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INTEGRATED VACCINATION AND BIOSECURITY APPROACHES IN MILITARY OPERATIONAL READINESS

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ABSTRACT: Military operational readiness is increasingly challenged by infectious diseases and emerging biological threats that may disrupt mission continuity, particularly in geographically diverse settings such as Indonesia. As an archipelagic country with heterogeneous endemic disease patterns and frequent military deployments to remote and maritime areas, strengthening force health protection represents a critical public health priority. This systematic literature review aimed to examine the strategic role of vaccination and biosecurity in enhancing military operational readiness and to identify implications for national defense health systems. A systematic literature review design was conducted following PRISMA guidelines. Electronic searches were performed in PubMed, Scopus, Semantic Scholar, CrossRef, and Google Scholar for peer-reviewed studies published between January 2020 and December 2024. Studies addressing vaccination programs, biosecurity measures, and their impact on military readiness were included, and 25 eligible articles were analyzed using qualitative thematic synthesis. Four principal domains were identified: Force Health Protection, Biodefense, Operational Logistics, and Civil–Military Cooperation. Preventive vaccination and pre-deployment biosecurity training were the most emphasized strategies and were associated with reduced disease transmission and improved operational continuity. However, logistical constraints, physiological stressors, and vaccine hesitancy emerged as key implementation barriers. These findings highlight the need for an integrated biodefense framework tailored to Indonesia's defense health system to strengthen preparedness, resilience, and sustainable operational readiness.

Keywords: Military Medicine; Vaccination; Biosecurity; Operational Readiness; Force Health Protection, Indonesia Health Defense

1. INTRODUCTION

Effectiveness depends fundamentally on the physical and psychological resilience of personnel. Historical evidence consistently indicates that infectious diseases have inflicted greater losses on armed forces than enemy action. From the Napoleonic campaigns to the American Civil War, communicable disease outbreaks significantly reduced troop strength and undermined operational capability. These historical patterns remain relevant, particularly as contemporary military forces are frequently deployed to regions with endemic diseases and limited public health infrastructure. [1], [2], [3]

In the modern security environment, the biological threat landscape has become increasingly complex. Military personnel often operate in austere environments such as remote forward operating bases, naval vessels, and multinational deployments, where high population density and environmental stressors facilitate rapid disease transmission. In such contexts, exposure to pathogens for which immunity is limited or absent may occur. Consequently, Force Health Protection (FHP) has evolved into a strategic component of military readiness rather than a purely supportive medical function. [3], [4]

The COVID-19 pandemic illustrated the vulnerability of military operations to biological threats. Operational disruptions aboard naval vessels demonstrated how infectious disease outbreaks may rapidly degrade mission capability. In addition to naturally occurring pathogens, concerns regarding the deliberate misuse of biological agents and the dual-use nature of modern life sciences further underscore the necessity of robust biosecurity measures. Nevertheless, the implementation of vaccination and biosecurity protocols in military settings is challenged by logistical constraints, including cold-chain maintenance in conflict zones, as well as physiological stressors such as sleep deprivation that may diminish vaccine-induced immune responses. Ethical concerns and vaccine hesitancy among service members introduce additional complexities in policy implementation. [5], [6], [7], [8]

Although a growing body of literature addresses vaccination, outbreak response, and biodefense individually, integrative analyses within a unified operational readiness framework remain limited. This systematic literature review

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was conducted to address this gap by synthesizing current evidence regarding the strategic role of vaccination and biosecurity in military contexts. The objectives were to identify application domains, assess strategic benefits, examine implementation barriers, and highlight emerging technologies relevant to enhancing operational readiness. Review articles and original research predominate in the literature, as seen in Figure 1, demonstrating a combination of theoretical synthesis and empirical study.

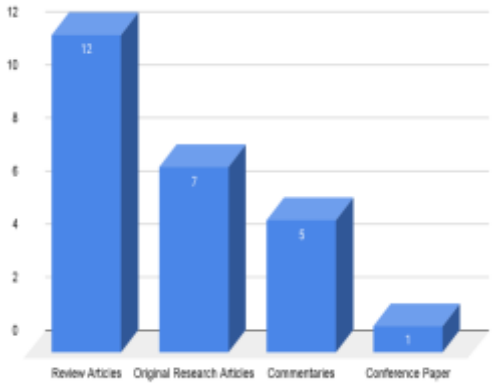

Figure 1: Distribution of Documents by Type

II. RESEARCH METHOD

A systematic literature review (SLR) design was employed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A comprehensive search strategy was conducted across five electronic databases: PubMed, Scopus, Semantic Scholar, CrossRef, and Google Scholar. Publications released between January 2020 and December 2024 were targeted to capture developments associated with the COVID-19 pandemic and evolving biosecurity practices.

Search terms were combined using Boolean operators and included keywords such as military vaccination, biosecurity, biodefense, operational readiness, and infectious disease outbreak. Retrieved records were imported into a reference management system, and duplicate entries were removed. Titles and abstracts were screened for relevance, followed by full-text assessment against predefined inclusion and exclusion criteria.

Studies were included if they: (1) addressed vaccination programs or biosecurity measures within military populations; (2) examined the impact of infectious diseases or biological threats on military readiness; (3) analyzed logistical, ethical, or policy dimensions; and (4) provided empirical, modeling-based, or systematic analytical insights. Non-English publications, studies published prior to 2020, and non-peer-reviewed sources were excluded. The results of inclusion and exclusion criteria are shown in Figure 2.

A total of 25 studies met eligibility criteria and were included in the final synthesis. Data extraction focused on study characteristics, application domains, operational phases, strategic objectives, and reported outcomes. Qualitative appraisal was conducted based on methodological transparency, contextual relevance to military operations, and coherence of findings. Extracted data were organized according to four guiding research questions addressing application domains, strategic benefits, implementation barriers, and emerging technologies.

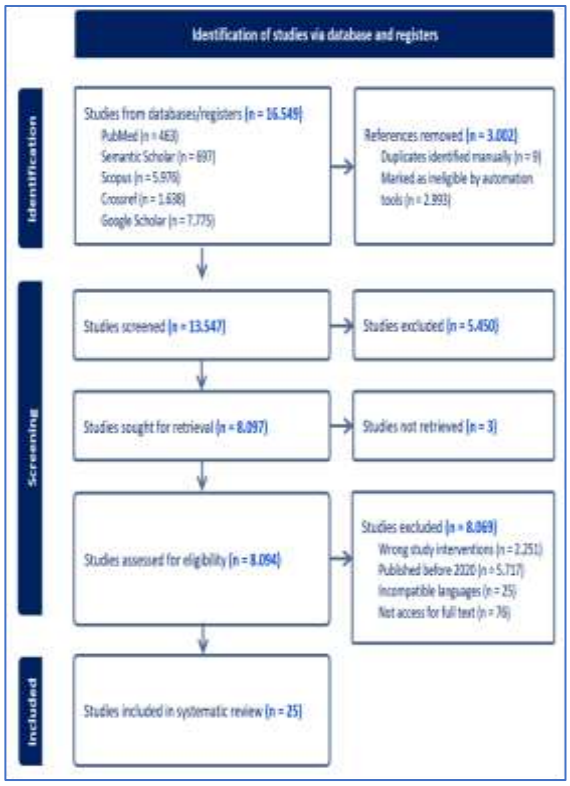

Figure 2. Systematic Search PRISMA Diagram

The novelty of this study lies in its integration of vaccination and biosecurity into a comprehensive military operational readiness framework, rather than examining them as separate issues. This study offers a new perspective that operational readiness is not determined solely by personnel, defense equipment, and combat logistics, but also by force health protection through vaccination, biodefense, operational logistics, and civil–military cooperation. Another key novelty is the adaptation of this framework to Indonesia's context as an archipelagic country facing diverse endemic diseases, remote deployment areas, and the need for an adaptive, integrated, One Health-based, and sustainable defense health system.

III. RESULTS AND DISCUSSIONS

Study Characteristics and Publication Trends

The 25 included studies reflect increased scholarly attention to military vaccination and biosecurity following the onset of the COVID-19 pandemic (Supplementary table 1). Publication frequency peaked in 2022 (Figure 3). Publication frequency peaked in 2022, corresponding with heightened global concern regarding operational continuity during biological crises. The literature consisted of review articles, original research, modeling studies, and policy analyses, indicating balanced

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engagement between theoretical synthesis and empirical investigation.

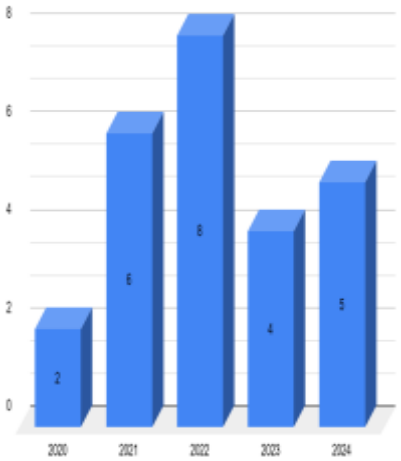

Figure 3. Evolution of Documents by Year

Application Domains of Vaccination and Biosecurity

Analysis identified four principal domains (Supplementary table 2). Force Health Protection was most frequently addressed, emphasizing routine immunization, health screening, and management of vaccine-related adverse events to preserve deployability (Figure 4). Biodefense-focused studies examined countermeasures against biological warfare agents, early-warning systems, and oversight of dual-use research. Operational Logistics studies highlighted vaccine supply chains, cold-chain infrastructure, mobile diagnostic capacity, and infection control systems. Civil–Military Cooperation addressed military contributions to civilian public health response and mitigation of bidirectional disease transmission during large-scale outbreaks. The proportional distribution of studies across these domains appears to reflect research emphasis rather than relative operational importance.

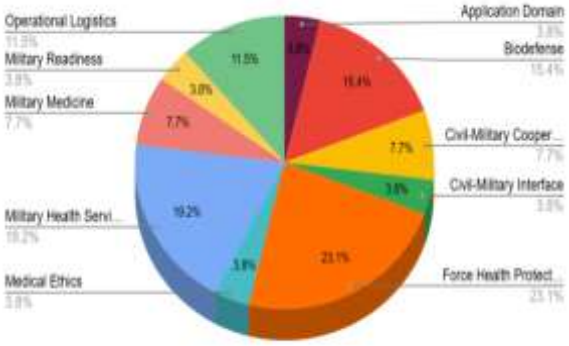

Figure 4. Pie Chart - Application Domains

Distribution Across Operational Phases

Interventions were unevenly distributed across the operational cycle (Figure 5). Most studies emphasized pre-deployment measures, including mandatory vaccination, health screening, and biosecurity training, reflecting a preventive orientation. Fewer studies addressed deployment-phase interventions, which focused primarily on outbreak containment, mobile diagnostics, and shipboard infection control. Post-deployment surveillance and long-term health outcome evaluation received comparatively limited attention. Supplementary table 3 provides a comprehensive summary of the interventions by military operational phase.

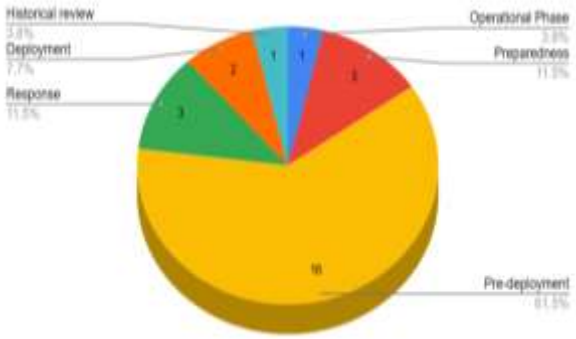

Figure 5. Pie Chart - Operational Phases

Implication for Indonesian Defense Health System

The findings of this review have profound implications for the Indonesian defense health system. As a geographically dispersed archipelagic nation characterized by diverse endemic disease profiles, Indonesia faces unique biosecurity challenges in maintaining military operational readiness, particularly given the high burden of tropical infectious diseases [9]. The Indonesian National Armed Forces (TNI) frequently deploy personnel to remote border regions, maritime territories, and international peacekeeping missions, where exposure to vector-borne pathogens like malaria is substantial and logistical infrastructure is often severely constrained [10]. Consequently, strengthening Force Health Protection within the Indonesian context requires integrating vaccination strategies with field-adapted cold-chain systems, mobile laboratory capacity, and digital medical readiness monitoring to overcome geographical barriers [11]. Furthermore, aligning immunization schedules with operational deployment cycles and incorporating structured health communication programs are essential to enhance vaccine acceptance and mitigate hesitancy among service members [12]. Finally, institutional collaboration between military medical services, the Ministry of Health, and national research agencies is critical to operationalize a "One Health" approach, ensuring preparedness against emerging infectious threats [13]. By adopting a proactive and integrated biodefense framework tailored to Indonesia's operational realities, the defense health system can enhance resilience, protect personnel, and sustain long-term operational readiness.

Strategic Value and Implementation Barriers

Synthesized evidence suggests that vaccination and biosecurity protocols function as important force multipliers in modern military operations. By reducing disease incidence and preventing large-scale outbreaks, these measures contribute directly to sustaining operational readiness. Integrated strategies combining immunization with environmental and

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organizational biosecurity practices appear to mitigate training disruptions and operational downtime. [1], [14], [15]

However, translation of strategic benefits into practice is constrained by interrelated challenges. Mandatory vaccination programs may involve measurable risks of adverse events that temporarily affect deployability. Physiological stressors, including chronic sleep deprivation and operational fatigue, have been associated with impaired immune responses. Logistical dependence on ultra-cold storage for certain vaccines presents additional challenges in austere or contested environments. Ethical considerations and vaccine hesitancy further complicate policy implementation and highlight the need for effective risk communication strategies. [7], [16]

Technological Innovation and Future Directions

Addressing these vulnerabilities requires sustained technological and organizational innovation. Emerging vaccine delivery platforms, such as microneedle patches, may enhance thermostability and simplify field administration. Rapid-response mobile laboratories provide diagnostic capability during deployment, enabling timely outbreak detection and containment. Digital health systems, including virtual medical readiness processing, may improve efficiency while reducing exposure risk. [16], [17], [18]

Future research should prioritize optimization of interactions between soldier physiology and immunization strategies, particularly regarding sleep management and immune response. Additional investigation is warranted to validate field performance of novel vaccine technologies against high-threat agents and to evaluate engineering controls such as ventilation improvements in confined operational environments. Strengthening international governance mechanisms for dual-use research remains important in mitigating misuse of biological advances.

Research Implications

The implications of this study indicate that military operational readiness should no longer be understood solely in terms of personnel preparedness, defense equipment, and combat logistics, but must also include an integrated force health protection system through vaccination, biosecurity, biodefense, and civil–military cooperation. In the Indonesian context, as an archipelagic country with vast geographical dispersion, remote deployment areas, and diverse endemic disease profiles, the defense health system needs to be strengthened through the alignment of immunization schedules with deployment cycles, the development of field-adapted cold-chain systems, mobile laboratory capacity, digital medical readiness monitoring, and risk communication strategies to reduce vaccine hesitancy among service members. This study also implies the need for a more adaptive national biodefense framework based on the One Health approach and supported by synergy among the Indonesian National Armed Forces, the Ministry of Health, research institutions, and relevant stakeholders to prevent, detect, and control biological threats before they disrupt mission continuity. Therefore, vaccination and biosecurity should be positioned as strategic components of the national defense health system to protect military personnel, sustain operational continuity, and strengthen national defense resilience.

Strengths and Limitations of the Study

The strength of this study lies in its ability to integrate two strategic issues, namely vaccination and biosecurity, into a comprehensive military operational readiness framework, thereby extending the discussion beyond the health of military personnel to include force health protection, biodefense, operational logistics, and civil–military cooperation. The use of a systematic literature review based on PRISMA guidelines, covering studies published between 2020 and 2024, also strengthens the study's relevance because it captures recent developments following the COVID-19 pandemic and the evolving dynamics of modern biological threats. In addition, the study is highly relevant to Indonesia, as it is linked to the country's archipelagic geography, military deployments in remote areas, and exposure to diverse endemic diseases. However, the limitation of this study lies in its literature-based design, which means that it does not yet provide direct empirical data from Indonesian National Armed Forces units, military health personnel, or actual field operations. The study also relies on 25 selected articles, which may limit the breadth of perspectives, particularly in explaining the specific realities of Indonesia's defense health system. Therefore, further research is needed through field studies, interviews, surveys, or policy evaluations to examine the practical effectiveness of integrated vaccination and biosecurity strategies in supporting military operational readiness.

V. CONCLUSION

Vaccination and biosecurity protocols represent foundational components of military operational readiness rather than peripheral medical concerns. Modern armed forces face a dual-threat environment characterized by naturally occurring infectious diseases and the potential emergence of engineered biological agents. In this context, mission continuity increasingly depends on the capacity to prevent, detect, and contain biological threats before force capability is compromised. A transition from reactive care models toward integrated biodefense architectures is warranted. Emphasis on thermostable vaccine technologies, alignment of immunization schedules with physiological realities, and strengthened civil–military cooperation in surveillance and response may enhance long-term readiness. Integration of biomedical innovation with operational planning is therefore considered essential for preparedness against future biological challenges. The author was responsible for conceptualization, study design, literature search, data extraction, qualitative synthesis, analysis, manuscript drafting, critical revision, and final approval of the submitted version.

The author state that there are no potential conflicts of interest associated with this research.

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