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Development and validation of an explainable rule-based clinical decision support system for childhood immunization using rule traceability

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ABSTRACT

Childhood immunization is essential for preventing vaccine-preventable diseases, yet immunization decisions in primary healthcare are often affected by false contraindications, inconsistent guideline interpretation, and dynamic clinical conditions. This study developed and evaluated an Explainable Clinical Decision Support System (X-CDSS) that integrates rule-based reasoning, dynamic clinical variables, and explainable rule traceability to provide transparent, guideline-compliant immunization recommendations. A Research and Development (R&D) approach with iterative prototyping was employed. Knowledge from the Indonesian national immunization guideline, scientific literature, field observations, and healthcare professionals was formalized into 35 IF–THEN production rules implemented using a forward-chaining inference mechanism in a web-based application. The system was evaluated through functional testing, clinical validation using 40 representative scenarios, performance evaluation, and User Acceptance Testing involving seven healthcare professionals. The proposed system achieved an accuracy of 92.5%, precision of 96.6%, recall of 93.3%, an F1-score of 94.9%, and a Cohen's Kappa coefficient of 0.81, with an overall usability score of 4.3/5.0. These findings demonstrate that the proposed X-CDSS provides reliable, transparent, and clinically accountable decision support for routine childhood immunization in primary healthcare.

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Introduction

Childhood immunization is one of the most effective public health interventions for preventing vaccine-preventable diseases and reducing child mortality. According to the World Health Organization (WHO), immunization prevents approximately 3.5–5 million deaths annually from diseases such as measles, diphtheria, tetanus, pertussis, and influenza (World Health Organization, 2024). In addition to protecting individual health, immunization strengthens herd immunity, reduces healthcare expenditure, and supports sustainable public health development (Andrade-Guerrero et al., 2023). Therefore, achieving timely and complete childhood immunization remains a global public health priority.

In Indonesia, childhood immunization is regulated under the Ministry of Health Regulation No. 12 of 2017 concerning Immunization Administration (Kementerian Kesehatan Republik Indonesia, 2017). Although immunization coverage has improved, healthcare professionals continue to face challenges in determining vaccination eligibility under varying clinical conditions. Decisions frequently involve multiple factors, including child age, immunization history, fever, upper respiratory tract infection (URTI), nutritional status, allergy history, delayed immunization schedules, and vaccine availability. Inconsistent interpretation of these conditions often leads to false contraindications and unnecessary vaccination postponement despite the absence of absolute contraindications (Huynh et al., 2022). These delays may reduce immunization coverage and increase the risk of vaccine-preventable disease outbreaks (Fitrian et al., 2025).

Healthcare Information Systems (HIS) and Clinical Decision Support Systems (CDSS) have increasingly been adopted to improve consistency in clinical decision-making (Salem et al., 2021). Among various Artificial Intelligence (AI) approaches, rule-based expert systems are particularly suitable for guideline-driven healthcare because they explicitly represent expert knowledge using IF–THEN production rules, enabling transparent and auditable reasoning (Arrieta et al., 2020). Moreover, rule-based systems provide explainable recommendations that support accountability and regulatory compliance without requiring large annotated datasets (Bharati et al., 2023).

Previous studies have applied intelligent decision-support systems across various healthcare domains. Forward-chaining has been successfully implemented for childhood disease diagnosis (Yanto et al., 2017), while the Dempster–Shafer method has been applied to mental disorder diagnosis (Mayatopani et al., 2022). Decision-support interventions have also been shown to improve childhood vaccination uptake (Shegog et al., 2023). More recently, explainable artificial intelligence has received increasing attention because of its ability to improve transparency in healthcare decision support (Prentzas et al., 2023). Explainable AI has also been reported to increase users' confidence in AI-assisted clinical recommendations (Nasarian et al., 2023). Furthermore, a systematic review highlighted the growing adoption of expert systems and machine-learning techniques in healthcare practice (Salem et al., 2021).

Despite these advances, important research gaps remain. Existing immunization decision-support systems generally focus on vaccination promotion or static eligibility assessment and rarely integrate multiple dynamic clinical conditions within a single reasoning mechanism. In addition, many systems emphasize recommendation accuracy while providing limited transparency regarding how recommendations are derived from clinical rules and national immunization guidelines (Prentzas et al., 2023). The absence of explainable reasoning and auditable rule traceability may reduce user trust and clinical accountability, thereby limiting implementation in primary healthcare settings (Gambetti et al., 2025). Moreover, no previous study has comprehensively translated the Indonesian Ministry of Health childhood immunization guideline into an explainable rule-based decision-support framework capable of handling dynamic clinical conditions.

To address these gaps, this study adopts a Design Science Research (DSR) approach combined with knowledge engineering to develop and evaluate an Explainable Clinical Decision Support System (X-CDSS). This design was selected because the study aims to develop and validate a decision-support artifact that improves consistency in immunization recommendations rather than testing a clinical hypothesis. The proposed system is intended to support healthcare professionals providing routine immunization services for children aged 0–5 years in primary healthcare settings. System reliability and practical applicability are evaluated through functional testing, expert clinical validation, Cohen's Kappa agreement analysis, computational performance evaluation, and User Acceptance Testing (UAT). Detailed sampling procedures and sample size determination are presented in the Methods section.

Accordingly, this study addresses the following research question:

How can an explainable rule-based Clinical Decision Support System integrate multiple dynamic clinical conditions into childhood immunization recommendations while ensuring transparent reasoning, decision consistency, and compliance with the Indonesian national immunization guidelines?

To answer this question, this study proposes an Explainable Clinical Decision Support System (X-CDSS) that integrates forward-chaining rule-based reasoning with dynamic clinical condition handling. The system incorporates child age, immunization history, fever status, URTI, nutritional status, allergy history, delayed immunization schedules, and vaccine availability into an inference mechanism derived from the Indonesian Ministry of Health immunization guidelines. In addition, an Explainable Rule Traceability mechanism enables healthcare professionals to review activated rules, inspect the reasoning process, and verify compliance with national clinical guidelines, thereby improving the transparency, reliability, and accountability of immunization decision support.

The scientific contributions of this study are threefold. First, it proposes a dynamic rule-based immunization decision model that integrates multiple real-world clinical conditions into a unified reasoning mechanism. Second, it introduces an Explainable Rule Traceability framework that enhances transparency, accountability, and user trust through auditable recommendations. Third, it provides a comprehensive evaluation framework consisting of functional testing, clinical validation, Cohen's Kappa agreement analysis, performance evaluation, and User Acceptance Testing involving healthcare professionals. Table 1 summarizes the research gap and scientific novelty of the proposed study.

Method

This study adopted a Design Science Research (DSR) approach integrated with knowledge engineering to design, develop, and evaluate an Explainable Clinical Decision Support System (X-CDSS) for childhood immunization recommendations. DSR was selected because the research objective was not merely to analyze an existing phenomenon but to develop and rigorously evaluate an innovative decision-support artifact capable of improving the consistency, transparency, and accountability of childhood immunization recommendations in primary healthcare settings. The methodology emphasizes iterative artifact development and evaluation through continuous refinement based on domain knowledge, expert feedback, and system performance assessment. The research process consisted of four sequential stages: (1) requirements analysis, (2) knowledge acquisition and rule formalization, (3) system development, and (4) system validation and performance evaluation, as illustrated in Figure 2.

The requirements analysis stage aimed to identify functional and clinical requirements for the proposed system. Information was collected through a review of national immunization policies, scientific literature on clinical decision support systems, direct observation of childhood immunization services at Puskesmas Kuranji, and semi-structured interviews with healthcare professionals. The primary knowledge source was the Indonesian Ministry of Health Regulation No. 12 of 2017 concerning Immunization Administration, which defines routine childhood immunization schedules, contraindications, vaccination eligibility, and immunization procedures. Complementary knowledge was obtained from recent studies on clinical decision support systems and explainable artificial intelligence to ensure that the proposed system reflected both national clinical guidelines and current technological developments.

Knowledge acquisition involved five healthcare professionals selected using purposive sampling based on their direct involvement in routine childhood immunization services. The participants consisted of two physicians, two midwives, and one immunization nurse with practical experience in vaccination decision-making. Semi-structured interviews were conducted to identify common clinical scenarios, decision-making practices, and factors influencing immunization recommendations. Information obtained from interviews, observations, clinical guidelines, and scientific literature was compared and synthesized to establish a consistent knowledge base. When differences were identified between expert opinions and documentary sources, the final decision was determined according to the Indonesian Ministry of Health immunization guideline to ensure regulatory compliance.

The acquired knowledge was subsequently transformed into a structured rule base through a rule formalization process. Clinical concepts extracted during knowledge acquisition were translated into IF–THEN production rules representing routine immunization decision-making in primary healthcare settings. The final knowledge base consisted of thirty-five production rules integrating multiple clinical variables, including child age, immunization history, fever status, upper respiratory tract infection (URTI), nutritional status, allergy history, delayed immunization schedules, and vaccine availability. Each rule was independently reviewed by the participating healthcare professionals to verify clinical correctness, logical consistency, and conformity with national immunization guidelines before being incorporated into the inference engine.

The proposed X-CDSS was implemented as a web-based application using Laravel 12 with PHP 8.2 and MySQL 8.0. The system employed a three-tier software architecture comprising presentation, application, and data layers. The presentation layer provided interfaces for healthcare professionals and administrators to manage patient information and review immunization recommendations. The application layer implemented the forward-chaining inference engine, rule evaluation module, recommendation generator, and Explainable Rule Traceability mechanism. The data layer managed patient records, immunization schedules, vaccine availability, rule repositories, and recommendation histories. During system execution, clinical information entered by healthcare professionals was evaluated using forward-chaining reasoning to identify applicable production rules and generate immunization recommendations accompanied by transparent explanations describing activated rules and their corresponding provisions within the national immunization guideline.

System validation was conducted using a multi-stage evaluation framework to assess functional correctness, clinical reliability, and practical usability. Functional verification was first performed using black-box testing to ensure that all system functions operated according to predefined functional requirements, including user authentication, patient management, rule execution, recommendation generation, reporting, and database operations. Subsequently, clinical validation was performed using forty representative immunization scenarios reflecting common situations encountered in primary healthcare practice. The scenarios represented various combinations of child age, immunization history, fever status, upper respiratory tract infection, nutritional status, allergy history, delayed immunization schedules, and vaccine availability. For each scenario, recommendations generated by the proposed system were independently compared with recommendations provided by healthcare professionals. The validation focused on evaluating rule correctness, recommendation consistency, and compliance with the Indonesian Ministry of Health immunization guideline rather than estimating disease prevalence or diagnostic accuracy. The selected validation scenarios were designed to adequately represent the diversity of routine childhood immunization decision-making conditions addressed by the proposed knowledge base.

Practical usability of the proposed system was assessed through User Acceptance Testing (UAT) involving seven healthcare professionals comprising physicians, midwives, and immunization nurses. Participants evaluated the system using a structured questionnaire based on a five-point Likert scale covering ease of learning, interface clarity, navigation efficiency, system responsiveness, recommendation accuracy, explainability, and overall usefulness. The number of participants was considered appropriate because usability evaluation primarily aims to identify practical strengths and weaknesses of interactive systems through representative end users rather than to estimate population parameters.

Three evaluation instruments were employed throughout the study, consisting of a black-box functional testing checklist, a collection of representative clinical validation scenarios, and a structured User Acceptance Testing questionnaire. Prior to implementation, all evaluation instruments were reviewed by a medical informatics specialist together with senior healthcare professionals to establish content validity and ensure that each evaluation item appropriately represented the intended functional, clinical, and usability constructs. System performance was evaluated by comparing system-generated recommendations with expert clinical judgments using a confusion matrix. Classification performance was quantified using Accuracy, Precision, Recall, and F1-score to evaluate the correctness of immunization recommendations. In addition, Cohen's Kappa coefficient was calculated to measure the level of agreement between the proposed system and healthcare professionals beyond chance alone. The inclusion of Cohen's Kappa provided a more rigorous assessment of clinical decision consistency because agreement statistics better reflect the reliability of clinical decision-support systems than classification accuracy alone.

Quantitative data obtained from clinical validation and User Acceptance Testing were analyzed using descriptive statistical methods. Classification performance was summarized using Accuracy, Precision, Recall, F1-score, and Cohen's Kappa coefficient, whereas usability evaluation was summarized using mean scores for each assessment dimension based on the predefined five-point Likert scale interpretation. These analyses were conducted to comprehensively evaluate the functional reliability, clinical consistency, explainability, and practical usability of the proposed Explainable Clinical Decision Support System. This study involved healthcare professionals exclusively for knowledge elicitation, expert validation, and usability evaluation. No identifiable patient information or clinical records were collected during system development or evaluation because all validation activities employed representative simulated immunization scenarios derived from national clinical guidelines. Participation by healthcare professionals was voluntary, and all participants provided informed consent before interviews and evaluation activities were conducted.

Results and Discussions

This section presents the results obtained from the development, implementation, and evaluation of the proposed Explainable Clinical Decision Support System (X-CDSS) for childhood immunization recommendations. The results include the knowledge engineering process, system implementation, clinical validation, performance evaluation, and user acceptance assessment.

Knowledge Engineering Results

The knowledge engineering process successfully produced a structured knowledge base by integrating information obtained from the Indonesian Ministry of Health Regulation No. 12 of 2017, scientific literature, direct observations at Puskesmas Kuranji, and semi-structured interviews with five healthcare professionals consisting of two physicians, two midwives, and one immunization nurse. Information collected from these sources was analyzed and transformed into a set of production rules representing routine childhood immunization decision-making.

The rule development process began with the identification of clinical decision variables extracted from regulatory documents and interview transcripts. Similar concepts obtained from different knowledge sources were consolidated into a unified representation. When differences occurred between expert opinions and practical observations, the Indonesian Ministry of Health immunization guideline was used as the primary reference to ensure regulatory compliance. Draft production rules were subsequently reviewed by all participating healthcare professionals, revised where necessary, and accepted after confirming their consistency with routine clinical practice and national immunization guidelines.

The final knowledge base consisted of 35 IF–THEN production rules representing the most common immunization scenarios for children aged 0–5 years. The rules incorporated multiple clinical variables that influence vaccination decisions in primary healthcare settings.

Table 1 <Dynamic Clinical Variables Used in the Knowledge Base>

Variable	Description
Age	Child age according to immunization schedule
Immunization History	Previous vaccination records
Fever Status	Normal, Mild Fever, High Fever
URTI	Presence of Upper Respiratory Tract Infection
Nutritional Status	Normal or Mild Malnutrition
Allergy History	Previous vaccine-related allergy
Vaccination Delay	Delayed immunization schedule
Vaccine Availability	Availability of required vaccine stock

Table 2 <Sample Production Rules>

Rule ID	Rule Description
R1	IF Age ≥ 2 Months AND Vaccine Available = Yes AND Fever = Mild THEN Administer DPT-HB-Hib Dose 1
R2	IF High Fever = Yes THEN Delay Vaccination and Reassess Patient Condition
R3	IF Immunization Schedule Delayed = Yes AND Vaccine Available = Yes THEN Recommend Catch-up Immunization

Overall, the knowledge engineering process resulted in a structured rule base that integrates regulatory requirements and clinical decision variables into machine-readable production rules supporting childhood immunization recommendations.

System Architecture and Explainable Rule Implementation

The proposed Explainable Clinical Decision Support System (X-CDSS) was successfully implemented as a web-based application using Laravel 12, PHP 8.2, and MySQL 8.0. The system employs a three-tier architecture comprising the Presentation Layer, Application Layer, and Data Layer.

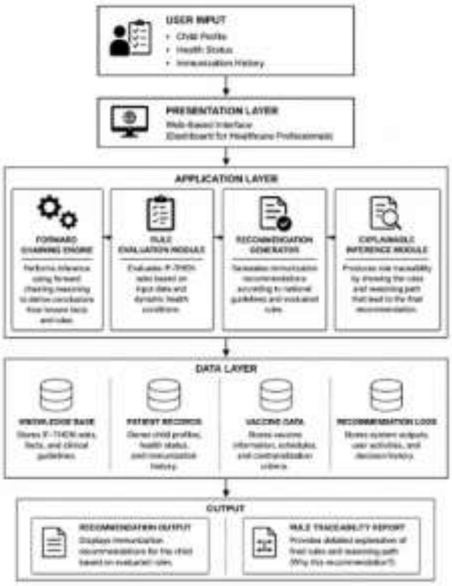

Figure 1 <Architecture of the Proposed Explainable Clinical Decision Support System>

During system execution, healthcare professionals enter patient information including age, immunization history, fever status, nutritional status, allergy history, upper respiratory tract infection, delayed immunization schedule, and vaccine availability. These data are processed by the Forward Chaining inference engine to evaluate the production rules stored in the knowledge base and generate immunization recommendations. An Explainable Rule Traceability module was incorporated to record every rule activated during the inference process. For each recommendation, the system displays the evaluated clinical variables, activated production rules, intermediate reasoning steps, and the final recommendation.

Figure 2 <Example of Explainable Rule Traceability>

The implementation demonstrates that the proposed system is capable of generating childhood immunization recommendations together with transparent reasoning based on predefined production rules.

Clinical Validation Result

Clinical validation was performed using 40 representative childhood immunization scenarios developed from routine clinical situations encountered in primary healthcare services. Each scenario represented different combinations of child age, immunization history, fever status, upper respiratory tract infection, nutritional status, allergy history, delayed immunization schedules, and vaccine availability. System-generated recommendations were independently compared with recommendations provided by healthcare professionals.

Table 3 <Clinical Validation Results>

Evaluation Metric	Result
Total Scenarios	40
Correct Recommendations	37
Incorrect Recommendations	3
Agreement Rate	92,5%

The proposed system correctly generated recommendations for 37 of the 40 validation scenarios, corresponding to an agreement rate of 92.5%.

System Performance Results

The performance of the proposed X-CDSS was evaluated by comparing system recommendations with expert clinical judgments. Classification performance was measured using Accuracy, Precision, Recall, F1-score, and Cohen's Kappa coefficient.

Table 4 <Performance Evaluation Results>

Evaluation Metrics	Value
Accuracy	92,5%
Precision	96,6%
Recall	93,3%
F1-score	94,9%
Cohen's Kappa	0,81

The proposed system achieved an Accuracy of 92.5%, Precision of 96.6%, Recall of 93.3%, and an F1-score of 94.9%. The calculated Cohen's Kappa coefficient of 0.81 indicates a high level of agreement between system recommendations and expert judgments.

User Acceptance Results

User Acceptance Testing (UAT) was conducted involving seven healthcare professionals, including physicians, midwives, and immunization nurses. Participants evaluated the system using a five-point Likert scale covering ease of learning, interface clarity, navigation efficiency, response speed, recommendation accuracy, and overall usefulness.

Table 5 <User Acceptance Testing Results>

Evaluation Aspect	Mean Score
Ease of Learning	4.4
Interface Clarity	4.3
Navigation Efficiency	4.2
Response Speed	4.3
Recommendation Accuracy	4.5
Overall Usefulness	4.3
Overall Mean Score	4.3 / 5.0

The highest score was obtained for recommendation accuracy (4.5), while the overall mean usability score was 4.3 out of 5.0, indicating positive user acceptance of the proposed system.

The present study addressed the research question of how an explainable rule-based Clinical Decision Support System (X-CDSS) can integrate dynamic clinical conditions into childhood immunization recommendations while maintaining transparency, consistency, and compliance with the Indonesian national immunization guidelines. The findings demonstrate that the proposed framework successfully combines rule-based reasoning, dynamic clinical condition handling, and explainable rule traceability within a unified decision-support system. The high agreement between system recommendations and expert judgments indicates that the developed knowledge base reliably represents routine clinical decision-making, while the positive usability evaluation confirms its practical applicability in primary healthcare. Recent evidence suggests that Clinical Decision Support Systems should be evaluated not only by predictive performance but also by transparency, usability, and integration into clinical workflows (Kim et al., 2024). Explainability has likewise been identified as a key factor influencing successful clinical implementation (Abbas et al., 2025).

A major contribution of this study is the development of a comprehensive rule-based knowledge base that integrates multiple dynamic clinical variables, including immunization history, fever status, upper respiratory tract infection (URTI), nutritional status, allergy history, delayed immunization schedules, and vaccine availability into a unified reasoning mechanism. Unlike conventional schedule-based systems, the proposed framework evaluates these variables simultaneously before generating recommendations, thereby reflecting routine clinical practice while maintaining compliance with the Indonesian national immunization guideline. The knowledge base was constructed by systematically translating national immunization guidelines, scientific literature, field observations, and expert knowledge into explicit IF–THEN production rules. This structured representation improves transparency, reproducibility, and knowledge maintenance. Similar findings have shown that ontology-based and rule-based knowledge representation enhances semantic consistency and interoperability in Clinical Decision Support Systems (Jing et al., 2023). Reusable rule modules have also been reported to facilitate consistent implementation of immunization recommendations across healthcare settings (Orlioglu et al., 2025).

Another important contribution is the Explainable Rule Traceability mechanism, which records the complete reasoning process by displaying evaluated clinical variables, activated production rules, intermediate inferences, and the corresponding regulatory basis for each recommendation. This enables healthcare professionals to understand and verify how recommendations are generated before making clinical decisions. Such transparency is essential because immunization decisions require clear justification and accountability. Unlike many data-driven artificial intelligence models that function as black boxes, the proposed rule-based approach exposes every inference step, allowing recommendations to be inspected and validated. Transparent reasoning has been recognized as a fundamental requirement for trustworthy healthcare artificial intelligence (Arrieta et al., 2020). Explicit rule representation has also been recommended as an effective strategy for implementing explainable Clinical Decision Support Systems (Prentzas et al., 2023). A systematic review further reported that explainability improves clinician confidence and regulatory compliance (Kim et al., 2024). A recent meta-analysis likewise concluded that transparent recommendations enhance usability and clinician acceptance (Abbas et al., 2025). Explainable and bias-aware AI has also been shown to strengthen fairness and accountability in healthcare decision-making (Sharma et al., 2026).

The clinical validation results demonstrate that the proposed X-CDSS generates recommendations that are highly consistent with expert clinical judgment. The agreement rate of 92.5% and a Cohen's Kappa coefficient of 0.81 indicate that the developed knowledge base effectively represents expert reasoning while maintaining compliance with the Indonesian national immunization guideline. These findings confirm that the forward-chaining inference mechanism provides reliable and transparent support for routine childhood immunization decisions.

Although three validation scenarios differed from expert judgments, these discrepancies mainly involved complex clinical situations requiring contextual interpretation beyond the predefined production rules. This finding reflects an inherent limitation of deterministic rule-based reasoning and highlights the importance of continuously refining the knowledge base through expert feedback and guideline updates. The proposed framework also achieved high Accuracy, Precision, Recall, and F1-score, demonstrating balanced classification performance while preserving explainability. Unlike many black-box AI models, the proposed system enables healthcare professionals to inspect every inference step before accepting recommendations. This finding is consistent with previous studies emphasizing that transparency is essential for trustworthy pediatric Clinical Decision Support Systems (Ramgopal et al., 2023). Similar observations were reported in the development of the ePOCT+ platform, where transparent clinical algorithms supported safer implementation of pediatric decision-support tools (Tan et al., 2023).

Compared with previous studies, the proposed framework advances existing Clinical Decision Support Systems by integrating dynamic clinical reasoning, explainable rule traceability, and compliance with national immunization guidelines within a single operational framework. Previous studies by Yanto et al. (2017) and Mayatopani et al. (2022) focused primarily on disease diagnosis, while Shegog et al. (2023) emphasized vaccination uptake rather than vaccination eligibility. Salem et al. (2021) highlighted the need for clinically applicable implementation of Clinical Decision Support Systems, and the present study addresses this need by providing an operational framework specifically designed for routine childhood immunization. The explainable reasoning mechanism also supports responsible AI adoption by improving clinician trust and transparency (Nasarian et al., 2023). Furthermore, the use of explicit knowledge representation rather than purely data-driven prediction ensures that every recommendation can be directly traced to clinical regulations. Similar observations have been reported in infectious disease decision support (Kim et al., 2022). Recent systematic evidence also recommends explainability as a core design principle for Clinical Decision Support Systems intended for routine clinical practice (Kim et al., 2024).

From a practical perspective, the proposed X-CDSS has the potential to improve the consistency, transparency, and quality of childhood immunization services in primary healthcare. By providing standardized recommendations based on the Indonesian national immunization guidelines, the system may reduce false contraindications and unnecessary vaccination delays while supporting evidence-based clinical decision-making. The Explainable Rule Traceability mechanism also facilitates communication among physicians, midwives, and immunization nurses by providing a clear reasoning pathway for every recommendation. This capability has been recognized as an important factor for improving clinician confidence and facilitating the integration of Clinical Decision Support Systems into routine practice (Ramgopal et al., 2023). Similar findings have been reported for transparent pediatric decision-support platforms implemented in resource-constrained healthcare settings (Tan et al., 2023). In addition, reusable rule-based modules have been shown to improve the consistency and interoperability of immunization recommendations across healthcare institutions (Orlioglu et al., 2025). Ontology-based knowledge representation has likewise been reported to facilitate semantic consistency and long-term maintenance of clinical rules (Jing et al., 2023).

Despite these promising findings, several limitations should be acknowledged. Clinical validation was conducted using representative scenarios rather than real patient data, and knowledge acquisition involved a limited number of healthcare professionals from a single primary healthcare center. Moreover, the rule-based mechanism depends on predefined production rules that require manual updates following changes in immunization guidelines, which may limit generalizability. Future studies should validate the proposed framework using multicenter clinical datasets, integrate it with Electronic Medical Record (EMR) and national immunization information systems, and investigate hybrid explainable AI approaches that combine rule-based transparency with machine learning adaptability (Kierner et al., 2025). Future development should also prioritize explainability, usability, fairness, and clinical accountability as core design principles for Clinical Decision Support Systems (Kim et al., 2024). Similar recommendations have been reported in recent meta-analytic evidence (Abbas et al., 2025). The incorporation of explainable and bias-aware AI is also expected to improve fairness and clinician trust in healthcare decision support (Sharma et al., 2026)

Overall, the proposed X-CDSS demonstrates that integrating rule-based reasoning with explainable artificial intelligence provides a transparent, reliable, and clinically accountable approach for supporting childhood immunization decisions. By combining dynamic clinical reasoning, explicit knowledge representation, explainable rule traceability, and compliance with national immunization guidelines, the proposed framework contributes to the development of trustworthy Clinical Decision Support Systems for evidence-based imunization practice

Conclusions

This study developed and evaluated an Explainable Clinical Decision Support System (X-CDSS) for childhood immunization recommendations in primary healthcare. The proposed framework successfully integrates rule-based reasoning with multiple dynamic clinical variables, including child age, immunization history, fever status, upper respiratory tract infection, nutritional status, allergy history, delayed immunization schedules, and vaccine availability. By combining these variables within a forward-chaining inference mechanism, the system generates transparent, context-aware, and guideline-compliant immunization recommendations. The evaluation demonstrated high agreement between system recommendations and expert clinical judgments, together with positive usability among healthcare professionals, indicating that the proposed framework is both clinically reliable and practically applicable. In addition to recommendation accuracy, the Explainable Rule Traceability mechanism enables healthcare professionals to review the activated production rules and underlying reasoning process, thereby improving transparency, accountability, and compliance with the Indonesian national immunization guidelines. The principal contribution of this study is the integration of dynamic clinical condition handling, explicit rule-based knowledge representation, and explainable reasoning within a single Clinical Decision Support System for routine childhood immunization. Unlike previous studies that primarily addressed disease diagnosis or vaccination promotion, the proposed framework supports vaccination eligibility assessment under diverse clinical conditions while maintaining transparent and auditable decision-making. From a practical perspective, the proposed X-CDSS can assist physicians, nurses, and midwives in reducing false contraindications, minimizing unnecessary vaccination delays, and improving consistency in interpreting national immunization guidelines. Consequently, the system has the potential to enhance the quality, transparency, and standardization of childhood immunization services in primary healthcare. This study is limited by the use of representative clinical scenarios and a relatively small number of healthcare professionals during validation. Future research should evaluate the proposed framework using multicenter clinical datasets, integrate it with Electronic Medical Record (EMR) and national immunization information systems, and investigate hybrid Explainable Artificial Intelligence approaches that combine the transparency of rule-based reasoning with the adaptability of machine learning to further improve scalability, generalizability, and clinical applicability.

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