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REVIEW

Recent Progress in Underwater Tactile Sensing Based on Triboelectric Nanogenerator

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ABSTRACT

The rapid advancement of underwater vehicles and the Internet of Underwater Things (IoUT) necessitates core sensing components capable of withstanding high-pressure, low-visibility, and high-humidity environments. Although tactile perception mechanisms present a promising alternative to traditional underwater sensing, existing reviews lack a systematic analysis of the interdisciplinary integration of triboelectric nanogenerators (TENGs). This review addresses this gap by providing a comprehensive analysis of the latest developments in TENG-based underwater tactile sensors, with a focus on their self-powered operation, material versatility, and bio-inspired design innovations. Our survey encompasses triboelectric principles, waterproofing strategies, bionic structures, material properties, and signal processing. Notably, we emphasize the transformative potential of TENGs in achieving zero-power-consumption and high-sensitivity sensing—key to overcoming challenges in long-term energy autonomy and adaptability to extreme marine conditions. The application potential in underwater mobile equipment, wearable devices, and monitoring networks is elucidated, alongside a discussion of technical challenges and future trends. This work ultimately establishes a foundational framework for next-generation underwater perception systems by advocating for the synergy of TENG technology with artificial intelligence and sustainable material science.

1 | Introduction

The rapid advancement of the Internet of Underwater Things (IoUT) and underwater vehicle technologies has driven significant growth in underwater resource exploration and exploitation activities [1–5]. As the primary modalities for underwater sensing, acoustic and optical sensors, although widely deployed across various underwater vehicles, face fundamental limitations in complex marine environments: water turbidity, impurities, and optical scattering effects can degrade their performance by more than 60% [6–8]. Furthermore, these technologies suffer from three critical shortcomings—dependence on external energy sources, structural redundancy, and high energy consumption—which severely constrain long-term monitoring capabilities [9, 10]. Consequently, there is an urgent need to develop new self-powered, easily integrated underwater sensing technologies to overcome the high-precision perception bottleneck for targets and environmental states in underwater vehicles [11–15].

Tactile perception technology acquires target information through physical contact and has evolved from basic contact detection to multimodal information analysis encompassing

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morphology, texture, and rigidity [16–19]. Although this technology is well-established in terrestrial applications, its development in complex underwater environments has progressed relatively slowly [19–21]. In recent years, triboelectric nanogenerator (TENG) technology has emerged as a transformative solution through its unique in situ mechanical-to-electrical energy conversion mechanism [22–26]. TENG-based underwater tactile sensors offer millisecond-level response times, micronewton force resolution, and zero-power consumption operation, while their compatibility with eco-friendly materials significantly reduces disturbance risks to marine ecosystems [27–29]. These sensors efficiently convert subtle mechanical stimuli into electrical signals, effectively bridging the capability gap in close-range, high-precision detection scenarios where traditional acoustic and optical sensing methods fall short [30–33].

To precisely delineate the scope of this review, we adopt a functional, broad definition of tactile sensing: the process by which a system detects, transduces, and extracts information from mechanical stimuli originating from either the external environment or the carrier itself. This encompasses not only traditional "exteroception"—perceiving object attributes like morphology, hardness, and texture through direct physical contact—but also extends to monitoring the carrier's internal mechanical state changes, termed "interoception" or somatosensory simulation. For instance, strain from joint movement or pulse waves from blood flow are inherently mechanical signals that can be captured via the triboelectric effect. The underlying mechanism of TENG, which directly convert various forms of mechanical energy (pressure, vibration, stretch) into electrical signals, provides an ideal platform for unifying these diverse perceptual capabilities. Consequently, the "underwater tactile sensing" discussed herein constitutes a comprehensive system. Its core lies in leveraging TENG technology to empower underwater agents—from robots to wearable devices—with holistic mechanical perception of both their external interactive environment and their internal dynamics [34–37].

Currently, the integration of TENG and tactile perception primarily serves three core domains: underwater robotics, underwater wearable devices, and underwater monitoring networks, as illustrated in Figure 1. Specifically, underwater vehicles such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) leverage this technology for pipeline inspection, underwater object grasping and identification, wake perception, vehicle trajectory prediction, and attitude estimation [38–42]. The wearable technology domain supports emergency rescue operations, motion monitoring, visuo-tactile fusion, marine organism behavior tracking, health monitoring, and underwater interaction [43, 44]. Monitoring networks encompass underwater environmental surveillance, array-based sensing, structural health monitoring, and flow velocity measurement [45, 46]. Through diverse materials and operational mechanisms, this technology delivers innovative solutions with exceptional underwater adaptability and reliability, substantially advancing marine IoT development and providing critical technical support for complex underwater exploration missions.

A fundamental limitation in this field stems from a fragmented research paradigm, where literature prioritizes isolated technological advances over a holistic integration of material innovation, bio-inspired design, signal processing, and application challenges. This compartmentalized view hinders the maturation of underwater tactile sensing as a unified discipline. To bridge this gap, this review constructs a hierarchical framework tracing the path from fundamental principles (triboelectric mechanisms, materials, waterproofing) to practical applications (mobile/ wearable/wearable monitoring systems) and future outlook. Its unique contribution lies in pioneering a unified cross-analysis of TENG electromechanical transduction, bio-inspired morphology, and AI-driven data processing, critically evaluating their disruptive potential for achieving millisecond-level and micronewton-level sensing. We posit that synergistic multi-parameter optimization—not isolated progress—is fundamental to overcoming the critical bottlenecks of energy dependency and environmental fragility in conventional sensing. Consequently, this work provides a strategic roadmap to guide future research, aiming to fundamentally reshape underwater perception systems and thereby advance strategic priorities, including deep-sea exploration and the IoUT.

2 | Design Strategies for Underwater Tactile Sensors

Underwater tactile sensing technology, as a fundamental component of intelligent marine systems, leverages the triboelectric effect to achieve self-powered and highly sensitive signal output. Its advancement involves multiple critical facets, including bio-inspired structural design, waterproofing strategies, core material optimization, and advanced signal processing techniques. By drawing inspiration from natural sensory mechanisms, these sensors realize miniaturization and multifunctionality; robust waterproofing ensures signal stability; flexible, self-healing, biodegradable, and high-pressure-resistant materials improve device durability and environmental compatibility; meanwhile, deep learning methods enable sophisticated multimodal intelligent recognition. The following sections systematically review recent advances in these five key domains of underwater tactile sensing, establishing a solid foundation for future research. This review begins by elucidating the fundamental triboelectric principles governing energy conversion, then progresses to the essential waterproofing strategies required for underwater deployment. Building upon this foundation, it explores how bio-inspired architectures and advanced material properties enhance sensor functionality, followed by signal processing techniques for interpreting complex data. Finally, it examines the fabrication processes that integrate these elements into functional devices, thereby constructing a cohesive pipeline from fundamental mechanisms to practical implementation.

2.1 | Triboelectric Principles

The explosive proliferation of triboelectric applications across diverse scenarios is directly attributable to profound investigations into their underlying physical mechanisms, with sustained investment in fundamental research yielding critical breakthroughs that require systematic elucidation. Pioneered by Professor Zhong Lin Wang's team in 2012, the TENG fundamentally leverages the synergistic interplay of contact electrification (CE)

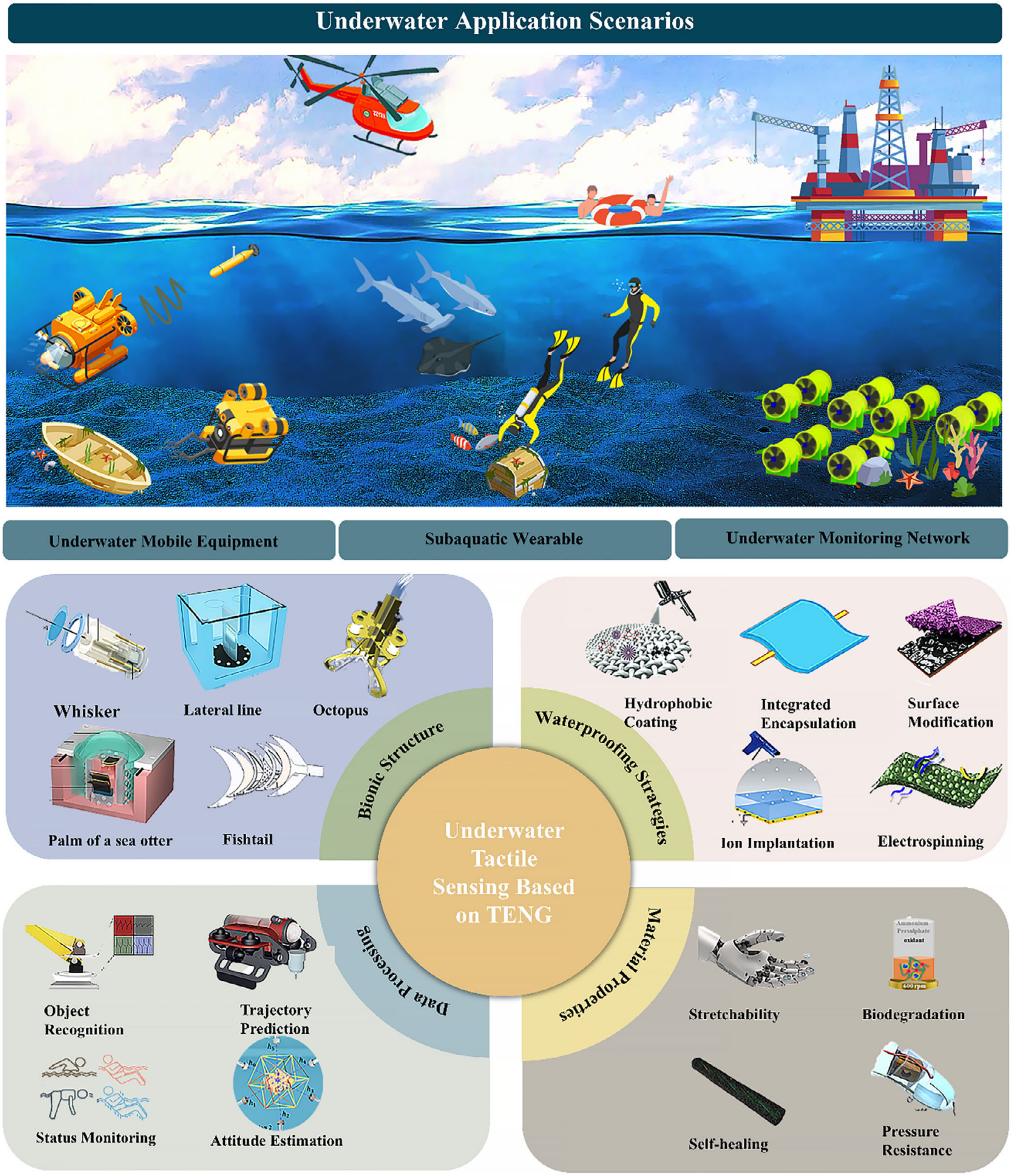

FIGURE 1 | Research progress and application scenarios of TENG-based underwater tactile sensors. Reproduced with permission [47–53]. Copyright 2022–2025, Elsevier. Reproduced with permission [54]. Copyright 2023, Springer Nature. Reproduced with permission [55]. Copyright 2025, Elsevier. Reproduced with permission [56]. Copyright 2022, Springer Nature. Reproduced with permission [57]. Copyright 2024, Elsevier. Reproduced with permission [58]. Copyright 2024, John Wiley and Sons. Reproduced with permission [59]. Copyright 2022, Springer Nature. Reproduced with permission [60, 61]. Copyright 2019–2020, John Wiley and Sons. Reproduced with permission [62]. Copyright 2021, Royal Society of Chemistry. Reproduced with permission [63]. Copyright 2022, American Chemical Society. Reproduced with permission. [64]. Copyright 2024, John Wiley and Sons.

and electrostatic induction, uniquely enabling the conversion of irregular, low-frequency, and spatially distributed mechanical energy into electricity [65]. Contact electrification, an ancient and ubiquitous natural phenomenon (e.g., static generation in clothing, hair standing during combing), at its microscopic essence, involves charge transfer across contacting interfaces [66]. From an atomic perspective, as illustrated in Figure 2a, when external forces like friction bring two materials into physical contact and compress them to interatomic distances below the equilibrium bond length, strong overlap of their electron clouds significantly lowers the potential barrier between atoms, facilitating electron transfer predominantly via tunneling mechanisms—a process widely recognized as the dominant driver of the triboelectric effect (TE) in solids, liquids, and gases [67]. Following separation, a net charge resides on the material surfaces, establishing an interfacial electrostatic charge layer which ultimately dissipates through pathways like thermionic emission or photonic excitation. This atomic-scale charge transfer model provides a universal framework, illustrating initial attraction at larger distances, potential bond formation upon contact, asymmetric double-well potential development enabling electron tunneling under compression, and net charge trapping post-separation. For triboelectrification at solid–liquid interfaces, the formation of the electric double layer (EDL) constitutes the core mechanism, governed by a two-step process: initial atomic-scale electron migration leading to ionization and charge transfer primarily via electron exchange at the solid surface, followed by ion adsorption-driven charge redistribution; electron exchange and ion adsorption coexist spatially and temporally, jointly defining the ultimate EDL charge distribution. The difference in surface work functions between materials critically dictates the direction and magnitude of contact electrification, as materials possessing higher work functions tend to accept electrons from those with lower work functions, resulting in the former becoming negatively charged and the latter positively charged; friction primarily amplifies charge transfer by increasing contact area and enhancing interfacial intimacy. Upon separation of contacted materials, the resulting gap functions as a capacitive structure where the separated charges generate a potential difference; connecting an external load induces electrostatic induction, driving electron flow in the external circuit to neutralize this potential. Each complete contact-separation cycle thus constitutes a mechanical-to-electrical energy conversion cycle. Crucially, while CE is universal, its quantification and standardization are paramount for triboelectric technology advancement [68]. Consequently, standardized methodologies for Triboelectric Charge Density (TECD) characterization were established, as illustrated in Figure 2b, providing universal quantification of contact-induced surface charge behavior under defined conditions; based on TECD, the intrinsic electron-gain/loss tendencies of materials like polymers were revealed, enabling the construction of a quantitative triboelectric series encompassing over 50 diverse substances.

TENGs operate in four principal modes differentiated by their mechanical triggers and structural designs, as illustrated in Figure 2c. The first, vertical contact-separation mode (CS), the most prevalent, harnesses energy through periodic modulation of vertical polarization: contact under normal force generates equal and opposite interfacial charges on tribo-layers with differing permittivity/work functions, and subsequent separation disrupts electrostatic equilibrium, driving directional free charge flow in the external circuit to generate electrical output [69, 70]. The second, lateral sliding mode (LS), utilizes relative lateral displacement of dielectric layers to induce a dynamic polarization gradient: initial contact electrification establishes spatially matched opposing charge pairs on the interfaces, and applied lateral force induces relative sliding, causing charge distribution misalignment and asymmetry that establishes a lateral polarization field; this drives directional free charge migration in the external circuit, generating continuous alternating current [71]. The third, single-electrode mode (SE), exploits contact-free relative motion between a freely moving object and a fixed dielectric, innovatively utilizing the surrounding environment or earth for capacitive coupling to complete the electrical loop: contact electrification generates bound charges on the dielectric surface, separation creates spatial charge imbalance and a potential gradient, driving environmental free electrons through ground to the primary electrode to restore balance; this mode, offering simple design and multi-dimensional motion compatibility, suffers from reduced charge transfer efficiency compared to CS and LS modes due to electrostatic screening by the surrounding medium, particularly underwater [72]. The fourth, free-standing triboelectric-layer mode (FT), an evolutionary innovation addressing SE limitations, employs a contact-free suspended tribo-layer (free-standing layer) isolated by an air/vacuum gap to circumvent electrostatic screening: initial vertical contact-separation generates charges, and subsequent parallel movement of the free-standing layer dynamically redistributes these charges; the resulting dynamic potential difference drives highly efficient energy transfer via external terminals connected to a fixed dual-electrode pair operating in a closed loop, with studies demonstrating performance potentially exceeding the CS mode by up to 300% [73]. Critically, these modes are non-exclusive and can be flexibly selected, adapted, or combined based on the constraints of mechanical degrees of freedom (e.g., vertical, sliding, rotational) and specific application requirements within a given scenario; for instance, CS and LS modes have been successfully integrated for shear force detection, while exploration beyond single-mode reliance often catalyzes innovative synergistic designs [74].

To systematically assess the application potential of different technological pathways in underwater tactile perception, Table 1 presents a comparison of five mainstream sensing principles based on their core mechanisms, performance merits/demerits, key data, and application scenarios. This comparison reveals the core competitiveness and application boundaries of each technological route, providing a clear basis for technology selection tailored to specific applications. Triboelectric sensing technology demonstrates significant potential as a core technology for next-generation, long-duration, autonomous underwater perception systems, primarily due to its disruptive "fully self-powered" characteristic. Its core mechanism operates without external power sources, directly harvesting energy from environmental flows or mechanical contact, thereby offering a promising solution to the energy bottleneck challenge for traditional sensors in long-term underwater deployments. In terms of performance, triboelectric technology also excels. Its millisecond-level (19 ms) response time and 100% vortex recognition accuracy make it highly competitive for dynamic flow field perception. In contrast, while piezoelectric technology is also self-powered, its brittle materials (e.g., PZT) are difficult to adapt to flexible deformations, limiting its application

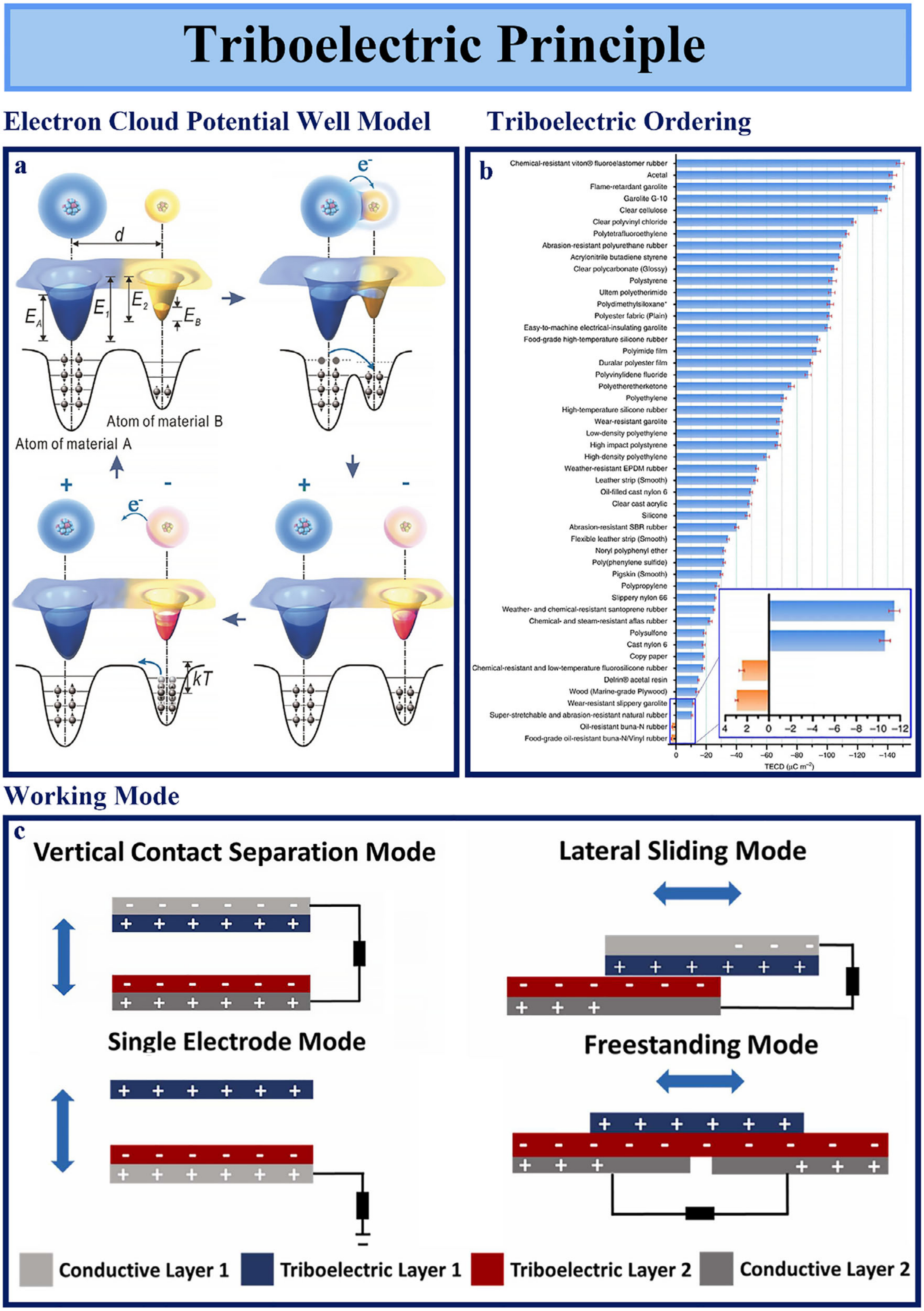

FIGURE 2 | Triboelectric principle. (a) The electron cloud model. Reproduced with permission [67]. Copyright 2018, John Wiley and Sons. (b) The quantified triboelectric series. Reproduced with permission [75]. Copyright 2019, Springer Nature. (c) Operation modes of TENG. Reproduced with permission [76]. Copyright 2025, Elsevier.

TABLE 1 | Comparative analysis of working principles for underwater tactile sensors.

Working principle	Core mechanism	Advantages	Disadvantages	Key performance metrics	Application scenarios	Refs.
Triboelectric	Contact-separation electrification coupled with electrostatic induction	Self-powered operation; High sensitivity and fast response; Excellent material flexibility	Signal attenuation in high humidity; Long-term stability requires improvement	Response time: 19 ms; Vortex recognition accuracy: 100%; Pressure gradient sensitivity: 2.1 $mV \cdot Pa^{-1} \cdot m^{-1}$	Underwater target grasping; Flow and vortex monitoring; AUV/ROV integration	[77]
Piezoelectric	Charge generation in piezoelectric materials under stress	High sensitivity; Self-power capability; High conversion efficiency	Limited strain tolerance of brittle materials; Temperature sensitivity	Flow velocity threshold: 3.4 mm/s; Array sensitivity gain: ~12 dB	Underwater acoustic detection; Vector hydrophones; Vortex detection	[78]
Piezoresistive	Resistance variation with strain in materials	Simple structure and low cost; Direct signal processing	Requires external power source; Temperature sensitivity requires compensation	Flow detection lower limit: 0.5 mm/s; Linearity: $R^2 > 0.99$	Large-scale sensor arrays; Static pressure detection	[79]
Capacitive	Capacitance variation detection between electrodes	Good linear response; Flexible structural design	External power dependent; Sensitive to environmental interference	High-sensitivity detection achievable with hydrogel-based sensors	Underwater smart skins; Soft robot tactile perception	[80]
Magneto-sensitive	Magnetic field variation detection	High measurement accuracy; Strong anti-interference capability	Affected by external magnetic fields; Relatively complex system structure	Flow velocity accuracy: <0.061 m/s; Direction error: <7°	High-precision flow measurement; 3D flow field perception	[81]

in soft robotics. Piezoresistive and capacitive technologies require an external power supply, which increases system complexity and deployment costs. Although magneto-sensitive technology offers high accuracy, it is susceptible to external magnetic field interference and has a relatively complex system structure. In summary, for application scenarios such as underwater robots and long-term environmental monitoring, which place extremely high demands on energy autonomy, environmental adaptability, and flexible integration, the triboelectric principle currently represents the most comprehensively advantageous technological pathway. Future research will focus on enhancing its long-term stability in high-humidity and high-pressure environments and integrating it with artificial intelligence algorithms to further unlock its potential in the field of intelligent underwater perception.

While the triboelectric principle provides a versatile mechanism for mechanical energy harvesting, the practical implementation of TENGs in aqueous environments introduces a critical challenge: the rapid dissipation of electrostatic charges due to water ingress and ion screening. Addressing this challenge necessitates the development of robust waterproofing strategies, which are discussed in the following section.

2.2 | Waterproofing Strategies

The fundamental challenge impeding the effective deployment of TENG technology in aqueous environments is rapid charge dissipation [82–84]. This phenomenon originates intrinsically from the coupled electrostatic processes of interfacial charge transfer during contact-separation cycles of dielectric materials and subsequent electrostatic induction. At the microscopic scale, the underlying mechanism involves directional ion migration across material interfaces: disparities in the migratory propensity of cations and anions when mobile ions are present at contacting surfaces lead to net charge separation. In aquatic settings, the formation of an H_3O^+/OH^- electric double layer (EDL) at solid–liquid interfaces induces inherently asymmetric charge distributions. Humidity critically modulates charge dynamics: relative humidity (RH) below 40% promotes surface charge accumulation, whereas RH exceeding 80% triggers a synergistic triple-mechanism attenuation process. Without effective waterproofing, aqueous-induced charge interference can degrade sensor signal-to-noise ratios by over 15 dB, often culminating in functional failure [85–88]. Consequently, developing reliable waterproofing strategies to mitigate humidity effects is paramount for ensuring long-term operational stability. Prevalent waterproofing methodologies encompass full encapsulation, material surface modification, and applied waterproof coatings.

Full encapsulation, leveraging its procedural simplicity, cost-effectiveness, and substantial barrier capability, represents a widely adopted strategy for underwater TENG sensors. Hydrophobic polymers such as PDMS, PET, or Ecoflex are commonly employed encapsulants [89]. Initial efforts on structurally simple sensors with minimal deformation requirements utilized vacuum lamination techniques to seal PET sheet edges, effectively isolating internal components; the lightweight nature of PET avoided significant mass penalties [90]. However, the complete elimination of entrapped air during sealing proved difficult. Investigations into this impact revealed that deliberately introducing a controlled air gap—exemplified by encapsulating electrodes within PDMS while maintaining a fixed 2 mm spacing between tribolayers—reduced performance degradation to below 10% following a 12-h immersion, exploiting the air as a buffer [91]. To overcome limitations inherent to single materials, composite encapsulation incorporating micro-/nanostructured reinforcements emerged. For instance, utilizing sponge-like PMMA featuring a bionic bird nest nanopartitioned structure implemented a dual waterproofing mechanism: the inherent high hydrophobicity (static water contact angle ∼148°) and microstructure of PMMA repelled bulk water, while the dense encapsulation layer impeded moisture permeation, shielding copper electrodes from corrosive electrolyte oxidation [92]. Parallel efforts focus on enhancing intrinsic hydrophobicity, as illustrated in Figure 3a,employing EVA film for external encapsulation sealed at the edges with high-performance synthetic sealants, combined with sandpaper-textured rubber tribolayers to augment surface texture and electrodes crafted from intrinsically conductive blends of silver fiber and lyocell fiber (eliminating hydrophilic coating failure risks), successfully mitigating interfacial charge neutralization caused by water adsorption [60]. Nevertheless, full encapsulation often exhibits limited applicability for sensors featuring highly intricate architectures or stringent mechanical deformation requirements.

For applications requiring intricate morphology conformance, spray-applied waterproof coatings, despite involving more complex processes and potentially higher costs than encapsulation, offer superior shape adaptability and precise film-forming capability [93]. Enhancing hydrophobicity through engineered microscale roughness involves techniques such as spraying Ecoflex substrates with SiO_2 particles of varying diameters, forming a micro-nano composite structure upon curing; optimal results, including static contact angles >150°, water droplet shedding at 15° tilt angles, and a fourfold increase in underwater signal fidelity, were achieved using 30-µm particles, leveraging elastomeric-rigid synergy for mechanical durability. Altering the substrate material, such as spraying FAS-modified silica onto flexible PET to form dendritic micro/nano networks (∼5 µm thick), similarly enhanced waterproofing [74]. Further optimization is achieved by compositing PDMS with silica, MWCNTs, and surfactants, exploiting multiscale roughness and ultra-low surface energy to yield static contact angles up to 164%; such coatings maintained superhydrophobicity after 12,000 abrasion cycles, ensuring droplet roll-off at 6°–9° tilt and preventing performance loss from droplet accumulation [94]. A notable three-step coating methodology employs a polyester substrate, as illustrated in Figure 3c, where uniform coating with a CNT/TPE composite (1:1 mass ratio in cyclohexane) followed by ethanol etching creates a bioinspired lotus-like micro/nano structure, achieving a 151.7° contact angle, capitalizing on TPE's inherent hydrophobicity and CNT-induced roughness for cost-effective scalability [61].

Surface modification techniques, advantageously minimizing impact on device flexibility by altering the substrate directly rather than adding layers, primarily enhance hydrophobicity via hierarchical micro/nano structuring and low surface energy chemical treatment, though their high hydrostatic pressure resistance may be limited [95]. Hierarchical structuring

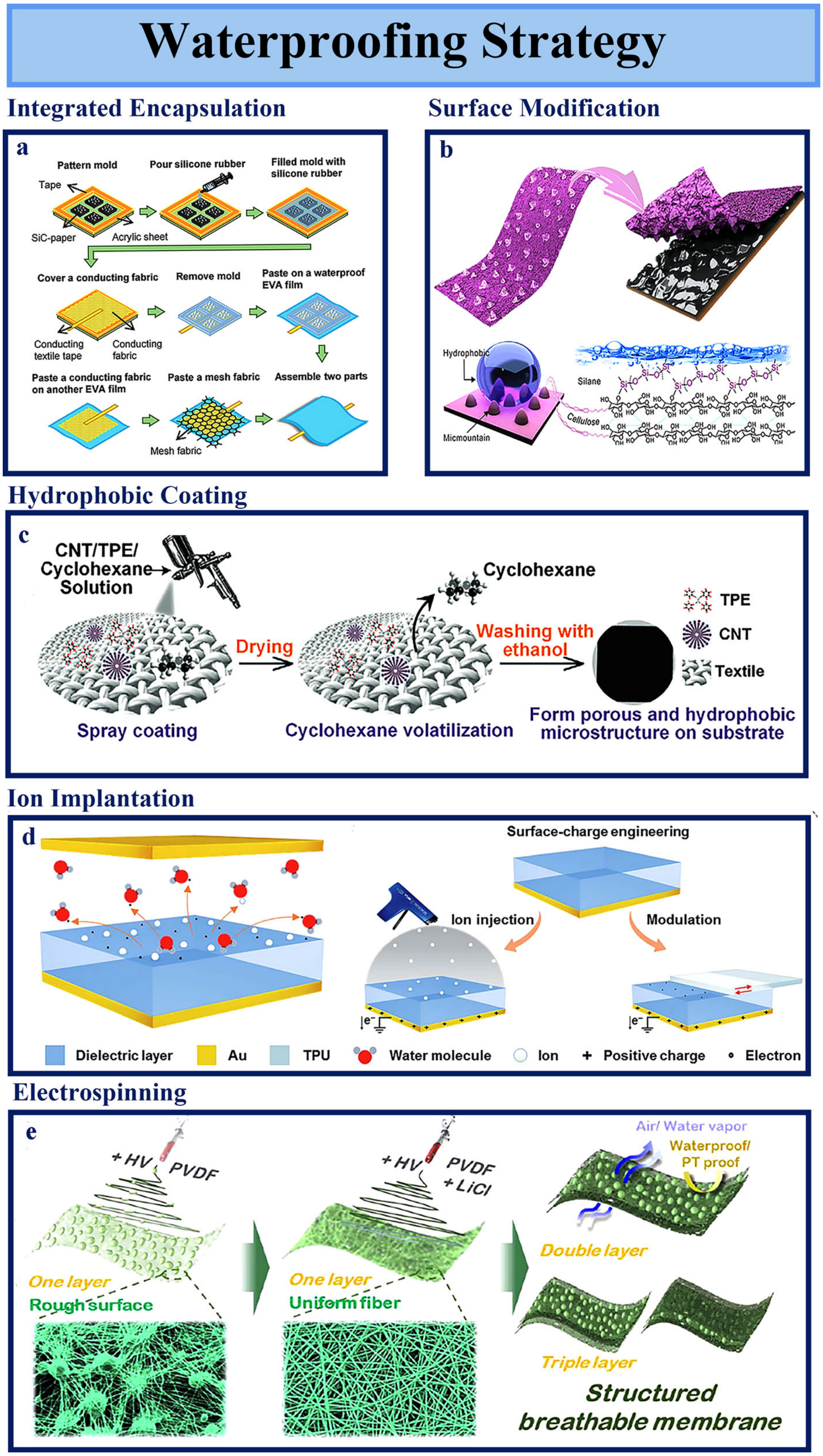

FIGURE 3 | Waterproofing Strategies. (a) Fabrication process of an integrated waterproof packaging. Reproduced with permission [60]. Copyright 2019, John Wiley and Sons. (b) A microcavity array sensor, a hydrophobic micromountain surface, and the methylsilane paper chemical structure. Reproduced with permission [47]. Copyright 2023, Elsevier. (c) Manufacturing process of superhydrophobic textiles. Reproduced with permission [61]. Copyright 2020, John Wiley and Sons. (d) Humidity-induced surface charge dissipation and controlled negative charge patterning through surface charging engineering on dielectric substrates. Reproduced with permission [62]. Copyright 2021, Royal Society of Chemistry. (e) Design strategy for electrospun membranes featuring structural layers with controllable particles and nanofibers. Reproduced with permission [63]. Copyright 2022, American Chemical Society.

involves fabricating features like 3D micropillar arrays on intrinsically hydrophobic materials (PDMS, silicone) and bioinspired approaches such as replicating lotus leaf topography using combined micropillar arrays with nanogrooves, often fabricated via lithographic micromolding or direct etching [96]. Chemical modification focuses on molecular-level hydrophobization, exemplified by perfluorosilane functionalization of boron nitride nanosheets (introducing -CF_3/-CF_2 groups with ultra-low surface energy), subsequently dispersed into a PVDF matrix to yield m-BN/PVT composites (contact angle ~156°). The resultant m-BN/TENG exhibited exceptional waterproofing and chemical resistance, showing <6% performance degradation after immersion in pH 1–14 solutions and negligible change after 20 000 mechanical cycles [97]. Composite modification strategies combine structural and chemical approaches, as illustrated in Figure 3b, where mechanical sanding creates “micro-mountain” array roughness, while acidic hydrolysis of methyltrimethoxysilane facilitates grafting of hydrophobic methyl (-CH_3) groups onto cellulose hydroxyl groups via heterogeneous condensation, imparting superhydrophobicity and robust electrical stability under high humidity [47].

Beyond these mainstream approaches, emerging techniques include ion implantation, electrospinning, and composite strategies. As illustrated in Figure 3d, Ion implantation relies on corona discharge to embed stable charges via covalent bonding with surface atoms, significantly reducing charge dissipation. Sequential negative ion implantation cycles on dielectrics (e.g., PTFE) build durable charge layers, retaining 91% initial performance after 50 000 cycles and achieving superior charge density under humid conditions [62]. As illustrated in Figure 3e, electrospinning exploits the shape-conformability of micro/nanoscale fibrous mats (e.g., PVDF); engineered morphologies like “microbead-nanofiber” sandwich architectures (SB/SF/SB) leverage inherent polymer hydrophobicity, surface roughness, and capillarity to achieve contact angles of 151° and water pressure resistance up to 62.3 kPa [63]. Composite waterproofing integrates methods like sequential layer-by-layer (LbL) electrostatic deposition of PAH/PAA layers on a substrate, acidic treatment to induce multiscale porosity, and subsequent fluorination to achieve a 148° contact angle; the fluorinated layer critically blocks conductive water pathways, suppressing charge dissipation rates to one-fifth of untreated surfaces [98].

The comparative performance of these waterproofing strategies is summarized in Table 2. Material modifications, including layer-by-layer assembly and magnetic-field-induced microstructures, offer high hydrophobicity and good mechanical durability with moderate processing complexity and low cost, although some are sensitive to organic solvents or temporary chemical exposure. Spray-applied coatings provide excellent adaptability to complex morphologies and maintain superhydrophobicity under repeated mechanical stress, albeit with higher process requirements. Full encapsulation ensures effective barrier protection and simple implementation but is less suitable for intricate geometries or high-deformation applications. Ion implantation and composite surface modifications present robust long-term performance in humid conditions, yet their applicable pressure ranges are limited. Collectively, these data underscore the necessity of selecting waterproofing techniques based on a balance among hydrophobic performance, durability, mechanical compatibility, process feasibility, and cost for optimal underwater TENG operation. With the integrity of the sensing interface secured against the aquatic environment, the next frontier in enhancing sensor performance lies in the strategic design of their physical form. Drawing inspiration from nature, bio-inspired architectures offer sophisticated blueprints for optimizing sensitivity, adaptability, and multifunctionality, as explored in the next section.

2.3 | Bio-Inspired Architectures

In sensor design, morphological configuration is paramount. Ingenious external form design can significantly achieve miniaturization while enabling diversified functional expansion. The geometric structure of sensors and their mechanisms for detecting external physical signals are not conceived arbitrarily; the enigmatic natural world provides an exceptionally rich source of inspiration [102–105]. Researchers have extensively explored the sensory modalities of various organisms, mimicking their morphologies and sensing strategies. The convergence of sensor design and bionics has catalyzed numerous innovative research concepts, pioneering novel design paradigms for sensors. For sensors deployed in underwater applications, design inspiration is frequently drawn from aquatic or amphibious organisms. Current predominant research directions encompass biomimetic designs based on fish, seals, otters, and octopuses.

Among aquatic fauna, fish are the most familiar. Biomimetic design based on fish primarily manifests in two categories: one centers on their sensory organ—the lateral line system. The perception mechanisms and structural morphology of the lateral line offer valuable insights for sensor development [106]. Taking the Mexican tetra (Astyanax mexicanus) as an example, inhabiting lightless cave environments renders vision functionally negligible in daily life, making the lateral line crucial for prey capture and predator avoidance [107]. The lateral line comprises two types of neuromasts: superficial neuromasts and canal neuromasts. When the external flow field alters, displacement of the neuromasts occurs, enabling the acquisition of flow field data. This unique mechanism offers solutions for sensing challenges in turbid environments [108]. Inspired by the fish lateral line, researchers developed a triboelectric dynamic pressure sensor for underwater perception. This biomimetic lateral line sensor (BLLS) specifically emulates the canal neuromasts, as illustrated in Figure 4d, a base is 3D-printed from PLA, an acrylic enclosure forms a cavity structure, a triboelectric sensing unit is positioned centrally on the base, and two circular apertures are drilled directly above it. Changes in the external flow field generate a pressure differential between the apertures, inducing deflection of the sensing unit which produces a voltage signal; analysis of this signal yields flow field information. The BLLS can provide supplemental data to impaired acoustic and optical sensors in complex underwater environments [58]. Research indicates that superficial neuromasts exhibit greater sensitivity to flow velocity, while canal neuromasts are more attuned to acceleration. Leveraging this characteristic, researchers designed another biomimetic lateral line sensor variant for underwater vehicles, mimicking the morphology of superficial neuromasts. Its body consists of two parts: a cap and trigger assembly, and a PLA cylinder housing four triboelectric sensing units uniformly spaced at 90-degree intervals. The top structure simulates the

TABLE 2 | Comparative performance of waterproofing techniques.

Waterproofing strategy	Water contact angle	Cost (Relative)	Process complexity	Durability test (Conditions)	Pressure range	Advantages	Limitations	Refs.
Material modification (Layer-by-layer assembly)	150°	Low (≈1/5 of lithography)	Medium (multilayer deposition & acid treatment)	Static CA; stable after 18 000 cycles	10–90 N	Compatible with complex 3D structures	Hydrophobicity decreases under long-term wear	[98]
Waterproof coating (Sacrificial template deposition)	162°	Medium (no noble-metal sputtering; multiple chemical steps)	Medium	Static CA; stable output after 15 000 compressive cycles	1–20 N	CA >150° in pH 1–14 liquids	High process-control requirements	[99]
Material modification (Magnetic-field-induced microstructure)	170°	Low (low-cost materials)	Medium (magnetic-induced microstructure formation)	Dynamic CA; 10 000 cycles at 150% strain, CA remains 160°	7–53.8 N	Impact-resistant, fluorine-free, and eco-friendly	Ethanol temporarily degrades hydrophobicity	[100]
Laser micro-texturing	150°	High (precision equipment required)	Low (programmable patterning)	Aging-resistant substrate; long-term water immersion not reported	0–7 N	Scalable fabrication; high structural resolution	Degraded by organic solvents	[101]
Integral encapsulation (Barrier-based)	NA	Low	Low (no chemical treatment)	Stable operation >100 h at 80% RH	0–30 N	Simple, rapid, low-cost process	Not suitable for complex geometries	[60]
Ion implantation	113 ± 3°	Low (no coating or encapsulation)	Low (≈10 implantation cycles)	Static CA; 91% output retained after 50 000 cycles at 90% RH	0–0.4 N	Material-universal applicability	Unsuitable for high-pressure operation	[62]
Waterproof coating (CNT/TPE spray)	150°	Low (no noble metals, no extra encapsulation)	Medium (strict spray parameter control)	Static CA; 92% output retention after 50,000 cycles at 90% RH	0–30 N	No additional encapsulation required	Degrades in acidic or alkaline environments	[63]

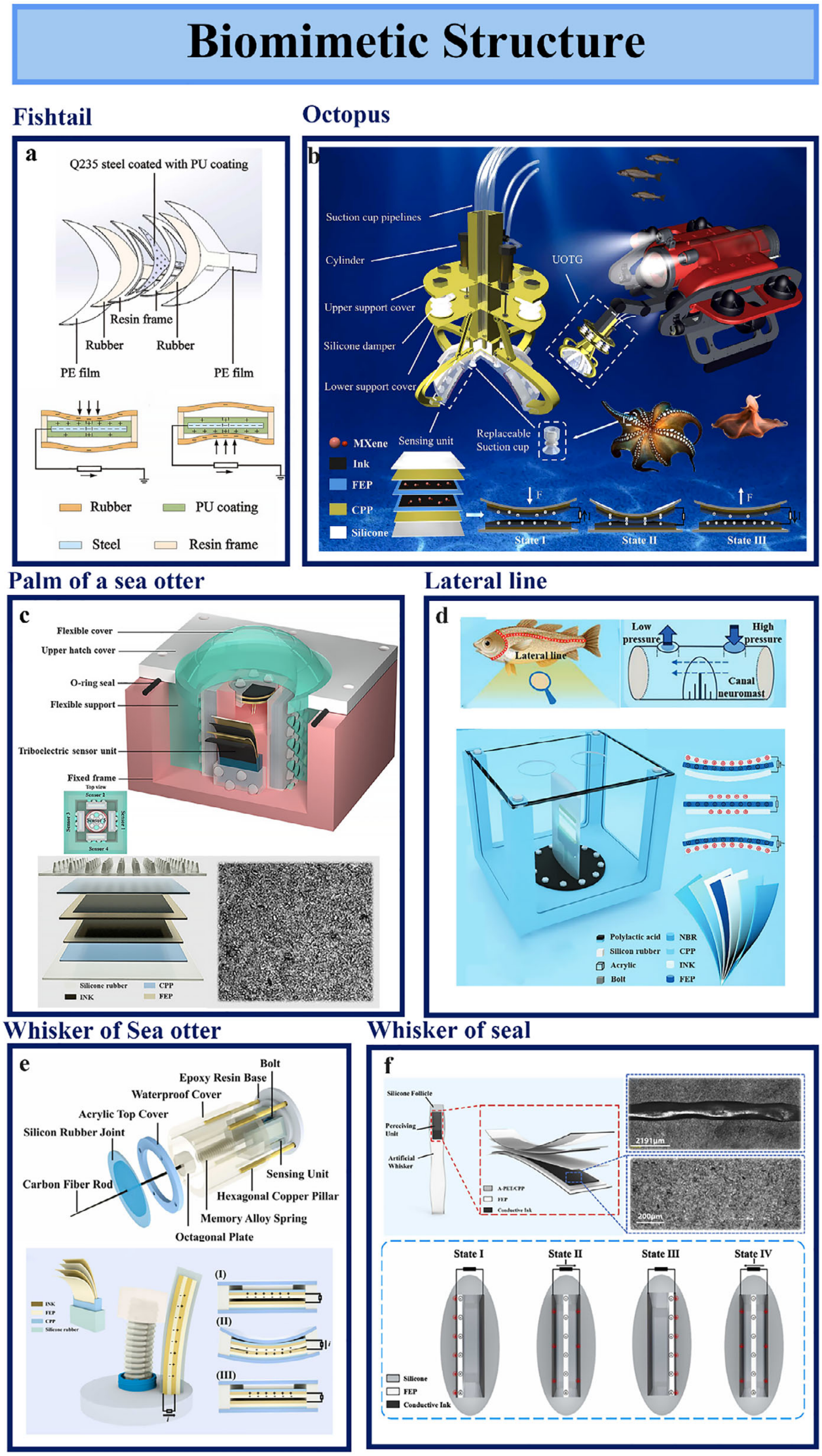

FIGURE 4 | Bionic structures (a) Schematic of a bionic fish-tail structure and its underlying sensor mechanism. Reproduced with permission [53]. Copyright 2023, Elsevier. (b) Schematics of the gripper mechanism, operational principle of the sensor, and material composition diagram. Reproduced with permission [48]. Copyright 2025, Elsevier. (c) Top-view distribution of sensor array layout, structural diagram of sensing unit, and SEM micrograph of FEP membrane surface. Reproduced with permission [59]. Copyright 2022, Springer Nature. (d) Biomimetic lateral line hydrodynamic sensing principle, microstructured sensor architecture, and functional material schematic. Reproduced with permission [58]. Copyright 2024, John Wiley and Sons. (e) Exploded-view diagram of sensor assembly, functional sensing material composition, and sensing mechanism schematic. Reproduced with permission [49]. Copyright 2022, Elsevier. (f) Structural schematic of sensing unit and illustrative charge distribution dynamics during charge migration in FEP membrane. Reproduced with permission [110]. Copyright 2022, Elsevier.

gelatinous cupula of the neuromast, while rod-like components replicate the ciliary bundles of hair cells. The triboelectric sensing units convert mechanical deflection into electrical signals, functioning analogously to hair cells. When mechanical stimulation deflects the top structure and subsequently the rod components, the triboelectric sensor is triggered, effectively replicating the signal transduction principle of neuromasts in the fish lateral line system.

Beyond lateral line biomimetics, another design inspiration stems from the physical structure of fish, such as fins and tails. During tuna locomotion, their fins also serve a sensory role: nerves distributed within the fin membranes and rays of the pectoral and adipose fins allow tuna to actively adjust fin posture for directional control; in scenarios with low visibility, pectoral fins can sense obstacles through contact to gather supplemental information. Inspired by the fins of bluefin tuna (Thunnus thynnus), researchers designed and fabricated a stretchable liquid metal sensor using eutectic gallium–indium (EGaIn). Applied to biomimetic soft robotic fins, this sensor detects flow direction and velocity. This work establishes a foundation for investigating the sensory mechanisms of biological fins and provides underwater robots with a novel method for perceiving complex flow environments [109]. Furthermore, as illustrated in Figure 4a, researchers drew inspiration from the lunate tail of swordfish (Xiphias gladius), known for superior hydrodynamic performance compared to forked, emarginate, or rounded tails. Consequently, they developed a triboelectric-based tail sensor for biomimetic robotic fish. A triboelectric sensing unit is positioned at the tail's center; during tail undulation, the triboelectric layers undergo vertical contact and separation, generating electrical signals. This effort demonstrates the integration of triboelectric technology with biomimetic underwater robotics [53].

For underwater robots performing specific tasks like search and rescue or exploration, effective grasping of target objects is a key enabling technology. Consequently, the unique sensing modalities of octopuses and otters have garnered significant scientific interest. Consider the bioluminescent deep-sea octopus (Stauroteuthis syrtensis)—its suckered tentacles achieve grasping without damaging targets, facilitated by soft tissue structures. During grasping, as illustrated in Figure 4b, real-time tactile feedback allows fine discrimination of object properties. This specialized structure enables the octopus to grasp and manipulate objects of varying sizes, shapes, and hardness—capabilities urgently needed by underwater robots [48]. Researchers designed a biomimetic octopus-inspired gripper for underwater robots based on the morphology and grasping traits of Stauroteuthis syrtensis. The main body comprises two parts: a silicone-backed membrane, replicating the octopus's intrinsic softness and fabricated via layered casting in a 3D-printed mold; and a pneumatically actuated mechanism (including cylinders, suction cup tubing, silicone dampers, and support caps) providing grasping power. Triboelectric sensing units are symmetrically embedded within the membrane, utilizing friction layers made of conductive ink (enhanced with MXene for improved charge transfer efficiency and sensitivity) and FEP film. This research offers a reliable solution for scenarios like underwater salvage and archaeology. The sea otter (Enhydra lutris), a unique marine mammal, also offers highly instructive sensing strategies: it relies synergistically on whiskers and forepaws to complement external tactile information. Particularly when vision is constrained, tactile information becomes critical. Their exceptional tactile acuity arises from the leathery texture of the palm densely innervated with subcutaneous nerve endings, enabling detection of subtle water movements and precise discrimination of object hardness and contours. Underwater tactile sensors have been developed mimicking the structure and function of the sea otter's palm. As illustrated in Figure 4c, researchers designed a distinctive biomimetic sensor: a silicone casing simulates the palm's softness for transmitting external stimuli; internally, a sensing unit integrates four square sensing elements spaced peripherally on the support, with one circular element centrally located; friction layers similarly employ conductive ink and FEP film. External stimuli from different directions induce contact-separation in the corresponding sensing element's friction layers, generating electrical signals and enabling 3D force sensing. This sensor provides a novel tactile perception strategy for autonomous underwater operations, with future applicability in underwater monitoring and deep-sea exploration [59].

Among diverse biomimetic tactile sensors, whisker-inspired sensors stand out due to their versatility in detecting various stimuli, including static and dynamic touch, fluid variations, and vibrations. As highly sensitive modified hairs, traditional tactile sensors often struggle to discern subtle variations in touch, pressure, or texture. In contrast, whisker sensors, featuring flexible and responsive whisker-like structures, can meticulously distinguish numerous environmental changes. Since being clearly defined by the scientific community, biomimetic whisker sensor iterations have continued. As illustrated in Figure 4e, researchers constructed a structure emulating sea otter whiskers using carbon fiber rods, octagonal plates, and shape-memory alloy (SMA) springs: external force applied to the carbon fiber rod causes deflection (as its tip is fixed to the SMA spring base), prompting the attached octagonal plate to actuate a triboelectric sensor and generate an electrical signal. By replicating the perception mechanism of sea otter whiskers, this biomimetic sensor integrated onto underwater vehicles successfully achieved obstacle avoidance and seabed topography detection [49]. Whisker biomimetics extends beyond otters; harbor seal (Phoca vitulina) whiskers are equally noteworthy. As illustrated in Figure 4f, researchers simplified the fabrication process and substituted springs with flexible PDMS to enhance sensitivity. This biomimetic harbor seal whisker sensor features a housing entirely made from PDMS, shaped into the characteristic undulating morphology of real seal whiskers to passively capture pressure differences induced by vortices. The sensing element resides at the root, encapsulated in silicone material. The disparity in flexibility between the silicone and PDMS concentrates deflection forces onto the sensing area, enhancing perception. This represents the first instance combining triboelectric principles with biomimetic harbor seal whisker morphology, achieving underwater passive vortex flow sensing. This design offers a novel bionic strategy for marine equipment sensing in turbid waters, potentially enhancing the environmental adaptability of underwater unmanned systems [110].

Beyond these major directions, the unique sensing abilities of other organisms have inspired related biomimetic sensor designs. The platypus (Ornithorhynchus anatinus), though less commonly considered, possesses a remarkable sensory capability:

while hunting in muddy substrates where vision, smell, and hearing are ineffective, it primarily relies on electroreception augmentation and mechanosensation to locate prey. Its bill plays a pivotal role, densely populated with exceptionally sensitive receptor organs capable of detecting faint bioelectrical signals associated with prey movement. Mechanoreceptors within the bill also respond to contact stimuli. Changes in receptor potential are ultimately converted into neural impulses transmitted to the brain. Researchers implemented a triboelectric sensor array mimicking the electroreceptors on the platypus bill: liquid metal and conductive ink were sprayed onto a silicone surface to form a 3D finger-like array of electrodes (enabling omnidirectional perception), with the surface entirely encapsulated in PDMS to prevent oxidation of the liquid metal. This sensor can assist robots in underwater tasks, including wireless communication via electrical stimulation, tactile perception, and object manipulation, significantly advancing underwater exploration [111]. The vocalization mechanism of frogs (Anura) provides another distinct source of inspiration: male frogs produce sound by muscularly contracting the mouth, drawing air into the vocal sac, which then deforms the elastic, thin vocal cords, forming bubbles. Acoustic amplification occurs when the deformation frequency resonates with the vocal cord vibration frequency. A bio-inspired Triboelectric Ultrasonic Sensing Emitter (BTUSE) sensor, inspired by this, integrates a motion module (amplification function) and a triboelectric module (signal generation). The motion module contains a sensing membrane (mimicking the oral cavity) and a vibrating membrane (mimicking the vocal sac), separated by a spacer layer that forms an air channel. Movement of the sensing membrane, driven by simulated "muscle" action (contraction/relaxation), drives deformation of the vibrating membrane. Both membranes are circular (identical boundary curvature minimizes and distributes stress). The sensing unit comprises a bottom electrode (silver nanowires integrated with the underlying spacer layer), a composite pyramid layer (silver nanowires/barium titanate nanoparticles/PDMS), and a top electrode (carbon-based, connected to the vibrating membrane). Movement of the vibrating membrane induces contact/separation between the top electrode and the bottom piezoelectric materials, generating electrical signals and enhancing performance [112].

Table 3 presents a systematic comparison of six bioinspired underwater sensors, including those modeled after the sea otter's palm, octopus, fish lateral line, swordfish tail, seal whiskers, and electronic fish skin. The comparison covers structural features, key performance metrics (e.g., response time, recognition accuracy, sensitivity), advantages, limitations, and typical applications. Sensor performance is closely linked to structural design. The electronic fish skin, with a biomimetic blind-hole architecture, achieves ultrahigh sensitivity and rapid response, primarily due to the pseudo-capacitive MXene/HrGO electrode and L-cysteine crosslinking, which enhance antioxidant stability and increase ion-accessible surface area. The octopus-inspired sensor offers the fastest response but requires complex algorithms for three-dimensional force processing, while the sea otter palm sensor excels in recognition accuracy, though its larger size may limit integration flexibility. Overall, these designs demonstrate significant advantages in sensitivity, adaptability, and long-term stability; for example, the electronic fish skin operates over a wide pressure range suitable for deep-sea conditions, and the seal whisker sensor reduces energy consumption through passive vortex sensing.

These sensors have been successfully applied in underwater robotic grasping, biological behavior monitoring, and environmental sensing. The electronic fish skin captures instantaneous fish posture changes, with its blind-hole encapsulation effectively filtering shear disturbances and improving signal-to-noise ratio. The fish lateral line, deployed in arrays, enables trajectory tracking, demonstrating the potential of multi-sensor fusion. Despite challenges in material complexity and fabrication cost, iterative optimization—such as the anticorrosion coating of the swordfish tail sensor—has brought these designs closer to their biological prototypes.

This chapter's analysis demonstrates that bio-inspired structures, drawing inspiration from nature, constitute a pivotal strategy for significantly enhancing the environmental adaptability, perceptual sensitivity, and functional integration of underwater tactile sensors. Looking forward, propelling this technology toward practical application necessitates continued advancements at the macro-system level, encompassing environmental robustness, intelligent signal processing, and scalable manufacturing. However, it must be recognized that breakthroughs in all these macro-level performances hinge on a reliable micro-foundation—namely, the core materials constituting the sensors. The flexibility of the materials determines the deformability of the structures; their self-healing capability is crucial for the device's service lifetime, and environmental durability is a prerequisite for ensuring long-term stable perception. Consequently, research into novel materials possessing specific functional properties has become an imperative requirement for deepening bio-inspired underwater tactile sensing and represents the focal point of the next research phase.

2.4 | Material Properties

The escalating complexity in underwater tactile sensor design renders sole reliance on breakthroughs in waterproofing technology or exploration of biomimetic structures insufficient to fully address the rigorous challenges presented by diverse application scenarios [115–117]. Achieving high-performance, high-robustness underwater sensing critically hinges on imbuing the sensor's core materials with specific functional attributes—superior flexibility, reliable self-healing capabilities, controlled environmental degradability, and high-pressure tolerance for deep-sea environments. The attainment of these core performance indicators largely depends on the meticulous design and optimization of the sensor materials.

Flexibility constitutes a fundamental requirement for stable perception and adaptation to complex environmental interactions. Whether enhancing the comfort of wearable devices or ensuring non-destructive grasping of fragile objects by end-effectors, highly flexible materials like silicone rubber and hydrogels have become essential choices [118–121]. Recently, sensors based on the triboelectric principle have demonstrated significant advantages, broadening the material selection spectrum and proving compatible with unconventional fluidic materials. Liquid metals, such as eutectic gallium-indium (EGaIn), stand out due to their

TABLE 3 | Comparative analysis of bionic structures.

Bioinspired prototype	Structural features	Key performance	Advantages	Limitations	Applications	Refs.
Fish Fin	Leading edge rigid, trailing edge flexible; TENG at base	Sensitivity ~50 mN; Swing angle ~120°; Detects Kármán vortex	Multi-directional flow sensing, signal amplification	Limited long-range detection	Near-field flow monitoring (≤25 mm)	[113]
Fish Tail	Central TENG layer undergoes contact-separation during tail swing	Voc 7.21 V; J 231.1 $\mu A/m^2$; σ 1.23 $\mu C/m^2$; P 1.67 mW/m^2	Coupled propulsion and sensing, energy harvesting	Requires decoupling from motion and external noise	Bioinspired fish propulsion and posture monitoring	[53]
Lateral Line	Dual-pore pressure differential drives central TENG	Minimum detectable flow ~0.02 m/s	Robust in turbulent/murky environments, passive sensing	Sensitive to structural design and packaging	AUV near-field flow and trajectory detection	[58]
Seal Whisker	Flexible corrugated whiskers, TENG at root	Peak voltage ~1.2 V; SNR ~19 dB	Passive, tail-trace sensitive	Limited sensing distance	Underwater target trail tracking	[110]
Otter Palm	Multi-point TENG array (central + four surrounding units)	3D force/direction recognition	Fine tactile sensing, suitable for grasp control	Trade-off between flexibility and sensitivity	Precision manipulation, object characterization	[77]
Octopus Arm	Soft, elongatable arm with distributed TENG array along surface	3D force mapping; high spatial resolution	High dexterity and multi-point tactile sensing	Complex signal processing, mechanical fatigue over time	Soft robotic manipulation, underwater exploration and grasping	[114]

excellent conductivity and fluidity [115, 117]. For instance, as illustrated in Figure 5a, a fingerprint-like triboelectric tactile sensor (FTTS) applied to a gripper ingeniously combines silicone rubber (Ecoflex 00–30) with liquid metal encapsulated within three internal cavities. This design endows the sensor with exceptional stretchability (reaching up to 225% of its original length) and rapid elastic recovery with unchanged performance upon force removal. Operating in a single-electrode TENG mode, the flow of the liquid metal increases its contact area with the silicone during stretching or contact, driving charge transfer (e.g., electron inflow/outflow to ground) and generating detectable electrical signals. More notably, leveraging the properties of liquid metal, this sensor demonstrated ultra-high sensitivity (capable of detecting minute forces as low as 16.88 mN) and an extremely fast response time of merely 1.01 ms, establishing a solid foundation for high-precision underwater tactile sensing [51]. The flexibility advantage of liquid metal is also evident in underwater electronic textiles. For example, a research-developed smart glove for deep-sea exploration utilized hydrophobic polyurethane (PU) fibers (fabricated via coaxial wet-spinning to form a hollow structure) internally infused with a liquid metal alloy (Ga:In:Sn = 62.5:25:12.5%). This sensor exhibited an impressive maximum tensile strain capability of 600%. Although diameter changes in the PU fiber during stretching affect sensitivity (necessitating attention to this dynamic performance variation), its maximum detectable pressure of 30 MPa provides valuable safety protection and sensing solutions for deep-sea exploration [122].

Beyond liquid metal, magnetically responsive ferrofluid (Ferrofluid) serves as another effective material for achieving ultra-flexibility. Its fluidity grants the sensor excellent dynamic responsiveness. A sensor design employing helically coiled copper wire electrodes and ferrofluid encapsulated in silicone achieved a stretchability of 300%. The capability of ferrofluid to undergo controlled deformation under external magnetic fields offers unprecedented freedom in sensor functional design compared to traditional solid structures [123]. Furthermore, enhancing flexibility isn't limited to fluidic materials; special processing of solid substrates is equally effective. Prof. Zhang's team developed an elastic substrate through specific modification of a polymer. Combining this substrate with carbon nanotubes (CNTs) formed an electrode material capable of withstanding tensile deformation up to 400%. Its inherent asymmetric polar functional groups (e.g., maleic anhydride, MAH) and block structure not only impart superior mechanical stability but also significantly enhance resistance to stress damage, maintaining stable electrical signal output even under significant deformation [124].

While enhancing sensor performance, the long-term environmental impact of deployed devices has become an increasingly critical focus. Particularly with the widespread adoption of IoUT devices, the potential accumulation of non-environmentally friendly materials poses a severe threat to marine ecosystems [27]. Consequently, developing biocompatible materials with controllable degradation is a key direction for the sustainable advancement of underwater sensing technology. Synthetic polymers such as poly(lactic-co-glycolic acid) (PLGA) and polyvinyl alcohol (PVA), known as biodegradable materials, can decompose into environmentally benign components after fulfilling their designated tasks. Researchers designed a sensor by combining PLGA and PVA with silver nanowires (AgNWs): PVA exhibits rapid hydrolysis in water (90% degradation within 3 days, complete degradation in 30 days); PLGA degradation is initially slower (negligible loss observed within 21 days), but accelerates after 30 days due to hydrolytic scission of the polymer backbone [125]. By adjusting the thickness ratio of the two polymers, the degradation timeframe can be flexibly tuned from hours (pure PVA) to weeks (PLGA-rich composition). However, a significant trade-off exists between this controllable degradation characteristic and sensor performance, as prolonging the degradation cycle often results in substantial performance degradation—a challenge that device design must confront. To specifically address the challenge of underwater device retrieval, Prof. Qu's team innovatively developed an environmentally friendly ionic hydrogel (PXGN, composed of polyvinyl alcohol PVA, xanthan gum XG, glycerol GL, and sodium chloride NaCl). This hydrogel electrode material exhibits unique rapid spontaneous dissolution characteristics (achieving 100% degradation within 5 h), offering a novel perception solution for soft underwater robots that is easy to deploy and enables harmless post-mission disposal [126]. Nevertheless, relying solely on conventional hydrogel architectures struggles to simultaneously satisfy the tripartite demands of robust mechanical properties, high conductivity, and controllable degradability. To bridge this gap, as illustrated in Figure 5b, researchers developed a multifunctional macroscopic fiber based on bacterial cellulose (BC/CNT/PPy): incorporating carbon nanotubes (CNTs) to enhance conductivity, polypyrrole (PPy) to optimize functionality, and utilizing a wet-stretching and twisting process. This fiber demonstrates exceptional comprehensive performance: a tensile strength as high as 449 MPa, high conductivity, excellent flexibility, and complete degradation within 108 h in cellulase solution [56]. This material design successfully reconciles the traditional gap between mechanical strength, conductivity, and environmental degradability, overcoming the limitations of conventional metal electrodes and paving a robust technical pathway for next-generation high-performance, sustainable underwater wearable electronics.

The inherent physical hazards of the underwater environment make sensors highly susceptible to structural damage caused by contact with sharp objects or exposure to high-frequency impacts, potentially leading to severe leaks and jeopardizing device function and operational safety. Therefore, developing materials capable of effectively triggering self-healing functions underwater is paramount [116, 127–129]. A novel polymer incorporating a design featuring hydrogen-bonding clusters and non-bonding electrostatic centers emerged for this purpose. This material can not only function effectively as a sensor electrode but, more crucially, as illustrated in Figure 5c, enables rapid self-repair mechanisms when damaged underwater. Its straightforward and efficient fabrication process significantly enhances sensor reliability and lifespan. The material can restore key electrical properties, such as conductivity, after damage, effectively ensuring the continuity of sensing functions [50]. It is important to note that early self-healing material research primarily focused on relatively benign underwater conditions. Pioneering work by Prof. Dai's team aimed to extend the applicability boundaries of such materials, successfully developing novel materials that maintain efficient self-healing capabilities under extreme underwater conditions (encompassing varying salinities, a wide pH range, temperature fluctuations, and high pressure). Rigorous experimental validation (including self-healing tests in

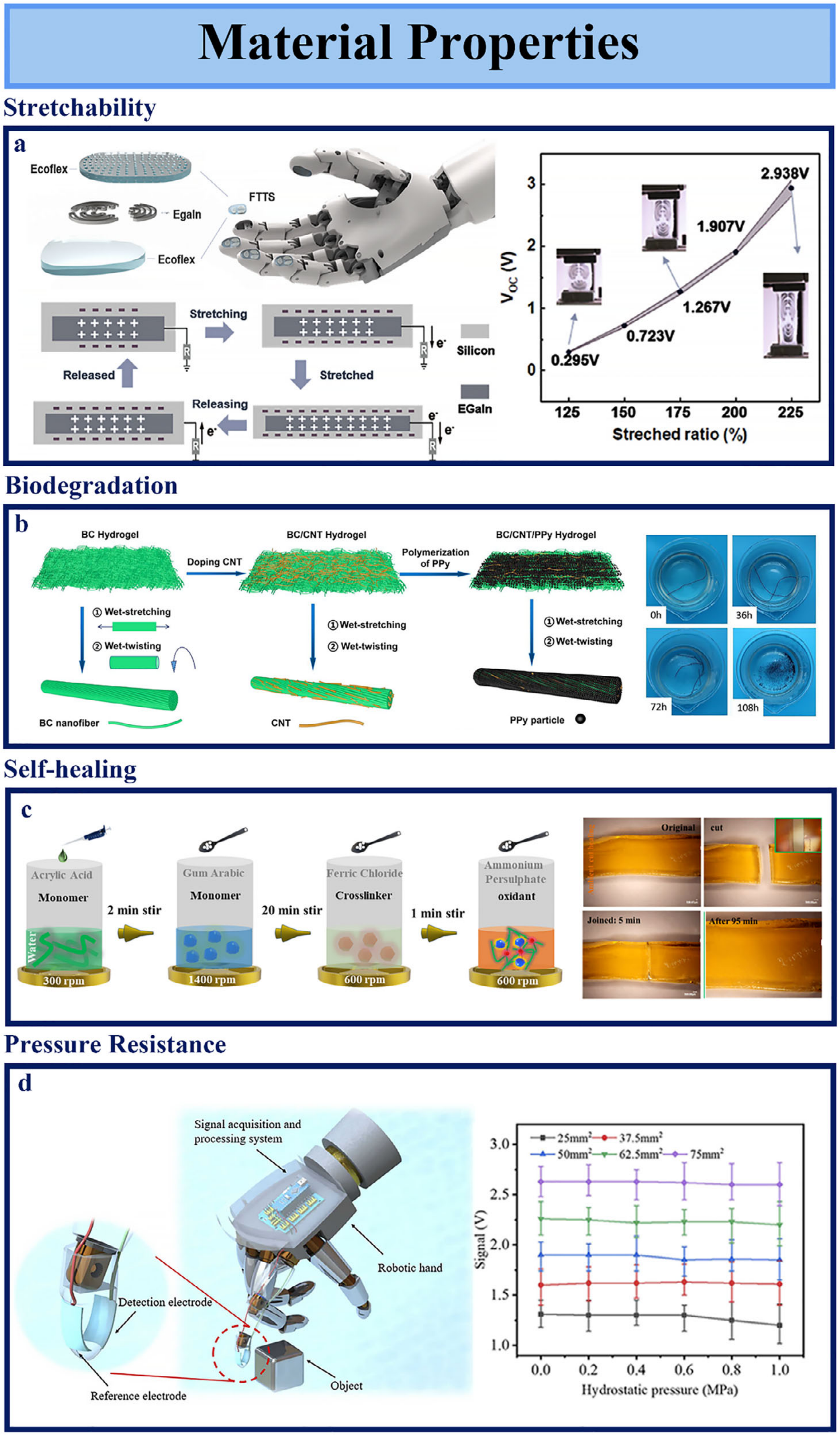

FIGURE 5 | Material Properties (a) Sensor architecture schematic and sensing transduction principle. Reproduced with permission [51]. Copyright 2022, Elsevier. (b) Schematic diagram of coarse fiber manufacturing and degradation process. Reproduced with permission [56]. Copyright 2022, Springer Nature. (c) Process flow diagram of one-pot synthesis route and experimental diagram of self-healing. Reproduced with permission [50]. Copyright 2023, Elsevier. (d) Schematic diagram of perception system and pressure-resilience performance data plot. Reproduced with permission [57]. Copyright 2024, Elsevier.

various saline concentrations, strong acids/bases, and temperature gradients) conclusively demonstrated the material's robust self-repair capabilities in harsh aquatic environments, substantially enhancing the survivability and long-term operational reliability of sensors in complex, real-world marine settings [130]

For extreme deep-sea applications, immense hydrostatic pressure poses a critical dual challenge: it directly threatens the mechanical integrity of the sensor and completely compromises the core sensing mechanism of conventional TENG that rely on a contact-separation mode—sustained high pressure forces the sensing unit into a permanently contacting state, preventing separation and nullifying its operation [131–133]. To overcome this depth limitation barrier, as illustrated in Figure 5d, researchers developed an innovative ionic tactile sensor based on the dynamic response of the electric double layer (EDL) at a solid–liquid interface. Its core lies in a dual-electrode design (both immersed in an electrolyte solution): a detection electrode (DE) makes direct contact with the target object, while a reference electrode (RE) is dedicated to capturing the environmental noise background. The key sensing mechanism involves: when a target object contacts the DE surface (e.g., coated with an indium tin oxide, ITO, film), ions at the interface (within the solution) undergo dynamic redistribution, disrupting the original electrostatic equilibrium and inducing rapid charge transfer/release processes, generating a characteristic voltage pulse signal. A fundamental advantage of this design is its differential amplification strategy: signals from the DE (containing the contact signal superimposed on environmental noise) and the RE (containing only environmental noise) are acquired synchronously. Precise subtraction of the RE signal from the DE signal effectively eliminates common-mode noise, significantly enhancing the output signal's signal-to-noise ratio (SNR). Its ability to withstand extreme pressure fundamentally stems from its complete independence from mechanical deformation or solid dielectric materials. Instead, it ingeniously exploits ion migration at the liquid-solid interface as the primary driver for responding to contact events. This characteristic makes it inherently immune to the constraints and disruptive effects of deep-sea pressure and water permeation that plague traditional solid-state electronic sensors and rigid ionic skins [57]. Consequently, it provides a highly promising solution for enabling highly robust, pressure-resistant, and reliable tactile perception in deep-sea underwater robots.

Extreme marine environments, characterized by high salinity (e.g., seawater salinity up to 3.5%), wide temperature ranges (−30°C to 50°C), and high pressure (e.g., >10 MPa in the deep sea), impose multidimensional challenges on material selection, requiring corrosion resistance, anti-swelling properties, thermal stability, and mechanical durability [12]. Current research addresses these challenges through innovative material design. For example, elastomers such as PDMS achieve self-healing and high stretchability via dynamic hydrogen-bond networks; PDMS elastomers at room temperature exhibit a self-healing efficiency of 85% and a fracture energy of 24,000 J/m^2, suitable for fluctuating marine environments [50]. Nanofiber membranes formulated with styrene-ethylene-butylene-styrene(SEBS), through mechanical interlocking structures (PVDF-HFP nanofibers are electrospun while), achieve 490% strain and water repellency (contact angle 140°), although high salinity may accelerate ion penetration and aging [134]. Hydrogel materials, such as PVA-based and cellulose-based hydrogels, with high water content (>90%) and biocompatibility, are applicable for sensing; PAA-GaF hydrogels maintain >80% self-healing efficiency under dry, wet, and frozen conditions with an output power of 11.1 W/m^2, while anti-swelling cellulose hydrogels show <1% volume change in saline solutions, though high pressure (>50 MPa) may compress their porous structures [50, 135]. Conductive materials such as MXene monolayer films remain stable at 400°C with electromagnetic shielding efficiency of 20 dB, whereas liquid metals like EGaIn can stretch up to 600% but require mitigation of oxidation and deformation [136]. Biodegradable materials, such as cellulose macrofibers, fully degrade in enzymatic solutions within 108 h while maintaining a mechanical strength of 449 MPa, though degradation rates are affected by temperature [56]. To enhance reliability, composite strategies (e.g., elastomer–hydrogel hybrids), environment-responsive dynamic bonds, and biomimetic structural optimization are recommended, combined with standardized testing [125]. Future development of intelligent, stimuli-responsive materials (e.g., pH- or temperature-adaptive systems) is expected to provide dynamic regulation under extreme marine conditions.

In conclusion, the critical advances in underwater tactile sensing technology are intimately linked to these breakthroughs in material innovation. By leveraging highly flexible and resilient elastomers, self-healing polymers, hydrogels with controlled swelling, conductive materials with stability under extreme conditions, and biodegradable and environmentally adaptive systems, sensors now address key challenges of mechanical flexibility, environmental compatibility, structural reliability, and high-pressure tolerance in the deep sea. The synergistic integration of these material properties not only lays a robust foundation for high-performance, durable, and sustainable underwater sensors but also paves the way for the next generation of intelligent marine exploration technologies. However, the sophisticated physical designs and advanced materials are only one part of the equation; the electrical signals generated by these sensors contain complex information that must be accurately decoded. This brings us to the critical role of signal processing and data interpretation techniques, which empower these sensors to transition from simple transducers to intelligent perception systems.

2.5 | Signal Processing

Underwater tactile sensors ensure operational reliability through advanced waterproofing strategies. Their unique biomimetic structural designs optimize performance while diverse material properties address specialized functional requirements. Nonetheless, as research advances, exclusive reliance on electrical signals for rudimentary contact information and distance measurement proves increasingly inadequate to fulfill escalating underwater sensing demands [137]. Multimodal perception has consequently emerged as a critical development trajectory, targeting complex capabilities such as object texture discrimination, shape recognition, trajectory tracking, temperature sensing, collision avoidance, and pose estimation. Achieving these sophisticated functions necessitates robust signal processing methods operating in concert with sensor hardware.

Deep learning, representing the state-of-the-art in data processing technologies, draws inspiration from the operational principles of biological neural networks [138–140]. This paradigm excels at autonomously learning and extracting salient data features through tailored network architectures, exhibiting formidable capabilities in processing nonlinear and dynamically evolving data streams. TENG-based tactile sensors intrinsically offer self-powering characteristics and high-sensitivity signal outputs. Coupling these sensors with deep learning, which provides automated feature extraction and sophisticated pattern recognition capabilities, significantly enhances signal processing efficiency and precision. The synergistic integration of TENGs and deep learning has demonstrably enabled advanced functionalities in practical applications, including the identification of material composition and object geometry, the fusion of visual and tactile data, underwater vehicle pose estimation, trajectory prediction, and human motion monitoring.

The sustainable exploitation of marine resources underpins continued technological and economic advancement. However, the inherently complex, dynamic, and turbid underwater milieu poses significant challenges for accurately discerning surface textures and material types. Addressing this, researchers developed a multi-channel tactile perception system inspired by the sucker morphology of octopus tentacles [55]. This system leverages the triboelectric effect to transduce physical interactions into electrical signals. Input data from four distinct triboelectric sensing units underwent analysis, as illustrated in Figure 6a, with features extracted based on absolute signal amplitude, numerical sequence, peak-trough characteristics, and waveform trends. A dataset comprising 120 voltage signal samples representing 10 distinct materials (including FEP and PDMS) was partitioned into an 80% training set and a 20% test set. Convolutional Neural Networks (CNNs) were employed to hierarchically extract spatiotemporal features from the signals, effectively accommodating the high-dimensional, multi-channel nature of the data. Visualization via t-SNE dimensionality reduction confirmed well-defined clustering with sharp boundaries between material classes, robustly demonstrating excellent feature separability. Model validation on the test set achieved a 98% recognition accuracy, with confusion matrices indicating infrequent misclassification. The system further maintained robust performance against signal variations induced by differing contact pressures. This work established a comprehensive underwater material identification pipeline: material detection initiates with sensor-object contact, generating quad-channel electrical signals. These signals are subsequently transmitted to a processing terminal where Convolutional Neural Network (CNN) analysis occurs in real-time, ultimately culminating in the determination of the material type. The integration of triboelectric sensing with CNNs provides marine exploration systems with high-precision, environmentally robust intelligent perception capabilities. Notably, Support Vector Machines (SVMs) demonstrate superior performance over CNNs under conditions of limited sample data [141, 142]. Researchers thus proposed a biomimetic multimodal tactile sensing approach utilizing a TENG coupled with a micro-thermoelectric generator (μ-TEGs) specifically for underwater actuator temperature and pressure perception. Within this framework, the TENG unit transduces applied force, while the μ-TEG unit exploits the Seebeck effect to detect thermal gradients—contact-induced heat transfer to the target object generates corresponding voltage signals. Experiments involved contacting sample materials with a controlled 7 N force, recording μ-TEG voltage changes over a 3-s interval. Six material classes—aluminum, iron, zinc, limestone, polypropylene, and pine wood—were evaluated. Acquired voltage data was processed using an SVM model trained on 70% of the data and tested on the remaining 30%. Maximizing interclass margins enhanced classification robustness, yielding a peak identification accuracy of 92.4% at 7 N pressure, significantly outperforming results obtained at 3 N. The sensor's biomimetic hierarchical architecture (comprising CM-MTEG + TENG + Peltier unit) effectively decoupled multidimensional signals. Combined with the SVM's classification based on voltage change rates, this method furnishes a reliable tactile solution for underwater manipulators requiring efficient material identification [143].

Contrasting with robotic manipulators that utilize analytical data extraction for material and shape recognition, wearable sensors for human state detection and gesture monitoring also extensively leverage deep learning. The Intelligent Self-Powered Life Jacket (SPLJ) system, illustrated in Figure 6d, exemplifies this approach by employing triboelectric fiber sensors as its core sensing elements. Signals from six sensors, strategically positioned at the shoulder, elbow, and knee joints, were used to capture kinematic fluctuations. Extracted features included signal peak value, frequency, peak–valley interval, and temporal sequencing. The dataset was split into 60% for training, 20% for validation, and 20% for testing, with each sample annotated with one of four activity states (swimming, distress, trembling, immobility). Achieving 100% recognition accuracy enabled real-time classification of potential drowning states, providing critical information for rescue protocols [64]. The integration of triboelectric fiber sensing with a CNN-based deep learning model enables high-accuracy action recognition, advancing the development of intelligent marine wearables. Progress in wearable sensor technology further facilitates the deployment of sensitive tactile interfaces in everyday scenarios, where gesture recognition is particularly important for human–computer interaction and motion analysis. Researchers subsequently developed a palm-wearable superhydrophobic sensor system, feeding the acquired signals into a Multilayer Perceptron (MLP) neural network [144]. Four participants were asked to perform each defined gesture 25 times, generating 1,000 datasets (five sensor channels corresponding to five fingers). The MLP architecture comprised three hidden layers with twenty neurons each and used ReLU activation functions. Training with the Adam optimizer resulted in a 99.34% gesture recognition accuracy. The study successfully demonstrated MLP-based underwater gesture recognition, supported by the sensor's operational robustness, including a wide strain range (50%), rapid response (62 ms), and resilience under extreme conditions. This solution offers novel pathways for underwater wearable technology and soft robotics.

The domains of underwater vehicle trajectory prediction and pose estimation are similarly reliant on sophisticated data processing techniques. A biomimetic underwater TENG whisker sensor developed by researchers facilitates near-field perception and online state estimation through deep learning integration. Deep learning was selected primarily because sensor signals are vulnerable to perturbation from complex flow fields, vehicle-induced vibrations, and multiphysics coupling, rendering conventional

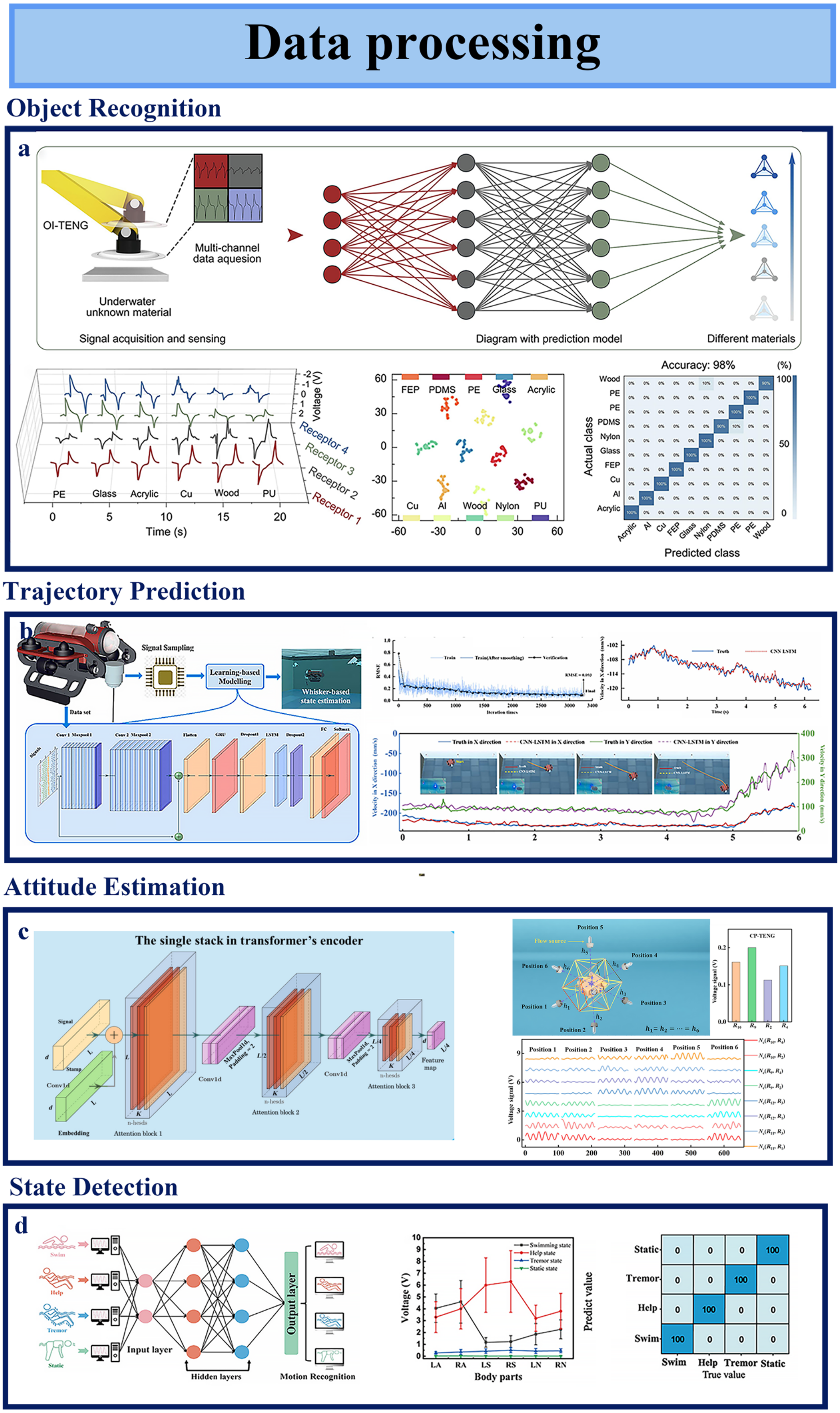

FIGURE 6 | Data processing. (a) Material-featured signal processing, t-SNE clustering analysis, and confusion matrices (training set 100%/prediction set 98%). Reproduced with permission [55]. Copyright 2025, Elsevier. (b) Online hydrodynamic estimation: underwater signal acquisition, AI modeling execution, whisker-based state resolution. Reproduced with permission [52]. Copyright 2024, Elsevier. (c) 36-channel signals processed by a transformer network for 12-node spatial positioning. Reproduced with permission [54]. Copyright 2023, Springer Nature. (d) Average motion amplitude of different body parts and movements, a CNN model developed for drowning motion recognition, and a confusion matrix of deep learning analysis for four motion types. Reproduced with permission [64]. Copyright 2024, John Wiley and Sons.

statistical models inadequate for capturing the requisite complex, nonlinear mappings. Consequently, as illustrated in Figure 6b, transforming the four-channel voltage signals into accurate operational states necessitated a hybrid CNN and Long Short-Term Memory (LSTM) architecture. The CNN extracts spatial features from the multi-channel data, discerning inter-channel dependencies, using the quad-channel voltage time series as input. The LSTM processes temporal dependencies, learning the sequential mapping between evolving signal dynamics and vehicle state, taking the CNN-derived feature sequences as input and outputting the estimated state. The model demonstrated high fitting precision, exhibiting a validation loss of 0.093 and a training loss of 0.004. Predictions for linear motion trajectories showed close congruence, turning maneuvers registered a maximum deviation of 7.69 mm, and angular velocity estimates during circular motion aligned with the motion capture system ground truth. Employing deep learning effectively addressed the nonlinear coupling challenges intractable to classical fluid dynamics models. The hybrid model design markedly enhanced the robustness of underwater state inference. Empirical validation confirmed the method's generalization capacity across complex trajectories, establishing a new paradigm for underwater local navigation [52].

Subsequently, the research team implemented a distributed whisker sensor array across the vehicle structure. By synergistically fusing CNN and LSTM processing to map multi-channel signal spaces, joint estimation of the vehicle's 3D motion (trajectory, velocity, direction, including angular velocity and motion angles) was achieved. Compared to the preceding configuration, this yielded reduced error (RMSE $\approx$ 0.02) and enabled higher-fidelity real-time predictions. The enhanced CNN-LSTM model leverages CNNs to extract spatial features at the array level (emphasizing inter-sensor correlations) and LSTMs to handle sequential dependencies. Incorporation of frequency-domain analysis further empowered the model to identify vortex characteristics and obstacle signatures. The spatial dimensionality of the input data (governed by sensor placement) is encoded by the CNN layers, while the LSTM layers manage dynamic variations (such as continuously evolving angles of attack). Sensor arrays inherently provide redundant information during motion estimation tasks, substantially bolstering model robustness within intricate hydrodynamic conditions. The system facilitates concurrent real-time operations, such as integrating obstacle awareness with trajectory tracking, augmenting the vehicle's comprehensive navigational capacity [145]. Building on this progression, as illustrated in Figure 6c, a TENG sensor array integrated with a Transformer model was explored. This system utilizes 36-channel sensor signal inputs sampled at 120 Hz to predict the real-time 3D positions of 12 defined nodes. The voltage time-series data feeds into the model architecture, featuring a three-layer stacked encoder and a two-layer decoder, optimized using Adam, outputting relative node poses. Testing employed 50 datasets (80% training, 20% test) encompassing scenarios with flow perturbations and obstacle collisions. Testing yielded a nodal displacement root mean square error (RMSE) of 1.732 and an average pose prediction RMSE of 0.76, realizing a highly articulated and impact-resistant underwater tactile system. The underlying machine learning framework successfully maps the 36-dimensional sensory inputs onto a 36-dimensional pose space, endowing underwater robots with optical-independent, real-time environmental perception capabilities [54].

Signal processing in extreme marine environments faces multifaceted challenges imposed by high salinity, wide temperature ranges, and elevated pressures. These conditions directly affect sensor performance, signal quality, and the reliability of analysis models. Sensor data acquisition is particularly sensitive: triboelectric nanogenerators (TENGs) offer self-powered operation and demonstrate stable voltage outputs under moderate pressure and salinity, yet high salinity accelerates charge leakage, leading to signal attenuation [64]. Ion-conductive sensors maintain linear resistance changes across wide temperature ranges but are prone to cross-interference from competing ions, whereas electromagnetic sensors resist salinity-induced corrosion but require pressure compensation to mitigate coil deformation. Multi-sensor fusion approaches enhance robustness by compensating for individual sensor limitations [146].

Signal preprocessing is critical for mitigating environmental noise. Adaptive filtering (e.g., LMS) effectively improves signal-to-noise ratio under fluctuating conditions, while wavelet-based transforms offer frequency-band adaptability across temperature variations. Dynamic baseline correction strategies resist temperature-induced drift, though high-pressure-induced sensor deformation may require segmented calibration. Incorporating environmental parameters, such as real-time temperature feedback, further enhances preprocessing robustness [142].

Feature extraction and selection are likewise impacted by environmental variability. Time-domain features can be sensitive to salinity fluctuations, while differential or normalized metrics improve robustness. Frequency-domain features require temperature compensation to maintain accuracy, and nonlinear features such as entropy demonstrate resilience to pressure variations, albeit necessitating adaptive windowing under high-salinity conditions. Prioritizing features with environmental robustness reduces reliance on absolute signal values and enhances model generalization [54].

Machine learning models underpin high-level signal interpretation but must contend with data sparsity and abrupt environmental changes. Convolutional neural networks (CNNs) handle time-series data effectively, although sudden salinity changes may distort features. Graph convolutional networks (GCNs) capture sensor topology correlations, and transfer learning can accelerate model convergence under low-temperature conditions. Online learning strategies, including incremental and reinforcement learning, address long-term stability and high-pressure data scarcity. Future directions should emphasize environmental-adaptive frameworks to improve generalization, integrating physical-informed features and minimizing dependence on extensive labeled datasets [144].

Despite the multifaceted challenges posed by extreme marine environments, the integration of deep learning with advanced signal processing techniques enables effective mitigation of these limitations. Collectively, deep learning-driven signal processing technologies constitute the core engine propelling underwater tactile sensing beyond fundamental contact perception toward sophisticated multimodal and high-intelligence functionalities. They effectively mitigate the challenges of signal nonlinearity and variability endemic to complex underwater environments, significantly elevating the analytical precision and cognitive level attainable from multimodal tactile information. This advancement underpins the intelligent evolution of underwater exploration platforms, wearable systems, and autonomous vehicles. The journey from theoretical principles and material concepts to a functional, reliable sensor culminates in the fabrication process. The final section of this chapter, therefore, examines the manufacturing techniques that integrate triboelectric principles, waterproofing, bio-inspired structures, functional materials, and electronic interfaces into scalable and robust underwater tactile sensor devices.

2.6 | Fabrication Processes

Although material properties, bio-inspired structural designs, and waterproofing strategies fundamentally determine the sensitivity, operational stability, and environmental adaptability of underwater TENG tactile sensors, the extent to which these advantages can be fully realized in practical applications ultimately depends on the reliability, scalability, and substrate compatibility of their fabrication processes. Therefore, a systematic overview of representative fabrication workflows not only clarifies the underlying technological foundations of current devices but also provides a structured framework for addressing the procedural fragmentation frequently observed in existing studies. Based on experimentally validated data and well-established processing routes reported in the literature, the fabrication of underwater TENG-based tactile sensors can be categorized into four essential modules: electrode fabrication, triboelectric-layer construction, microstructure engineering, and device integration and encapsulation [126, 147, 148].

The fabrication of flexible electrodes must simultaneously satisfy the requirements of low-temperature processing, mechanical compliance, and underwater operational stability. In nanofiber-based systems, a representative approach—illustrated in Figure 7a—is the one-step electrospinning–electrospraying process, in which PVDF-HFP nanofibers are electrospun while SEBS elastomer microbeads are electrosprayed synchronously. This method produces a mechanically interlocked, multi-point anchoring structure within the fiber network. Conducted entirely at room temperature and without any thermal curing, it is inherently compatible with low-modulus substrates and thermally sensitive materials, making it particularly suitable for soft robotic components and conformal underwater interfaces. Beyond nanofiber electrodes, metallic thin-film electrodes—such as Au, Ag, or Cu layers deposited onto PET or PDMS substrates via sputtering or thermal evaporation—and screen-printed conductive inks based on Ag, MXene, or CNTs remain robust and industrially reliable options, especially for applications requiring high conductivity under moderate deformation. Additionally, textile-based electrodes fabricated through wet-spinning or dip-coating processes offer excellent cuttability and conformability, rendering them highly suitable for constructing large-area, flexible underwater sensing arrays [134].

As the primary functional component of a TENG, the triboelectric layer plays a decisive role in governing charge generation and output stability. Electrospun PVDF-HFP membranes have emerged as an ideal choice for underwater TENGs due to their high β-phase content, intrinsic hydrophobicity, and abundant surface microstructures. Typical electrospinning parameters allow the fiber diameter to be tuned within 200–600 nm and the membrane thickness within 50–200 μm. Adjusting the collector configurations further enables control over porosity and areal density, thereby increasing the effective contact area and promoting interfacial drainage to mitigate ion accumulation and charge screening in aqueous environments. For friction layers with bioinspired features—such as flexible fin rays, whisker-like arrays, or epidermal ridge patterns—high-fidelity replication can be achieved using 3D-printed molds combined with PDMS/Ecoflex casting. For example, as illustrated in Figure 7b, researchers have fabricated a microstructured silicone interlocking layer that significantly increases the contact area with a liquid-metal electrode, leading to markedly enhanced output amplitude and improved signal fitting accuracy. Such biomimetic fingerprint-inspired architectures not only boost interfacial triboelectric charge density but also improve the sensor's adaptability to dynamically varying underwater conditions [51].

Microstructures serve as a critical strategy for enlarging the effective contact area and enhancing charge-transfer efficiency, and are particularly valuable in underwater environments where they help suppress ion-induced charge screening. Commonly used microstructure fabrication techniques include soft lithography/replica molding, sandpaper-assisted imprinting, laser ablation, and electrospinning-induced embedding. Soft lithography enables the formation of well-defined micropillar or microcavity arrays; sandpaper imprinting generates stochastic roughness that increases surface asperities; laser ablation allows programmable periodic textures; and electrospinning-induced embedding creates self-interlocked architectures through microsphere incorporation or phase separation. As illustrated in Figure 7c, combining double-layer photolithography, polystyrene nanoparticle self-assembly, and PDMS soft lithography yields a three-dimensional hierarchical micro/nanostructured superhydrophobic PDMS triboelectric layer, exhibiting a static contact angle of 161°. This hierarchical topology substantially enhances interfacial roughness and drainage capability, resulting in a pronounced improvement in TENG output: the open-circuit voltage increases from 40 to 221 V. Furthermore, the superhydrophobic surface demonstrates markedly improved stability under high humidity and contamination. In addition, chemically etched CNT/TPE-based ultrahydrophobic coatings can achieve contact angles up to 151.7°, offering favorable conditions for charge retention and interfacial dewetting in underwater environments [149].

The system-level integration of TENG devices typically relies on lamination, solution-based adhesion, or in situ deposition to couple the triboelectric layer, electrodes, and flexible substrates such as TPU, Ecoflex, or polyester textiles. As illustrated in Figure 7d the combination of PCB–Cu electrode machining, PTFE triboelectric layer lamination, Ecoflex-molded T-shaped air-chamber structures, and large-area spray-coated SiO_2-based superhydrophobic treatments enables a highly integrated architecture in which the electrode module, friction layer, air-buffer structure, and underwater anti-interference interface are

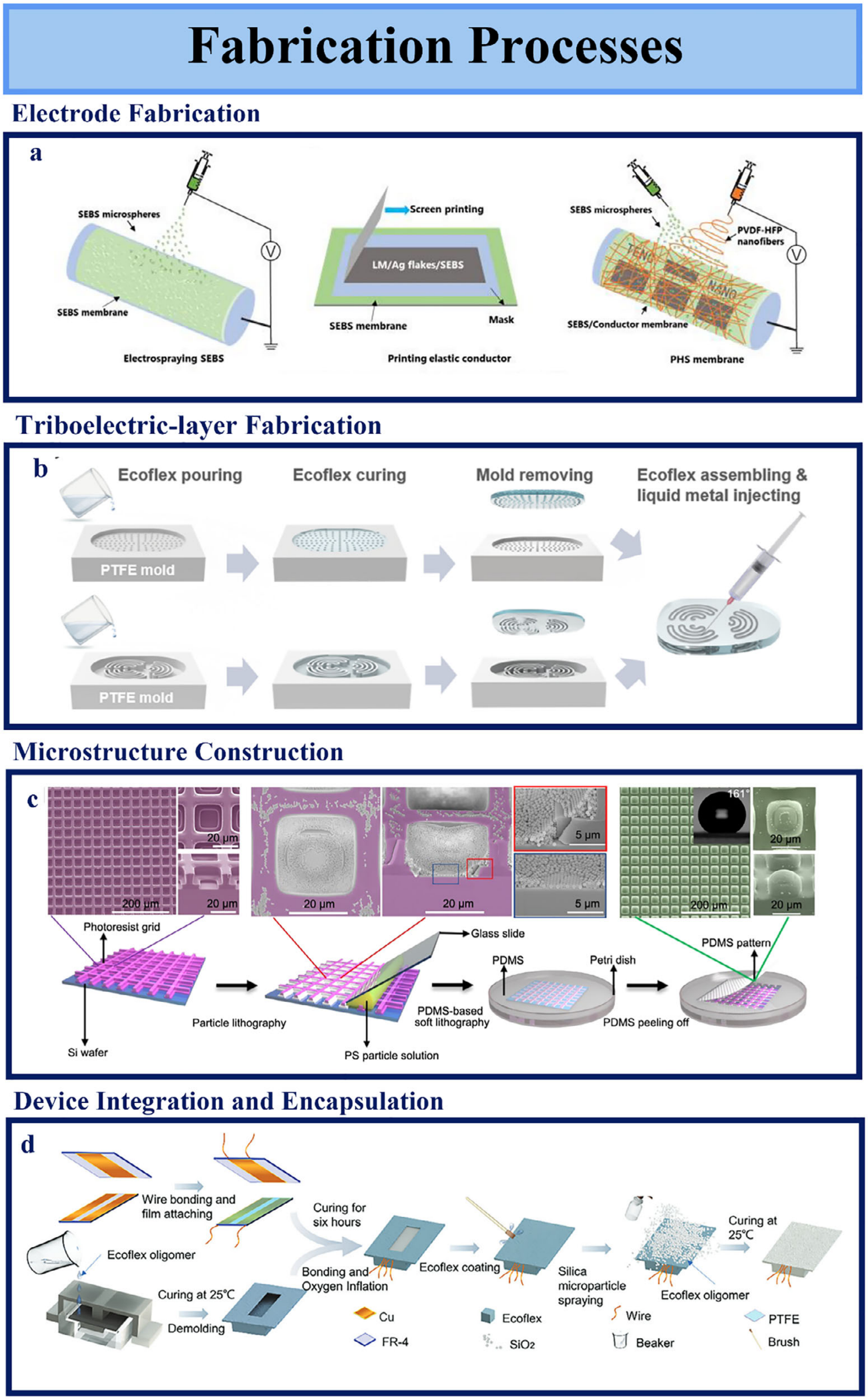

FIGURE 7 | Fabrication Processes. (a) PVDF-HFP/SEBS mechanically interlocked nanofiber–microbead electrodes fabricated via a one-step electrospinning–electrospraying process. Reproduced with permission [134]. Copyright 2020, Elsevier. (b) Bioinspired microstructured silicone layer replicated from 3D-printed molds to enhance the effective contact interface. Reproduced with permission [51]. Copyright 2022, Elsevier. (c) Hierarchical micro/nanostructured PDMS triboelectric layer formed through photolithography, nanoparticle self-assembly, and soft lithography. Reproduced with permission [149]. Copyright 2019, Elsevier. (d) Integrated TENG module combining PCB–Cu electrodes, PTFE friction layers, Ecoflex T-shaped air-chamber structures, and SiO_2 superhydrophobic spray-coated encapsulation [74]. Reproduced with permission. Copyright 2023, John Wiley and Sons.

seamlessly consolidated. This encapsulation strategy ensures mechanical robustness under submerged conditions and significantly enhances signal fidelity in ion-rich aqueous environments, thereby establishing a reliable manufacturing foundation for underwater force sensing. For applications requiring intimate conformity to complex three-dimensional surfaces, sprayable superhydrophobic coatings—such as fluoroalkylsilane-modified silica—can be further combined with layer-by-layer deposition to enhance interfacial drainage, achieving contact angles of 150°–170° and retaining over 90% of the output performance after 10^4–5×10^4 operational cycles. Furthermore, ion-implantation treatments can introduce deep-trapped charges within the dielectric layer, markedly extending device lifetime (>50 000 cycles), although their long-term stability under deep-sea hydrostatic pressures remains to be fully validated [74].

Overall, the manufacturing framework for underwater TENG-based tactile sensors—encompassing integrated nanofiber membrane fabrication, controlled micro/nanostructure engineering, and multi-modal waterproof encapsulation—has become increasingly mature, substantially enhancing device flexibility and underwater operational stability. Nevertheless, challenges persist in large-scale fabrication, device-to-device consistency, and adaptation to extreme marine environments. Continued co-optimization of manufacturing processes and material systems will be essential to advance these technologies toward practical deployment.

3 | Potential Underwater Application Scenarios

With the increasing demand for marine resource exploitation and deep-sea exploration, underwater environmental sensing technologies are evolving toward greater intelligence, integration, and diversification. Addressing the complexities and variability of underwater environments, tactile sensing technologies—particularly those featuring self-powered capabilities—provide robust support for underwater robotics, wearable devices, and monitoring networks. These advances not only enhance the perception and operational safety of autonomous underwater systems but also facilitate real-time intelligent monitoring of marine ecosystems and infrastructure management. The following sections systematically present the latest developments and representative applications within these three critical domains.

3.1 | Underwater Robotics

The intensifying exploitation of marine resources, coupled with rapid advancements in underwater robotics and submersible technologies, has significantly heightened human exploration of the ocean. As core platforms for executing underwater operations, mobile subsea equipment confronts substantial challenges posed by complex flow fields and unstructured terrains distinct from terrestrial environments. Even minor disturbances during missions can stir sediment, drastically reducing visibility, while increased diving depths further degrade optical conditions [150]. In such scenarios, conventional optical and acoustic sensors often fail to meet operational demands. Tactile sensors have thus emerged as a critical solution, endowing subsea systems with tactile perception capabilities through direct physical contact. Recent collaborative research has successfully integrated tactile sensors into underwater mobile platforms, enabling functionalities such as object grasping and identification, pipeline inspection, wake detection, pose estimation, trajectory prediction, and collision avoidance, warranting systematic discussion of their applications.

Underwater object identification is paramount for marine resource development and complex operations, directly determining task precision. Environmental interference frequently compromises traditional perception methods, creating an urgent need for biomimetic tactile technology to deliver high detection accuracy and reliability. As illustrated in Figure 8a, researchers have developed a multi-channel biomimetic octopus-inspired tactile sensor based on the triboelectric effect. Integrated onto underwater robots and utilizing wireless communication for data transmission, this system establishes a comprehensive underwater object classification platform. By employing sensor arrays to extract features such as voltage amplitude and waveform trends, it achieves precise differentiation among ten complex materials—including FEP, PDMS, PE, glass, acrylic, copper, aluminum, wood, nylon, and PU—some of which are indistinguishable to human touch. Its unique hermetic structure ensures stable underwater operation, with experiments confirming consistent classification performance unaffected by water salinity variations, demonstrating pan-aquatic applicability. The platform further supports continuous multi-target identification, offering innovative solutions for enhancing underwater exploration and infrastructure maintenance efficiency [55].

The biomimetic design inspired by octopuses proves particularly effective for object classification tasks. By emulating the dorsal membrane architecture and sucker network of octopus tentacles, researchers achieved compliant adaptive grasping. Coupled with deep learning algorithms for high-accuracy classification, the gripper—equipped with triboelectric sensors—exhibits exceptional sensitivity and stable grasping performance. This significantly improves salvage efficiency while preserving target integrity. Integrated onto underwater vehicles, the gripper extends beyond prior capabilities by identifying objects of varying hardness and demonstrating successful manipulation of aquatic organisms like crabs, sea cucumbers, and pufferfish, thereby advancing marine biological research methodologies [48].

Intelligent underwater operations require extremely high environmental perception accuracy and decision-making capabilities from submersibles. Real-time trajectory prediction is crucial for navigation safety. Triboelectric tactile sensors present a transformative approach due to their biomimetic sensing mechanisms, superior environmental adaptability, and self-powering properties. As illustrated in Figure 8b, researchers created a single-point perception system using triboelectric whisker sensors, enabling passive flow velocity measurement, angle-of-attack determination, and real-time speed estimation in flow fields—laying groundwork for subsequent 3D flow applications. Subsequent upgrades transformed this into a sensor array capable of comprehensive 3D motion estimation, encompassing vehicle velocity, orientation angle, and 3D trajectories. This facilitates path planning and collision avoidance during navigation. As an enhanced iteration, the array supports more sophisticated motion analysis and delivers greater estimation precision compared to its predecessor, achieving fully autonomous near-field perception

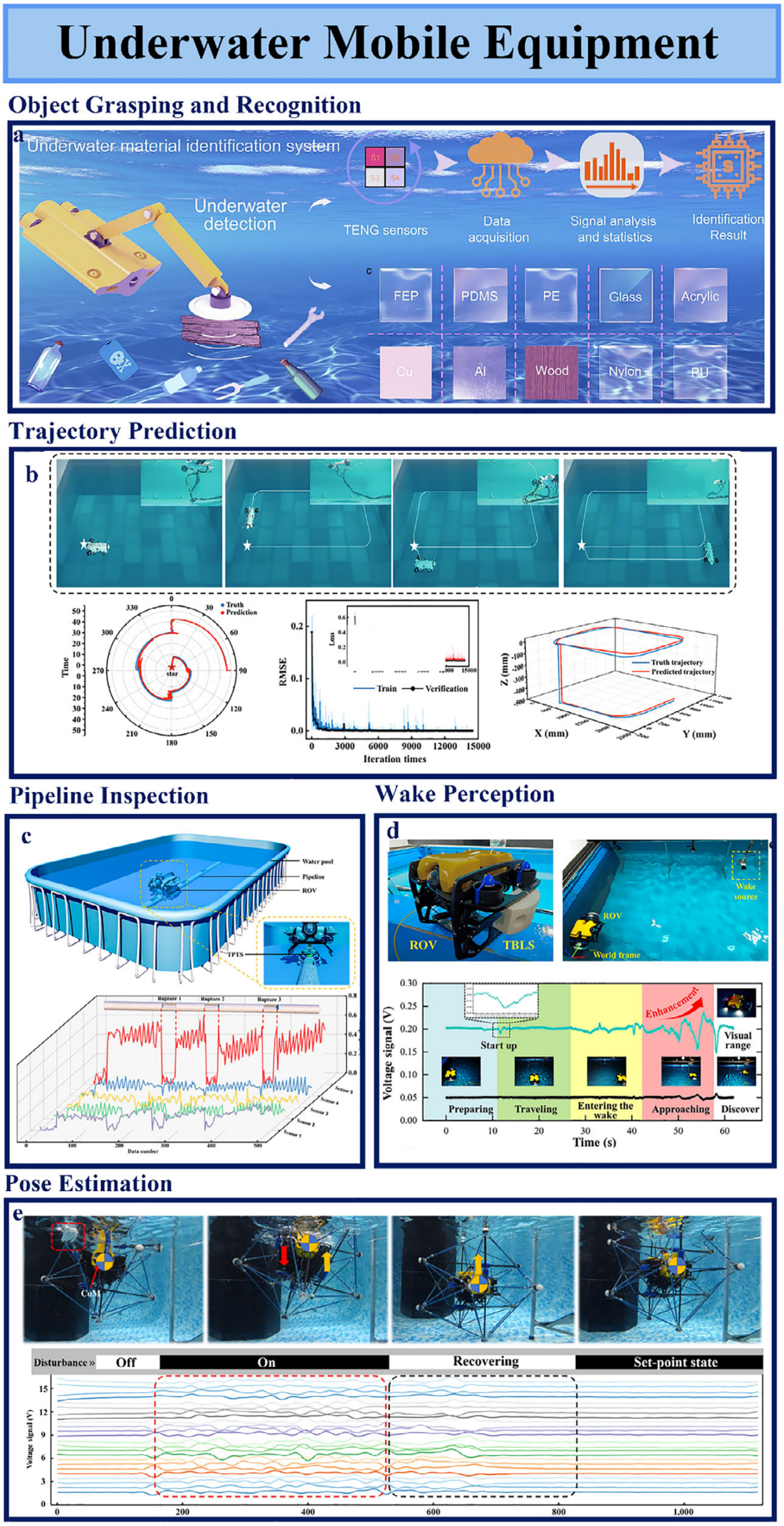

FIGURE 8 | Underwater mobile equipment. (a) Underwater multi-material recognition system. Reproduced with permission [55]. Copyright 2025, Elseiver. (b) ROV motion trajectory, rotational velocity along the entire path, root mean square deviation, and training data loss, and comparison between actual and TWSA-estimated trajectories and velocities. Reproduced with permission [145]. Copyright 2025, John Wiley and Sons. (c) Pipeline inspection diagram and signal analysis. Reproduced with permission [59]. Copyright 2022, Springer Nature. (d) Wake sensing in dark environments. Reproduced with permission [152]. Copyright 2025, John Wiley and Sons. (e) The AUV autonomously returns to the setpoint after disturbance, and the U3DTT generates a voltage response to impact force. Reproduced with permission [54]. Copyright 2023, Springer Nature.

and motion control with marked improvements in accuracy, functional diversity, and environmental adaptability—signifying substantial progress in underwater biomimetic sensing [145].

Collision avoidance capability critically determines mission survivability of underwater vehicles. Ocean currents, dynamic obstacles (e.g., fish schools), and marine debris elevate collision risks, particularly in confined terrains where impacts frequently cause equipment damage. For proactive obstacle detection, researchers integrated biomimetic whisker sensors onto underwater robots' heads. Collision-induced deformations generate voltage signals enabling real-time obstacle monitoring. In water tunnel experiments, the system successfully guided robots to evade overhead obstacles by adjusting diving depth. During constant-speed cruising, signal rising/falling edges detected wall irregularities (e.g., protrusions/depressions), enabling real-time seabed topography mapping. This work provides complementary perception in low-visibility conditions, expanding operational capacity [49].

Subsea pipelines serve as critical infrastructure for offshore oil and gas transport, where stable operation directly impacts national energy security and marine ecological sustainability, making non-destructive inspection imperative. As illustrated in Figure 8c, a self-powered biomimetic tactile sensor based on the triboelectric effect was developed. When integrated with an underwater manipulator, it distinguishes object hardness via signal slope analysis and provides grasp force feedback control. Mounted on AUV traversing pipelines, it identifies cracks through signal variations and assesses surface roughness via vibration amplitude analysis. This solution offers an integrated approach featuring self-powering, high stability, and multi-dimensional force perception for precise operations, including object grasping and infrastructure inspection [59].

Wake signatures encode vital information about submerged moving objects, holding irreplaceable strategic value for military defense and ecological monitoring. Leveraging seals' vibrissal vortex detection capabilities, as illustrated in Figure 8b, researchers created a self-powered tactile whisker sensor for passive underwater vortex perception. Fluid disturbances trigger electrical signals processed in real-time via MATLAB to resolve target oscillation angles and frequencies for motion monitoring. Integration onto robotic fish enabled underwater target tracking beyond visual constraints, pioneering new avenues in wake perception [145, 151]. Subsequent work drew inspiration from fish lateral line neuromasts, as illustrated in Figure 8d, yielding a triboelectric biomimetic lateral line sensor. This enhanced the underwater vehicles' perception of complex flow phenomena like propeller wakes and oscillatory flows. Functioning in low-light conditions, the sensor localizes propeller positions and deduces vehicle motion direction from signal waveform fluctuations. Its deployment in a sea-trial-verified monitoring platform featuring wireless data transmission to land-based terminals established a novel flow-field sensing paradigm for submersibles [152].

Precise attitude control directly governs navigation accuracy and equipment safety during underwater vehicle operations. Real-time attitude prediction and feedback control in dynamic marine environments constitute essential autonomous technologies. A 3D tactile sensor based on a tension network structure was introduced, synergizing triboelectric nanogenerators (TENGs) with deep learning. This system simultaneously resolves force magnitude, position, direction, and impact protection in real time. Employing a Transformer model to fuse 36 sensor channels, as illustrated in Figure 8e, it achieves real-time 3D pose prediction. Validated in low-light/confined underwater spaces, it successfully accomplishes collision localization and flow direction identification. The design mimics terrestrial animals' skeletal-muscular systems, featuring rigid elements and flexible actuators. Integrated with subsea vehicles, it demonstrates multi-degree-of-freedom adaptability, ultra-high sensitivity, and rapid response. With an average real-time 3D pose prediction RMSE of 0.76 in pool tests, this technology exhibits considerable potential for tactile feedback applications in subsea equipment [54].

3.2 | Underwater Wearable Devices

Advances in miniaturization and intelligentization have transformed underwater sensing systems from standalone devices toward multimodal integrated architectures. Sensors are now ubiquitously embedded in robotic platforms and submersibles while simultaneously driving innovation in biometric wearable integration [153–155]. Such wearable devices fulfill dual requirements of operational comfort and life-safety assurance through flexible encapsulation, ergonomic design, and real-time biosignal acquisition. They demonstrate irreplaceable value, particularly in acoustic telemetry-limited environments or scenarios requiring biological carrier collaboration. Six principal application domains have emerged: emergency response, human/animal motion monitoring, visual-tactile fusion perception, underwater interaction, and health surveillance—all strategically significant for advancing marine science and underwater IoT development.

Global economic integration has intensified maritime shipping activities, escalating safety concerns alongside economic benefits. High fatality rates in maritime accidents stem from extreme environmental conditions and rescuers' inability to obtain real-time positional and biometric data of victims. This necessitates intelligent, comfortable life jackets capable of monitoring wearers' kinetic states during submersion. Conventional life jackets provide only buoyancy and thermal insulation, lacking physiological monitoring capabilities that delay critical rescue decisions. Addressing this gap, as illustrated in Figure 9a, researchers developed an autonomous smart lifejacket system integrating six triboelectric sensors at the shoulders, elbows, and knees. After 72-h seawater immersion, the system retains 50% tensile strain performance with omnidirectional contact-separation sensing. It captures subtle limb movements, enabling convolutional neural network (CNN) classification of four submersion states: swimming (normal thermoregulation, active survival), distress signaling (core temperature decline), shivering (hypothermia phase I muscle discoordination), and immobility (hypothermia phase II cognitive impairment). Rescue teams receive real-time status alerts within 3 s, substantially improving maritime survival rates through enhanced operational precision [64].

TENG-based wearable systems demonstrate unique advantages for motion analysis by directly converting biomechanical energy during joint flexion or muscle contraction into electrical signals. As illustrated in Figure 9b, researchers engineered a highly elastic

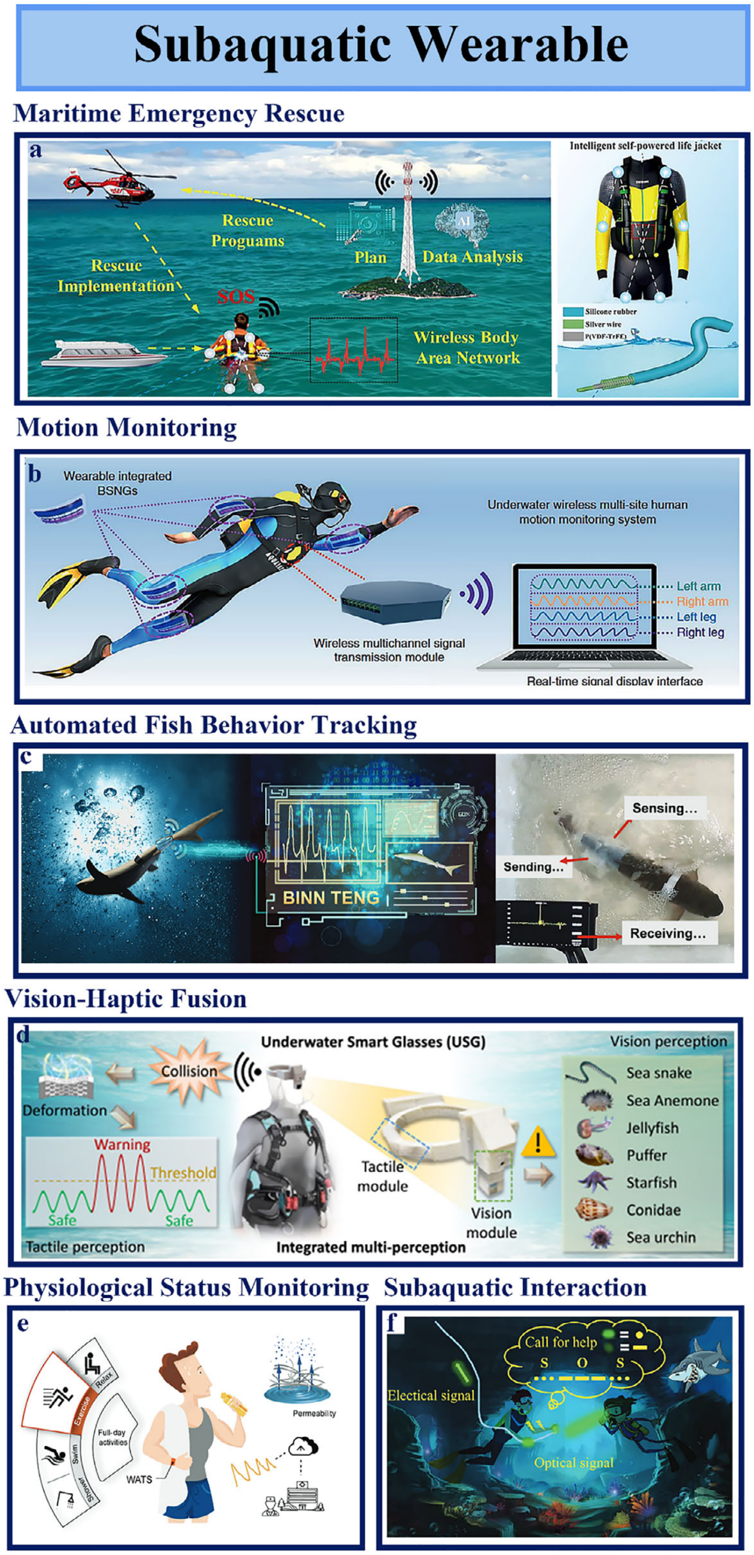

FIGURE 9 | Subaquatic wearable (a) Rescue process diagram and sensor structure diagram. Reproduced with permission [64]. Copyright 2024, John Wiley and Sons. (b) Illustration of underwater wireless multi-Station human motion monitoring system. Reproduced with permission [156]. Copyright 2019, Springer Nature. (c) Underwater wireless fish motion monitoring system based on FDSP, with schematic diagrams illustrating the system architecture and operation for fish behavior monitoring. Reproduced with permission [162]. Copyright 2022, John Wiley and Sons. (d) Underwater smart glasses for hazard detection system based on tactile and visual perception. Reproduced with permission [159]. Copyright 2024, Elsevier. (e) Continuous all-day monitoring of wearer's status with real-time data acquisition to assist doctors in diagnosis and treatment. Reproduced with permission [160]. Copyright 2024, Springer Nature. (f) Photonic coordinated communication using Morse code for triboelectric pressure sensors in aquatic environments. Reproduced with permission [161]. Copyright 2024, John Wiley and Sons.

triboelectric sensor positioned at elbow/knee joints with multi-channel wireless transmission. Pool tests distinguish breaststroke, freestyle, backstroke, and treading water through characteristic waveforms, laying groundwork for underwater haptic feedback systems. Beyond human movement tracking, aquatic animal behavioral monitoring serves as a crucial ecosystem health indicator. Anthropogenic activities increasingly disrupt marine behavioral patterns; tracking tailbeat frequency anomalies in pollutant-exposed fish enables water quality early-warning systems [156]. Marine animals function as mobile sensing platforms whose autonomous mobility overcomes detection blind spots inherent in ship-mounted static sensors. As illustrated in Figure 9c, a fish-wearable monitoring platform leverages TENG mechanisms for consistent underwater operation, eliminating battery replacement needs. By reconstructing tail amplitude, oscillation frequency, and behavioral postures from signal characteristics, it identifies escape maneuvers and predatory behaviors. Accumulated caudal movement data simultaneously advances biomimetic robotic fish propulsion design, with expandable applications to marine mammal research [157].

Underwater personnel face multiple hazards including marine organism attacks and debris collisions, creating urgent demand for wearables enabling environmental awareness and operational efficiency. Conventional devices (e.g., smartwatches, earbuds) designed for terrestrial use fail underwater, while limited visibility compounds sensory constraints. As illustrated in Figure 9d, this makes visual-tactile fusion imperative: an innovative smart diving mask combines visual algorithms for detecting toxic organisms with head-mounted triboelectric collision sensors. Integrating AR optical pathways and microcontroller units provides real-time warning overlays. Sea trials validate accurate distinction between safe/impactful collisions at sediment concentrations <6g/L (accuracy declines with turbidity increase). This hybrid architecture extends threat detection range—tactile sensors address near-field collisions while visual processing handles distant biological threats—significantly reducing diver risks [158, 159].

Wearables drive transformative health monitoring paradigms by delivering continuous, personalized, actionable biometrics, shifting healthcare from reactive episodic assessment to proactive holistic management. Whereas conventional medicine relies on symptom-initiated consultations, modern sensors enable unobtrusive vital sign tracking. For prolonged subaquatic operations, as illustrated in Figure 9e, researchers developed a fully textile-based 3D interlocked triboelectric pressure sensor for precise epidermal pulse-wave monitoring across environments. It overcomes conventional e-textiles' humidity-induced performance degradation, reliably detecting motion states (exercise, rest, swimming, bathing), drowning risks, and cardiovascular parameters (underwater heart rate, hemodynamics), enabling remote medical intervention [160]. To enhance underwater interaction, as illustrated in Figure 9f, a carbon-nanotube-fiber-based stretchable self-powered mechanoluminescent fiber was engineered. Exhibiting coupled triboelectric-mechanoluminescent effects, it synchronously generates electrical signals and green visible light under 200% tensile strain. Different stretching amplitudes produce distinguishable voltage signals convertible to Morse code, establishing underwater optical-electrical communication. This innovation overcomes three limitations of traditional optoelectronic fibers—excessive mass, limited elasticity, and non-contact functional deficiency—yielding amphibious smart textiles for contactless human-machine interaction [161].

3.3 | Underwater Monitoring Networks

Continual breakthroughs in underwater sensing technologies propel humanity's exploration of deep-sea environments toward increasingly systematic and comprehensive frontiers. The establishment of underwater Internet of Things (IoT) networks spanning vast oceanic regions has become an imperative, fundamentally enabling real-time, continuous, and intelligent perception of critical environmental parameters [163–166]. Within this context, the strategic significance of high-performance real-time underwater monitoring networks is profoundly accentuated across three pivotal domains: National Security, where distributed monitoring networks constitute the backbone of coastal defense and maritime domain awareness systems, deploying high-precision sensor arrays for persistent surveillance and early warning in key maritime zones; Offshore Resource Development & Infrastructure Integrity Management, necessitating real-time structural health diagnostics for subsea structures (e.g., oil/gas platform foundations, pipelines, deep-sea production facilities), demanding dynamic acquisition of stress, deformation, and risk indicators to ensure long-term operational safety and maintenance optimization; and Marine Hazard Mitigation, wherein underwater data acquisition underpins precise forecasting of tsunamis, storm surges, and internal waves—particularly reliant on rapid, accurate capture and modeling of complex hydrodynamic fields (e.g., flow velocity, direction) to decipher disaster mechanisms, enhance prediction accuracy, and enable timely alerts. Collectively, these capabilities significantly mitigate threats to coastal infrastructure, maritime traffic, and human safety. To address these pressing needs in national security, engineering resilience, and disaster preparedness, cutting-edge research focuses on four core technological frontiers: real-time intelligent environmental monitoring, high-precision distributed underwater sensing, smart structural health diagnostics, and high-fidelity hydrodynamic field quantification.

Conventional underwater monitoring systems are constrained by limited temporal resolution, prohibitive maintenance costs, ecological disruption, and frequent battery replacements. Triboelectric sensing principles offer transformative advantages: leveraging low-cost, self-powered operation coupled with tactile transduction mechanisms enhances accuracy while minimizing environmental impact. As illustrated in Figure 10a, researchers have harnessed this potential to develop a cable-structured triboelectric sensor network. Nodes are vertically staggered and passively activated by mechanical disturbances, eliminating energy-intensive active signal emission. This configuration enables precise detection of submersible planar positioning, directional vectors, instantaneous velocity, and trajectories. Vertically distributed sensors capture depth information through an inverse correlation between signal amplitude and immersion depth, while waveform characteristics facilitate rudimentary object classification. A multi-channel signal processing module (LabVIEW platform) achieves real-time 3D target visualization, triggering red alerts upon sensor impact damage. This approach resolves key challenges in energy autonomy, spatial accuracy,

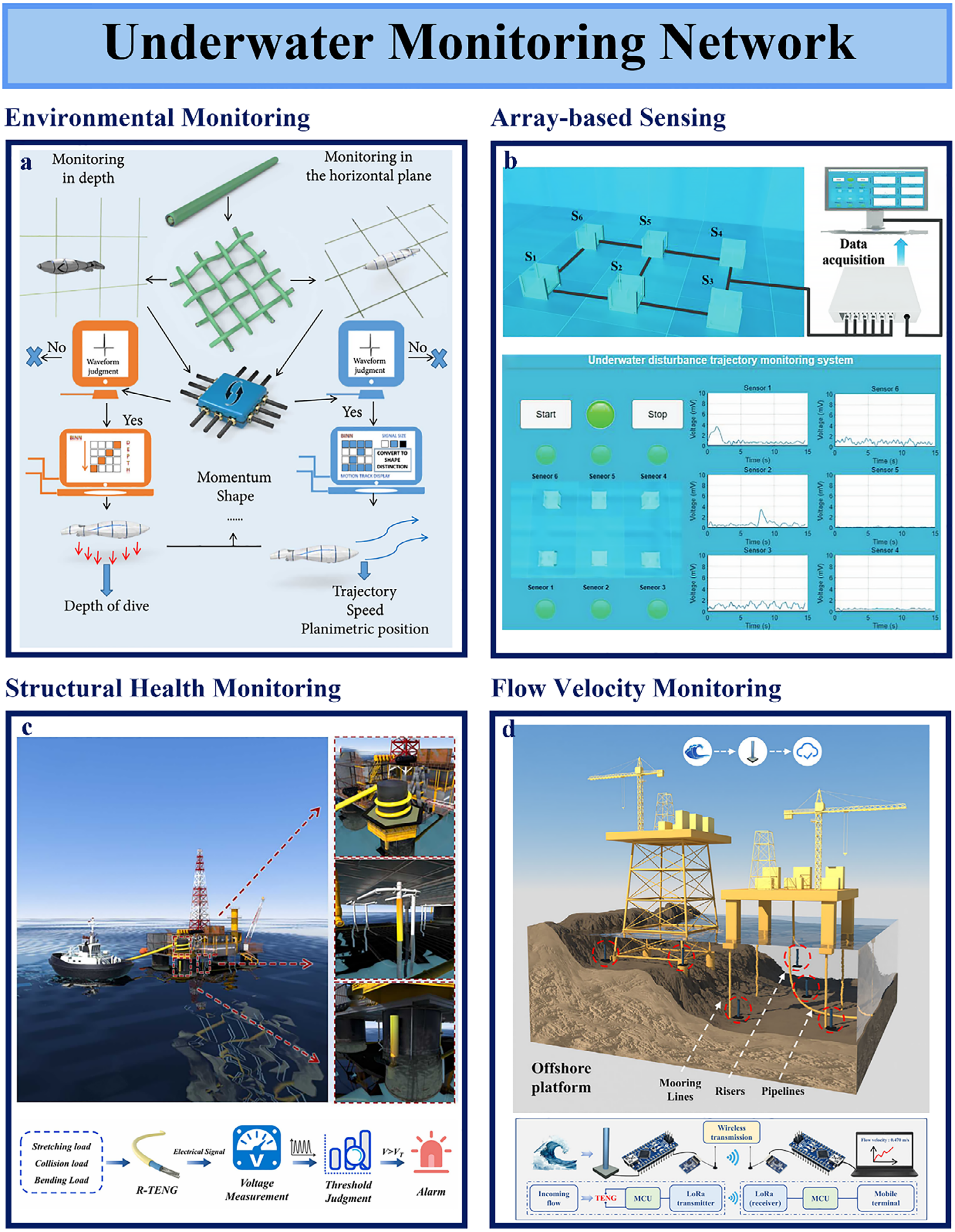

FIGURE 10 | Underwater monitoring network. (a) CConceptual diagram of real-time underwater object monitoring via a combined vertical and horizontal network. Reproduced with permission [167]. Copyright 2022, Springer Nature. (b) BLLS in disturbance source trajectory profiling, featuring logic block for trajectory display and angular trajectory monitoring by BLLS. Reproduced with permission [58]. Copyright 2024, John Wiley and Sons. (c) R-TENG applications and structure in marine monitoring, featuring typical uses, structural schematic, latex SEM image, fabrication process, and photo, illustrating system workflow. Reproduced with permission [168]. Copyright 2022, Elsevier. (d) Workflow of an underwater flow monitoring system based on CSTENG, showing its environmental monitoring application, response mechanism to flow excitation, and structural design (inner core and outer sheath) Reproduced with permission [169]. Copyright 2025, John Wiley and Sons.

and environmental robustness, establishing a new paradigm for marine exploration, rescue operations, and defense, pending further refinement in real-time multi-target signal processing [167].

Expansive maritime coverage demands sensor array deployment rather than isolated nodes. Researchers designed a biomimetic lateral-line inspired array operable when traditional sensors fail. Strategically positioned arrays detect pressure fluctuations generated by underwater vehicles (e.g., robotic fish, bio-mimetic seals, ROVs). Within the sensor grid, sequential passage through nodes S1S2S3 generates temporally resolved signals for real-time trajectory reconstruction. As illustrated in Figure 10b, phase-shift analysis discerns directional changes, with MATLAB interfaces enabling simultaneous trajectory visualization and alert generation, advancing subsea target localization. Compared to single-node systems, array deployments dramatically expand the spatial domain and functional dimensionality, enabling multi-parameter monitoring essential for underwater autonomous systems and marine IoT ecosystems [58].

Offshore engineering structures—oil/gas platforms, deep-sea installations, ship hulls, subsea pipelines—endure harsh marine environments involving severe weather, dynamic wave loading, corrosive currents, biofouling, collision impacts, and complex mechanical stresses. These cumulative loads precipitate structural deformation, fatigue cracking, and critical damage, jeopardizing safety and asset integrity. Predominant structural health monitoring (SHM) technologies face an existential challenge in marine settings: unsustainable energy supply. Traditional battery reliance or cabled power compromises long-term in situ, real-time monitoring viability, while intricate wiring heightens system fragility. Addressing this, as illustrated in Figure 10c, researchers devised a self-powered solution: rope-like stretchable TENG. Deployed along ship hulls, these sensors monitor mooring states via voltage escalations proportional to tensile loading under vessel oscillation; installation on platform support columns detects collisions; mounting on pipelines generates continuous voltage output quantifying bend deformation. This breakthrough surmounts the energy barrier for real-time marine structural monitoring, pioneering localized, facile-to-deploy, energy-autonomous condition assessment paradigms for critical offshore infrastructure [168].

Traditional flow velocity sensors face persistent limitations in precision, environmental interference resilience, and external power dependency. TENG emerges as disruptive energy-sensing integrated solutions for high-accuracy flow measurement. A core-sheath structured TENG was engineered, as illustrated in Figure 10d, utilizing innovative compliant material configurations and encapsulation for enhanced mechanical stability and environmental tolerance. Operating via vortex-induced vibration (VIV), fluid flow generates periodic von Kármán vortices downstream, inducing forced oscillations that transduce hydrodynamic energy into electrical signals. Output frequency exhibits strong linear correlation with flow velocity (correlation coefficient = 0.992 within 0.297–0.931 m/s range). Integrated LoRa-based wireless nodes incorporate microcontrollers (MCUs) converting raw frequencies into real-time velocity data for remote transmission via low-power wide-area networks (LPWAN). Sea trials validate its frequency-dependent response, exceptional environmental robustness, and self-sufficiency, heralding an era of high-precision active hydrodynamic sensing and enabling next-generation intelligent marine monitoring networks [169].

Underwater monitoring networks are fundamentally reconfiguring real-time oceanic perception paradigms through synergistic breakthroughs in self-powered sensing and intelligent distributed arrays. By resolving the core antagonism between pervasive spatial coverage and persistent energy constraints, they establish the technological bedrock for constructing minimally invasive, round-the-clock underwater IoT monitoring infrastructures.

4 | Conclusion and Perspective

Underwater resource development, information interaction, and exploration of unknown environments demand robust perception capabilities. Especially under low visibility, harsh hydrological conditions, and in confined spaces, the zero-light-dependency and near-field high-precision advantages of tactile sensing are fully activated. Combined with the self-powered characteristics and broad-spectrum material compatibility of triboelectric technology, this approach innovatively fills capability gaps left by traditional optical/acoustic sensing in blind-spot scenarios [34] This paper reviews recent advances in triboelectric-based underwater tactile sensors and discusses sensor design optimization from perspectives including: triboelectric principles, waterproof strategies, biomimetic structures, material properties, and data processing techniques. Current application scenarios are categorized into three primary domains: underwater mobile devices, subaquatic wearable, and underwater monitoring networks, with detailed perception mechanisms and sensitivity metrics systematically compared in Table 4. Despite significant progress in underwater tactile sensing technology, several challenges and issues still need to be addressed to fully realize its potential in enhancing underwater operations. These challenges involve algorithm optimization, durability, high sensitivity, miniaturization, and manufacturing process improvements, which are expected to be the main focus of future development in underwater tactile sensing technology.

4.1 | Durability

Compared to terrestrial environments, underwater conditions pose more stringent challenges for triboelectric tactile sensors. Ensuring their long-term stability and reliability requires breakthroughs in three directions. First, theoretically quantifying the effects of temperature fluctuations and salinity gradients on charge generation and transfer mechanisms is key to addressing signal attenuation. In the material field, multifunctional composite triboelectric layers that offer high durability, mechanical robustness, and efficient charge transfer capabilities need to be developed to withstand extreme underwater environments. Second, environmentally friendly materials, such as biodegradable biopolymers, should be prioritized to minimize potential environmental impacts while maintaining performance, promoting sustainable technological development [171, 172].

TABLE 4 | Recent advances in Triboelectric-Based Underwater Tactile Sensors.

Function	Working Mode	Friction Layer Material	Detection Range	Sensitivity	Accuracy	Scenario	Refs.
underwater material identification	SE	FEP/PE/Nylon/PU	5–160 N	0.195 V/kPa	98%	Underwater Robot	[55]
Trajectory Prediction	CS	FEP/Ink	0–0.5 m/s	0.2 V/(m/s)	81.2%	Underwater Robot	[145]
Pipeline Monitoring	CS	FEP/Ink	1–5 N	NA	NA	Underwater Robot	[59]
Wake Perception	CS	FEP/Ink	0.1–0.5 m/s	2.1 mV/Pa·m^{-1}	100%	Underwater Robot	[152]
Pose Estimation	CS	Cu/CNT/Silicone	1–17 N	1.8 V/N	NA	Underwater Robot	[54]
Emergency Rescue	CS	P (VDF-TrFE)	1–5N	NA	100%	Human Wearable	[64]
Motion Monitoring	SE/CS	Silicone/PDMS	NA	NA	NA	Human Wearable	[156]
Behavioral Analysis	CS	PTFE/Al	0.5°–180°/0.5–2 Hz	0.6V/0.5°	NA	Biological Wearable	[162]
Visual-Tactile Fusion	CS	PTFE/Cu	0.5–3m	NA	84.8%	Human Wearable	[159]
Health Detection	CS	PTFE/ACY/Silicone	0–2.5 kPa	0.433 V·kPa^{-1}	98.8%	Human Wearable	[160]
Underwater Interaction	CS	Ni-Cu/P (VDF-TrFE)	0%–200%	NA	NA	Human Wearable	[170]
Structural Health Monitoring	SE	Latex/Silicone	0%–140%/1–50 N/ 45°–180°	0.6 V/N	NA	Underwater Monitoring Network	[168]
Flow Velocity Monitoring	CS	Cu/Silicone	0.297–0.931 m/s	NA	NA	Underwater Monitoring Network	[169]
Array-based Sensing	CS	FEP/Ink	5.0–25.0 mm	NA	NA	Underwater Monitoring Network	[58]
Underwater Environmental Monitoring	CS	P(VDF-TrFE)/Ag	0–100 cm/10–50 cm/s	0.758 mV/Pa	NA	Underwater Monitoring Network	[167]

4.2 | High Sensitivity

High sensitivity is a critical characteristic to ensure that sensors can execute specified tasks accurately, especially in complex environmental conditions. Conversely, low sensitivity hinders functions like collision avoidance, as it cannot make accurate judgments at critical moments. A viable strategy to enhance sensor sensitivity is to employ novel composite materials. For example, using composite materials with porous structures can increase charge capture rates, and multi-layer stacking can enable highly sensitive responses to mechanical stimuli. Furthermore, specific material processing techniques can form microstructures on the sensor surface to improve sensitivity. Enhancing sensitivity is crucial for underwater detection, particularly when performing complex tasks [173, 174].

4.3 | Algorithm Optimization

Despite the support of deep learning in analyzing nonlinear information, achieving multimodal perception, fault diagnosis, and real-time prediction to complete the monitoring feedback loop, the accuracy and robustness of these systems still need further improvement. To this end, new multimodal fusion algorithms can be developed to integrate sensing data from other types of sensors, while enhancing the algorithm's noise suppression capability and optimizing key feature extraction efficiency in underwater environments. Continuous iteration and optimization of algorithms will significantly drive the advancement of triboelectric-based underwater tactile sensing technologies [175, 176].

4.4 | Miniaturization

The rapid growth of underwater interaction and marine rescue applications continues to push wearable sensors toward miniaturization and high integration. This trend offers dual benefits: on the one hand, it significantly improves wearability and biocompatibility, aiding in situ monitoring of vital signs and precise behavior information capture; on the other hand, it extends to space-constrained scenarios, such as implantable biosensor nodes and miniature underwater robotic joint sensors. However, the physical scale reduction inevitably leads to performance constraints—miniaturization results in reduced effective frictional area and diminished charge transfer efficiency. To overcome this bottleneck, advancements in micro-nano manufacturing techniques are urgently needed to construct high-precision frictional structure arrays at sub-millimeter scales. Concurrently, interface charge enhancement technologies should be developed to balance the conflict between size reduction and functional maintenance. The future strategy of deeply integrating precision manufacturing and smart materials in miniaturization will be a core technological pathway for overcoming spatial limitations and realizing pervasive sensing in underwater sensor devices [177–179].

4.5 | Industrialization

The industrialization process poses significant challenges for the future development of underwater triboelectric tactile sensors, particularly in large-scale deployments of underwater IoT systems. Building a comprehensive monitoring network requires the dense placement of numerous sensor nodes, but the high manufacturing costs severely hinder progress. Breaking through this bottleneck requires a multi-pronged approach. In terms of materials, exploring low-cost alternatives to reduce unit costs while ensuring core performance is essential. At the manufacturing level, implementing standardization and modularization can reduce performance discrepancies across batches and improve yield rates. During the research and design phase, maintenance requirements should be prioritized by incorporating easy-to-replace structures and maintenance interfaces to reduce post-operation complexity. On the ecological collaboration front, resources from fields like marine engineering, communication, and material science should be integrated to promote technological integration and application ecosystem development, accelerating the unveiling of deep-sea mysteries [23, 180, 181].

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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