selected for this comparative assessment [13], [14]. These standards were chosen because they represent authoritative global references for weather radar performance, calibration, and operation.

The gap analysis employed a clause-by-clause comparison method, systematically examining each proposed technical parameter from the draft SNI framework against its counterpart in the reference standards. This process allowed for the identification of three principal outcomes. First, areas of alignment were recognized where the proposed requirements directly corresponded with the international clauses, demonstrating adherence to global best practices. Second, enhanced specificity was observed where the proposed SNI provided additional details suited to Indonesia's operational environment, such as stricter requirements for humidity tolerance, lightning protection, and maintenance under tropical conditions. Third, gaps were detected where certain stakeholder-driven needs, such as requirements for local data interoperability and calibration traceability, were not adequately addressed in the international standards.

The results of this comprehensive comparison were compiled into a detailed matrix, as shown later in Table 3. This matrix provided a structured overview of how the proposed SNI framework aligns with, extends, or supplements existing international references. The findings from this analysis guided the refinement of the draft standard, ensuring that it harmonizes with global conventions while maintaining national relevance for Indonesia's tropical meteorological conditions.

Table 3. Gap analysis with international standards

Technical requirements	Rain radar standard	ISO 19926-1:2019(en)	WMO no.8 chapter 7 CIMO guide 2
Working frequency	Clause 3.2.2.1	Clause 5.1	Clause 7.6.2
Minimum power output	Clause 3.3	-	-
Resolution	Clause 4.4	Clause 6.2.2	Clause 7.6.6
Sensitivity	-	Clause 6.2.1	Clause 7.6.3
Accuracy	-	Clause 6.2.4	Clause 7.2.1
Coverage area	Clause 3.3	Clause 9.4	
Data transfer speed	Clause 8.3	Clause 9.3	-
Antenna specifications	Clause 3.2.2.2	Clause 5.2.3.1	Clause 7.6.6
Radar rotation speed	Clause 3.2.2.2	Clause 6.3.4	Clause 7.6.8
Transmitter type	Clause 3.2.2.3	Clause 5.2.3.3	Clause 7.6.8
Pulse repetition frequency	Clause 3.2.2.3	Clause 5.2.3.3	Clause 7.6.5
Duty cycle	Clause 3.2.2.3	Clause 5.2.3.3	-
Pulse length	Clause 3.2.2.3	Clause 5.2.3.3	Clause 7.6.4
Operating temperature	Clause 4.3	-	-
Enclosure type	Clause 3.2.2.8	-	-
Test method	Clause 5	Annex A	-
Calibration and maintenance	Clause 6	Clause 7	Clause 7.7
Installation procedures and location criteria	Clause 7	Clause 9	Clause 7.8
System control and monitoring	Clause 8	Clause 9.3	Clause 7.8.2

2.4. Phase 4: validation via structural equation modeling and expert consensus

The final phase validated the proposed standard using both statistical and expert-based approaches. Quantitative validation was employed covariance based (CB)-SEM, while qualitative validation was achieved through a forum group discussion (FGD). A CB-SEM model was developed with five latent constructs—performance parameters, testing methods, calibration and maintenance, operational procedures, and system control and monitoring—hypothesized to shape an effective "rain radar standard" [24], [25]. 5-point Likert questionnaire (n >120 experts) operationalized phase 2 variables. Data were analyzed using IBM AMOS v.27, confirming reliability (CR >0.7), validity (average variance extracted (AVE) >0.5), good model fit (χ^2/df<3, root mean square error of approximation (RMSEA)<0.08, comparative fit index (CFI) >0.90, and Tucker-Lewis's index (TLI) >0.90).

Subsequently, FGD with the same expert pool reviewed SEM results, providing interpretive insights and resolving weaker statistical paths through discussion and consensus. This process validated the practicality and clarity of the framework's technical clauses. The integration of SEM and FGD confirmed both empirical robustness and stakeholder consensus, ensuring the final SNI draft embodies the principle of "standardization by consensus" [11], [12].

3. RESULTS AND DISCUSSION

This section presents the results of the integrated FACTS–SEM approach for developing and validating the proposed framework of the SNI for rain radar systems. The findings progress from stakeholder requirement analysis to international benchmarking and framework validation. Providing a comprehensive, evidence-based standard that aligns national needs with international best practices.

3.1. Translation of stakeholder needs into technical requirements

The stakeholder analysis produced a comprehensive set of requirements representing five key stakeholder groups: government regulators, end-users, domestic manufacturers, research and development institutions, and testing laboratories. Table 1 presents these requirements in detail, showing that regulators emphasized frequency allocation and power limits in accordance with the Ministry of Communication and Information, while end-users such as BMKG and BNPB prioritized safety, calibration, and operational durability. Manufacturers and research institutions focused on core technical metrics including radar sensitivity, range, and resolution, whereas testing laboratories highlighted the need for unified test procedures and compliance verification. These findings illustrate the diversity of perspectives that must be reconciled in a consensus-based national standard.

The translation of these diverse stakeholder requirements into measurable technical parameters was achieved through the Zachman framework, ensuring clarity and traceability. As shown in Table 2, qualitative needs such as "system durability" were converted into quantifiable parameters like enclosure protection rating (IP65) and operational temperature range. Similarly, stakeholder emphasis on "data reliability" was mapped to specifications for signal loss, pulse repetition frequency, and beam width parameters that directly influence radar accuracy and reliability [31]. This systematic translation ensures that all stakeholder needs are represented in the technical clauses of the standard, preventing ambiguity and ensuring testability in future verification processes.

The resulting table of technical parameters thus serves as a cornerstone of the proposed SNI framework. Each parameter is linked to an objective measurement or performance index, creating a foundation that bridges policy, engineering, and compliance requirements. This alignment reflects international best practices, where stakeholder-driven standards must be both technically measurable and operationally verifiable.

3.2. Gap analysis against international benchmarks

The second stage compared the translated technical requirements with international benchmarks to evaluate the degree of conformity and identify areas requiring national adaptation. The comparison employed a clause-by-clause analysis against ISO 19926-1:2019 and WMO no. 8, which serve as authoritative references for weather radar systems [13], [14]. Table 3 summarizes the alignment results, revealing that the proposed SNI corresponds strongly with ISO and WMO specifications in areas such as pulse repetition frequency, pulse length, and antenna design, while introducing additional detail for environmental durability and operational temperature limits.

This enhanced specificity for tropical operation is a major strength of the proposed SNI framework. Indonesia's climatic conditions, marked by high humidity and extreme rainfall, necessitate stricter standards for enclosure sealing, thermal stability, and corrosion resistance. These features are often underrepresented in international documents developed for temperate climates [8], [9]. The inclusion of such parameters ensures that the national standard not only aligns globally but also addresses domestic environmental realities. Conversely, the analysis identified notable gaps in explicit definitions of "sensitivity" and "accuracy" thresholds. These aspects remain loosely defined in international frameworks due to the ongoing evolution of radar calibration technologies [30].

The identified gaps, as shown in Table 3, represent key opportunities for the Indonesian standard to contribute to international knowledge by proposing empirically validated thresholds derived from local testing. This comparative exercise also aligns with the recommendations of [17], [19], who emphasize that localization of standards improves both implementation success and long-term sustainability. Thus, the proposed SNI for rain radar achieves a balance between harmonization with global norms and contextual adaptation for Indonesia's tropical operational environment.

3.3. Validation of the framework through SEM and expert consensus

The final validation phase assessed the structural integrity and practical feasibility of the proposed standard through a combination of SEM and FGD. Figure 3 presents the validated SEM model, where the first five-order latent constructs, performance parameters, testing methods, calibration and maintenance, operational procedures, and system control and monitoring collectively influence the overarching construct of an effective rain radar standard. The model demonstrated a strong fit with empirical data, achieving $\chi^2/df = 2.21$, RMSEA $= 0.06$, CFI $= 0.94$, and TLI $= 0.92$, which are within the accepted thresholds for good model fit [24], [25].

The path coefficients indicate that testing methods ($\beta = 0.76$, $p < 0.001$) and performance parameters ($\beta = 0.70$, $p < 0.001$) are the most influential contributors to the effectiveness of the standard. This finding reinforces the view that measurement and verification mechanisms are as crucial as the technical specifications themselves. Calibration and maintenance also exhibited a substantial effect ($\beta = 0.68$, $p < 0.001$), underscoring

the importance of life-cycle quality assurance. These quantitative results confirm that the framework is statistically robust, reflecting internal consistency across constructs that correspond directly to the stakeholder-derived technical domains presented earlier in Tables 1 to 3.

The SEM findings were then discussed and validated qualitatively through an expert FGD involving over 120 participants from the five stakeholder groups. The discussion confirmed that standardized test methods form the backbone of practical implementation, ensuring that performance parameters are not only specified but also verifiable under real-world conditions. Experts further highlighted that those operational procedures, though showing a weaker loading (β =0.40), remain vital for field deployment, particularly for institutions such as BMKG that manage long-term radar operations in remote areas. This consensus aligns with the standardization philosophy that technical rigor must be balanced with operational feasibility [10]–[12], [17].

The integration of quantitative (SEM) and qualitative (FGD) validation ensures that the proposed framework is both empirically grounded and socially accepted. This process establishes a validated linkage between stakeholder-derived requirements, measurable technical criteria, and confirmatory model results. Such dual validation represents a methodological advancement over conventional consensus-only approaches, moving the national standardization process toward a more evidence-based paradigm [10], [11].
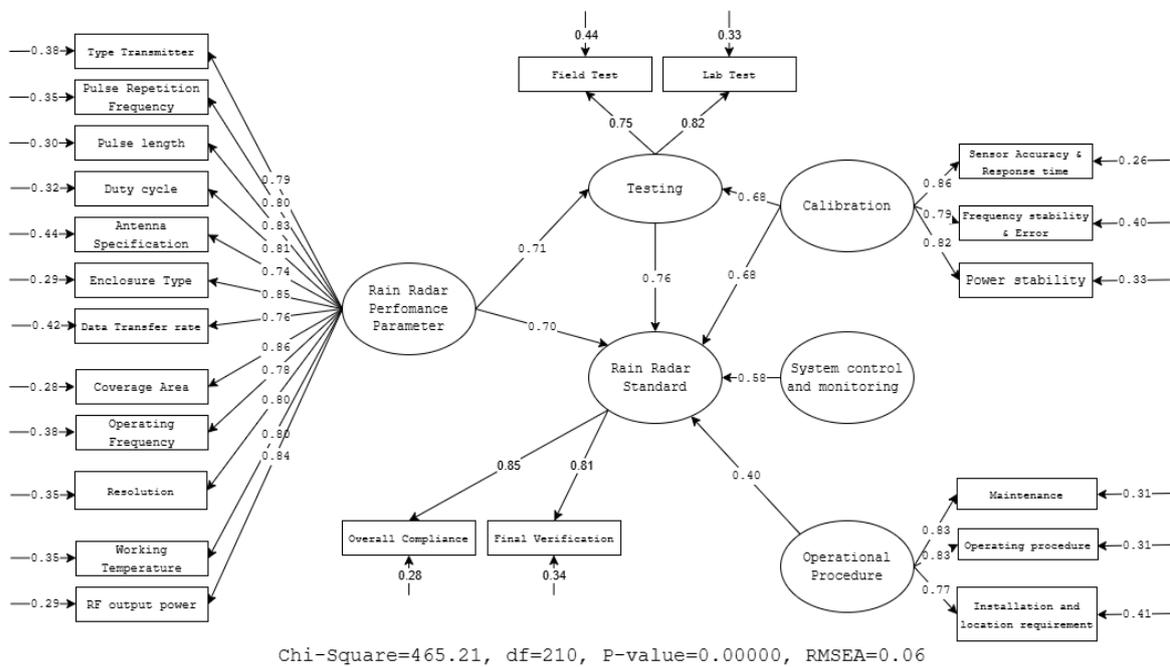

Chi-Square=465.21, df=210, P-value=0.00000, RMSEA=0.06

Figure 3. Validated SEM model: path coefficients between latent constructs (note: p <0.001, p <0.01, p <0.05)

3.4. Critical discussion and implications

The results demonstrate that the integrated FACTS-SEM approach provides a rigorous pathway for developing a national standard that is both globally aligned and locally optimized. The validated model, with R^2 =0.76, confirms that stakeholder-derived parameters strongly predict the perceived effectiveness of the standard. This outcome supports the argument advanced in [24], [25] that SEM can reveal the structural interdependence among complex technical domains, providing empirical grounding to what was previously an expert-driven process.

From a policy perspective, this framework provides an evidence-based tool for the BSN to streamline standard development and certification. For the domestic industry, the verified performance and testing parameters offer a transparent reference that supports quality assurance and accelerates product conformity assessment. For end-users such as BMKG and BNPB, the standardized operational and installation guidelines ensure reliable radar data across diverse regions, ultimately enhancing early warning capabilities for hydro-meteorological hazards.

Nevertheless, several limitations must be acknowledged. The study's validation was primarily domestic, and cross-verification with international experts would further strengthen its universality. In addition, the relatively lower factor loading observed for laboratory testing (λ =0.33) suggests that additional

indicators may be required to fully capture this construct. Future work should include pilot deployments to empirically refine sensitivity and accuracy thresholds, dynamic maintenance of the standard through periodic review, and capacity-building programs for radar technicians to ensure consistent nationwide implementation.

Overall, the FACTS–SEM framework presented here demonstrates that systematic integration of stakeholder input, technical translation, international benchmarking, and statistical validation can produce a robust, adaptive, and credible standardization model. By combining consensus and evidence, the proposed SNI for rain radar sets a precedent for developing standards for other advanced meteorological and environmental technologies.

4.   CONCLUSION

This study successfully designed and validated a comprehensive framework for the SNI for rain radar by integrating the FACTS methodology with SEM. The process identified five critical, empirically-validated domains essential for the standard: system specifications, testing methods, calibration and maintenance procedures, installation and location criteria, and system control and monitoring. The SEM analysis quantitatively confirmed that performance parameters and testing methods are the most significant drivers of an effective standard, highlighting that verifiable quality is as crucial as technical performance targets. This integrated FACTS-SEM approach not only addresses the immediate need for a robust national standard to foster domestic industry growth and enhance disaster resilience but also provides a replicable, evidence-based model for developing standards for complex meteorological technologies. By ensuring the standard is both internationally aligned and specifically tailored to Indonesia's tropical context and stakeholder needs, this work provides a clear roadmap for policymakers, manufacturers, and end-users to improve the reliability of rainfall monitoring and strengthen early warning systems across the archipelago.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Iqbal Vernando		✓	✓			✓		✓	✓					
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C : **C**onceptualization		I : **I**nvestigation		Vi : **Vi**sualization		
M : **M**ethodology		R : **R**esources		Su : **Su**pervision		
So : **So**ftware		D : **D**ata Curation		P : **P**roject administration		
Va : **Va**lidation		O : Writing - **O**riginal Draft		Fu : **Fu**nding acquisition		
Fo : **Fo**rmal analysis		E : Writing - Review & **E**diting				

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Informed consent was obtained from all research participants.

ETHICAL APPROVAL

This study complies with the research ethics code, ensures that all procedures are carried out by established ethical standards, and has received approval from the relevant ethics committee.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [HES], upon reasonable request.

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