DIJEMSS:
Dinasti International Journal of Education Management and Social Science
E-ISSN: 2686-6331
P-ISSN: 2686-6358
https://dinastipub.org/DIJEMSS dinasti.info@gmail.com +62 811 7404 455
DOI: https://doi.org/10.38035/dijemss.v7i5

Enhancing Maritime Education and Risk Management Practices for LPG Mixed Loading: A Qualitative Analysis

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Abstract: This study investigates the effectiveness of LPG mixed loading risk management strategies and the alignment of maritime education with industry needs, focusing on preparation of graduates for handling high-pressure risks in maritime operations. A qualitative methodology was employed, utilizing in-depth interviews and focus group discussions with 7 maritime professionals (each with over 20 years of industry experience), 13 maritime vocational lecturers, and 13 graduates of four-year maritime polytechnic programs — totaling 33 participants across three stakeholder groups. Data were analyzed through a systematic three-stage thematic analysis procedure with intercoder verification. Key findings reveal significant score differentials across groups: maritime professionals rated the effectiveness of LPG mixed loading risk management strategies at 9.0, while lecturers scored 7.0 and graduates only 6.5 — a gap of 2.5 points that constitutes the study's most diagnostically significant finding. Similar divergences were observed across safety practice efficiency, vocational training effectiveness, and sustainability in risk management. The study identifies a structural education–industry gap in which current maritime vocational curricula provide theoretical foundations but inadequately develop the practical, operational competencies required for high-pressure LPG loading environments. The principal contribution of this study is a multi-stakeholder evidential base demonstrating that the education–industry gap in maritime risk management competence is measurable, persistent, and amenable to curriculum reform — specifically through simulator-based practical training, industry immersion, and sustainability-integrated assessment — providing Indonesian maritime polytechnics with an empirically grounded rationale for curriculum redesign.

Keywords: LPG Mixed Loading, Maritime Education, Risk Management, Vocational Training, Maritime Sustainability

INTRODUCTION

The Risk Landscape of LPG Mixed Loading

The global maritime industry faces intensifying safety challenges in hazardous cargo operations, with LPG mixed loading presenting some of the most technically demanding risk profiles in the sector. LPG mixed loading involves transferring multiple types of liquefied petroleum gas products — principally propane and butane — into the same carrier simultaneously. Because these substances differ in vapor pressure and thermal characteristics, mixed loading operations are inherently prone to high-pressure occurrences, pressure imbalances, phase changes, and unsafe conditions (Joseph & Dalaklis, 2021). Risks are compounded by improper loading sequences, inadequate vapor return management, and overfilling of tanks — technical failures that have contributed to port and vessel incidents documented in international maritime safety investigation databases (Godet et al., 2023). The consequence of inadequate risk management in this domain extends beyond operational inefficiency to encompass catastrophic safety events, environmental harm, and loss of life — making LPG mixed loading risk competence a direct safety-critical outcome of maritime vocational education.

Despite the severity of these risks, a critical gap persists between the risk management competencies that maritime vocational curricula develop and those that the industry requires (Cicek et al., 2019; Mallam et al., 2019). The International Maritime Organization's emphasis on competency-based certification through the STCW convention establishes minimum proficiency standards but does not systematically address the safety culture dispositions, incident-informed judgment, and adaptive risk reasoning that professional practice in hazardous cargo operations demands (Wulandari & Cahyadi, 2025; Zheng et al., 2025). This gap between certified competence and operational safety readiness constitutes the central problem this study addresses.

The Education–Industry Gap and Its Consequences

Maritime vocational education in Indonesia operates within a certification-driven framework that prioritizes procedural knowledge and standardized examination performance (Komaro et al., 2022; Widaningsih et al., 2025). While this framework produces graduates who meet minimum STCW certification requirements, it does not ensure that graduates possess the practical, contextually applied risk management competencies that high-pressure LPG loading environments require. Ghosh et al. (2014) demonstrated that authentic assessment of seafarers requires engagement with real operational contexts beyond what STCW standards specify — a finding directly applicable to the LPG risk management domain where operational judgment cannot be adequately assessed through written examinations alone. Nidhom et al. (2025), in a systematic review of vocational teacher professional education, confirmed that the interaction among professional competence, institutional support, and working conditions determines whether vocational graduates develop genuine operational capability — a finding that frames the education–industry gap as a systemic institutional challenge rather than a curriculum content problem alone.

A further dimension of this gap is the underdevelopment of sustainability competencies in maritime vocational training. As the maritime sector increasingly faces regulatory pressure to integrate environmental responsibility into operational practice, the absence of sustainability-focused risk management instruction in curricula creates graduates who are technically qualified but environmentally underprepared (de la Peña Zarzuelo et al., 2020; Mutohhari et al., 2025). Li et al. (2023), assessing green technology knowledge deficits among vocational educators, found that 68 percent lacked necessary expertise — a deficit directly applicable to maritime sustainability risk management instruction.

Research Gap

No existing qualitative study has systematically examined the perspectives of three stakeholder groups — maritime professionals, lecturers, and graduates — on LPG mixed loading risk management effectiveness and educational alignment simultaneously. This multi-stakeholder approach is essential because the education–industry gap, by definition, can only be measured when the perceptions of those at the industry demand end (professionals), the pedagogical delivery end (lecturers), and the educational experience end (graduates) are examined together and compared. This study fills this gap by providing exactly that three-dimensional evidence base.

Research Questions

This study addresses four research questions: (RQ1) What are the primary causes of high-pressure occurrences in LPG mixed loading operations? (RQ2) How do maritime professionals manage high-pressure risks, and what strategies have proven effective in mitigating these risks? (RQ3) What role does maritime education play in preparing graduates to handle such risks, and how can vocational training be improved? (RQ4) How do the perspectives of lecturers and graduates align with the operational needs of the maritime industry in the context of LPG mixed loading?

Literature Review

LPG Mixed Loading: Operational Risks and Safety Protocols

LPG mixed loading risk management is governed by a complex intersection of technical, procedural, and human factors. Joseph and Dalaklis (2021), examining the International Convention for the Safety of Life at Sea (SOLAS), demonstrated that effective risk mitigation in maritime hazardous cargo operations requires the interrelation of multiple safety measures — regulatory compliance, crew competency, and real-time monitoring systems — none of which is independently sufficient. Godet et al. (2023), analyzing operational cycles for maritime transportation, established that energy efficiency benchmarks and operational safety are deeply intertwined in hazardous cargo contexts, where pressure management and load optimization are simultaneously safety and sustainability concerns. De la Peña Zarzuelo et al. (2020), reviewing Industry 4.0 applications in ports, demonstrated that digital monitoring technologies offer significant risk reduction potential in cargo handling operations — a finding directly applicable to LPG pressure monitoring and vapor management systems.

Maritime Vocational Education: Competency Frameworks and Limitations

The competency-based paradigm dominates maritime vocational education globally, providing structured frameworks for certification-aligned professional development (Daryono et al., 2023; Aminah et al., 2025). Cicek et al. (2019), through a future skills requirements analysis in the maritime industry, identified that technical expertise must be supplemented by digital literacy, critical thinking, and adaptive problem-solving — competencies that conventional maritime curricula do not systematically develop. Mallam et al. (2019), examining digital applications in maritime education, training, and operations, argued that immersive technologies — simulation, virtual reality — offer transformative potential for developing the applied operational competencies that classroom instruction cannot produce.

The limitations of certification-focused maritime education have been documented across multiple studies. Ghosh et al. (2014) argued that authentic assessment of seafarers requires context-specific performance evaluation beyond STCW standards. Hattingh et al. (2022), examining competency-based education in aviation — a parallel safety-critical vocational domain — found that instructors possessed limited theoretical understanding of competency assessment, with direct implications for safety outcomes. This finding transfers directly to maritime education: if those who design and administer maritime competency assessment do not fully understand competency-based evaluation principles, the assessment systems they administer cannot reliably certify genuine operational readiness. Oroh et al. (2023) confirmed that assessment context significantly influences competency demonstration, with students in large industry placements achieving substantially higher capability scores than those in small industries — an empirical argument for expanding maritime students' exposure to authentic operational environments.

Safety Culture and Risk Disposition in Maritime Contexts

Safety culture in maritime education extends beyond procedural knowledge to encompass the dispositions, attitudes, and behavioral norms that determine how professionals respond to risk in real operational conditions (Wulandari & Cahyadi, 2025; Ardiyanto et al., 2023). Ardiyanto et al. (2023), assessing Indonesian vocational students' comprehension of international safety signs, found that cultural familiarity and repeated contextual exposure to safety-relevant stimuli were essential for developing reliable safety comprehension — a finding that supports experiential, immersive approaches to safety risk instruction over declarative classroom teaching. Zheng et al. (2025), examining institutional learning frameworks for safety transitions, established that effective safety knowledge transmission requires coordinated intervention across educational institutions, regulators, and industry — the three-stakeholder configuration this study examines empirically.

Wahyudi et al. (2025), examining successful university–industry partnerships in vocational education, confirmed that adaptability and continuous improvement drive effective industry–education collaboration — a structural condition essential for closing the education–industry gap in maritime risk management. Suyetno et al. (2024) further established that genuine industry involvement in curriculum design, rather than formal consultative mechanisms, produces substantially stronger alignment between educational content and operational demands.

Sustainability in Maritime Risk Management

The integration of sustainability into maritime risk management education reflects the sector's increasing environmental regulatory burden. Mutohhari et al. (2025), documenting low maturity levels of green skills among Indonesian vocational teachers, established an urgent professional development need directly applicable to maritime sustainability risk instruction. Othman et al. (2025), reviewing digitalisation challenges in TVET, confirmed that sustainability-oriented technology integration requires coordinated institutional investment in faculty capacity, curriculum redesign, and assessment realignment — all three of which this study's findings implicate in the maritime LPG education context. Song and Xu (2024) cautioned that rapid expansion of vocational education without corresponding quality improvement in practical skill formation produces certification without genuine professional capability — a pattern this study's cross-group score differentials empirically illustrate in the maritime risk management domain.

METHOD

Research Design

This study employed a qualitative research design situated within an interpretivist paradigm (Creswell & Poth, 2018), selected for its capacity to capture the nuanced, experientially grounded perspectives of maritime stakeholders whose understanding of LPG risk management reflects different positional relationships to operational practice and educational delivery. The qualitative approach was appropriate given the study's objective of understanding not merely what risk management practices exist but how practitioners at different levels of the maritime education-to-practice ecosystem perceive their adequacy — a question requiring interpretive depth that quantitative instruments cannot provide.

Participants: Selection Criteria and Characteristics

Participants were selected through purposive criterion sampling ensuring that each group possessed the positional authority and experiential grounding necessary to provide credible, contextually specific data.

Maritime Professionals (n=7): Inclusion criteria required a minimum of 20 years of professional experience in port management, ship operations, or maritime cargo handling, with documented direct involvement in LPG or hazardous cargo operations. Exclusion criterion: individuals without direct operational (as opposed to purely administrative) maritime experience. Participants included former and current senior officers in port management corporations, maritime safety advisors, and operational managers in LNG/LPG shipping companies.

Lecturers (n=13): Inclusion criteria required active teaching responsibilities in maritime safety, risk management, or cargo handling subjects, with a minimum of three years of maritime vocational instruction experience. Exclusion criterion: lecturers without direct instructional involvement in safety-related subjects. Participants taught across nautical deck engineering, naval marine engineering, and port and shipping management programs.

Graduates (n=13): Inclusion criteria required completion of a four-year maritime polytechnic program in nautical deck engineering, naval marine engineering, or port and shipping engineering, with graduation within the preceding three years. Exclusion criterion: graduates without any post-graduation professional maritime experience. All participants had completed minimum six months of maritime industry employment.

Table A. Summary of Participant Characteristics

Group	n	Experience/Qualification	Gender (M/F)	Age Range
Maritime Professionals	7	Min. 20 years LPG/hazardous cargo operations	6M / 1F	42–58 years
Lecturers	13	Min. 3 years maritime safety instruction	10M / 3F	34–52 years
Graduates	13	4-year maritime polytechnic; min. 6 months employment	11M / 2F	22–27 years
Total	**33**			

Data Collection Procedure

Semi-structured interviews were conducted with individual participants, supplemented by focus group discussions with groups from each stakeholder category. All interviews were conducted face-to-face at participants' institutional or professional locations. Sessions lasted 60 to 90 minutes per participant. With participants' written informed consent, all sessions were audio-recorded using a digital recorder. Recordings were transcribed verbatim within one week of each session. Transcripts were returned to participants for member verification, and any requested corrections were incorporated prior to analysis. Institutional ethical approval was obtained from Sekolah Tinggi Ilmu Pelayaran Jakarta prior to data collection.

The interview protocol organized questions around three thematic domains corresponding to the research questions: (1) risk identification and management in LPG mixed loading operations; (2) effectiveness and limitations of current safety practices; and (3) alignment of maritime education with industry risk management requirements. Interview guides were developed from the theoretical framework and reviewed by two senior maritime safety specialists before deployment.

Scoring Methodology

Participant evaluations were obtained through a structured evaluation instrument administered within the interview sessions, in which participants rated each of six risk management and educational indicators on a 10-point Likert-type scale (1 = very ineffective/inadequate; 10 = very effective/adequate). The reported scores in Table 1 represent mean ratings calculated from all participants within each group for each indicator. This methodology provides a quantified representation of qualitative assessment data that allows cross-group comparison while retaining the contextual nuance captured through the accompanying interview discussions. It is important to note that these scores reflect perceived effectiveness from stakeholders' positional perspectives rather than objective performance metrics.

Thematic Analysis: Step-by-Step Procedure

Qualitative interview and focus group data underwent a six-phase thematic analysis following Braun and Clarke (2006).

Phase 1 — Data Familiarization: All 33 transcripts were read in full twice, with initial researcher notes on recurring patterns, striking expressions, and potential thematic directions, establishing holistic dataset understanding before systematic coding.

Phase 2 — Open Coding: Each transcript was coded line-by-line in NVivo 14, generating descriptive initial codes from participants' own language without predetermined categories. This inductive phase produced 164 initial codes across the dataset.

Phase 3 — Focused Coding and Theme Generation: Initial codes were grouped and reorganized into candidate themes by identifying patterns of shared meaning, producing four overarching themes: risk management competency divergence, education–practice alignment, practical training adequacy, and sustainability integration.

Phase 4 — Theme Review: Candidate themes were validated against the full dataset to confirm internal coherence and thematic accuracy. One theme was merged with another during this phase.

Phase 5 — Theme Definition: Each theme was assigned a precise analytical definition distinguishing it from adjacent themes.

Phase 6 — Cross**-Group Comparison and Triangulation:** Coded data were disaggregated by stakeholder group to identify convergences and divergences. To strengthen credibility, a second independent coder coded 20 percent of the transcript corpus; Cohen's Kappa was calculated at $\kappa = 0.80$, indicating strong intercoder agreement (Landis & Koch, 1977). Source triangulation was achieved by cross-referencing interview findings with focus group data and institutional curriculum documentation. Member checking was conducted with three participants (one per group) who reviewed preliminary theme summaries and confirmed their interpretive accuracy.

RESULTS AND DISCUSSION

The analysis produced cross-group score differentials across six indicators and four qualitative themes. The themes were derived through the coding process described above, with credibility established through intercoder reliability ($\kappa = 0.80$), member checking, and source triangulation. Scores represent group mean ratings (see Section 3.4 for methodology).

Quantitative Overview

Table 1. Research Results Overview — Cross-Group Mean Scores (Scale 1–10)

Indicator	Maritime Professionals (n=7)	Lecturers (n=13)	Graduates (n=13)	Max Gap
Effectiveness of LPG Mixed Loading Risk Management Strategies	9.0	7.0	6.5	2.5
Efficiency of Safety Practices in LPG Mixed Loading	8.5	6.5	7.0	2.0
Alignment of Maritime Education with Industry Needs	7.5	8.0	7.5	0.5
Effectiveness of Vocational Training in Handling High-Pressure Risks	8.5	7.5	7.0	1.5
Competency Development in Maritime Safety	9.0	7.0	7.0	2.0
Sustainability in Maritime Risk Management Practices	8.0	6.5	7.0	1.5

The most significant score differential appears in the effectiveness of LPG mixed loading risk management strategies (professionals: 9.0; graduates: 6.5; gap = 2.5 points), followed by safety practice efficiency and competency development in maritime safety (both showing 2.0-point gaps between professionals and lecturers). Notably, alignment of maritime education with industry needs showed the smallest gap (0.5 points), with lecturers rating it highest of all groups (8.0) — a pattern with significant interpretive implications discussed in Section 5.

Qualitative Findings with Participant Quotations

Theme 1 — Risk Management Competency Divergence

Maritime professionals consistently described their high confidence in established risk management protocols as grounded in long operational experience with real-world incident management. One maritime professional with 24 years of LPG cargo operations stated:

"The current loading sequence protocols have significantly reduced pressure fluctuations during mixed LPG operations. When you follow the vapor pressure management sequence correctly and run continuous monitoring, you can prevent the high-pressure events that used to cause delays and equipment stress. But this knowledge only comes from doing it — from standing in the cargo control room when something goes wrong and learning how to read the system."

This emphasis on embodied, experiential knowledge contrasts sharply with graduates' accounts of their preparation. One graduate with eight months of post-qualification experience reported:

"We learned about LPG properties and the loading calculations in class. The theory was clear. But when I was actually on board during my first mixed loading operation, I felt completely unprepared for how fast conditions could change. The gap between the textbook and the cargo control room was bigger than I expected."

Theme 2 — Education–Practice Alignment Gap

Lecturers rated alignment of maritime education with industry needs highest of all groups (8.0), while professionals (7.5) and graduates (7.5) gave lower scores. Lecturers' relatively positive self-assessment was qualified, however, by the gap they acknowledged between curriculum design and practical delivery capacity. One lecturer noted:

"We design the curriculum to be industry-aligned. The topics are correct — vapor pressure management, loading *sequences, safety regulations. But the delivery is still mostly theoretical. We do not have LPG cargo simulators. We cannot create the actual conditions of a pressurized cargo control room in a classroom. The students know the content; they just haven't experienced it."*

Theme 3 — Practical Training Adequacy

The efficiency of safety practices in LPG mixed loading showed the second-largest gap (professionals: 8.5; lecturers: 6.5). Lecturers' lowest rating across all indicators for this domain — lower even than graduates — reflects educators' awareness of the gap between what they teach and what industry practice requires. One experienced lecturer stated:

"I know our safety practice instruction is not at the level the industry needs. We teach the regulations and the procedures, but we cannot give students the experience of pressure situations. Without *simulation, without incident case studies, the training produces students who know the rules but cannot feel the risk."*

Theme 4 — Sustainability Integration Deficit

Sustainability in maritime risk management received the lowest ratings from lecturers (6.5) of any indicator, while professionals rated it at 8.0 — a 1.5-point gap. One maritime professional with port management experience observed:

"Environmental compliance is now inseparable from safety in LPG operations. The pressure to manage vapor *emissions for environmental reasons has changed how we think about loading sequences. But when I interview graduates, they barely mention environmental factors when they talk about LPG risk. It's not part of how they were taught to think about safety."*

Discussion

Mapping Findings to Research Questions

The cross-group score differentials and qualitative themes collectively address all four research questions. **RQ1** (primary causes of high-pressure occurrences) is answered through professional accounts identifying inadequate loading sequence management, insufficient vapor return monitoring, and lack of real-time system response experience as the primary operational causes. **RQ2** (effective risk management strategies) is addressed by professional participants' consistently high ratings and their descriptions of protocol-driven loading sequences, continuous monitoring, and experience-based adaptive response — strategies graduates have not been trained to implement in realistic conditions. **RQ3** (maritime education's role and improvement pathways) is addressed by the education–practice alignment and practical training themes, which collectively identify simulation, industry immersion, and incident-based case study instruction as the most critical instructional improvements. **RQ4** (alignment of lecturer and graduate perspectives with industry needs) is addressed by the convergence–divergence pattern in Table 1: graduates and professionals converge on recognizing the practical training gap, while lecturers diverge by rating curriculum alignment higher than either professionals or graduates would validate from their positions.

The Score Differential as Evidence of a Structural Gap

The 2.5-point gap between professional and graduate ratings of LPG risk management effectiveness constitutes the study's most theoretically significant finding. This gap is not a measurement artifact — it reflects a structural condition in which operational experience produces a fundamentally different understanding of risk management effectiveness than educational exposure does. This finding confirms and extends Ghosh et al.'s (2014) argument that authentic seafarer assessment requires context beyond STCW specifications: the study demonstrates empirically that STCW-aligned vocational training produces graduates whose perceived effectiveness scores are substantially lower than those of experienced practitioners, indicating that certification does not assure operational risk readiness in complex LPG operations.

The pattern aligns with Daryono et al.'s (2023) finding that assessment context significantly influences competency demonstration — graduates who have not been exposed to authentic LPG loading environments cannot accurately assess the effectiveness of practices they have not applied. Oroh et al. (2023) corroborated this principle, demonstrating that students in large-industry placements achieved substantially higher capability scores than those in small industries, confirming that exposure quality determines perceived and actual competency levels.

Lecturers' Divergent Self-Assessment and Its Institutional Cause

The most diagnostically interesting finding in Table 1 is that lecturers rated curriculum alignment with industry needs at 8.0 — higher than both professionals (7.5) and graduates (7.5). This divergence is not explained by superior insight but by the institutional KPI dynamic identified in adjacent maritime vocational education research (Nidhom et al., 2025; Suyetno et al., 2024): lecturers are evaluated on the theoretical currency and formal completeness of their curriculum design, not on the operational readiness of their graduates. When institutional performance indicators measure curriculum quality through content coverage rather than graduate performance, educators have structural incentives to rate alignment positively regardless of what graduates and industry professionals experience. Wahyudi et al. (2025) confirmed this dynamic, finding that genuine university–industry partnership quality — as opposed to formal curriculum review mechanisms — is the variable that actually predicts graduate operational readiness.

Sustainability as an Emerging Competency Gap

The lecturers' lowest score of any indicator for sustainability in risk management practices (6.5) reflects what Mutohhari et al. (2025) documented as a systemic green skills maturity deficit among Indonesian vocational educators. This finding connects maritime LPG risk management to the broader sustainability education challenge: as the maritime sector's environmental regulatory burden intensifies — with IMO emissions regulations directly affecting LPG fleet operations — the absence of sustainability competencies from maritime risk management curricula produces graduates who are procedurally qualified but environmentally underprepared. Othman et al. (2025) established that sustainability integration in TVET requires coordinated institutional investment rather than individual instructor initiative — an institutional condition that this study's institutional context has not yet created.

Implications for Maritime Education

The findings carry three specific practical implications. First, maritime vocational curricula require simulator-based LPG risk management instruction — specifically, cargo control room simulation under realistic pressure scenario conditions — as the primary mechanism for closing the 2.5-point effectiveness gap between professionals and graduates. Mallam et al. (2019) established immersive technology's transformative potential in maritime education; this study provides the score-differential evidence that this potential is currently unrealized in the LPG risk domain. Second, industry immersion programs must be redesigned to include structured LPG cargo operations exposure, incorporating the loading sequence management and pressure monitoring protocols that currently reside only in professional operational experience. Third, sustainability-integrated risk management must be embedded within LPG safety instruction rather than treated as a separate curricular domain, reflecting the professional reality that environmental compliance and safety practice are now operationally inseparable (de la Peña Zarzuelo et al., 2020).

Limitations of the Study

The study is limited by its relatively small sample (n=33), drawn from a single maritime institution's stakeholder network, which constrains generalizability across the full diversity of Indonesian maritime vocational institutions. The scoring methodology translates qualitative assessment into quantified ratings that, while analytically useful for cross-group comparison, should be interpreted as perceptual indicators rather than objective performance measures. The qualitative design, while enabling interpretive depth, does not permit causal inference about the relationships between educational inputs and operational outcomes. Cultural factors — particularly Indonesia's high power-distance institutional culture, which shapes how junior maritime personnel express safety concerns and evaluate their own preparedness relative to senior figures — may have influenced participants' scores and quotations in ways this study cannot fully isolate.

CONCLUSION

This study provides systematic multi-stakeholder evidence that a measurable and structurally significant gap exists between maritime professionals' assessment of LPG mixed loading risk management effectiveness (9.0) and graduates' assessment of the same dimension (6.5) — a 2.5-point differential that directly answers RQ1 and RQ2 by establishing that professional-level risk management confidence is grounded in operational experience that educational programs do not currently replicate. The education–practice alignment analysis (RQ3 and RQ4) reveals that lecturers' relatively positive curriculum assessment (8.0) diverges from both professional and graduate perceptions, reflecting an institutional dynamic in which curriculum design quality is evaluated independently of graduate operational readiness.

The study contributes three evidence-based recommendations. For maritime educational institutions: simulator-based LPG cargo operations instruction must be developed as a core curricular component, not a supplementary enrichment activity, to close the practical training gap that the score differentials document. For industry–education partnerships: structured industry immersion in LPG cargo operations must be redesigned as an assessed curriculum component with mentored exposure to real loading sequences and pressure management protocols, consistent with Wahyudi et al.'s (2025) evidence that substantive partnership quality determines graduate readiness. For policy: sustainability-integrated risk management — specifically, environmental compliance as a dimension of LPG safety practice — must be incorporated into STCW-aligned curriculum specifications before the green skills maturity deficit documented by Mutohhari et al. (2025) produces graduates systematically underprepared for environmentally regulated maritime operations.

Future research should employ quantitative designs to measure the impact of simulator-based LPG instruction on operational competency scores in experimental versus control groups, and should develop a risk-based curriculum model that formally integrates environmental compliance within LPG safety training standards.

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