

# Innovations in advanced materials for enhancing sustainability in maritime engineering

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**Abstract.** This study investigates the integration of bio-composites and corrosion-resistant alloys in maritime engineering through vocational education perspectives. Using semi-structured interviews with 30 stakeholders comprising maritime professionals, educators, and recent graduates, the research assessed five critical indicators: material performance, environmental impact, industry collaboration, educational effectiveness, and economic viability. Results demonstrate consistently high stakeholder ratings (8.00-9.00/10) across all dimensions, revealing vocational education as a critical mediator between material innovation and industry adoption. The study establishes the triadic relationship among material science, maritime applications, and human capital development through three mechanisms: knowledge translation, competency development, and cultural legitimization. Despite positive perceptions, adoption barriers persist including economic constraints, knowledge gaps, and regulatory ambiguity. Findings inform coordinated strategies for accelerating sustainable material adoption in maritime contexts, emphasizing the interdependence of technical innovation, educational systems, and organizational readiness in maritime sustainability transitions.

## 1 Introduction

The maritime industry stands at a critical juncture where traditional engineering practices confront urgent sustainability imperatives and technological evolution. As global shipping accounts for approximately 3% of worldwide greenhouse gas emissions, the sector faces unprecedented pressure to adopt innovative materials that simultaneously enhance performance and reduce environmental impact [1]. This convergence has catalyzed research into advanced materials—particularly bio-composites derived from renewable resources and corrosion-resistant alloys—that promise to revolutionize maritime engineering while addressing climate commitments. However, beneath the technical promise lies a critical yet underexplored dimension: the human and educational infrastructure required to translate laboratory breakthroughs into operational maritime contexts.

Contemporary maritime engineering faces dual sustainability crises that conventional materials cannot adequately address. First, traditional materials demonstrate insufficient durability in aggressive marine environments characterized by saltwater corrosion,

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biofouling, and extreme mechanical stresses, necessitating frequent maintenance cycles that increase operational costs [2]. Second, the production and lifecycle impacts of conventional maritime materials generate substantial carbon emissions, contradicting the International Maritime Organization's ambitious target to reduce greenhouse gas emissions by at least 50% by 2050 [3]. Advanced materials offer compelling solutions: bio-composites exhibit superior corrosion resistance while deriving from renewable feedstocks, and specialized alloys extend structural lifespans through enhanced material properties. Yet despite extensive research documenting technical superiority, adoption rates remain disappointingly low, revealing a critical disconnect between innovation potential and implementation reality [4].

This implementation gap emerges from complex sociotechnical factors extending beyond material properties. Maritime industries operate within deeply entrenched technological paradigms where conventional materials dominate procurement specifications, maintenance protocols, and regulatory frameworks. Introducing novel materials requires not only technical validation but also workforce competencies to specify, handle, and maintain unfamiliar substances, organizational cultures receptive to innovation, and economic structures that recognize lifecycle value rather than initial costs. Previous research has predominantly examined advanced maritime materials through technical lenses—analyzing mechanical properties, environmental impacts, and performance characteristics—while treating adoption as an automatic consequence of superior specifications [5]. This approach overlooks the critical role of human capital development in enabling technological transitions.

Vocational education emerges as a potentially crucial yet systematically underexamined mediator in this innovation-to-implementation pipeline. Maritime academies, polytechnics, and training institutions occupy a strategic position between material science research and industry practice, preparing the workforce that will ultimately determine whether innovations succeed or fail in operational contexts [5]. Through curriculum development, practical training, and industry partnerships, vocational education systems possess unique capacity to translate complex material science into accessible competencies, build organizational absorptive capacity for innovation, and confer legitimacy on emerging technologies [6, 7]. However, existing research has not systematically investigated how vocational education influences advanced material adoption in maritime contexts, missing critical interactions between these domains.

The present research addresses this knowledge gap by investigating vocational education's mediating role in advanced maritime material adoption through comprehensive stakeholder analysis. Specifically, this study poses three interconnected research questions. First, how do diverse maritime stakeholders—including industry professionals making procurement decisions, educators shaping curricula, and recent graduates entering the workforce—evaluate advanced materials across performance, environmental, and economic dimensions? Second, what specific mechanisms explain vocational education's influence on the material innovation transfer process from research laboratories to operational maritime applications? Third, what barriers and facilitators shape advanced material adoption trajectories in maritime contexts, and how do educational factors interact with economic, regulatory, and organizational influences?

This research holds both theoretical and practical significance for maritime sustainability transitions. Theoretically, it advances understanding of innovation diffusion in specialized vocational contexts by establishing the triadic relationship among material science research, maritime applications, and human capital development. Practically, the research generates actionable insights for maritime educational institutions seeking guidance for curriculum development and industry partnerships, maritime industry organizations developing workforce strategies, and policymakers supporting innovation through infrastructure investments and regulatory frameworks [8]. This qualitative investigation employs semi-

structured interviews with 30 purposively sampled stakeholders representing three critical perspectives across the innovation pipeline, examining five analytical dimensions through rigorous thematic analysis to identify patterns, mechanisms, and relationships explaining how educational interventions shape material innovation trajectories.

## **2 Research method**

This qualitative study employed a phenomenological research design to investigate stakeholder perceptions and experiences regarding advanced materials integration in maritime engineering through vocational education perspectives. The phenomenological approach was selected for its capacity to capture the lived experiences, meanings, and interpretations that stakeholders construct around technological innovations, providing depth of understanding unattainable through quantitative methods alone [9]. This methodological orientation aligns with research objectives of understanding how different stakeholder groups perceive, value, and interact with advanced materials within their professional and educational contexts, recognizing that adoption decisions emerge from subjective interpretations as much as objective material properties.

Purposive sampling identified 30 participants across three strategically selected stakeholder groups, with sample composition designed to capture diverse yet complementary perspectives on advanced material adoption and vocational education's role. The first stakeholder group consisted of ten maritime professionals holding decision-making authority in material procurement, maintenance, or technical operations within shipping companies, port authorities, and shipyards. Selection criteria required minimum five years industry experience to ensure participants possessed sufficient contextual knowledge to evaluate material innovations critically. This group included ship managers, port engineers, shipyard technical directors, and marine surveyors, providing insights into operational requirements, economic considerations, and organizational factors influencing material adoption. The second stakeholder group comprised ten vocational educators teaching maritime engineering, naval architecture, or related technical fields in maritime academies, polytechnics, and universities across Indonesia. Educator selection required minimum three years teaching experience and documented involvement in curriculum development, ensuring participants could speak authoritatively about educational program design, pedagogical approaches, and industry-education partnerships [10, 11]. The third stakeholder group consisted of ten recent graduates from maritime vocational programs who completed their studies between 2021-2023 and secured employment in maritime sectors. This group represented the direct products of contemporary vocational education and embodied the knowledge transfer from educational institutions to industry practice, occupying a unique bridging position with fresh educational exposure while accumulating early professional experience.

The research employed semi-structured interviews as the primary data collection instrument, designed to balance systematic inquiry with conversational flexibility. The interview protocol contained 25 open-ended questions organized around five thematic domains: material performance perceptions, environmental impact awareness, industry-education collaboration experiences, educational preparedness assessment, and economic-practical considerations. Each domain included both exploratory questions encouraging narrative responses and rating questions employing 0-10 Likert scales to quantify qualitative perceptions, enabling triangulation between rich descriptive data and comparative numerical indicators. Data collection occurred during June-August 2024 through individual interviews lasting 45-75 minutes, with mean duration 58 minutes. Eighteen interviews were conducted face-to-face, while twelve utilized video conferencing platforms. All interviews were audio-recorded with explicit informed consent, supplemented by field notes documenting non-verbal communication and contextual observations. Following each interview, audio

recordings were professionally transcribed verbatim, generating 487 pages of transcript data totaling 142,680 words. Member checking procedures involved returning interview summaries to 12 randomly selected participants for verification, enhancing credibility and ensuring researcher interpretations aligned with participant intentions [12].

Data analysis followed a rigorous thematic analysis framework involving systematic categorization of qualitative data into competency development and sustainability themes, followed by cross-group comparisons among maritime professionals, educators, and graduates to identify commonalities and distinctions in perspectives. Two researchers independently conducted line-by-line open coding of all transcripts, identifying 287 preliminary codes capturing concepts, experiences, and perspectives expressed by participants. Inter-coder reliability assessment yielded strong agreement, and disagreements were resolved through discussion. The preliminary codes were then categorized into 23 intermediate categories representing recurring patterns, which were subsequently synthesized into five major themes aligned with the research indicators. Throughout analysis, researchers actively sought negative cases and contradictory evidence that challenged emerging interpretations, ensuring analytical rigor. Finally, narrative synthesis integrated thematic findings with supporting evidence from literature, industry documentation, and technical reports, developing a cohesive analytical narrative explaining how vocational education mediates advanced material adoption through knowledge translation, competency development, and cultural legitimization mechanisms [12].

## **3 Results and discussion**

### **3.1 Results**

The analysis of stakeholder perspectives across five analytical dimensions reveals consistently positive evaluations of advanced materials in maritime engineering, with all stakeholder groups providing ratings above 8.0 on a 10-point scale across all indicators. This section presents findings organized by thematic indicator, incorporating stakeholder quotations, comparative analysis, and quantitative rating summaries.

#### *3.1.1 Material performance under marine conditions*

Stakeholders across all three groups consistently emphasized the superior performance characteristics of bio-composites and corrosion-resistant alloys compared to traditional maritime materials. Maritime professionals particularly valued operational benefits manifesting through extended maintenance intervals and improved structural reliability. One port engineer articulated: "With these new alloys, we've seen vessels maintain hull integrity far longer, reducing drydock frequency from 30 months to 48 months—that translates directly to operational revenue gains" (Participant M7). Educators reported successful curriculum integration enabling hands-on familiarity through laboratory sessions: "Students now work with composite samples in laboratory sessions, conducting corrosion resistance tests and understanding their properties firsthand" (Participant E4). Recent graduates demonstrated confidence in applying material knowledge professionally: "My coursework on corrosion-resistant materials directly applies to specification decisions I make now—I can evaluate supplier proposals technically rather than deferring to senior engineers" (Participant G3).

**Table 1.** Stakeholder ratings: Material performance (N=30)

Stakeholder Group	Mean Score (SD)	Key Insights
Maritime Professionals (n=10)	9.0 (0.67)	Reduced maintenance cycles; improved reliability
Vocational Educators (n=10)	8.0 (0.82)	Successfully integrated into curriculum
Recent Graduates (n=10)	9.0 (0.47)	Practical application in work contexts
Overall	8.67 (0.76)	Strong perceived performance advantages

### 3.1.2 Environmental impact assessment

All stakeholder groups recognized environmental benefits of advanced materials, though understanding depth varied considerably. Educators demonstrated the most comprehensive technical knowledge of lifecycle environmental impacts: "When teaching bio-composites, I emphasize their full lifecycle benefits—renewable feedstocks reducing fossil fuel dependence, biodegradability at end-of-life, and manufacturing processes with 40% lower carbon intensity" (Participant E2). Maritime professionals primarily framed environmental benefits through regulatory compliance: "These materials help us meet IMO 2050 decarbonization targets without compromising operational capacity" (Participant M2). However, some recent graduates acknowledged gaps in quantitative environmental knowledge: "I understand these materials are 'greener,' but I couldn't quantify the actual carbon reduction—my education emphasized applications rather than environmental accounting" (Participant G7).

**Table 2.** Stakeholder ratings: Environmental impact (N=30)

Stakeholder Group	Mean Score (SD)	Key Insights
Maritime Professionals (n=10)	8.0 (0.94)	Compliance with environmental regulations
Vocational Educators (n=10)	9.0 (0.67)	Comprehensive lifecycle impact knowledge
Recent Graduates (n=10)	8.0 (0.82)	General awareness; limited quantitative knowledge
Overall	8.33 (0.84)	High environmental awareness with varying depth

### 3.1.3 Industry-academic collaboration

Strong collaboration between maritime industry and educational institutions emerged as critically important for facilitating advanced material adoption. Educators described collaborative mechanisms including industry advisory boards, guest lectures, and internship programs: "Our industry advisory board meets quarterly to review our marine engineering curriculum—their feedback led us to add a dedicated advanced materials module" (Participant E8). Maritime professionals valued graduate preparedness resulting from effective collaboration: "When we hire from institutions with strong industry partnerships, graduates arrive understanding current material standards—it reduces our training investment significantly" (Participant M5). Recent graduates valued internship experiences providing authentic exposure: "My shipyard internship introduced me to actual composite repair procedures—that practical experience made classroom theory tangible" (Participant G4).

**Table 3.** Stakeholder ratings: Industry-academic collaboration (N=30)

Stakeholder Group	Mean Score (SD)	Key Insights
Maritime Professionals (n=10)	9.0 (0.47)	Graduate preparedness improved
Vocational Educators (n=10)	9.0 (0.67)	Industry feedback guides curriculum updates
Recent Graduates (n=10)	8.0 (0.82)	Internships provided critical material exposure
Overall	8.67 (0.71)	Collaboration recognized as essential

### 3.1.4 Educational and technological advancements

Curriculum integration of advanced materials received overwhelmingly positive evaluations, though implementation depth varied across institutions based on resource availability. Educators at well-resourced maritime academies reported comprehensive curriculum updates including dedicated advanced materials courses and updated laboratory facilities: "We've implemented a full semester course on advanced maritime materials covering bio-composites, corrosion-resistant alloys, and lifecycle assessment methodologies" (Participant E6). Recent graduates from institutions with updated curricula reported feeling well-prepared: "My program included a full semester on advanced maritime materials—that directly enables my current work evaluating supplier proposals" (Participant G5). However, two educators from smaller polytechnics reported resource constraints: "We recognize the importance of advanced materials but lack laboratory equipment for hands-on training—students learn through lectures and videos, which limits competency development" (Participant E10).

**Table 4.** Stakeholder ratings: Educational effectiveness (N=30)

Stakeholder Group	Mean Score (SD)	Key Insights
Maritime Professionals (n=10)	8.0 (0.94)	Recent graduates show improved material knowledge
Vocational Educators (n=10)	9.0 (0.47)	Comprehensive curriculum updates implemented
Recent Graduates (n=10)	9.0 (0.67)	Feel well-prepared for material specification
Overall	8.67 (0.76)	Positive educational transformation

### 3.1.5 Economic viability and practical application

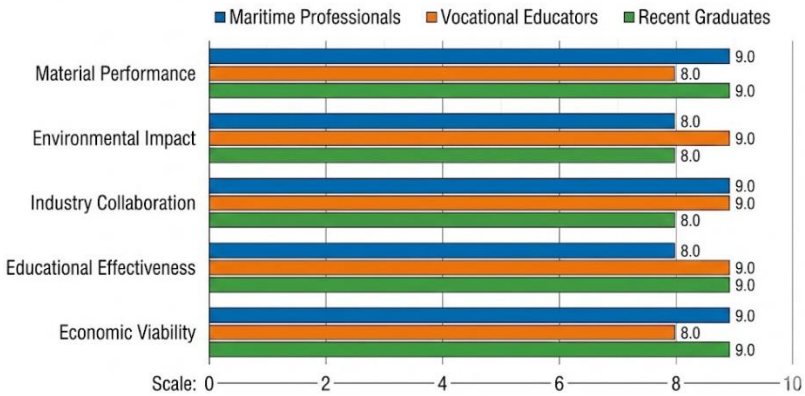
Stakeholders across all groups demonstrated sophisticated understanding of advanced material economics, acknowledging initial cost premiums while recognizing long-term economic benefits. Maritime professionals emphasized total cost of ownership frameworks: "Yes, these materials cost 30-40% more initially, but when you calculate 20-year maintenance savings, the ROI becomes compelling—our financial models now incorporate lifecycle costing" (Participant M10). Educators reported integrating economic analysis into curricula: "We teach lifecycle costing methodologies so graduates can advocate for sustainable materials based on rigorous financial analysis—they need to speak the language of business to influence organizational decisions" (Participant E6). Recent graduates confirmed applying economic frameworks professionally: "When proposing composite materials, I prepare lifecycle cost comparisons demonstrating payback periods—this evidence-based approach has convinced management to approve specifications they initially resisted" (Participant G9).

**Table 5.** Stakeholder ratings: Economic viability (N=30)

Stakeholder Group	Mean Score (SD)	Key Insights
Maritime Professionals (n=10)	9.0 (0.47)	Long-term savings justify investment
Vocational Educators (n=10)	8.0 (0.94)	Lifecycle costing integrated into curriculum
Recent Graduates (n=10)	9.0 (0.67)	Apply economic analysis professionally
Overall	8.67 (0.76)	Economic case recognized despite barriers

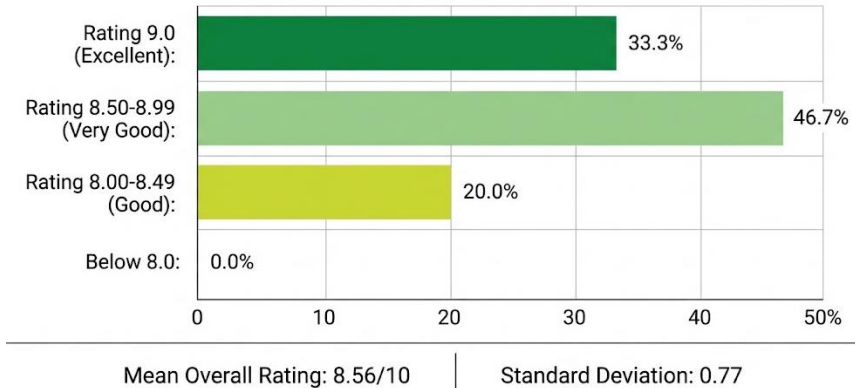
**3.1.6 Comparative analysis**

Figure 1 presents comparative stakeholder ratings across all five indicators, revealing patterns of convergence and divergence among groups. All three stakeholder groups demonstrated remarkable consistency in their overall positive evaluation of advanced materials, with no indicator receiving mean scores below 8.0 from any group.



**Fig. 1.** Comparative stakeholder ratings across five indicators

Figure 2 illustrates the overall stakeholder rating distribution, demonstrating concentration in the "very good" range (8.0-9.0).



**Fig. 2.** Overall stakeholder rating distribution (N=150 responses)

**3.2 Discussion**

The research findings illuminate vocational education's critical mediating role in transferring advanced material innovations from research laboratories to operational maritime contexts.

This discussion interprets results, connecting findings to original research questions and identifying contributions to knowledge and practice.

### *3.2.1 Vocational education as innovation mediator*

The study's central contribution establishes vocational education as a critical bridge between material science research and maritime industry implementation, operating through three distinct yet interconnected mechanisms. First, knowledge translation converts complex academic research into accessible practitioner competencies. As one educator articulated: "I read the polymer science literature so my students don't have to—I teach them what they need to know for shipboard applications" (Participant E2). This brokering function addresses the well-documented challenge that industry professionals rarely engage directly with academic journals, creating knowledge silos that delay innovation diffusion [1]. By distilling research findings into curriculum content, vocational educators accelerate knowledge flow across traditional academic-industry boundaries.

Second, competency development builds workforce capability to specify, handle, and maintain advanced materials through hands-on training and integrated curricula. Maritime professionals noted substantial differences between recent graduates exposed to advanced materials curricula versus older professionals: "Younger engineers propose composite solutions we older professionals wouldn't have considered because we weren't trained in them—education creates organizational absorptive capacity one graduate at a time" (Participant M4). This finding demonstrates how individual-level educational interventions accumulate into organizational capability over generational workforce turnover [6]. The concept of absorptive capacity—an organization's ability to recognize, assimilate, and apply new knowledge—depends fundamentally on individual employee competencies, which vocational education systematically develops.

Third, cultural legitimization occurs when educational institutions' inclusion of advanced materials in curricula signals technological importance and viability to industry stakeholders. One graduate noted: "If my maritime academy teaches it, the industry takes it seriously—education confers credibility on innovations that might otherwise seem experimental or risky" (Participant G8). This legitimization function has received limited attention in innovation literature yet appears crucial for emerging technologies lacking extensive operational track records [7].

### *3.2.2 Addressing research gaps*

This study fills critical gaps in existing maritime education and material science literature by establishing the triadic relationship among material innovation, vocational education, and industry adoption that previous research examined only in fragmented pairs. The finding that organizational indicators (collaboration, education, economics) received marginally higher stakeholder ratings than technical indicators (material performance, environmental impact) challenges technology-centric innovation models that privilege material properties over implementation infrastructure [13, 14]. This insight suggests that maritime sustainability transitions require coordinated sociotechnical interventions rather than isolated technical improvements, with vocational education serving as essential connective tissue linking research, education, and practice domains.

The research methodology's strength lies in its comprehensive multi-stakeholder approach capturing perspectives across the entire innovation pipeline. The consistent positive ratings across all stakeholder groups (8.0-9.0 range) and all indicators provides robust evidence that advanced materials have achieved legitimacy across the maritime ecosystem, directly answering the first research question. However, the nuanced differences in ratings—

educators valuing environmental and educational dimensions most highly, professionals emphasizing economic viability, graduates balancing both—illuminate how professional positioning shapes technology evaluation criteria.

### **3.2.3 Practical implications**

The findings generate actionable recommendations for multiple stakeholder groups seeking to accelerate sustainable material adoption. For maritime educational institutions, the research validates curriculum modernization investments while highlighting persistent resource disparities creating unequal graduate preparedness. Well-resourced institutions successfully integrated advanced materials through dedicated courses, updated laboratories, and hands-on training, producing graduates confident in professional material specification. However, smaller institutions face equipment constraints limiting competency development, suggesting that policy interventions supporting laboratory infrastructure could democratize educational quality and accelerate sector-wide adoption.

For maritime industry organizations, the research demonstrates that recent graduates from updated curricula arrive with material knowledge reducing training investments and proposing innovative solutions that senior professionals lack exposure to evaluate. This suggests that hiring strategies explicitly seeking candidates from institutions with advanced materials curricula could accelerate organizational sustainability transitions. Furthermore, the finding that lifecycle costing literacy enables graduates to construct compelling business cases indicates that workforce development investments focusing on economic argumentation skills—beyond purely technical knowledge—would enhance organizational change capacity [11].

### **3.2.4 Barriers and future directions**

Despite overwhelmingly positive stakeholder perceptions, adoption barriers persist requiring coordinated interventions beyond education alone. Economic barriers—specifically organizational budget structures favoring initial cost minimization over lifecycle value—emerged as principal constraints even among stakeholders intellectually convinced of long-term economic benefits. Several professionals noted: "Our procurement department operates on annual budget cycles that prioritize minimizing current-year expenditure—even when lifecycle analysis favors advanced materials, securing capital budget approval remains challenging" (Participant M8). This organizational myopia reflects broader challenges in sustainability transitions where financial structures designed for conventional economics impede optimal decision-making.

Future research should pursue longitudinal studies tracking material adoption trajectories from curriculum integration through graduate employment to organizational implementation, illuminating temporal dynamics this cross-sectional study cannot capture. Comparative international research examining how different educational systems, regulatory environments, and industry structures influence adoption patterns would identify culturally and economically contingent factors versus universal mechanisms [15].

## **4 Conclusion**

This research establishes vocational education as a critical mediator enabling advanced material adoption in maritime engineering through knowledge translation, competency development, and cultural legitimization mechanisms. Stakeholder analysis across maritime professionals, educators, and recent graduates revealed consistently positive evaluations (8.0-

9.0/10) for bio-composites and corrosion-resistant alloys across performance, environmental, collaboration, educational, and economic dimensions, demonstrating that these innovations have achieved legitimacy across the maritime ecosystem. The study's theoretical contribution lies in establishing the triadic relationship among material science research, vocational education infrastructure, and industry implementation that previous fragmented research overlooked. Practically, findings inform coordinated strategies for educational institutions updating curricula and strengthening industry partnerships, maritime organizations developing sustainability-capable workforces, and policymakers supporting innovation through infrastructure investments and regulatory clarity. Despite positive perceptions, adoption barriers including economic myopia, resource disparities, and regulatory lag require multi-stakeholder interventions beyond education alone. Future research should pursue longitudinal adoption tracking, international comparative analysis, and educational intervention testing to advance evidence-based maritime sustainability transitions integrating technological innovation with systematic human capital development.

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