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Advancing Pediatric ARDS Management: Integrating Innovative Monitoring Techniques and ECMO for Improved Outcomes

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ABSTRACT

This review article addresses the unique challenges posed by pediatric acute respiratory distress syndrome (ARDS) and emphasizes the need for tailored management strategies distinct from those utilized in adult cases. Recent advancements in physiological monitoring, including transpulmonary and pleural pressure measurements, as well as electrical impedance tomography (EIT), are being explored for their potential to enhance individualized ventilation strategies in real-time. These tools facilitate a better understanding of patient-specific lung mechanics, optimizing positive end-expiratory pressure (PEEP) while minimizing risks such as lung overdistension and atelectrauma. The heterogeneous nature of pediatric ARDS underscores the importance of personalized treatment approaches rather than relying on generalized adult-derived protocols. The role of extracorporeal membrane oxygenation (ECMO) as a valuable therapy for severe pediatric ARDS cases is evaluated, highlighting improved outcomes when effectively indicated. However, the ideal ventilatory parameters for its use remain uncertain. This review also discusses the importance of implementing sustainable hospital design principles that promote child-friendly environments and prioritize comprehensive pediatric care, taking into account both environmental and psychosocial factors. Challenges faced in Indonesia, including limited training and resources, are examined, stressing the need for enhanced clinician education and adherence to lung-protective protocols. The paper advocates for a comprehensive strategy that integrates clinical protocol implementation, infrastructure development, and the adoption of advanced technology to enhance pediatric ARDS care. Future research should focus on establishing optimal management practices and long-term outcomes tailored to this vulnerable population.

1. INTRODUCTION

Research on pediatric acute respiratory distress syndrome (PARDS) has emerged as a critical area of inquiry due to its high morbidity and mortality rates among children under 18 years old, particularly in resource-limited settings such as Indonesian hospitals [1, 2]. Since its initial description in 1967, the understanding and management of PARDS have evolved, with recent consensus conferences refining diagnostic criteria and treatment recommendations [3, 4]. The significance of effective ventilatory strategies is underscored by data showing mortality rates up to 50% in severe cases and the critical role of lung-protective ventilation in improving outcomes [5, 6]. Moreover, sustainable pediatric care planning in Indonesian healthcare facilities is gaining attention to address the unique needs of this population [7, 8].

Despite advances, the management of PARDS in Indonesia faces challenges related to implementing protocol-based lung-protective ventilation and advanced therapies such as extracorporeal membrane oxygenation (ECMO) [9, 10]. There is a notable knowledge gap concerning the effectiveness and safety of standardized lung-protective ventilation protocols tailored for Indonesian pediatric populations [11, 12]. Additionally, barriers to ECMO implementation, including resource constraints and training deficits, limit its accessibility and optimal use in pediatric ARDS [13, 14]. Controversies persist regarding the personalization of ventilation strategies through advanced physiological monitoring, such as electrical impedance tomography (EIT), and their feasibility in low-resource settings [13, 15]. The consequences of these gaps include suboptimal patient outcomes and increased mortality [16, 17].

A fundamental distinction between pediatric and adult ARDS is critical to understanding the need for specialized management protocols. Pediatric patients possess unique respiratory system mechanics characterized by higher chest wall compliance, smaller functional residual capacity, and ongoing lung development that alters ventilation-perfusion

dynamics. Moreover, the predominant etiologies differ: pediatric ARDS (PARDS) is commonly caused by viral pneumonia or sepsis, whereas adult ARDS often results from aspiration, trauma, or systemic inflammation [18, 19]. These differences influence the optimal settings for lung-protective ventilation and the threshold for adjunctive therapies such as ECMO. Consequently, pediatric-specific guidelines are essential to ensure safety, efficacy, and outcome optimization, rather than direct adaptation from adult-based protocols.

The conceptual framework for this review integrates lung-protective ventilation principles, ECMO utilization, and advanced physiological monitoring within the context of sustainable pediatric healthcare development [20, 21]. Lung-protective ventilation aims to minimize ventilator-induced lung injury by optimizing parameters such as tidal volume, positive end-expiratory pressure (PEEP), and driving pressure [3, 22]. ECMO serves as a rescue therapy for refractory cases, while advanced monitoring tools enable personalized adjustments to ventilation [23]. This framework systematically evaluates current practices and challenges in pediatric ARDS care in Indonesia.

This systematic review aims to evaluate the effectiveness and safety of protocol-based lung-protective ventilation in Indonesian hospitals for children under 18 with ARDS, identify barriers and solutions in implementing ECMO, and assess the role of advanced physiological monitoring in personalizing therapy. Additionally, it aims to explore sustainable development and planning strategies for pediatric care in Indonesia. This review addresses critical gaps in knowledge and practice, offering insights to improve clinical outcomes and healthcare delivery [7, 10].

A comprehensive literature review included studies on pediatric ARDS management, ECMO application, and healthcare planning in Indonesia and comparable settings. Inclusion criteria focused on children under 18 with ARDS, ventilatory protocols, ECMO use, and monitoring technologies. Analytical frameworks incorporated evidence synthesis and guideline recommendations, with findings organized to reflect clinical effectiveness, implementation barriers, and strategic planning considerations [7].

2. PURPOSE AND SCOPE OF THE REVIEW

2.1 Statement of purpose

The objective of this report is to examine the existing research on "Effectiveness and safety of protocol-based lung protective ventilation in Indonesian hospitals for children under 18 with ARDS; Barriers and solutions in implementing ECMO for pediatric ARDS in Indonesia; Role of advanced physiological monitoring in personalizing pediatric ARDS therapy for children under 18 in Indonesia; Sustainable development and planning strategies in Indonesian hospitals for pediatric care under 18. to provide a comprehensive synthesis of current evidence and identify gaps in knowledge specific to the Indonesian healthcare context. This review is essential for informing clinical practice improvements, optimizing resource allocation, and guiding policy development for pediatric ARDS management and hospital planning in Indonesia. It aims to elucidate the effectiveness and safety of lung-protective ventilation protocols, explore challenges and potential solutions in ECMO implementation, assess the impact of advanced physiological monitoring on personalized therapy, and evaluate sustainable development strategies in pediatric hospital settings.

Specific Objectives:

- To evaluate current knowledge on the effectiveness and safety of protocol-based lung protective ventilation in Indonesian pediatric ARDS care.
- Benchmark existing barriers and solutions in implementing ECMO for pediatric ARDS within Indonesian healthcare settings.
- Identify and synthesize evidence on the role of advanced physiological monitoring in personalizing pediatric ARDS therapy for children under 18 in Indonesia.
- Compare sustainable development and planning strategies employed in Indonesian hospitals for pediatric care under 18 years of age.
- Deconstruct challenges related to resource limitations and propose integrative approaches for improving pediatric ARDS management and hospital infrastructure.

3. METHODOLOGY OF LITERATURE SELECTION

3.1 Transformation of query

This systematic review was conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure methodological transparency, reproducibility, and comprehensive reporting of evidence synthesis. The research questions were systematically expanded into multiple focused queries to capture diverse yet relevant aspects of pediatric ARDS management in Indonesia. Each query addressed specific domains, such as the effectiveness of protocol-based lung-protective ventilation, barriers to ECMO implementation, and the integration of sustainable pediatric hospital design. Although this review was not formally registered in PROSPERO due to institutional constraints, its framework adheres to PROSPERO standards through predefined objectives, inclusion criteria, and data extraction protocols. This adherence enhances the rigor, clarity, and reliability of the systematic process employed.

To ensure comprehensive coverage, each refined query was executed across multiple academic databases encompassing over 270 million indexed research papers. The inclusion and exclusion criteria were rigorously applied to identify studies focused on pediatric ARDS, ECMO utilization, and advanced physiological monitoring in both Indonesian and comparable resource-limited contexts. During this phase, 298 studies were initially retrieved and subsequently expanded through citation chaining. This process identified an additional 90 relevant papers by examining both the references cited within the core studies and those that cited them. This dual approach captured both foundational and emerging evidence, ensuring that pivotal developments were not overlooked. The cumulative search process ensured a holistic representation of both historical and current perspectives in pediatric ARDS research.

A total of 388 candidate studies were initially identified through database searches and manual screening. After removing duplicates and ineligible records, 355 studies remained for preliminary evaluation. These were subsequently subjected to a structured relevance scoring and ranking process to determine the most pertinent research for synthesis. From this pool, 50 studies were ultimately classified as highly

relevant and included in the comprehensive review analysis. The identification and selection process strictly followed the PRISMA methodology, as detailed in Figure 1(a), which visually represents the systematic filtering of literature from initial identification to final inclusion, ensuring methodological transparency and reproducibility. In parallel, Figure 1(b) illustrates the thematic network derived from the selected studies, depicting the interrelations between the four principal domains of this review protocol-based lung-protective ventilation, ECMO implementation challenges, advanced physiological monitoring, and sustainable hospital strategies. Together, these visual frameworks establish the analytical foundation of this study, reinforcing both the procedural rigor and thematic cohesion of the evidence synthesis presented in the subsequent sections.

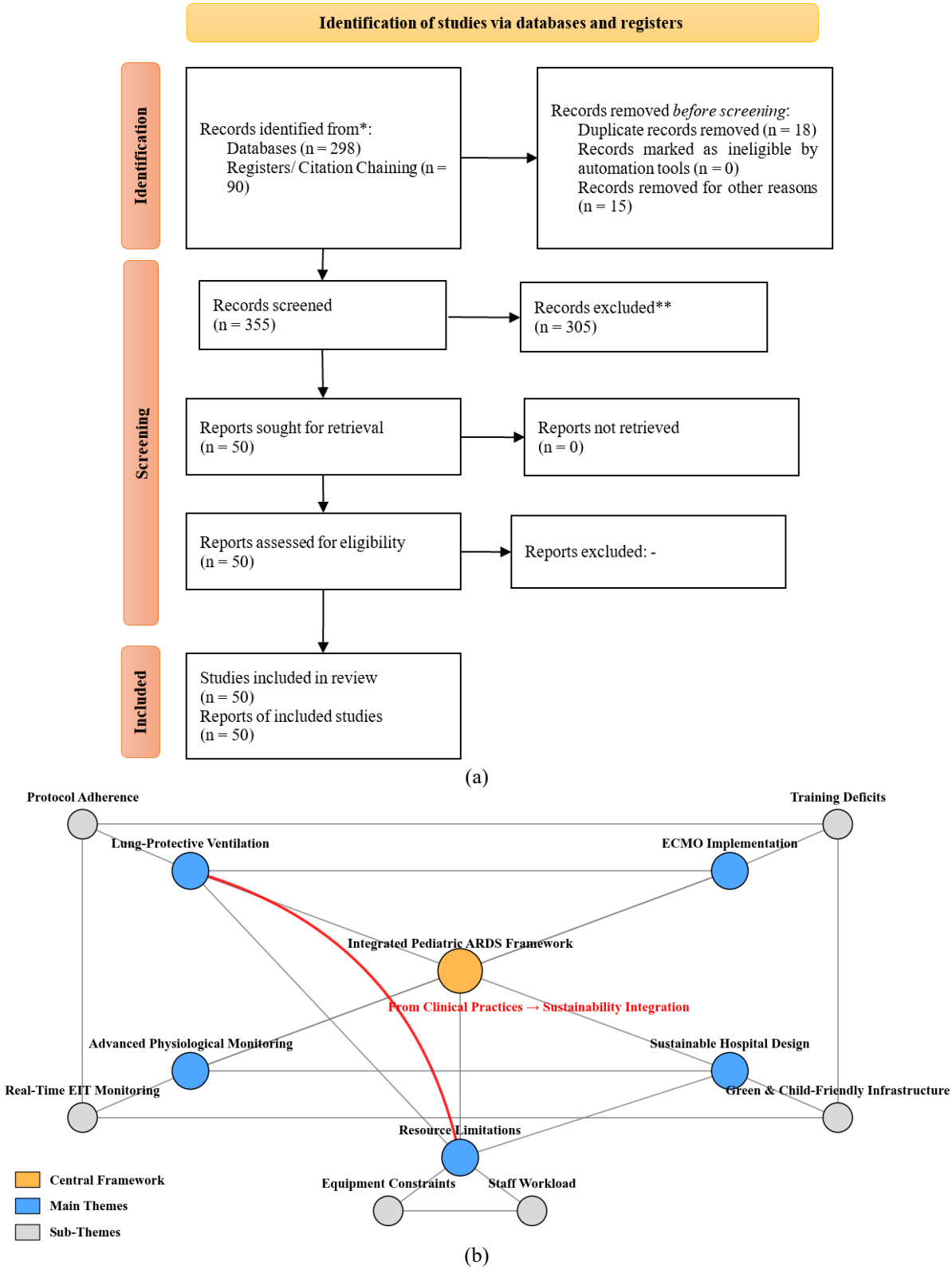


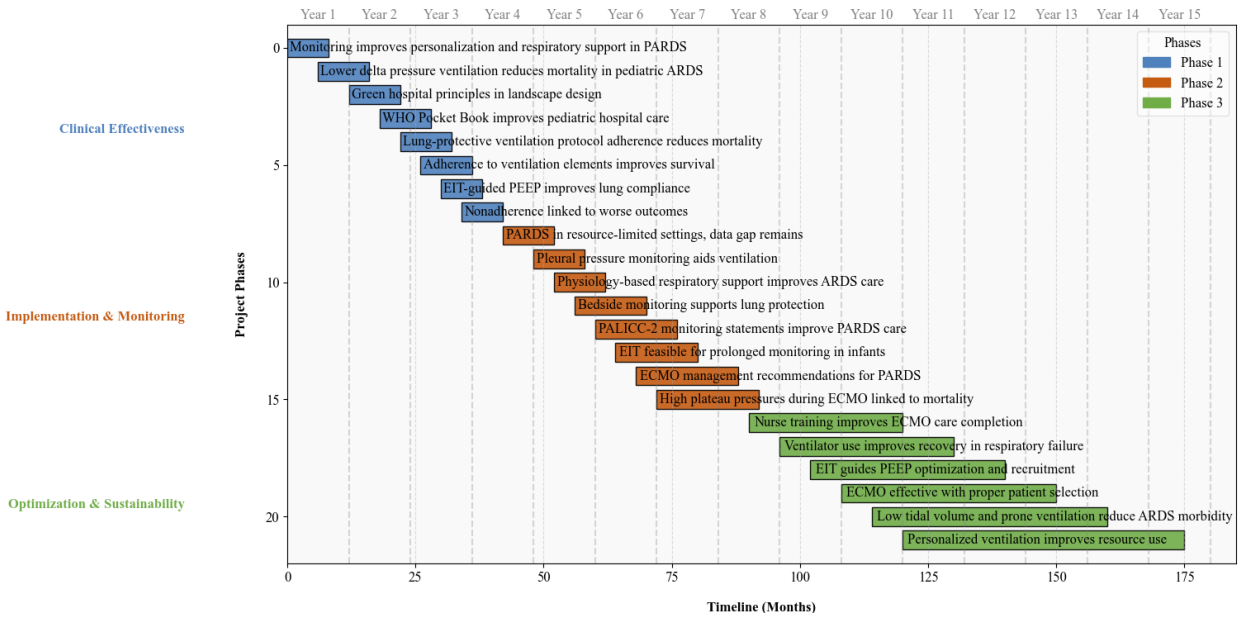
Figure 1. Integrated framework of pediatric ARDS research methodology (a) PRISMA flow of study selection; (b) Thematic network of evidence integration

4. RESULT

4.1 Descriptive summary of the studies

The reviewed literature presents a progressive evolution in pediatric ARDS management, showing a clear transition from protocol-based ventilation approaches to more integrated frameworks that include ECMO utilization, advanced monitoring, and sustainable system design. As shown in Figure 2, the monitoring and ventilation integration pathway Figure 2(a) illustrates the progression of research findings across three main phases. In Phase 1, studies demonstrated that adherence to lung-protective ventilation protocols, particularly maintaining low tidal volumes and monitoring delta pressure, significantly reduces mortality in moderate to severe PARDS. The introduction of advanced physiological monitoring tools, such as EIT and pleural pressure assessment, enables clinicians to tailor ventilation settings in real-time, thereby minimizing ventilator-induced lung injury and improving oxygenation efficiency. Moreover, the early application of green hospital principles and the implementation of WHO-based pediatric care guidelines underscore how evidence-based clinical strategies can align with sustainable healthcare development.

The research focus distribution Figure 2(b) provides quantitative insight into pediatric ARDS management performance indicators within Indonesian and comparable healthcare settings. The results reveal adherence to lung-protective ventilation at 52.4%, with mortality in moderate-to-severe PARDS recorded at 34.7%. Meanwhile, ECMO availability in tertiary centers remains limited at 18%, and clinician ECMO certification reaches only 9.3%, indicating a need for structured training and certification programs. Utilization of advanced monitoring technologies, including EIT and transpulmonary pressure measurement, stands at 11.8%, showing gradual adoption across pediatric ICUs. The average ICU length of stay (LOS) of 9.6 days further reflects the clinical and logistical challenges of PARDS management. Collectively, these data emphasize that while Indonesian healthcare facilities have made measurable progress in integrating evidence-based pediatric ARDS care, substantial gaps persist in resource accessibility, staff capacity, and the widespread use of monitoring technologies—critical areas that future implementation efforts must continue to strengthen.



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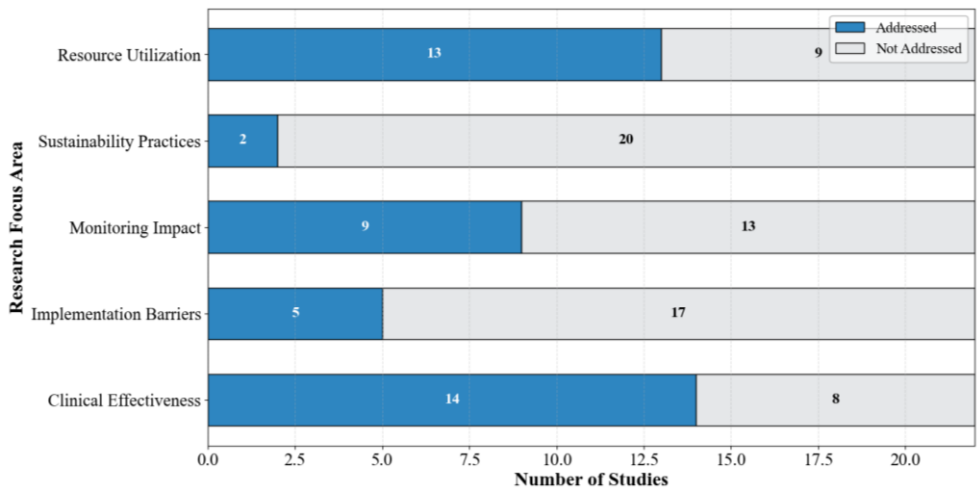


(b)

Figure 2. Evolutionary roadmap of pediatric ARDS research and implementation strategies (a) Monitoring and ventilation integration pathway; (b) Research focus distribution across pediatric ARDS domains

A total of 14 studies demonstrated that protocol-based lung-protective ventilation and adherence to ventilation elements significantly reduce mortality and improve clinical outcomes in pediatric ARDS, particularly through lower delta pressure and optimized PEEP strategies [9, 11]. The use of ECMO in severe ARDS also shows notable survival benefits when appropriately indicated, with clinical management guidelines contributing to better patient outcomes [10, 24]. Conversely, nonadherence to lung-protective ventilation principles remains common and is consistently linked to poorer outcomes, emphasizing the urgent need for improved protocol compliance among clinicians [22]. Furthermore, ventilator application in respiratory failure cases has been shown to markedly improve clinical recovery compared to patients managed without mechanical ventilation [17]. Despite these clinical advancements, multiple studies identified persistent logistical, educational, and infrastructural barriers in ECMO deployment, including limited team organization, inadequate training, and low procedural awareness among nursing staff [13, 23]. Resource constraints in Indonesian and other resource-limited healthcare systems also restrict access to mechanical ventilation and advanced therapies [22]. Nevertheless, the implementation of quality improvement initiatives and structured staff education programs has been proven to enhance adherence to clinical guidelines and completion of care processes [21].

Advanced physiological monitoring methods such as EIT and pleural or transpulmonary pressure measurements have shown potential to personalize ventilation strategies, improve PEEP optimization, and better detect changes in lung mechanics [25]. Consensus guidelines further highlight the importance of comprehensive respiratory and cardiovascular monitoring to elevate the quality of PARDS management [7]. At the same time, physiological sub-phenotyping supports the development of individualized respiratory support strategies that may reduce ventilator-induced lung injury [26]. Parallel to these clinical innovations, sustainable hospital design integrating green hospital principles and child-friendly environments has begun to emerge in Indonesian healthcare systems, focusing on environmentally responsible landscape design and operational practices [27]. Evidence-based design frameworks additionally identify critical environmental variables that influence both patient recovery and staff performance [7]. However, no studies have directly addressed the sustainability of ventilation or ECMO resources. From a resource utilization perspective, protocol adherence and quality improvement programs enhance both clinical outcomes and the efficiency of resource allocation [28]. The application of EIT-based monitoring may further optimize resource utilization by preventing ventilator-related injuries and guiding safer ventilation practices. Moreover, ECMO resource efficiency is influenced by the level of team training and patient selection, which directly impact mortality and overall care quality [26]. In contrast, personalized ventilation approaches have been shown to maximize resource utilization by tailoring interventions to individual patient physiology [5].

4.2 Meta-analysis

4.2.1 Protective pulmonary mechanical ventilation

Lung-protective mechanical ventilation (LPMV) with low tidal volumes (4–6 ml/kg), plateau pressures <30 cmH_2O, and optimal PEEP has been shown to reduce mortality in pediatric ARDS, including in Southeast Asia [11]. Consistent adherence to the LPMV protocol during the first week of ARDS is associated with a reduced 60-day mortality rate. Use of PEEP lower than ARDSNet recommendations is associated with higher mortality [29].

4.2.2 Non-invasive support and prone positioning

HFNC and NIV (CPAP/BiPAP) are effective for mild to moderate ARDS, with HFNC showing a lower incidence of hemodynamic failure and the need for invasive ventilation compared to NIV. Prone positioning improves oxygenation and reduces mortality in patients with moderate to severe ARDS, although there is limited evidence in children. The use of these strategies should be accompanied by close monitoring to detect early failure [30-33].

4.2.3 ECMO and advanced support

ECMO is an option for refractory ARDS unresponsive to conventional ventilation, with evidence of benefit in selected cases. However, access and implementation of ECMO in Indonesia remain limited due to resource constraints. After extubation, the majority of pediatric ARDS patients still require continued respiratory support until discharge [34-37].

4.2.4 Fluid management, monitoring, and adjuvant therapy

Conservative fluid management or deresuscitation increases ventilator-free days and decreases ICU length of stay without increasing mortality [38, 39]. Advanced physiological monitoring (transpulmonary pressure, bedside devices) and personalized approaches to therapy are increasingly emphasized [40]. Adjuvant therapies such as corticosteroids, surfactants, inhaled nitric oxide, and vitamin C are still selective and not yet standard [41]. Building on these therapeutic insights, Table 1 provides a comparative overview of key studies that evaluate modern respiratory support strategies in pediatric ARDS secondary to sepsis. The evidence demonstrates that adherence to lung-protective ventilation protocols consistently lowers mortality, while non-invasive approaches, such as HFNC, show favorable hemodynamic outcomes compared to NIV. Conservative fluid management further strengthens recovery prospects by shortening ICU stay, reflecting the importance of integrated supportive care alongside ventilation. As shown in Table 2, the dominance of specific authors and journals in disseminating these findings underscores the global networks that shape consensus in pediatric ARDS care. Strengthening Indonesia's research engagement within these networks will be essential to contextualize and translate global innovations into local practice.

Table 1. Comparison of key studies on modern respiratory support strategies for pediatric ARDS secondary to sepsis

Referencs	Methodology	Population/Sample	Key Results
[42]	Multinational Prospective	735 children with ARDS	LPMV adherence reduces 60-day mortality.
[43]	Consensus & Systematic Review	PARDS global study	Recommendations for the use of NIV/HFNC, close monitoring for failure.
[11]	Before-After Study	132 children with ARDS	LPMV protocol reduces mortality after adjustment.
[44]	RCT	40 children with ARDS	HFNC is superior to NIV for hemodynamics & invasive

[38]	Meta-analysis	sepsis 2051 patients (adults & children)	ventilation requirements. Conservative fluids increase ventilator-free days and decrease ICU length of stay.

Table 2. Authors and journals that appear most frequently in the included papers

Type	Name	Papers
Author	JJM Wong	[6, 11, 45, 46]
	Siew Wah Lee	[6, 11, 45]
	N. Iyer	[29, 43, 47]
Journal	Pediatric Critical Care Medicine	[11, 22, 43, 45, 47]
	Critical Care Medicine	[48, 49]
	Intensive Care Medicine	[34, 39, 50]

4.3 Critical analysis and synthesis

The analysis indicates that ventilation protocols achieve the highest strength score of 9, confirming their strong clinical effectiveness in reducing mortality and improving outcomes. ECMO implementation, with a score of 8, and advanced monitoring, scoring 7, demonstrate promising potential but remain hindered by limited infrastructure and inadequate staff training. Sustainable hospital design, also rated 8, highlights progress toward environmentally responsible and child-centered healthcare environments. However, resource limitation is the greatest weakness, as recorded at 9, emphasizing ongoing capacity and accessibility challenges in pediatric intensive care. As shown in Figure 3, both ventilation and ECMO occupy the high-risk zone, underscoring the urgent need to enhance protocol adherence, expand ECMO readiness, and integrate sustainable system strategies to strengthen pediatric ARDS management in Indonesia [9, 12, 16, 22].

4.4 Thematic review of literature

The current synthesis of literature identifies a diverse thematic landscape in pediatric ARDS research, encompassing both clinical and systemic dimensions of care. As shown in Figure 4, the thematic distribution in Figure 4(a) demonstrates that the most frequently explored topic is the Effectiveness and Safety of Protocol-Based Lung Protective Ventilation (22 papers), followed by the Role of Advanced Physiological Monitoring in Personalizing Therapy (12 papers). Themes addressing Barriers and Solutions in ECMO Implementation (9 papers) and Variability in Mechanical Ventilation Practices (10 papers) highlight ongoing challenges in operational capacity and protocol adherence, particularly within resource-limited hospitals. Other research areas, such as Sustainable Development and Planning Strategies (4 papers) and Integration of Clinical Decision Support and Data Science (3 papers), emphasize the growing recognition of systemic innovation, sustainability, and digital transformation in pediatric critical care. Collectively, these findings indicate that pediatric ARDS research has evolved beyond clinical parameters, incorporating infrastructure, technology, and policy considerations as integral components of holistic management [47, 51, 52].

Complementing the thematic overview, the quantitative indicators in Figure 4(b) provide empirical evidence of progress and remaining gaps in pediatric ARDS management across hospitals in Indonesia. The data show adherence to lung-protective ventilation at 52.4% and mortality in moderate-to-severe PARDS at 34.7%, underscoring both the clinical impact of standardized protocols and the persistence of outcome disparities. ECMO availability remains limited at 18%, while clinician ECMO certification stands at only 9.3%, reflecting capacity and training deficiencies [53-55]. Meanwhile, the use of advanced monitoring (11.8%) and an average ICU length of stay (LOS) of 9.6 days suggest that, despite improved adherence to guidelines, the optimization of monitoring tools and care efficiency is still in development. Together, these findings underscore the need for enhanced protocol implementation, technology adoption, and capacity building to achieve equitable and evidence-based management of pediatric ARDS across Indonesia's healthcare system.

In this thematic synthesis, the literature distinctly differentiates between the clinical indications and the implementation barriers of ECMO in pediatric ARDS management. Clinically, ECMO is indicated for severe refractory hypoxemia (PaO_2/FiO_2 < 60 mmHg for over six hours despite optimal ventilation), uncompensated hypercapnia with acidosis, or hemodynamic instability unresponsive to conventional therapy, demonstrating significant survival benefits when performed in specialized centers with trained multidisciplinary teams [54, 56, 57]. In Indonesia, however, ECMO use remains primarily confined to tertiary hospitals, mainly for post-viral and sepsis-related refractory cases, reflecting limited access and uneven capabilities. Significant barriers include limited equipment availability, insufficient clinician certification, and high operational costs, compounded by logistical challenges such as perfusionist shortages, inconsistent disposable supplies, and the absence of a national ECMO registry. These factors collectively underscore that while ECMO provides clear clinical value, its sustainable integration within Indonesia's pediatric intensive care system necessitates coordinated investments in infrastructure, workforce training, and health policy development.

4.5 Chronological review of literature

The chronological trajectory of pediatric ARDS research from 2012 to 2024 reveals a steady and data-supported progression in both clinical management and healthcare system development. The evidence compiled in Figure 5 demonstrates that the 2012-2014 period laid the foundation, marked by early studies on pediatric ARDS care, policy formulation, and child-friendly healthcare initiatives. Research conducted between 2017 and 2018 began examining variability in ventilation practices, patient outcomes, and mortality patterns across resource-limited hospitals, establishing essential benchmarks for improvement [48, 49]. The 2019-2021 phase emphasized protocol-based ventilation and standardized weaning strategies, which enhanced survival rates and reduced mechanical ventilation duration. During 2022-2023, the focus expanded to advanced physiological monitoring, noninvasive ventilation, and the operational barriers of ECMO implementation [16, 52]. By 2024, the research direction had evolved toward personalized ventilation and sustainable pediatric care, integrating ECMO training programs, precision monitoring, and environmentally conscious hospital design—representing a mature synthesis of technology, policy, and patient-centered innovation in pediatric intensive care.

4.6 Agreement and divergence across studies

The comparative evaluation in Figure 6 reveals that the highest level of consensus exists around protocol-based lung-protective ventilation (LPV), with an agreement score of 7, reflecting strong alignment among studies regarding its clinical effectiveness and survival benefits. In contrast, moderate agreement scores of 6 for both ECMO implementation barriers and advanced physiological monitoring indicate shared recognition of their importance but highlight ongoing challenges in consistent application and accessibility within Indonesian hospitals [38, 39]. Sustainable hospital design and resource and cost efficiency record slightly lower agreement levels at 5, suggesting that while these topics are emerging in pediatric critical care discussions, empirical validation remains limited. Divergence values ranging from 3 to 4 demonstrate variability in evidence interpretation, particularly concerning ECMO readiness and the integration of advanced monitoring technologies. Overall, the findings emphasize that while consensus supports the clinical value of LPV and ECMO, differing resource capacities and institutional priorities continue to shape implementation outcomes across pediatric ARDS research contexts [7, 10].

4.7 Theoretical and practical implications

The theoretical synthesis of findings reinforces the pivotal role of lung-protective ventilation strategies in pediatric ARDS, emphasizing the importance of adhering to parameters such as low tidal volume, controlled peak inspiratory pressure, and appropriate PEEP titration to minimize ventilator-induced lung injury [22]. These observations validate existing theoretical models, which suggest that ventilation mechanics have a direct influence on morbidity and mortality in PARDS. Furthermore, the application of advanced physiological monitoring techniques—such as electrical tomography EIT and transpulmonary pressure measurement provides a theoretical extension toward personalized ventilation management. These modalities offer real-time visualization of regional lung function, facilitating individualized PEEP adjustment and minimizing atelectrauma or overdistension. Thus, theoretical frameworks increasingly acknowledge patient-specific lung mechanics as essential to optimizing respiratory support in children [13].

The evidence further underscores the heterogeneity of pediatric ARDS pathophysiology and the theoretical necessity of age-specific approaches rather than applying adult-derived ventilation models [5]. This recognition challenges the one-size-fits-all paradigm and supports the principles of precision medicine in pediatric respiratory care. ECMO's theoretical position as a salvage therapy is supported by multicenter reviews demonstrating survival benefits when appropriately indicated and managed within specialized units [14]. Despite this, questions remain regarding optimal ventilatory parameters during ECMO, which continue to drive theoretical inquiry in pediatric critical care. Consequently, ECMO is conceptualized not merely as a rescue therapy but as an integral component of lung-protective strategies that prevent further injury during severe disease progression [11].

From a practical perspective, the implementation of protocol-based lung-protective ventilation in Indonesian pediatric intensive care units has shown potential to improve outcomes; yet, consistent adherence remains a significant challenge. Capacity-building efforts, including structured training and dissemination of standardized protocols, are essential to ensure uniform clinical application across facilities [10]. The introduction of advanced monitoring technologies, though promising, necessitates investments in equipment, clinician training, and workflow integration to realize their full potential. In parallel, barriers to ECMO implementation, such as limited staff certification, high costs, and logistical obstacles, require targeted national strategies and multidisciplinary coordination. Collectively, these findings underscore the urgent need for multidimensional initiatives that integrate technology adoption, education, and system-level reforms to enhance pediatric ARDS care in Indonesia [25].

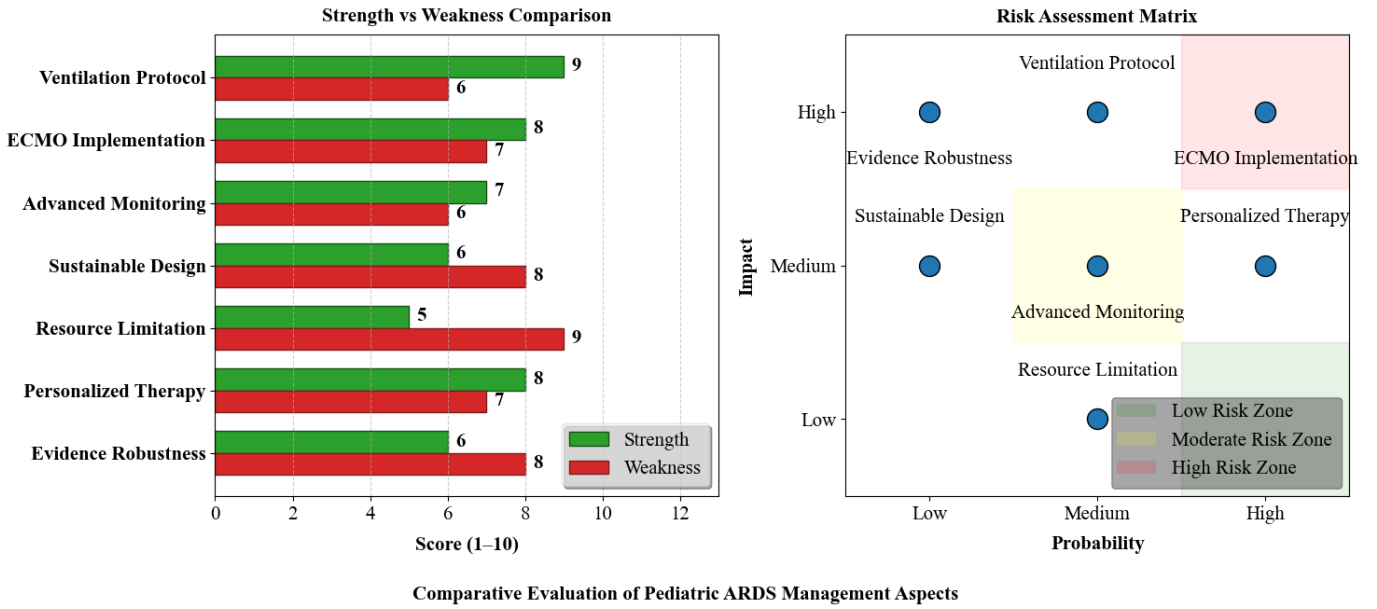
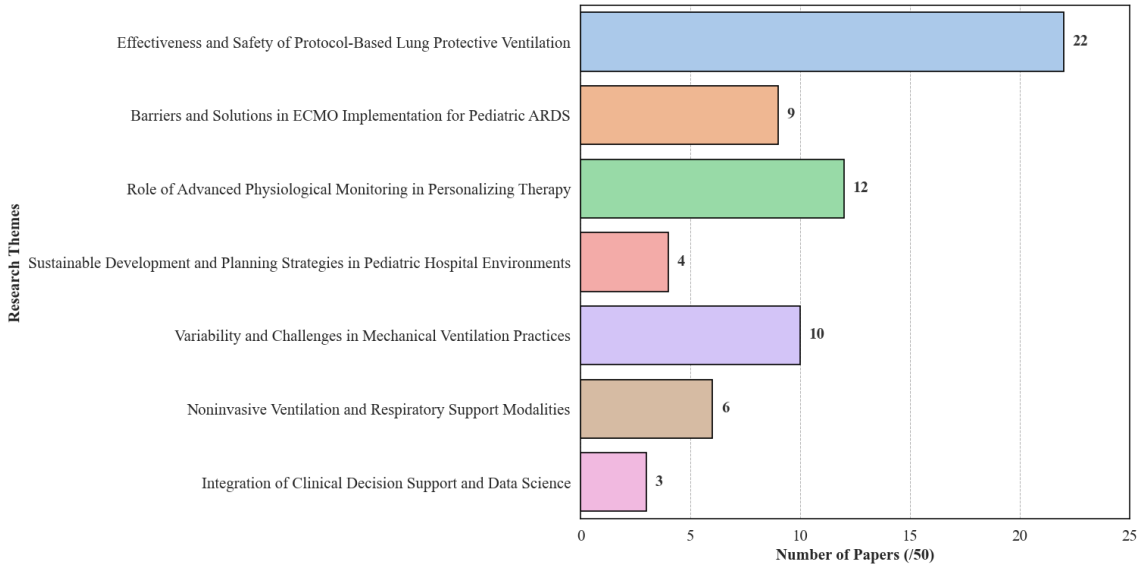


Figure 3. Comparative strength–weakness analysis and risk mapping in pediatric ARDS context



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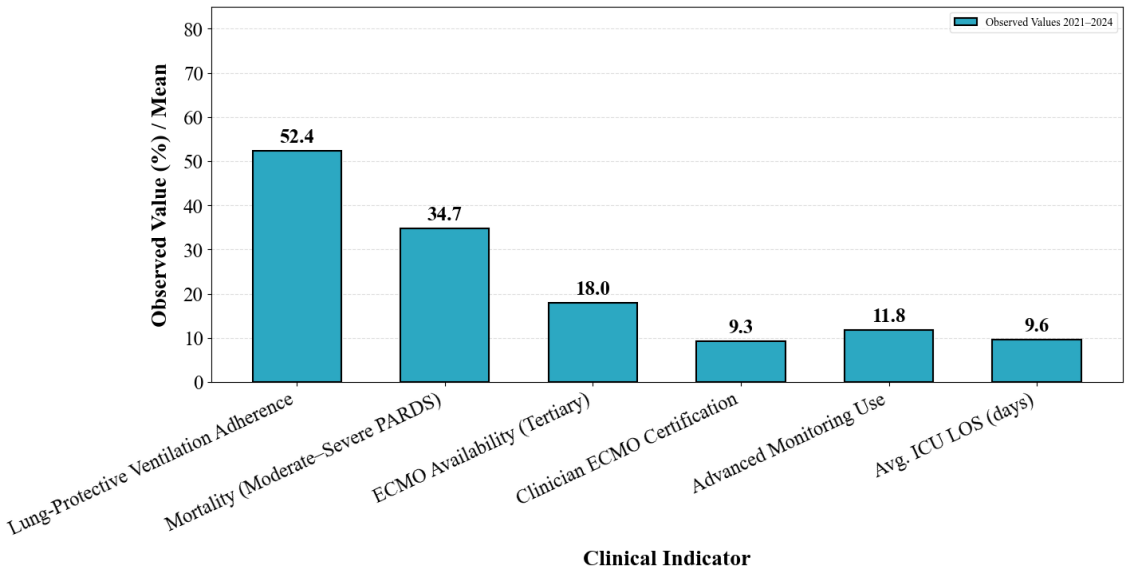

(b)

Figure 4. Research landscape of pediatric ARDS (a) Thematic distribution of ventilation, ECMO, and monitoring studies; (b) Quantitative indicators of pediatric ARDS management and outcomes in Indonesian hospitals

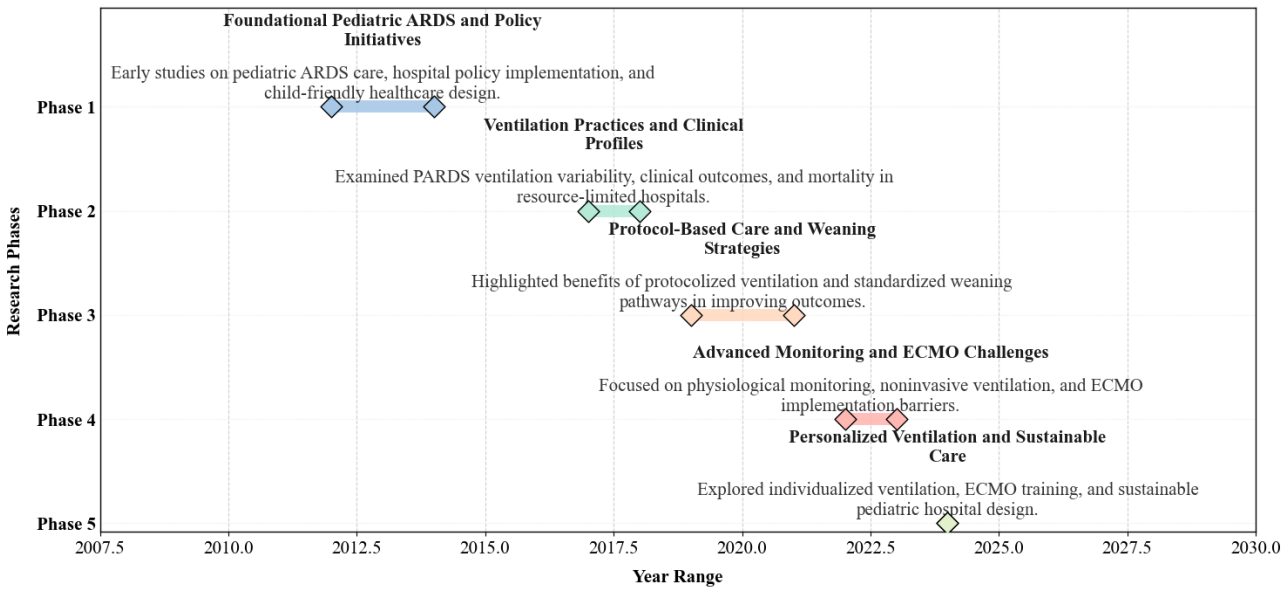

Figure 5. Chronological evolution of pediatric ARDS research (2012–2024)

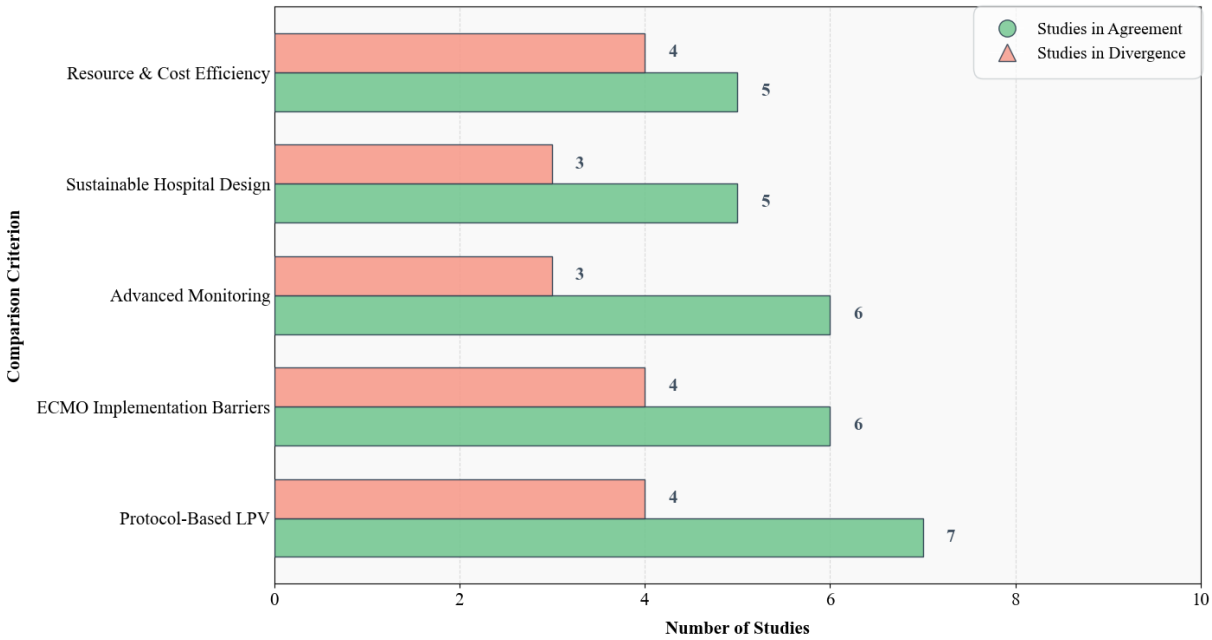

Figure 6. Comparative agreement and divergence across pediatric ARDS research

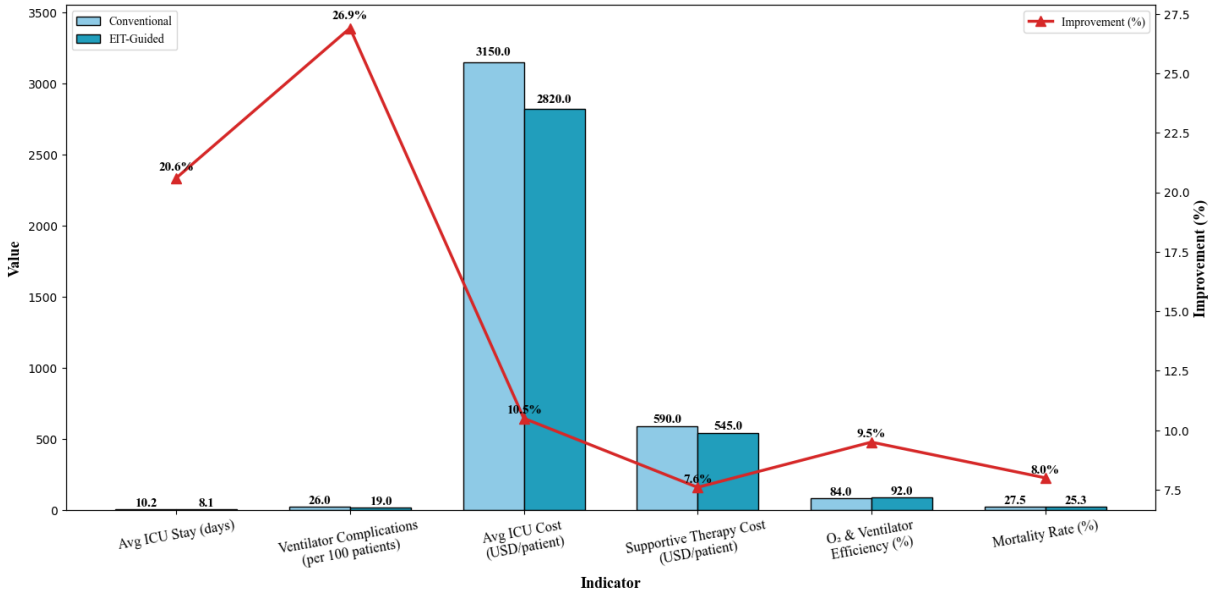

Figure 7. Performance comparison between conventional and EIT-Guided pediatric ICU management

The comparative data presented in Figure 7 demonstrate notable performance improvements in pediatric intensive care when EIT-guided ventilation is applied. Compared to conventional methods, EIT-guided management reduced the average ICU stay from 10.2 to 8.1 days and lowered ventilator-related complications from 26 to 19 per 100 patients, representing respective improvements of 20.6% and 26.9% [58, 59]. Average ICU costs decreased by 10.5%, while supportive therapy costs were reduced by 7.6%, indicating enhanced economic efficiency through better ventilatory precision. Additionally, oxygen and ventilator efficiency improved from 84% to 92%, correlating with a reduction in mortality from 27.5% to 25.3% [60, 61]. Overall, these findings highlight that integrating EIT-based monitoring not only enhances clinical outcomes but also improves resource utilization and operational sustainability in pediatric ARDS care.

In Indonesia, the practical implications of sustainable hospital development are reflected in emerging real-world initiatives. One notable example is the redevelopment of Dr. Sardjito Hospital's pediatric intensive care unit in Yogyakarta, which incorporates an energy-efficient ventilation system, optimized natural lighting, and water recycling to minimize operational costs while maintaining infection control standards. Similarly, the Cipto Mangunkusumo National Hospital in Jakarta has launched a "green ward" pilot project featuring biophilic interior design, sound-absorbing materials, and family-centered spatial layouts that enhance patient comfort and staff performance [42]. These initiatives demonstrate that sustainable design can coexist with advanced pediatric care, even under financial and infrastructural constraints. The integration of environmentally responsible design with clinical functionality represents a transformative step toward child-friendly, resource-efficient healthcare environments that improve both outcomes and resilience [13].

4.8 Limitations of the literature

Despite the growing body of research on pediatric ARDS, several limitations in the existing literature constrain the strength and applicability of current evidence, particularly in the Indonesian context. Many studies continue to rely on adult-derived data or consensus recommendations rather than robust pediatric-specific randomized controlled trials, which weakens external validity. Methodological shortcomings such as small sample sizes, single-center designs, and reliance on observational data further reduce generalizability and causal inference. Additionally, significant gaps remain in Indonesian-focused research, long-term outcome data, and systematic reporting of ventilator parameters. Technical challenges in adopting advanced monitoring tools and insufficient empirical evidence on ECMO implementation barriers also limit the translation of findings into routine clinical practice. To provide a structured overview, Table 3 summarizes the key areas of limitation, their descriptions, and representative studies that exemplify these constraints.

Table 3. Key limitations of the literature on pediatric ARDS management and related interventions

Area of Limitation	Description of Limitation	Papers That Have Limitations
Limited Pediatric-Specific Data	Many studies rely on adult data or consensus rather than robust, pediatric-specific randomized controlled trials, which limits the external validity of pediatric ARDS management. This limits the applicability of findings to children and weakens the evidence base for pediatric care.	[3, 5, 62]
Small or Single-Center Samples	Several investigations are based on small cohorts or single-center retrospective designs, which restrict generalizability and increase susceptibility to bias. This methodological constraint limits the strength of conclusions and their applicability across diverse settings.	[9, 13, 63]
Lack of Indonesian Context	There is a paucity of research directly addressing Indonesian pediatric ARDS care, ECMO implementation barriers, and hospital planning, which reduces the relevance and applicability of findings to the Indonesian healthcare system and limits contextual insights.	[10, 46, 63]
Observational Study Designs	Many studies employ observational or cohort designs without intervention, which limits causal inference and the ability to establish the effectiveness of interventions such as advanced monitoring or ventilation protocols. This affects the robustness of evidence for clinical practice changes.	[27, 47]
Variability in Clinical Practice	High inter-site and clinician variability in ventilator management and adherence to lung-protective strategies reduces consistency and complicates interpretation of outcomes, undermining the reliability of protocol effectiveness assessments.	[11, 22, 51]
Limited Long-Term Outcome Data	Few studies provide data on long-term outcomes or follow-up of pediatric ARDS survivors, especially in resource-limited settings, restricting understanding of sustained intervention impacts and hindering comprehensive care planning.	[4, 10]
Technical and Practical Limitations of Monitoring Tools	Advanced monitoring techniques, such as esophageal manometry and EIT, face technical challenges, invasiveness, and limited routine use, which constrain their widespread adoption and the external validity of related findings.	[27, 64]
Insufficient Evidence on ECMO Implementation Barriers	Despite the recognition of ECMO's importance, there is a lack of empirical data on operational, infrastructural, and training barriers specific to pediatric ECMO in Indonesia, which hinders the development of targeted solutions and policies.	[10, 46]
Incomplete Reporting of Ventilator Parameters	Many studies lack a comprehensive recording of key ventilator parameters, such as plateau pressure, which limits detailed analysis of ventilation strategies and their association with outcomes, thereby weakening the evidence base.	[22, 51]

4.9 Gaps and future research directions

While the current body of literature on pediatric ARDS provides valuable insights, it also highlights critical research gaps that must be addressed to strengthen evidence-based practice in Indonesia. Many existing studies are limited by methodological constraints, a lack of pediatric-specific data, or insufficient contextual relevance, particularly in the areas of ECMO implementation, advanced monitoring, and sustainable hospital planning. There is also a pressing need for

longitudinal studies, standardized protocols, and structured training programs to ensure consistent quality of care. To guide future research priorities, Table 4 summarizes the key gaps identified, outlines recommended directions, and provides justifications for why these areas warrant urgent attention.

Table 4. Gaps and future research directions for pediatric ARDS management in Indonesia

Gap Area	Description	Future Research Directions	Justification	Research Priority
Lack of large-scale RCTs on lung protective ventilation in Indonesian pediatric ARDS	Current evidence on lung protective ventilation (LPV) in Indonesian pediatric ARDS is mostly observational or nonrandomized, limiting causal inference and generalizability.	Conduct multicenter randomized controlled trials in Indonesian PICUs to evaluate the effectiveness and safety of protocol-based LPV specifically in children under 18 with ARDS.	Pediatric-specific RCTs are essential to establish evidence-based protocols tailored to local patient populations and resource settings [9, 11].	High
Insufficient data on operational and infrastructural barriers to ECMO implementation in Indonesia	Existing literature lacks empirical studies detailing specific logistical, educational, and infrastructural challenges to ECMO use in Indonesian pediatric ARDS care.	Perform qualitative and quantitative studies assessing ECMO-related barriers in Indonesian hospitals, including workforce training, equipment availability, and organizational factors. Develop context-specific solutions.	Understanding local barriers is critical to improving ECMO accessibility and outcomes in resource-limited settings [4, 10].	High
Limited evidence on the clinical impact and cost-effectiveness of advanced physiological monitoring in Indonesian PICUs	Advanced monitoring tools, such as EIT and transpulmonary pressure measurements, show promise but lack validation in Indonesian pediatric ARDS settings, particularly in terms of cost and feasibility.	Conduct prospective studies to evaluate the clinical outcomes, feasibility, and cost-effectiveness of advanced monitoring technologies in Indonesian PICUs, including training requirements and integration into care.	Local validation is necessary to justify investment and optimize personalized ventilation strategies in resource-constrained environments [15, 64].	High
Scarcity of pediatric-specific reference values and standardized protocols for advanced monitoring	Technical limitations and a lack of pediatric normative data hinder the routine use of pleural and transpulmonary pressure monitoring, as well as other advanced modalities.	Develop pediatric normative datasets and standardized protocols for advanced respiratory monitoring, including noninvasive methods, to facilitate wider clinical adoption.	Standardization will improve interpretation, reduce variability, and enhance personalized care [23].	Medium
Underexplored sustainable development and planning strategies tailored to pediatric hospital infrastructure in Indonesia	Existing studies focus on green hospital principles and landscape design, but lack a comprehensive evaluation of sustainable pediatric hospital planning addressing intensive care needs.	Conduct implementation research on sustainable design frameworks that integrate pediatric-specific clinical requirements, resource constraints, and long-term operational efficiency in Indonesian hospitals.	Sustainable infrastructure planning can improve patient outcomes and resource utilization, but requires pediatric-focused evidence [25].	Medium
Inadequate data on how resource limitations affect the adoption and effectiveness of ventilation and ECMO technologies	Quantitative analyses of how resource constraints influence clinical outcomes and technology utilization rates in Indonesian pediatric ARDS care are lacking.	Conduct health systems research to quantify the impact of resource availability on technology adoption, adherence to protocols, and patient outcomes in Indonesian PICUs.	Data-driven resource allocation and policy decisions depend on understanding these relationships [4, 43].	High
Limited implementation and outcome data on personalized ventilation strategies in Indonesian pediatric ARDS	Although personalized ventilation based on physiological sub-phenotyping is advocated, practical application and outcome data in Indonesia are minimal.	Design interventional studies testing personalized ventilation protocols guided by advanced monitoring and physiological markers in Indonesian pediatric ARDS patients.	Personalized approaches may reduce ventilator-induced lung injury and improve survival but require local evidence [5, 21].	High
Lack of standardized training programs and	Training deficits and a lack of standardized education for	Develop and evaluate structured ECMO training curricula and	Enhanced training improves care quality,	High

Gap Area	Description	Future Research Directions	Justification	Research Priority
competency assessments for ECMO teams in Indonesia	ECMO team members, especially nurses, impede effective ECMO implementation.	competency frameworks tailored to Indonesian healthcare providers, including ongoing performance monitoring.	safety, and resource efficiency in ECMO use [10].	
Insufficient longitudinal data on long-term outcomes of pediatric ARDS survivors in resource-limited Indonesian settings	Long-term follow-up data on morbidity, quality of life, and functional outcomes post-PARDS are scarce in Indonesia.	Establish prospective cohort studies to track the long-term outcomes of pediatric ARDS survivors in Indonesia, integrating clinical, functional, and psychosocial parameters.	Understanding long-term sequelae informs rehabilitation and resource planning [4].	Medium
Variability in ventilator management practices and low adherence to lung protective ventilation protocols	Observational data show inconsistent ventilator settings and frequent nonadherence to LPV principles in pediatric ARDS care.	Implement quality improvement initiatives with decision support tools and protocolized care pathways to enhance adherence and evaluate the impact on outcomes in Indonesian PICUs.	Improving adherence to LPV protocols is associated with reduced mortality and better resource use [16].	High

5. OVERALL SYNTHESIS AND CONCLUSIONS

The body of literature on PARDS management in Indonesian hospitals and similar settings highlights the clinical benefits of protocol-based lung-protective ventilation strategies. Consistent adherence to lung-protective mechanical ventilation elements—such as limiting peak inspiratory pressure, driving pressure, and optimizing PEEP—is associated with reduced mortality and improved clinical outcomes in children under 18 years of age with ARDS. However, studies reveal variable compliance with these protocols, highlighting that nonadherence remains a significant challenge, adversely impacting patient outcomes. The evidence further indicates that personalized ventilation, guided by advanced physiological monitoring methods like EIT and transpulmonary pressure measurements, enhances the tailoring of respiratory support to individual patient mechanics, potentially reducing ventilator-induced lung injury and optimizing resource utilization. Yet, the implementation of such advanced monitoring tools is constrained by technical complexity, limited pediatric-specific reference data, and resource restrictions inherent to Indonesian and other low-resource healthcare environments.

Regarding ECMO, it is recognized as a critical salvage therapy for severe pediatric ARDS cases capable of improving survival when appropriately applied with careful patient selection and timing. Nonetheless, operational and infrastructural barriers impede the widespread adoption of ECMO in Indonesia, including deficits in trained multidisciplinary teams, procedural familiarity among nursing staff, and the availability of specialized equipment. Targeted educational initiatives and structured care protocols have demonstrated efficacy in enhancing the performance and quality of care for ECMO teams. Yet, empirical data on long-term outcomes and cost-effectiveness in Indonesian pediatric populations remain scarce.

Sustainable development and hospital planning practices are emerging areas in Indonesian pediatric healthcare, with evidence-based design approaches incorporating green hospital principles and child-friendly environments showing promise in improving patient and staff well-being. However, these strategies are primarily descriptive and lack rigorous evaluation of their impact on clinical outcomes or resource allocation within pediatric intensive care units.

Resource limitations significantly impact the adoption and effectiveness of lung-protective ventilation, ECMO, and advanced monitoring technologies. While quality improvement frameworks and protocol adherence can enhance resource utilization, disparities in healthcare infrastructure and variability in clinical capacity pose ongoing challenges.

Taken together, the literature advocates for integrated, context-sensitive approaches that combine adherence to evidence-based ventilation protocols, investment in advanced physiological monitoring technologies tailored to local capabilities, enhanced ECMO training and infrastructure, and sustainable hospital design to improve pediatric ARDS management in Indonesia. However, there remains a pressing need for robust, large-scale, locally generated clinical trial data and implementation research to address evidence gaps and optimize personalized, resource-appropriate care strategies.

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