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Advances and Future Directions in Floating Buoy Technology for Marine Energy and Environmental Applications

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Conflicts of interest

The author declares that there is no conflict of interest.

Abstract. Floating buoy technology has rapidly advanced and is integral to marine science, renewable energy harvesting, and environmental monitoring applications. This study synthesizes recent innovations in buoy designs, energy conversion technologies, and hybrid system integration. Key advancements include modular construction techniques, bio-inspired and hydrodynamic optimizations for improved stability and efficiency, and novel energy-harvesting mechanisms utilizing oscillating buoys, piezoelectric, and triboelectric systems. The integration of floating buoys with hybrid platforms, such as floating breakwaters and offshore wind turbines, demonstrates considerable potential for cost sharing and enhanced performance. Despite substantial progress, critical gaps remain, particularly in long-term operational validation, real-world performance under extreme conditions, scalability, and comprehensive environmental impact assessments. This study identifies these research gaps and outlines future directions to facilitate the widespread adoption of floating buoy technologies. The insights provided are crucial for guiding ongoing innovation, addressing existing limitations, and supporting sustainable blue-economy initiatives.

Keywords: Floating buoy technology, Wave energy conversion, Hybrid marine systems, Environmental monitoring, Renewable energy harvesting

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Передовые разработки и перспективы применения плавучих буев в морской энергетике и экологическом мониторинге

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Заявление о конфликте интересов

Автор заявляет об отсутствии конфликта интересов.

Аннотация. Технология плавучих буев стремительно развивается и становится важным компонентом морских научных исследований, сбора возобновляемой энергии и экологического мониторинга. В этом исследовании обобщены последние инновации в конструкции буев, технологиях преобразования энергии и интеграции гибридных систем. Ключевые достижения включают в себя модульную конструкцию, биоинспекцию и гидродинамическую оптимизацию для повышения стабильности и эффективности, а также новые механизмы сбора энергии, использующие колеблющиеся буи, пьезоэлектрические и трибоэлектрические системы. Интеграция плавучих буев с гибридными платформами, такими как плавучие волнорезы и морские ветряные турбины, демонстрирует значительный потенциал для распределения затрат и повышения производительности. Несмотря на значительный прогресс, остаются нерешенные вопросы, такие как надежность работы в реальных условиях, масштабируемость и комплексная оценка воздействия на окружающую среду. В настоящем исследовании выявлены эти пробелы и намечены будущие направления, способствующие широкому внедрению технологий плавучих буев. Представленные выводы имеют решающее значение для руководства дальнейшими инновациями, устранения существующих ограничений и поддержки инициатив устойчивого развития голубой экономики.

Ключевые слова: технологии плавучих буев, преобразование энергии волн, гибридные морские системы, экологический мониторинг, сбор возобновляемой энергии

Финансирование

Исследование проведено при финансовой поддержке Департамента науки и технологий провинции Ба Риа — Вунг Тау (ныне Департамент науки и технологий города Хошимин), в рамках исследовательского проекта «Оценка и пилотная реализация системы сбора плавающего мусора вдоль прибрежной зоны г. Вунгтау» (2024—2026 гг.).

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Introduction

Floating buoy technology has evolved significantly and has become indispensable in modern marine science, renewable energy solutions, navigation, and environmental monitoring. These floating structures serve diverse roles, including wave energy conversion, oceanographic data collection, weather monitoring, and offshore wind and aquaculture platform support [1–10]. Recent research has focused on optimizing buoy designs to improve stability, enhance energy harvesting efficiency, and enable integration with hybrid systems, such as floating breakwaters and wind turbines [4–8; 11–14].

Technological advances have benefited from innovations in material science, modular construction methods, and enhanced power systems, including piezoelectric and triboelectric harvesters, solar panels, and hybrid energy modules. These developments have enabled buoys to operate autonomously and reliably under harsh marine conditions [10; 15–18]. Moreover, amid the rising global demand for high-resolution oceanographic data and renewable marine energy, environmental sustainability, cost-effectiveness, and scalability have become critical considerations [19–21].

Despite significant progress, the literature highlights persistent gaps in long-term operational reliability, environmental impact assessments, and scalable deployment solutions for diverse marine settings. This review aims to synthesize current advancements in floating buoy technology, identify existing knowledge gaps, and outline future research directions to support the broader adoption of these systems. The ultimate goal is to promote innovation while advancing sustainable practices in the global ocean economy.

1. Methodology

A systematic and comprehensive literature review was conducted using the Semantic Scholar and PubMed databases. The search queries covered foundational concepts, applications, design optimization, interdisciplinary perspectives, and adjacent technologies relevant to floating buoy systems. The review was limited to peer-reviewed journal articles published within the last five years to ensure relevance and currency.

A multi-stage filtering process was employed:

1. The initial search identified approximately 1,046 articles using targeted keywords related to buoy design, wave energy harvesting, environmental impact, and hybrid systems.
2. Articles were first screened based on their titles and abstracts, narrowing the selection to 642 relevant studies.
3. A full-text evaluation further reduced the pool to 597 eligible papers.
4. The 50 most rigorous and high-quality studies were selected based on criteria such as experimental validation, advanced simulation techniques, methodological rigor, and publication in Q1/Q2 journals indexed in the SCOPUS or Web of Science databases.

A flow diagram of the literature identification, screening, eligibility assessment, and inclusion process is shown in Figure 1. This visual representation outlines the structured approach to refining the initial pool of 1,046 studies to the 50 most relevant and high-quality papers selected for this review.

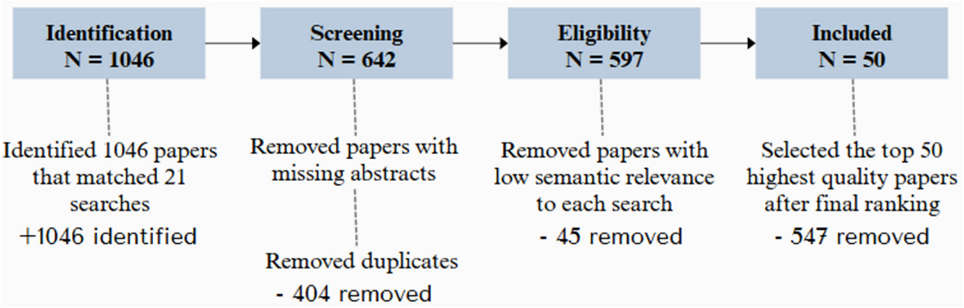

Figure 1. Flow diagram of the literature search and selection process

Source: by N.T. Pham.

The selected papers were categorized into key themes: design principles, energy harvesting technologies, practical applications, environmental concerns, and hybrid-system integration. The extracted data included research methods, key findings, scalability assessments, and identified gaps. A thematic synthesis and comparative analysis were conducted to highlight trends, commonalities, divergences, and research needs in the current state of buoy technology.

A bibliometric analysis complemented this thematic classification to identify the most frequently cited authors and journals in the selected studies. Figure 2 visualizes the key contributors, showing that scholars such as Cheng et al., Zhang et al., and Du et al. are among the most prominent authors. Additionally, journals such as Energy, Applied Energy, and Ocean Engineering appeared most frequently, reflecting the interdisciplinary and energy-focused nature of the field.

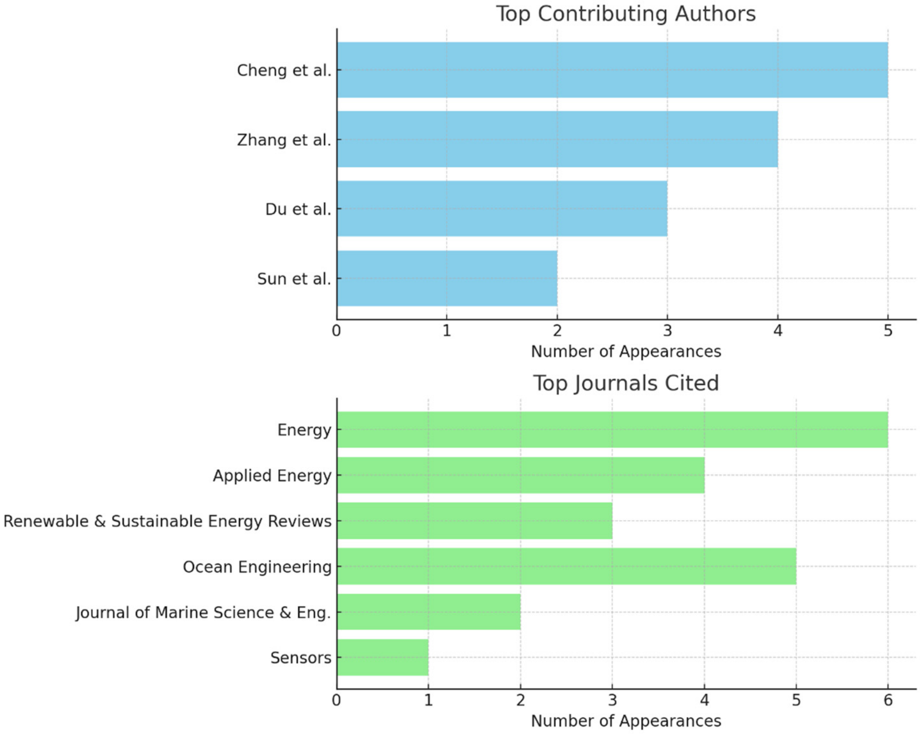

Figure 2. The authors and journals that appeared most frequently in the included papers.

Source: by Ngoc T. Pham.

2. Results

The analysis identified several major themes representing the current trends and innovations in floating buoy technology:

1. *Design principles and structural innovations.* Recent research has highlighted advancements in modular construction, composite materials, and hydrodynamic optimization. Novel buoy shapes, such as teardrop, turbinate, and top-shaped, have significantly reduced drag forces and improved energy capture efficiency [22–26]. Bio-inspired features, such as water lily shaped stabilizers, have contributed to buoy resilience in dynamic ocean environments.

2. *Energy harvesting and conversion technologies.* Wave energy conversion remains a central focus, with oscillating buoy systems and hybrid devices incorporating oscillating water columns showing substantial performance improvements. Innovations include multi-degree-of-freedom harvesters, piezoelectric and triboelectric generators, and dual-mode devices that combine wave and tidal energy [15–18; 27–31]. By integrating floating breakwaters with energy converters, hybrid systems also demonstrate cost efficiency and enhanced coastal protection [4–8].

3. *Applications in oceanography, monitoring, and renewable energy.* Buoys are widely used in ocean monitoring, weather forecasting, navigation support, and integration with offshore wind and aquaculture systems [32–36]. Advances in sensor technologies, wireless communication, and self-sustaining power systems have significantly improved data quality and system longevity [33; 36–37].

4. *Challenges, limitations, and environmental considerations*. These include optimizing energy capture in low-energy seas, maintaining operational stability under extreme conditions, reducing system costs, and addressing environmental impacts [28; 38]. The need for robust mooring, reliable data transmission, and sustainable materials is frequently emphasized [32; 37]. Environmental impact assessments remain limited, particularly for large-scale deployments [19– 21].

The key claims and their corresponding evidence strength are summarized in Table 1 to synthesize insights from the reviewed literature. The table categorizes the level of empirical support, ranging from strong evidence validated by multiple studies to areas where the evidence is weak or emerging.

This structured framework clarifies the maturity of research themes and highlights areas that require further validation.

Table 1. **Summary of key claims and the strength of supporting evidence**

Claim	Evidence Strength	Reasoning	Papers
Hybrid WEC-breakwater systems enhance both energy conversion and wave attenuation	Strong	Multiple experimental and simulation studies showed superior performance over single devices	[1, 3, 10, 12, 22, 23, 25, 30]
Optimized buoy geometry and array configurations significantly improve wave energy capture	Strong	Simulation and laboratory experiments confirmed up to 50% efficiency gains with optimized designs	[2, 17, 21, 39, 49, 50]
Piezoelectric and triboelectric harvesters enable self-powered, autonomous buoy operation	Moderate	Prototypes and field tests demonstrated reliable power for sensors and data transmission	[4, 15, 44]
Modular and eco-friendly buoy designs are feasible and scalable for large deployments	Moderate	Design studies and prototypes demonstrated cost-effectiveness and environmental benefits	[19, 27, 31, 33]
Real-world, long-term performance data for advanced buoy systems is limited	Weak	Most studies are laboratory-based or short-term field trials, and few long-term deployments have been reported	[16, 24, 31, 41, 42]
The environmental impacts of large-scale buoy deployments require further investigation	Weak	Limited research on ecological effects and sustainability at scale	[2, 34, 39, 50]

Source: by Ngoc T. Pham.

3. Discussion

Recent advancements in floating buoy technology have significantly expanded their role in marine energy harvesting, environmental monitoring, and multi-platform hybrid systems. The reviewed literature highlights significant improvements in buoy design optimization, energy harvesting mechanisms, and integration with other marine structures, such as floating breakwaters and offshore wind turbines. These innovations enable buoys to serve as multifunctional platforms for sustainable ocean observation and renewable-energy production.

Despite these achievements, several knowledge gaps remain. Long-term real-world performance data for many advanced buoy systems are limited. Although informative, laboratory and short-term field trials do not fully capture the operational challenges in harsh and dynamic marine environments. Similarly, the environmental sustainability and scalability of buoy deployments require further research. Modular and eco-friendly designs are promising; however, their ecological impacts and long-term viability for widespread implementation remain untested.

Interdisciplinary collaboration is essential to address these gaps. Future research should prioritize large-scale, long-duration field trials and comprehensive assessments of environmental impacts. The development of adaptive mooring solutions and robust communication networks is critical for improving the reliability and resilience of floating buoy systems under extreme conditions.

To illustrate ongoing efforts in advancing buoy-based observation systems, Figure 3 (adapted from Zhang et al. [50]) presents the conceptual design of the Mooring Buoys Observation System for Benthic with Electro-Optical-Mechanical Cable (MBOSBC).

This hybrid system integrates surface buoys and seafloor nodes through an Electro-Optical-Mechanical (EOM) cable, enabling simultaneous data and power transmission. The surface buoy is powered by wind and solar energy. It communicates via satellite, wireless radio, and acoustic links, whereas the benthic node collects environmental data such as temperature, pressure, salinity, and video imagery. The modularity of the system and its ability to coordinate with other underwater platforms (e.g., AUVs and landers) exemplify a next-generation approach to ocean observation. MBOSBC represents a transitional design that bridges traditional buoy networks and fully cabled observatories, offering enhanced monitoring capabilities with greater deployment flexibility. Floating buoy technology can evolve into an integral component of intelligent, sustainable ocean networks by incorporating hybrid observation platforms and novel energy-harvesting devices. Addressing current limitations through long-term trials and environmental studies and integrating multi-sensor, energy-autonomous systems will pave the way for scalable and eco-friendly solutions in the blue economy.

To further illustrate the state of research coverage and gaps, Table 2 presents a matrix that maps key research topics to five critical study attributes: lab-scale prototypes, field trials, long-term deployments, environmental impact, and hybrid integration.

The table shows that although wave energy conversion has received extensive lab-based study, there is a notable deficiency in real-world validations and environmental research, particularly for sustainable design and long-term deployment.

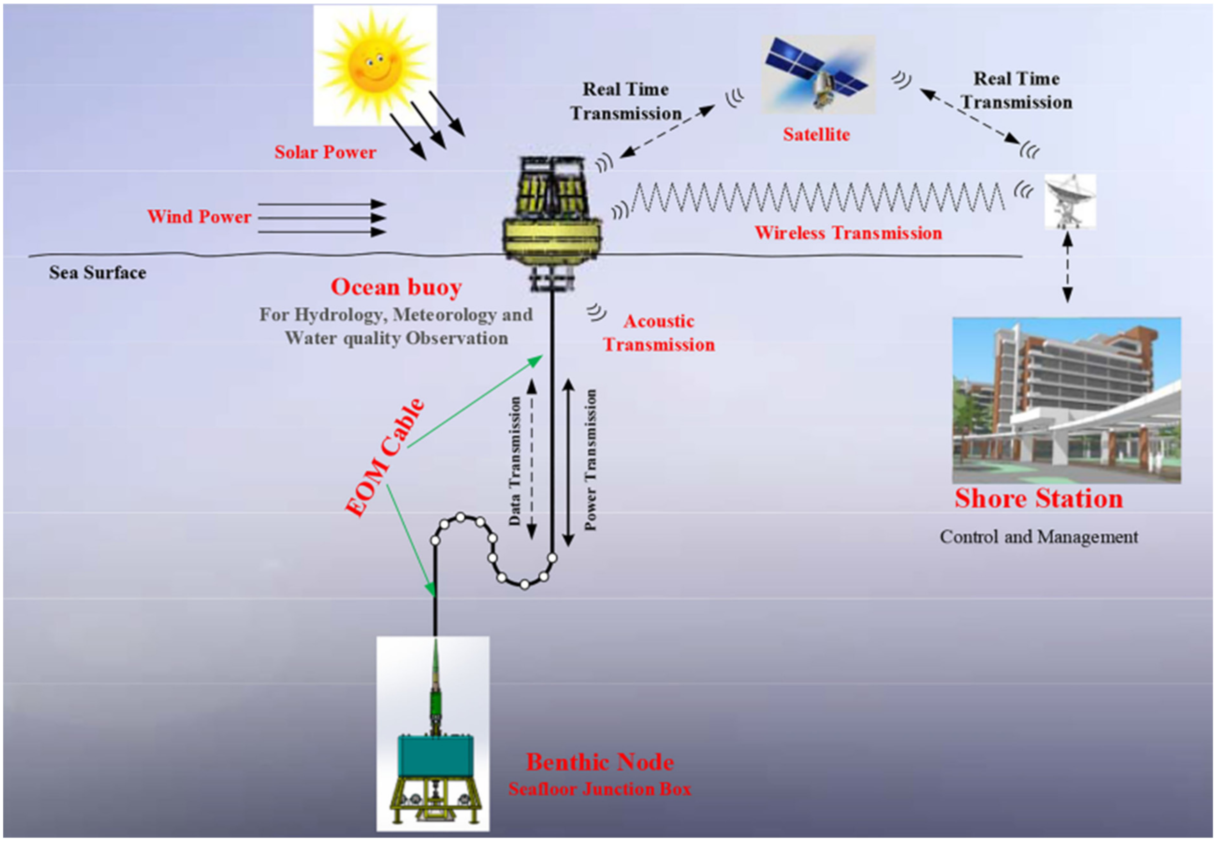

Figure 3. Concept design of mooring buoys observation system

Source: by Ali Azam et al. [50].

Table 2. **Research coverage matrix by topic and study attribute**

Topic / Attribute	Lab-scale Prototypes	Field Trials	Long-term Deployment	Environmental Impact	Hybrid Systems
Wave Energy Conversion	18	7	3	2	10
Oceanographic Monitoring	8	6	2	3	1
Offshore Wind / Aquaculture	4	2	1	1	2
Power / Data Transmission	5	2	1	1	GAP
Environmental Sustainability	3	1	GAP	2	GAP

Source: by Ngoc T. Pham.

Conclusions

This study reviewed the key innovations, challenges, and future directions in floating buoy technology. Based on this analysis, the following conclusions can be drawn:

1. Floating buoy technology has significantly improved, particularly in marine application design optimization, material engineering, and hybrid system integration.
2. Modular construction, bio-inspired hydrodynamics, and smart sensor integration have improved performance, enabling buoys to operate autonomously under harsh marine conditions.
3. Hybrid systems combining buoys with breakwaters or wind turbines demonstrate strong potential for cost efficiency and energy yield but require further real-world validation.
4. Major challenges remain in the long-term deployment of data, operational reliability under extreme sea states, and insufficient environmental impact assessments.
5. Future research should prioritize scalable designs, interdisciplinary collaboration, and comprehensive ecological assessments to enhance the role of buoys in a sustainable blue economy.

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