Received: 19 June 2025 | Revised: 4 September 2025 | Accepted: 23 September 2025 | Published online: 14 October 2025

REVIEW

Smart Wearable Technology
2026, Vol. 2, A16, 12 Pages
DOI: 10.47852/bonviewSWT52026516

BON VIEW PUBLISHING

Integrating Marine Mussel Distribution and Carbon Sequestration with Smart Wearable Technology: A Novel Intersection for Blue Carbon Monitoring and Environmental, Social, and Governance Innovation

Chee Kong Yap[1,*], Musefiu Adebisi Tiamiyu[2], Kennedy Aaron Aguol[3], Meng Chuan Ong[4,5], Wan Mohd Syazwan[1], Noor Azrizal-Wahid[1], Faridah Qamaruz Zaman[1], Rosimah Nulit[1], Yoshifumi Horie[6], Mohamad Saupi Ismail[7], Ahmad Dwi Setyawan[8,9], Krishnan Kumar[10], Wan Hee Cheng[10] and Chee Seng Leow[11]

[1]*Department of Biology, Universiti Putra Malaysia, Malaysia*

[2]*Department of Biosciences and Biotechnology, University of Medical Sciences, Nigeria*

[3]*Centre for the Promotion of Knowledge and Language Learning, Universiti Malaysia Sabah, Malaysia*

[4]*Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Malaysia*

[5]*Ocean Pollution and Ecotoxicology (OPEC) Research Group, Universiti Malaysia Terengganu, Malaysia*

[6]*Graduate School of Maritime Sciences, Kobe University, Japan*

[7]*Fisheries Research Institute, Malaysia*

[8]*Department of Environmental Science, Universitas Sebelas Maret, Indonesia*

[9]*Biodiversity Research Group, Universitas Sebelas Maret, Indonesia*

[10]*Faculty of Health and Life Sciences, INTI International University, Malaysia*

[11]*Humanology Sdn Bhd, Malaysia*

Abstract: Marine mussels contribute to blue carbon through biogenic calcification and filtration that enhance carbon burial in coastal sediments. Their ecological role is important yet under-quantified in many regions. Here, we present a practical framework that links mussel ecology with smart wearable sensing to enable continuous in situ observation of environmental drivers and organism responses relevant to carbon sequestration. We specify sensor modalities such as ion-sensitive field effect transistor pH, optical dissolved oxygen, temperature, salinity, turbidity, and inertial shell gape sensing. We detail device form factors for mussel-attached tags and habitat-mounted modules on buoys and autonomous platforms. Mussel-inspired adhesives and hydrogels are used as functional coatings for underwater attachment, encapsulation, and biofouling resistance. We describe renewable energy harvesting, energy storage, and power management for long deployments, together with an Internet of Things data pipeline, edge preprocessing, and cloud-based time series modeling and anomaly detection. We set measurable accuracy and resolution targets and a validation plan against standard instruments. The approach supports environmental, social, and governance reporting, aquaculture management, and citizen science. We discuss anti-biofouling strategies, ethics of bio-tagging, comparison with conventional monitoring, and future directions for robust blue carbon observatories.

Keywords: marine mussels, blue carbon, carbon sequestration, wearable sensors, biomimetic adhesives, Internet of Things, environmental, social, and governance (ESG)

***Corresponding author:** Chee Kong Yap, Department of Biology, Universiti Putra Malaysia, Malaysia. Email: yapchee@upm.edu.my

1. Introduction

Blue carbon ecosystems such as mangroves, seagrasses, bivalve beds, and associated sediments are central to climate mitigation in coastal zones [1–6]. Marine mussels including *Mytilus edulis* and *Perna viridis* sequester carbon through calcium carbonate shell formation and through filtration that transfers particulate organic carbon to the benthos, where it can be buried [7–10]. Mussel beds also stabilize sediments and improve water clarity, which indirectly supports other carbon-storing biota and increases the likelihood that organic matter is preserved in place [11, 12]. Despite this importance, continuous field quantification of mussel-mediated carbon processes is still limited due to the temporal and spatial heterogeneity of coastal systems and the challenges of long-term in situ observation [13–15].

Recent advances in wearable sensing and flexible materials, originally developed for health and agriculture, can now be adapted for marine ecological monitoring [16–19]. We integrate ecology, sensor engineering, and biomimetics to propose a practical mussel-centered monitoring framework that enables real-time observation of conditions and responses tied to carbon sequestration. The objectives are to define sensor types and form factors, show how mussel-inspired materials can harden devices for underwater use, describe power and data architectures for reliable long-term operation, set measurable performance targets and validation, and position the approach within environmental, social, and governance (ESG) applications and conventional ocean observing.

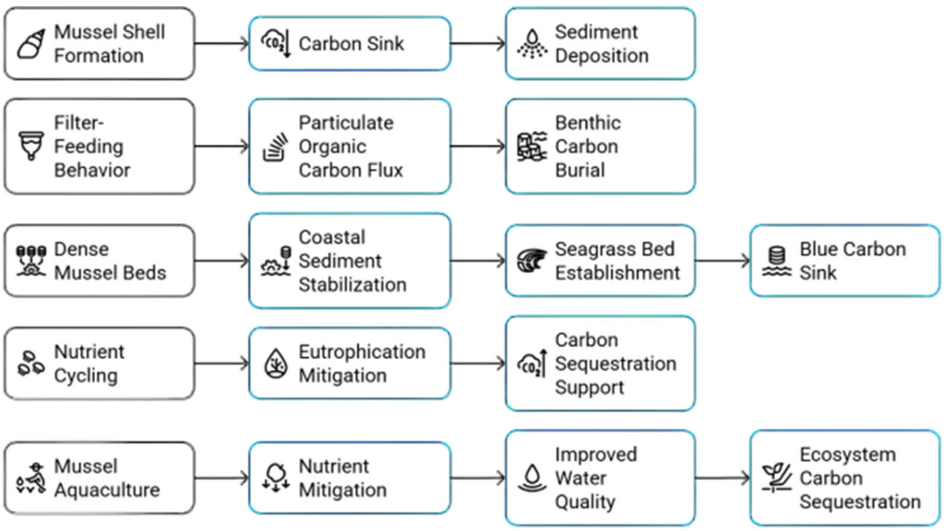
We clarify that “wearable” in this study refers to nonhuman deployments. We use two device classes: shell-mounted bio-tags and habitat-embedded modules [20]. The bio-tags are small, smooth packages that adhere to the exterior shell with a mussel-inspired primer and proven tag adhesives, a practice shown to allow secure retention with low short-term impacts when applied correctly [21]. Their dimensions and mass are kept well below accepted limits for attached tags, with hydrodynamically low-profile geometry guided by tag-design principles that minimize drag and disturbance [22, 23]. Habitat-embedded modules strap to aquaculture ropes, pilings, or small buoys within the reef so they sample the same conditions the mussels experience. Human-worn kits are used only for deployment, validation, or opportunistic sampling. This framing makes clear that our smart wearables function as animal-borne and habitat-integrated sensors to capture the mussel microenvironment continuously [24, 25].

We can instrument mussels and their immediate habitat with complementary biosensors that resolve proxies of carbon sequestration in real time: shell-mounted inertial units and Hall-effect valvometry track valve gaping as a proxy for filtration, while infrared photoplethysmography measures cardiac activity as an indicator of metabolic state; these biometric streams are paired with co-located environmental channels for pH, dissolved oxygen (DO), temperature, salinity, turbidity, and local flow to contextualize organismal responses and to drive mass-balance models of filtration, respiration, and calcification [13]. Practically, low-profile tags and nearby modules sample continuously in situ and relay data to a gateway, a configuration already demonstrated in multi-mussel deployments that use paired accelerometer–magnetometer units for valve kinematics and solar-powered backhaul; these proof-of-concept systems show that distributed “Fitbit-for-mussels” networks can stream behavioral and physiological data from dozens of animals simultaneously for environmental early warning and ecosystem monitoring [10, 26].

2. Roles of Marine Mussels in Carbon Sequestration

Figure 1 shows the flowchart illustrating the sequential framework for wearable biosensor deployment in mussel-based environmental monitoring. Mussels sequester carbon by fixing dissolved inorganic carbon into shells and by promoting organic carbon burial through filtration and biodeposition. First, shell calcification immobilizes carbon as calcium carbonate that can persist in sediments over long time scales [8]. Second, filtration removes suspended particles and enhances the flux of particulate organic carbon to the seabed, where it can be stabilized within cohesive sediments and biogenic structures [10]. Mussel beds also baffle currents and reduce resuspension, indirectly supporting seagrass and other primary producers that add to blue carbon

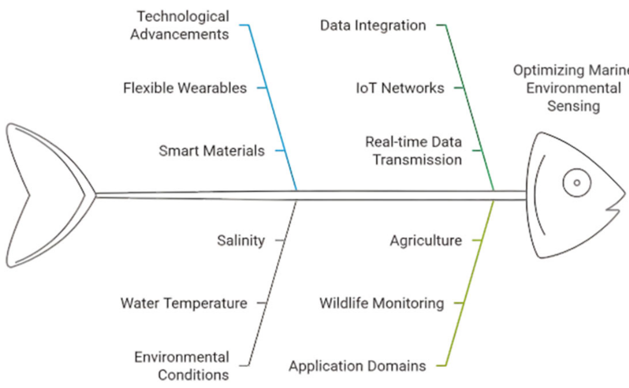
Figure 1
Role of marine mussels in carbon sequestration



stocks [11, 12]. Environmental stressors such as warming, eutrophication, acidification, and pollutants can impair these functions by altering feeding, byssal attachment, and shell growth [27, 28]. Continuous observation at the organism and habitat scales is therefore needed to resolve drivers and responses and to inform management.

Figure 1 illustrates the sequential framework for wearable biosensor deployment in mussel-based environmental monitoring. The process begins with sensor design and fabrication, progresses through laboratory calibration and field deployment, and advances to data acquisition from environmental variables such as water quality and mussel health. The collected data undergo preprocessing and validation, followed by analysis using statistical and modeling tools, which support environmental assessment and decision-making for carbon sequestration management. The structured flow highlights the integration of engineering, fieldwork, and data analytics in creating a scalable, real-time environmental monitoring system.

Figure 2
Enhancing marine environmental sensing with wearable technologies



2.1. Environmental stressors and device robustness

We recognize that pollutants can directly weaken mussel attachment and thereby affect both animal welfare and data quality, so we incorporated this risk into design and operations. Laboratory exposures show that perfluorooctanoic acid and nano-titanium dioxide reduce byssal thread number and length, narrow thread diameters, shrink adhesive plaque area, and lower breaking force, with additional impairment observed when $nTiO_2$ co-occurs with warming or dietary exposure [17]. Microplastics also reduce attachment strength and thread production in blue mussels, consistent with broader evidence that degraded conditions undermine byssus performance and condition [29, 30]. These findings motivate robust attachment that does not rely on the animal's own byssus: our tags use fully synthetic, mussel-inspired chemistries such as polydopamine primers and related coatings that adhere underwater and are manufactured independent of natural byssal supply, although surface contamination can still reduce adhesion and must be mitigated with protective, self-cleaning layers and site-specific maintenance [21, 30]. In short, we treat byssal degradation as both a monitoring target and an engineering constraint, using synthetic adhesives and antifouling interfaces to maintain secure attachment, while the sensors themselves provide early warning of stress through abnormal valve behavior or detachment signatures [17, 30].

3. Smart Environmental Sensing with Wearable Technologies

3.1. Sensor modalities and operational principles

Figure 2 shows the fishbone diagram illustrating key factors in optimizing marine environmental sensing through wearable and smart material technologies. The monitoring system uses multiparameter sensing at two levels. Environmental sensors measure temperature, salinity, pH, DO, and turbidity near or within mussel beds. Organism-level sensors measure shell gape dynamics, movement, and other proxies of filtration and growth.

For pH, we consider ion-sensitive field effect transistor probes that offer fine resolution suitable for field deployments when combined with temperature compensation and careful calibration. For DO, we consider optical optodes based on luminescence quenching that provide stable measurements with low drift. Electrical conductivity sensors inform salinity. Low noise thermistors provide temperature. Optical backscatter or nephelometry provides turbidity. A compact inertial unit or a magnetic Hall-effect pair mounted across the valves resolves shell opening and closing frequency and amplitude as a proxy of filtration activity. All sensors are available in miniature formats and can be combined within a single node.

Figure 2 illustrates key factors in optimizing marine environmental sensing through wearable and smart material technologies. The diagram maps three main factor groups: technological advancements, including flexible wearables and smart materials; environmental conditions, such as salinity and water temperature; and data integration, encompassing Internet of Things (IoT) networks and real-time data transmission. These elements converge within multiple application domains—notably agriculture, wildlife monitoring, and marine ecosystem assessment, thus demonstrating how integrated sensor networks can enhance environmental data collection and inform sustainable management practices.

3.2. Physical form factors and integration

We clarify the focus of wearable use. Devices are designed for mussel-attached and habitat-mounted deployment, not for human clothing. Three form factors are considered.

1) Mussel-attached tag. A sealed capsule, a few centimeters in length, that adheres to the outer shell. It carries one or more sensors such as gape and temperature and a short-range transmitter. Mussel-inspired adhesive and hydrogel layers provide strong underwater attachment and a fouling-resistant interface.
2) Buoy-mounted module. A rugged node fixed on a small surface or subsurface buoy located within a mussel bed. It carries a full suite of environmental sensors, energy harvesters, storage, and communications. This provides continuous context data with high uptime.
3) AUV attachment. A small pod mounted on an autonomous underwater vehicle (AUV) for periodic transects across mussel habitats to map spatial gradients and to intercompare with fixed nodes.

Electronics use conformal coatings and an encapsulating shell. Mussel-inspired hydrogels serve as soft encapsulants over sensor heads, preserving access to the medium while reducing fouling and mechanical shock.

3.3. Textile and optical elements for marine use

Side-emitting polymer optical fibers (POFs) can be integrated into straps or bands to sense bending and strain by monitoring distributed light leakage as the fiber curvature changes, which is useful for flexible mounts and for structural monitoring of aquaculture ropes [19]. Conductive textile elements provide piezoresistive sensing of stretch and pressure when coated or woven with conductive fibers. For marine use, all textile and optical elements are enclosed within waterproof, biofouling-resistant jackets and are used on buoys or structures rather than on humans to avoid ambiguity.

3.4. Sensors attached to mussels

We can use very small, streamlined tags to record individual behavior and physiology at high resolution. Shell-mounted devices include passive identifiers such as PIT or RFID tags and active packages with miniature accelerometers or Hall-effect gape sensors. Tags are bonded to the exterior shell with nontoxic adhesives or fitted with custom clamps, so there is no drilling or tissue contact. Prior studies show that such attachments can be retained reliably with low short-term mortality when applied with appropriate adhesives and geometries and that small tag sizes do not measurably impair survival, growth, or movement [31, 32].

3.5. Sensors in the surrounding environment

To minimize intrusion, most measurements come from compact modules placed within the mussel bed on ropes, pilings, or small buoys and from AUV pods when transects are needed. These nodes measure the same water the mussels experience and provide the environmental context for the bio-tags. In sensitive settings or with protected species, we rely entirely on habitat modules and omit on-animal tags.

3.6. Mitigating potential influences

Attachment methods and materials are tested for each species to ensure that shells can open fully and that burrowing and byssus production are not impeded. Device mass stays well below conservative thresholds, and packages have smooth, low-profile shapes. Individuals are monitored after tagging; any sign of stress triggers immediate removal or redesign. All work follows site-specific ethical review and retrieval plans that ensure every device is recovered at the end of deployment [32, 33].

4. Mussel-Inspired Materials and Functional Roles in the Device

Figure 3 shows the interlinked properties and applications of mussel-derived biomaterials. Mussel-inspired design is used as a functional engineering element. Adhesive coatings based on catechol chemistry provide strong wet adhesion to shells and substrates while retaining elasticity to endure waves and small shell movements [34, 35]. A thin adhesive layer serves as the interface for attachment. Above this layer, a pH-responsive hydrogel coating mimics mussel mucus and creates a hydrated barrier that reduces the settlement of fouling organisms while protecting optical and electrochemical surfaces. The hydrogel can self-heal minor abrasions and acts as a soft encapsulant for sensor heads and seams. These materials together improve mechanical stability, water sealing, and biofouling resistance in turbulent shallow waters. We emphasize that the device uses synthetic biomimetic materials and does not depend on harvesting natural byssus.

Figure 3
Mussel-inspired innovations in wearable materials

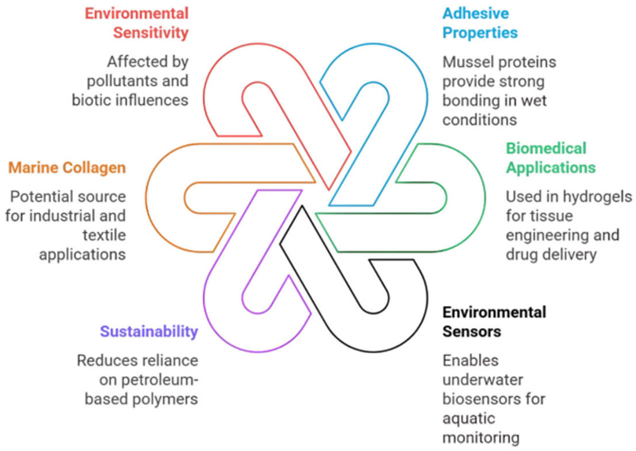


Figure 3 shows interlinked properties and applications of mussel-derived biomaterials. The diagram illustrates six key aspects of mussel-based materials: Environmental sensitivity, which highlights susceptibility to pollutants and biotic influences; marine collagen, a potential source for industrial and textile applications; sustainability, which reduces reliance on petroleum-based polymers; adhesive properties, reflecting the strong wet-condition bonding capacity of mussel proteins; biomedical applications, such as use in hydrogels for tissue engineering and drug delivery; and technological integration, where mussel-based materials enable underwater biosensors for aquatic monitoring. The interlinked design emphasizes the multifunctional and interconnected nature of these properties in advancing marine biotechnology and sustainable material science.

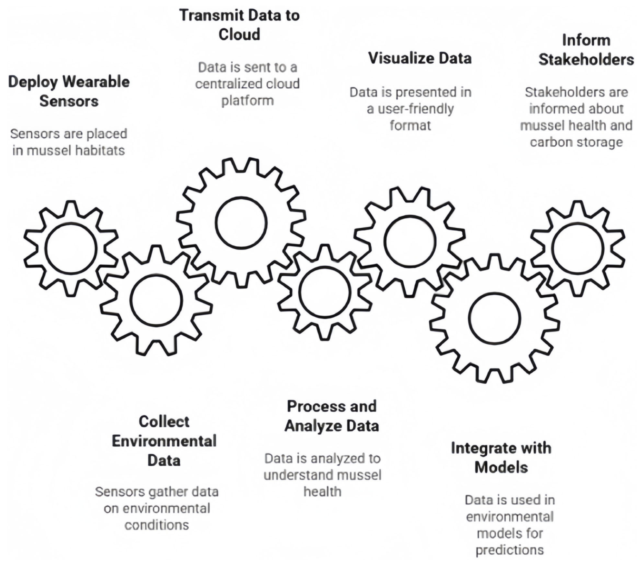
4.1. Wearable sensor design

We can design a family of modular, marine-ready wearable sensors that pair robust water-chemistry transducers with form factors tailored to mussel habitats: miniaturized ISFET pH sensors and optical DO optodes provide stable, accurate in situ measurements (ISFET resolution ~±0.02 pH units) and ~±0.1 mg L^{-1} O_2 precision, respectively [36]. Nodes are packaged either as compact shell-mounted tags or as pods integrated on AUVs and buoy frames to extend spatial coverage; shell tags are flexible, rounded patches that incorporate Hall-effect gaping sensors and, where flow permits, micro-ISFET pH, while habitat modules mount on pilings or buoys with replaceable optical windows and sealed cable glands. Core physicochemical channels include ISFET pH, luminescent optode DO, four-electrode conductivity for salinity, precision thermistors for temperature, and optical backscatter for turbidity. Each node uses a mussel-inspired hydrogel with catechol functionality as a thin, elastic encapsulant that waterproofs electronics, presents an antifouling surface, and provides a self-adhesive interface to wet substrates; a complementary mussel-protein-inspired adhesive layer supplies high shear strength while resisting barnacle and algal settlement, keeping devices secure and functional over long deployments in dynamic conditions. Integration employs polychlorinated biphenyls conformal coating, polydopamine-primed encapsulation, and connector strain relief to protect sensors and optics in seawater and under handling [37, 38].

4.2. Biomaterials integration

We can integrate mussel-inspired materials at two levels to improve underwater reliability and longevity: a thin catechol-rich adhesive primer on the housing that forms strong, compliant bonds to wet shells or substrates and a protective hydrogel overcoat that is pH-responsive, zwitterionic, and antifouling. The primer, modeled on mussel byssus chemistry, maintains adhesion under cyclic loading and shell flexure, while the hydrogel swells to create a hydration barrier that discourages settlement, sheds early biofilms through its slippery, dynamic surface, and self-heals minor damage to preserve sealing and signal quality. In practice, we pair a polydopamine primer with either a silicone or a zwitterionic foul-release top layer depending on optical and mechanical needs, and we add sacrificial pads for shell tags where appropriate. Together, these layers secure the device in turbulent conditions, limit corrosion and fouling-induced drift, and extend maintenance intervals while maintaining data fidelity [39, 40].

Figure 4
Mussel monitoring framework



5. System Architecture and Data Pipeline

Figure 4 shows the cycle diagram illustrating the operational workflow of wearable sensor integration for monitoring mussel health and carbon sequestration.

Figure 4 shows the operational workflow of wearable sensor integration for monitoring mussel health and carbon sequestration.

Figure 4 presents a closed data-lifecycle for mussel-habitat monitoring arranged radially around a central gear that symbolizes the system engine. At the lower left, sensors gather data on environmental conditions such as temperature, salinity, pH, DO, turbidity, and flow. At the far left, those sensors are shown as being physically placed in mussel habitats, indicating in situ deployment on reefs, pilings, or nearby infrastructure. At the top left, data is sent to a centralized cloud platform, which implies that a gateway or buoy aggregates packets from multiple nodes and forwards them to cloud storage and processing. At the top right, data is presented in a user-friendly format, suggesting dashboards and visualizations that turn raw streams into maps, timelines, and alerts. To the right, stakeholders are informed about mussel health and carbon storage, making the communication of indicators to managers, farmers, regulators, and the public an explicit objective. At the lower right, data is used in environmental models for predictions, connecting the live feed to forecasting tools that estimate near-term risk or long-term trends in habitat condition and carbon flux. At the bottom center, data is analyzed to understand mussel health, which closes the loop by translating measurements into biological status such as stress, growth, or filtration activity. The circular layout emphasizes that sensing, transmission, analysis, modeling, visualization, and decision support operate as a continuous cycle: deployments generate measurements, the platform standardizes and analyzes them, results inform people and models, and those insights guide subsequent monitoring and management.

5.1. Power harvesting, storage, and management

Power is the limiting factor for remote long-duration monitoring. We combine ambient energy harvesting, ample storage, and strict power budgets. Piezoelectric harvesters on buoy tethers and mounts convert wave-induced motion to electricity. In shallow sites with adequate light, underwater-tolerant photovoltaic cells contribute to daytime charging. Harvested energy is stored in a rechargeable lithium-polymer (Li-Po) cell in the range of two to three ampere hours, buffered by a supercapacitor to handle short bursts for transmission or a mechanical wiper. Firmware uses duty cycling. The microcontroller and radio remain in deep sleep between sampling epochs. Sensors are powered only for short acquisition windows. Transmission windows are scheduled and brief. This design reduces average current draw so that harvested energy can sustain operation.

5.2. Edge preprocessing and cloud analytics

Raw signals are conditioned on the device. Temperature compensation is applied to pH and DO. Salinity corrections are applied to DO. Digital filters suppress high-frequency noise. The device computes short-interval averages and quality flags, then transmits compact packets to a nearby gateway. Basic edge anomaly flags are raised when a variable crosses set limits to allow immediate alerts.

A shore or buoy gateway forwards data to the cloud. Time series models then capture trends and anomalies. We will use long short-term memory (LSTM) neural networks to forecast expected values given recent histories and to detect deviations in pH and DO that matter for calcification and respiration. Unsupervised clustering such as k-means or density-based methods group multivariate states to identify unusual environmental regimes. A dashboard visualizes live conditions and the derived indicators that relate to carbon sequestration such as shell activity indices and turbidity changes during filtration peaks.

5.3. Network synchronization and communication

The underwater network balances synchronization and energy through scheduled operation. Nodes sample and transmit in coordinated time slots set by a gateway timing beacon. Time Division Multiple Access reduces collisions while minimizing radio on time. Mussel tags send short packets to a local gateway using low-power radio at very short range within farms or acoustic pings when radio is impractical. The gateway, which has larger energy harvesters, handles backhaul to shore.

We run the network on strict duty cycling with synchronized wake windows so each node senses and transmits only in brief, scheduled intervals and then returns to sleep. A master clock at a surface buoy with GPS or a designated leader node coordinates time and assigns transmission slots using time division multiple access, so collisions are rare and idle listening is minimized. The synchronization protocol is delay tolerant and low message by design for acoustic channels with long propagation, drawing on methods that account for drift prediction and factor graph estimation to keep clocks aligned with very few exchanges [41, 42]. To reduce radio or acoustic use, each tag logs high-rate data locally and transmits summaries or event snippets, while a nearby gateway concentrates traffic and forwards batches to shore. Edge devices handle simple filtering, compression, and thresholding, and the cloud performs heavier analysis and model updates, so the nodes spend most of their time in deep sleep, following proven edge-computing patterns for energy-constrained systems [43].

Long life comes from combining efficient electronics with ambient energy harvesters. In shallow sites, we add underwater photovoltaics, and across sites, we mount piezoelectric or compliant wave harvesters and buffer their output with a supercapacitor ahead of a rechargeable cell, approaches shown to deliver useful power from waves and to extend mission duration without frequent battery swaps [44, 45]. The system tolerates temporary loss of sync or links because every record is timestamped and can be realigned at ingest. Together, the scheduled access, low-message synchronization, local logging with gateway aggregation, and hybrid harvesting keep energy use low while preserving time alignment and reliable data return in underwater conditions [41–44].

5.4. IoT data pipeline

We can run a staged pipeline that balances on-device responsiveness with cloud-scale analysis: at the edge, the ISFET pH voltage is digitized, de-noised with a short digital filter, and corrected in real time for temperature; optical oxygen readings are likewise corrected for temperature and salinity with standard oceanographic formulas, and short-interval averaging compresses the stream before transmission. Preprocessed packets travel over low-power Radio frequency (RF) to a nearby buoy or shore gateway in shallow water, or over acoustic telemetry in deeper sites, then on to a base station or cloud server for aggregation. Lightweight edge analytics raise immediate alerts using thresholds, one-class Support Vector Machine, or density-based local outlier detection such as Local Outlier Factor to flag unusual conditions [5, 46]. Cloud services handle the heavier work: an Long Short Term Memory (LSTM) model learns diurnal and tidal patterns to forecast expected values and detect subtle deviations in multivariate time series, while unsupervised clustering such as k-means or Density Based Spatial Clustering of Applications with Noise (DBSCAN) groups environmental states and isolates outliers; models are retrained centrally and updated to devices as rules or parameters, keeping edge computation and energy use low while preserving real-time responsiveness [43].

6. Performance Targets and Validation Plan

We define measurable targets so that monitoring quality is transparent.

1) Accuracy and precision. pH accuracy within plus or minus 0.02 units after temperature compensation. DO accuracy within plus or minus 0.1 milligram per liter. Temperature accuracy within plus or minus 0.1 °C. Turbidity repeatability within a few nephelometric turbidity units in the low range.
2) Temporal resolution. Five- to ten-minute sampling for environmental sensors. Shell gape at one hertz with on-device summarization to minute-level features.
3) Spatial resolution. One node per ten to twenty square meters across beds to resolve microhabitat gradients.
4) Validation. Laboratory calibration against buffers, Winkler titrations, and reference thermometers. Field cross-checks with a calibrated Conductivity–Temperature–Depth (CTD) profiler package at multiple depths and times. Periodic grab samples for dissolved inorganic carbon, total alkalinity, spectrophotometric pH, and dissolved oxygen (DO) for bias tracking. Biological validation by measuring shell growth and collecting short sediment cores below beds to relate sensor-indicated conditions to biogenic calcification and organic carbon burial. Discrepancies will be used to update calibration and conversion functions.

6.1. Performance targets and validation

We can set explicit performance targets and a clear validation plan. Each pH node is specified to achieve about ±0.02 pH units, DO to ±0.1 mg L^{-1} across 0–20 mg L^{-1}, and temperature to ±0.1 °C, with sampling every five to ten minutes and a deployment density of roughly one sensor per ten to twenty square meters to resolve microhabitat variability across mussel beds. Before field work, all sensors are bench calibrated against certified references, and at the site, we run side-by-side comparisons with a calibrated CTD and collect discrete samples for spectrophotometric pH, Winkler DO, dissolved inorganic carbon, and total alkalinity to quantify any drift or bias. We then ground truth carbon flux inferences against independent measurements, such as shell growth and sediment core carbon, and finally check that aggregated flux estimates are consistent with established models for bivalve systems. This combination of best-practice calibration, CTD cross-casts, and discrete reference analyses follows community guidance for ocean CO_2 system measurements and DO determination and provides a transparent accuracy check for the wearable network [47–49].

7. Antifouling and Durability

Biofouling is a primary failure mode. We use three complementary strategies. First, a mussel-inspired hydrogel topcoat reduces settlement on sensor faces by forming a hydrated, low-energy surface. Second, a small UV-C light-emitting diode (LED) near the sensing window activates on a schedule for brief exposure to suppress early biofilm formation without toxic release. Third, a compact mechanical wiper sweeps across optical windows once or twice daily to remove early deposits. The wiper uses a soft blade so it does not scratch optics and is geared for low-energy use. All exposed metals use corrosion-resistant alloys, and all seams are double sealed. These measures extend service intervals and preserve data quality.

8. Comparison with Conventional Monitoring

Conventional systems such as CTD profilers and fixed stations deliver precise, calibrated measurements and, when moored, can operate for many months with robust antifouling and large energy reserves. They excel at vertical profiling and establishing trusted baselines, but they sample sparsely in space and time relative to the fine-scale heterogeneity inside a mussel bed, so short events or meter-scale gradients can be missed by infrequent casts or a single fixed site. Our wearable network inverts that geometry: many small nodes sit on shells and nearby structures, streaming measurements continuously and exactly where the organisms live, so microhabitat variability and rapid dynamics are captured in real time. The trade-offs are real. Miniaturized sensors are more susceptible to drift and fouling and have tighter energy budgets, so they demand careful calibration, antifouling, and power management, and their distributed streams require cloud analytics to fuse and quality-control the data. For these reasons, we treat wearables as complementary rather than replacement tools: wearables provide dense, organism-proximal time series for event detection and process studies, while CTDs, gliders, and fixed stations supply the broader, highly accurate context for cross-checks and calibration [50].

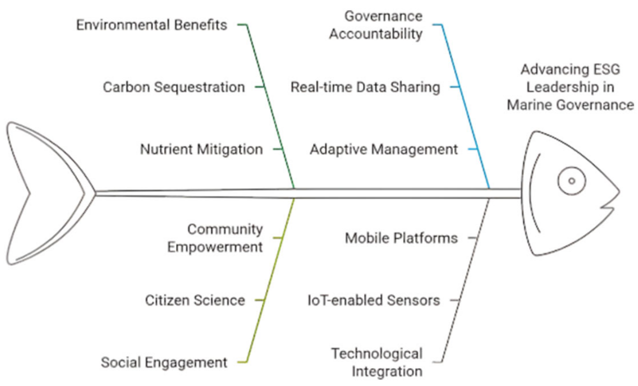
8.1. Biofouling mitigation

We can use a layered strategy that combines passive and active measures proven in ocean instrumentation. Sensor housings receive a polydopamine primer and either a silicone foul-release or a zwitterionic topcoat to lower surface energy and hydration-layer adhesion, which suppresses early microbial and algal settlement [51]. Critical optical and electrochemical interfaces are further protected with copper guards, sliding shutters, and scheduled self-cleaning. For active control, each unit carries a deep-UV emitter positioned by the sensing face; it pulses UV-C near 254 nm for short intervals every few hours to disrupt microbial DNA and prevent biofilm maturation with minimal energy cost from the harvested power budget [51]. A compact wiper sweeps lenses and electrodes once or twice daily to remove any incipient growth or silt without scratching, a method shown to prolong optical sensor performance in long deployments [52, 53]. Together, the nonstick coatings, UV-C bursts, shutters, copper guards, and low-duty wipers keep sensing surfaces clean over multi-month deployments and limit fouling-induced drift while avoiding toxic biocides [51].

9. Ethics and Environmental Considerations

Our deployments follow a minimally invasive, animal-welfare-first approach: sensors are bonded to the external shell with a mussel-inspired, biocompatible adhesive, so no drilling or tissue contact is required, and attachment methods draw on established, low-impact practices for mollusks [41, 52]. Packages are small, smooth, and hydrodynamically low profile; we keep tag mass well below common thresholds (≈5% body mass) and use geometry that minimizes drag to avoid altering behavior or energetics [43, 44]. Devices contain no trailing lines, and all materials in contact with seawater are inert; units are retrieved at the end of each deployment for reuse or proper e-waste handling. We add operational safeguards—tagging thresholds, minimal handling, and seasonal restrictions during sensitive periods—and default to habitat-embedded modules instead of animal tags where appropriate. If acoustic telemetry is used, transmissions are brief, low power, and scheduled at ultrasonic frequencies to reduce exposure, while network design emphasizes delay-tolerant, low-message synchronization and adaptive duty cycling to limit acoustic traffic and energy use [41, 54]. Continuous observation of valve behavior and activity provides an additional check; any indication of stress triggers tag removal or redesign, ensuring the system remains safe for mussels and benign for the broader ecosystem.

Figure 5
Enhancing marine governance with smart wearables technologies



10. Environmental, Social, and Governance, Policy, and Citizen Science

Figure 5 shows the fishbone diagram illustrating the integration of environmental, social, technological, and governance dimensions in advancing ESG leadership for marine governance; it also shows that the continuous, spatially explicit measurements enable credible ESG indicators for aquaculture and coastal management. Traceable, time-stamped data allow verification of ecosystem service claims such as nitrogen removal and carbon burial by mussel farming and restoration [11, 55]. Regulators can use alerts to respond to hypoxia or pollution events. Citizen science programs can integrate low-cost nodes and mobile applications that display local water quality and mussel activity, which builds awareness and supports stewardship [3, 56].

Figure 5 shows a fishbone diagram illustrating the integration of environmental, social, technological, and governance dimensions in advancing ESG leadership for marine governance. The diagram highlights interconnected factors contributing to the sustainable and accountable management of marine resources. Environmental benefits include carbon sequestration and nutrient mitigation, while social dimensions emphasize community empowerment, citizen science, and social engagement. Technological integration focuses on mobile platforms and IoT-enabled sensors, enabling real-time data sharing and adaptive management. Governance accountability ensures transparency and informed decision-making, collectively driving the goal of advancing ESG leadership in marine governance.

11. Energy Sustainability

We can enable long-term autonomous operation by harvesting ambient marine energy and pairing it with disciplined power management: each node integrates a piezoelectric harvester in the mooring or attachment to convert wave and current vibrations into electricity, with recent tests showing milliwatt-scale output on the order of 7.8 mJ s^{-1} at 0.4 Hz that can run low-draw sensors or recharge a battery [57]; in shallow water, the package also uses underwater photovoltaics to capture filtered sunlight, while steady-flow sites can host micro-turbines for supplemental generation, and all harvested energy is buffered in a rechargeable 3.7 V Li-Po pack of a few thousand mAh with a parallel ultracapacitor, for example, a 2400 mAh cell with a 1 F supercapacitor, to handle bursts [44, 57]. Firmware enforces an energy-aware schedule with deep sleep currents at the microamp level, duty-cycled sensing and transmissions such as brief measurements and uplinks every ten minutes, synchronized sampling across the network, and event-triggered bursts for anomalies, following low-power and edge-computing guidance that minimizes active time for the microcontroller and radio while meeting data requirements [43, 44].

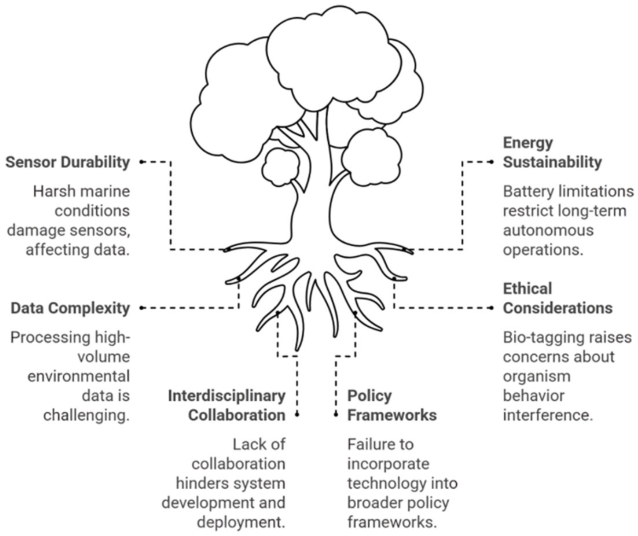
12. Challenges and Future Directions

Figure 6 shows the tree diagram illustrating the key challenges in deploying wearable sensor technologies for marine mussel carbon sequestration monitoring. Technical, ecological, and social challenges remain. Power budgets are tight, so more efficient harvesters and lower standby currents will be valuable. Biofouling in warm, nutrient-rich waters requires continued material innovation and practical cleaning schedules. Data models need to convert high-frequency sensor streams and shell activity into quantitative estimates of carbon fixation and burial with uncertainties. Future work should include long-duration demonstrations in farms and natural beds across seasons, protocol standardization for calibration and data exchange, and integration with coastal carbon accounting frameworks. Interdisciplinary teams of ecologists, engineers, data scientists, and policy actors will be essential. The long-term goal is a distributed blue carbon observatory where mussels and their habitats are instrumented gently and continuously to quantify their contribution to climate mitigation.

Figure 6 shows a tree diagram illustrating the key challenges in deploying wearable sensor technologies for marine mussel carbon sequestration monitoring. The central trunk represents the overall challenge, while the branching nodes depict six main categories of contributing factors: sensor durability (damage from harsh marine environments reducing data accuracy), energy sustainability (battery capacity limits constraining long-term operations), data complexity (difficulties in processing high-volume environmental datasets), ethical considerations (concerns over bio-tagging and potential behavioral impacts on mussels), interdisciplinary collaboration (lack of coordinated effort among marine scientists, engineers, and data specialists), and policy frameworks (failure to integrate new technologies into marine governance and conservation strategies). This hierarchical layout visually organizes the root causes and sub-factors that need to be addressed for effective, sustainable deployment of marine wearable sensing systems.

To support long-term, remote deployments, the wearable sensor platform is designed with sustainable power harvesting and management. Each unit scavenges ambient energy in the marine environment to recharge its power supply. For instance, a piezoelectric energy harvester is integrated into the device's mooring or attachment; it converts mechanical vibrations from waves and currents into electrical energy. Recent tests have shown that even a small piezoelectric or electromagnetic generator can produce on the order of milliwatts of power from ocean wave motion (e.g., ~7.8 mJ/s at 0.4 Hz wave frequency)—enough to continuously run several low-draw sensors or slowly recharge a battery [57]. In addition, for shallow deployments, underwater photovoltaic cells on the device can capture solar irradiance

Figure 6
Hindered marine mussel monitoring due to smart wearable technology limitations



filtered through the water. The harvested energy is stored in a rechargeable Li-Po battery (typically a 3.7 V pack of a few thousand mAh capacity), buffered by a supercapacitor. For example, our prototype uses a 3.7 V, 2400 mAh Li-Po cell in parallel with a 1 F ultracapacitor to store and deliver energy bursts [57].

12.1. Side-emitting polymer optical fibers (POFs)

These are flexible plastic waveguides—typically a PMMA core with a low-index fluorinated cladding—engineered to leak a controlled fraction of guided light along their length via embedded scatterers, micro-etching, or micro-bending, so illumination is distributed rather than point-like [58]. In a wearable node, an LED couples light into the POF and photodetectors sample either the emitted field along the fiber or the residual end-face intensity; changes in bend, strain, turbidity near the fiber, or biofouling at the surface modulate the measurable light, enabling simple optoelectronic sensing without any electrical contact in seawater. Practical design focuses on coupling efficiency at the LED–fiber interface, permissible bend radius, side-leak uniformity, and attenuation, which together bound sensing length and resolution; environmental sealing uses optical-grade epoxies and over-molding to exclude seawater at connectors while keeping the emitting surface accessible. Because the transduction is optical, POF sensors are intrinsically immune to electromagnetic interference, corrosion-safe at the measurement point, and fast enough to track wave- or tide-scale dynamics; the trade-offs are calibration of the LED–detector chain and managing longitudinal loss so that the final meters remain within detector dynamic range [58, 59].

12.2. Conductive textile sensors

These embed conductive pathways—metallic or carbon-based yarns, printed inks, or coated fibers—into knitted or woven structures that change resistance with stretch, pressure, or contact, yielding soft, conformal piezoresistive transducers that can wrap ropes, straps, or housings in the mussel bed [60, 61]. Sensitivity and linearity depend on yarn choice, stitch geometry, and pre-strain; encapsulation with thin elastomer films limits water ingress while preserving compliance, and seam architecture provides strain relief at electrical terminations. In practice, these textiles detect strains from about one to a few tens of percent with repeatable cycles when engineered to minimize hysteresis, and can be patterned into arrays for distributed sensing; they do, however, require temperature and humidity compensation, periodic recalibration to control drift, and careful waterproofing to prevent saltwater shorting or corrosion at interconnects [62, 63].

13. Conclusion

Marine mussels offer a natural pathway for carbon sequestration in coastal waters. Smart wearable sensing tailored for organisms and habitats now makes it feasible to observe the conditions and behaviors that drive these processes continuously and at relevant scales. By specifying sensor types and form factors, integrating mussel-inspired materials for adhesion and fouling control, solving power and data constraints, and defining targets and validation, this framework provides a concrete path to operational blue carbon monitoring. The approach supports ESG reporting, adaptive aquaculture, and participatory coastal stewardship.

Acknowledgement

The authors are grateful to the staff of the Department of Biology at Universiti Putra Malaysia for assistance in preparing this article.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Chee Kong Yap: Conceptualization, Methodology, Data curation, Writing – original draft, Supervision, Project administration. **Musefiu Adebisi Tiamiyu:** Methodology, Writing – original draft. **Kennedy Aaron Aguol:** Methodology. **Meng Chuan Ong:** Software, Project administration. **Wan Mohd Syazwan:** Software. **Noor Azrizal-Wahid:** Validation, Writing – review & editing, Visualization. **Faridah Qamaruz Zaman:** Validation, Writing – review & editing, Visualization. **Rosimah Nulit:** Validation, Writing – review & editing, Visualization. **Yoshifumi Horie:** Formal analysis, Writing – review & editing, Visualization. **Mohamad Saupi Ismail:** Formal analysis, Writing – review & editing. **Ahmad Dwi Setyawan:** Investigation, Writing – review & editing. **Krishnan Kumar:** Investigation, Writing – review & editing. **Wan Hee Cheng:** Resources, Writing – review & editing. **Chee Seng Leow:** Resources, Writing – review & editing.

References

[1] Jiang, C., Yan, S., Mao, L., Jiang, S., Wang, W., & Yu, J. (2026). Direct target localization in USNs with hybrid quantized multi-snapshot measurements: A geometric structure-aided approach. *Digital Signal Processing*, *168*, 105552. https://doi.org/10.1016/j.dsp.2025.105552

[2] Li, L.-S., Chen, M.-Q., Wu, M.-L., Li, Y.-D., & Zeng, J.-B. (2025). Sustainable conductive coating methodology toward superhydrophobic elastic fabric sensors for human motion monitoring, underwater sensing and photothermal conversion. *Chemical Engineering Journal*, *522*, 167266. https://doi.org/10.1016/j.cej.2025.167266

[3] Basconi, L., Rova, S., Stocco, A., & Pranovi, F. (2023). Ecosystem services for supporting coastal and marine resources management, an example from the Adriatic sea (Central Mediterranean sea). *Ocean & Coastal Management*, *235*, 106486. https://doi.org/10.1016/j.ocecoaman.2023.106486

[4] Saleem, K., Wang, L., Almogren, A. S., Ntizikira, E., Rehman, A. U., Bharany, S., & Hussen, S. (2025). Cognitive intelligence routing protocol for disaster management and underwater communication system in underwater acoustic network. *Scientific Reports*, *15*(1), 10004. https://doi.org/10.1038/s41598-025-94561-6

[5] Breunig, M. M., Kriegel, H.-P., Ng, R. T., & Sander, J. (2000). LOF: Identifying density-based local outliers. In *Proceedings of the 2000 ACM SIGMOD International Conference on Management of Data*, 93–104. https://doi.org/10.1145/342009.335388

[6] Zhang, Z., Wang, L., Wu, T., Jiang, J., & Zhang, Y. (2026). Smart textile interfaces based on protein structure-reconstructed bovine serum albumin hydrogel fibers for disability support. *Journal of Colloid and Interface Science*, *702*, 138864. https://doi.org/10.1016/j.jcis.2025.138864

[7] Gosling, E. M. (2022). *Marine mussels: Ecology, physiology, genetics and culture*. USA: Wiley. https://doi.org/10.1002/9781119293927

[8] He, J., Tao, Y., Shao, S., Wei, H., Yan, G., Tang, C., . . . , & Yan, X. (2024). The hidden acceleration pump uncovers the role of shellfish in oceanic carbon sequestration. *Science of the Total Environment*, *951*, 175699. https://doi.org/10.1016/j.scitotenv.2024.175699

[9] Kulurkar, P., Dixit, C. K., Bharathi, V. C., Monikavishnuvarthini, A., Dhakne, A., & Preethi, P. (2023). AI based elderly fall prediction using wearable sensors: A smart home care technology with IoT. *Measurement: Sensors*, *25*, 100614. https://doi.org/10.1016/j.measen.2022.100614

[10] Sea, M. A., Hillman, J. R., & Thrush, S. F. (2022). The influence of mussel restoration on coastal carbon cycling. *Global Change Biology*, *28*(17), 5269–5282. https://doi.org/10.1111/gcb.16287

[11] Pacifico, A. M., Brigolin, D., Mulazzani, L., Semeraro, M., & Malorgio, G. (2024). Managing marine aquaculture by assessing its contribution to ecosystem services provision: The case of Mediterranean mussel, *Mytilus galloprovincialis*. *Ocean & Coastal Management*, *259*, 107456. https://doi.org/10.1016/j.ocecoaman.2024.107456

[12] Tamburini, E., Turolla, E., Lanzoni, M., Moore, D., & Castaldelli, G. (2022). Manila clam and Mediterranean mussel aquaculture is sustainable and a net carbon sink.

Science of the Total Environment, *848*, 157508. https://doi.org/10.1016/j.scitotenv.2022.157508

[13] Cleary, D. F. R., Becking, L. E., Polónia, A. R. M., Freitas, R. M., & Gomes, N. C. M. (2015). Composition and predicted functional ecology of mussel associated bacteria in Indonesian marine lakes. *Antonie van Leeuwenhoek*, *107*(3), 821–834. https://doi.org/10.1007/s10482-014-0375-1

[14] Babu, M. V., Ramya, V., & Murugan, V. S. (2024). Implementation of wearable device for upper limb rehabilitation using embedded IoT. *International Journal of Engineering Systems Modelling and Simulation*, *15*(2), 90–95. https://doi.org/10.1504/IJESMS.2024.136972

[15] Zhang, X., Liang, S., Li, F., & Bai, Y. (2025). NIR light-triggered mechanically mutable mussel-inspired hydrogels for developing smart wearable sensing. *Chemical Engineering Journal*, *503*, 158603. https://doi.org/10.1016/j.cej.2024.158603

[16] Khoshmanesh, F., Thurgood, P., Pirogova, E., Nahavandi, S., & Baratchi, S. (2021). Wearable sensors: At the frontier of personalised health monitoring and assistive technologies. *Biosensors and Bioelectronics*, *176*, 112946. https://doi.org/10.1016/j.bios.2020.112946

[17] Li, D., Wang, S., & Wang, C. (2023). Application of flexible wearable sensing technology in smart fishery. *Transactions of the Chinese Society of Agricultural Engineering*, *39*(13), 1–13. https://doi.org/10.11975/j.issn.1002-6819.202304142

[18] Li, X., Yang, J., Zhao, Y., Zhou, S., & Wu, Y. (2024). Prediction and assessment of marine fisheries carbon sink in China based on a novel nonlinear grey Bernoulli model with multiple optimizations. *Science of the Total Environment*, *914*, 169769. https://doi.org/10.1016/j.scitotenv.2023.169769

[19] Lin, M.-T. (2022). Quadri-directional optical bending sensor using side-emitting POF integrated with wearable device technology in smart glove. *International Journal of Clothing Science and Technology*, *34*(4), 502–515. https://doi.org/10.1108/IJCST-06-2021-0080

[20] Tasjid, M. S., & Marouf, A. A. (2021). Leveraging smartphone sensors for detecting abnormal gait for smart wearable mobile technologies. *International Journal of Interactive Mobile Technologies*, *15*(24), 167–175. https://doi.org/10.3991/ijim.v15i24.25891

[21] Song, H., Rumon, M. M. H., Rahman Khan, M. M., & Jeong, J.-H. (2025). Toward intelligent materials with the promise of self-healing hydrogels in flexible devices. *Polymers*, *17*(4), 542. https://doi.org/10.3390/polym17040542

[22] Pájaro, M., Fuentes-Santos, I., Labarta, U., Alonso, A. A., & Álvarez-Salgado, X. A. (2024). MusselCF, a user-friendly toolbox to estimate the physiological carbon footprint of mussels in suspended aquaculture. *Aquacultural Engineering*, *105*, 102415. https://doi.org/10.1016/j.aquaeng.2024.102415

[23] Papageorgiou, N., Dimitriou, P. D., Chatzivasileiou, D., Tsapakis, M., & Karakassis, I. (2023). Can IMTA provide added ecosystem value services in the fish farms of Greece? *Frontiers in Marine Science*, *9*, 1083099. https://doi.org/10.3389/fmars.2022.1083099

[24] Ritzenhofen, L., Schumacher, J., Karstens, S., & Schernewski, G. (2022). Ecosystem service assessments within the EU Water Framework Directive: Marine mussel cultivation as a controversial measure. *Applied Sciences*, *12*(4), 1871. https://doi.org/10.3390/app12041871

[25] Rodríguez, F., Morán, L., González, G., Troncoso, E., & Zúñiga, R. N. (2017). Collagen extraction from mussel byssus: A new marine collagen source of industrial interest. *Journal of Food Science and Technology*, *54*(5), 1228–1238. https://doi.org/10.1007/s13197-017-2566-z

[26] Petersen, J. K., Holmer, M., Termansen, M., & Hasler, B. (2019). Nutrient extraction through bivalves. In A. C. Smaal, J. G. Ferreira, J. Grant, J. K. Petersen, & Ø. Strand (Eds.), *Goods and services of marine bivalves* (pp. 179–208). Springer. https://doi.org/10.1007/978-3-319-96776-9_10

[27] Gu, H., Wei, S., Tu, Z., Hu, M., Guo, B., & Wang, Y. (2023). Polybrominated diphenyl ether-47 and food shortage impair byssal attachment and health of marine mussels. *Science of the Total Environment*, *891*, 164415. https://doi.org/10.1016/j.scitotenv.2023.164415

[28] Szefer, P., Fowler, S. W., Ikuta, K., Osuna, F. P., Ali, A. A., Kim, B.-S., . . . , & Deslous-Paoli, M. (2006). A comparative assessment of heavy metal accumulation in soft parts and byssus of mussels from subarctic, temperate, subtropical and tropical marine environments. *Environmental Pollution*, *139*(1), 70–78. https://doi.org/10.1016/j.envpol.2005.04.031

[29] Khalaman, V. V., Lezin, P. A., & Galitskaya, A. D. (2009). Effect of the excretory-secretory products of some marine invertebrates on byssus production of the blue mussel *Mytilus edulis* (Bivalvia: Mytilidae). *Russian Journal of Marine Biology*, *35*(3), 224–229. https://doi.org/10.1134/S1063074009030055

[30] Newcomb, L. A., George, M. N., O'Donnell, M. J., & Carrington, E. (2019). Only as strong as the weakest link: Structural analysis of the combined effects of elevated temperature and pCO_2 on mussel attachment. *Conservation Physiology*, *7*(1), coz068. https://doi.org/10.1093/conphys/coz068

[31] Lee, A.-S., Chao, W.-S., Liou, S. Y. H., Tiedemann, R., Zolitschka, B., & Lembke-Jene, L. (2022). Quantifying calcium carbonate and organic carbon content in marine sediments from XRF-scanning spectra with a machine learning approach. *Scientific Reports, 12*(1), 20860. https://doi.org/10.1038/s41598-022-25377-x

[32] Zhao, S., Zhang, Y., Li, G., Zhou, Y., Xia, M., Hoang, A. T., . . . , & Ahn, J.-H. (2025). Mussel-inspired highly sensitive, stretchable, and self-healable yarns enabled by dual conductive pathways and encapsulation for wearable electronics. *Advanced Functional Materials*, *35*(7), 2412461. https://doi.org/10.1002/adfm.202412461

[33] Maroli, G., Rosati, G., Suárez–García, S., Bedmar-Romero, D., Kobrin, R. L., González-Laredo, Á., . . . , & Merkoçi, A. X. (2024). Wearable, battery-free, wireless multiplexed printed sensors for heat stroke prevention with mussel-inspired bio-adhesive membranes. *Biosensors and Bioelectronics*, *260*, 116421. https://doi.org/10.1016/j.bios.2024.116421

[34] George, M. N., Liu, X., Miller, A. L., Zuiker, E., Xu, H., & Lu, L. (2022). Injectable pH-responsive adhesive hydrogels for bone tissue engineering inspired by the underwater attachment strategy of marine mussels. *Biomaterials Advances*, *133*, 112606. https://doi.org/10.1016/j.msec.2021.112606

[35] Qin, C.-L., Pan, Q.-D., Qi, Q., Fan, M.-H., Sun, J.-J., Li, N.-N., & Liao, Z. (2016). In-depth proteomic analysis of byssus from *Mytilus coruscus*. *Journal of Proteomics*, *144*, 87–98. https://doi.org/10.1016/j.jprot.2016.06.014

[36] McLaughlin, K., Dickson, A., Weisberg, S. B., Coale, K., Elrod, V., Hunter, C., . . . , & Weis, K. R. (2017). An

evaluation of ISFET sensors for coastal pH monitoring applications. *Regional Studies in Marine Science*, *12*, 11–18. https://doi.org/10.1016/j.rsma.2017.02.008

[37] Johnson, K. S., Jannasch, H. W., Coletti, L. J., Elrod, V. A., Martz, T. R., Takeshita, Y., . . . , & Connery, J. G. (2016). Deep-Sea DuraFET: A pressure tolerant pH sensor designed for global sensor networks. *Analytical Chemistry*, *88*(6), 3249–3256. https://doi.org/10.1021/acs.analchem.5b04653.

[38] Quaranta, M., Borisov, S. M., & Klimant, I. (2012). Indicators for optical oxygen sensors. *Bioanalytical Reviews*, *4*(2), 115–157. https://doi.org/10.1007/s12566-012-0032-y

[39] Sheehy, J., Kerr, S., Bell, M., & Porter, J. (2024). Adaptive stacked species distribution modelling: Novel approaches to large scale quantification of blue carbon to support marine management. *Science of the Total Environment*, *949*, 174993. https://doi.org/10.1016/j.scitotenv.2024.174993

[40] Szalaj, D., de Orte, M. R., Goulding, T. A., Medeiros, I. D., DelValls, T. A., & Cesar, A. (2017). The effects of ocean acidification and a carbon dioxide capture and storage leak on the early life stages of the marine mussel *Perna perna* (Linneaus, 1758) and metal bioavailability. *Environmental Science and Pollution Research*, *24*(1), 765–781. https://doi.org/10.1007/s11356-016-7863-y

[41] Ouyang, Y., Han, Y., Wang, Z., & He, Y. (2024). Underwater network time synchronization method based on probabilistic graphical models. *Journal of Marine Science and Engineering*, *12*(11), 2079. https://doi.org/10.3390/jmse12112079

[42] Wang, J., Ma, J., Feng, Y., Feng, Q., Gao, G., & Lv, Y. (2022). PCDE-Sync: A time synchronization mechanism based on partial clustering and the Doppler effect for underwater acoustic networks. *Computational Intelligence and Neuroscience*, *2022*(1), 9554396. https://doi.org/10.1155/2022/9554396

[43] Shi, W., Cao, J., Zhang, Q., Li, Y., & Xu, L. (2016). Edge computing: Vision and challenges. *IEEE Internet of Things Journal*, *3*(5), 637–646. https://doi.org/10.1109/JIOT.2016.2579198

[44] Du, X., Du, L., Li, P., Liu, X., Han, Y., Yu, H., . . . , & Tang, L. (2023). A dielectric elastomer and electret hybrid ocean wave power generator with oscillating water column. *Nano Energy*, *111*, 108417. https://doi.org/10.1016/j.nanoen.2023.108417

[45] Du, X., Du, L., Li, P., Liu, X., Han, Y., Yu, H., ..., & Tang, L. (2023). A dielectric elastomer and electret hybrid ocean wave power generator with oscillating water column. *Nano Energy*, *111*, 108417. https://doi.org/10.1016/j.nanoen.2023.108417

[46] Liu, F. T., Ting, K. M., & Zhou, Z.-H. (2008). Isolation forest. In *2008 Eighth IEEE International Conference on Data Mining*, 413–422. https://doi.org/10.1109/ICDM.2008.17

[47] Dickson, A. G., Sabine, C. L, & Christian, J. R. (Eds.). (2007). *Guide to best practices for ocean CO_2 measurements (PICES Special Publication No. 3)*. National Centers for Environmental Information. https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/Handbook_2007.html.

[48] Langdon, C. (2010). Determination of dissolved oxygen in seawater by Winkler titration using the amperometric technique. In E. M. Hood, C. L. Sabine, & B. M. Sloyan (Eds.), *The GO-SHIP repeat hydrography manual: A collection of expert reports and guidelines* (IOCCP Report No. 14, ICPO Publication Series No. 134). UNESCO.

[49] Rérolle, V. M. C., Achterberg, E. P., Ribas-Ribas, M., Kitidis, V., Brown, I., Bakker, D. C. E., . . . , & Mowlem, M. C. (2018). High resolution pH measurements using a lab-on-chip sensor in surface waters of northwest european shelf seas. *Sensors*, *18*(8), 2622. https://doi.org/10.3390/s18082622

[50] Rudnick, D. L. (2016). Ocean research enabled by underwater gliders. *Annual Review of Marine Science*, *8*, 519–541. https://doi.org/10.1146/annurev-marine-122414-033913

[51] Delgado, A. G., Briciu-Burghina, C., & Regan, F. (2021). Antifouling strategies for sensors used in water monitoring: Review and future perspectives. *Sensors*, *21*(2), 389. https://doi.org/10.3390/s21020389

[52] Pennell, S. M., LeFevre, T. B., Bennett, J., Chouyyok, W., Daddona, J. D., Addleman, R. S., . . . , & Bonheyo, G. T. (2025). An improved method for quantitatively measuring antifouling coating performance using a mussel single thread tensile adhesion test. *Biofouling*, *41*(3), 300–311. https://doi.org/10.1080/08927014.2025.2476491

[53] Bresnahan, P. J., Martz, T. R., Takeshita, Y., Johnson, K. S., & LaShomb, M. (2014). Best practices for autonomous measurement of seawater pH with the Honeywell Durafet. *Methods in Oceanography*, *9*, 44–60. https://doi.org/10.1016/j.mio.2014.08.003

[54] YSI. (n.d.). *EXO optical dissolved oxygen smart sensor*. https://www.ysi.com/product/id-599100-01/exo-optical-dissolved-oxygen-smart-sensor?srsltid=AfmBOoqY_hjnIKwL4Jp5XPYPVjmWOnkor6D0V6Uo_hUjY1xkkLKFqlNK

[55] Olesen, I., Bonaldo, A., Farina, R., Gonera, A., Hughes, A. D., Navrud, S., . . . , & Zornoza, R. (2023). Moving beyond agriculture and aquaculture to integrated sustainable food systems as part of a circular bioeconomy. *Frontiers in Marine Science*, *10*, 1178014. https://doi.org/10.3389/fmars.2023.1178014

[56] McLoughlin, D., Browne, A., & Sullivan, C. A. (2020). The delivery of ecosystem services through results-based agri-environment payment schemes (RBPS): Three Irish case studies. *Biology and Environment: Proceedings of the Royal Irish Academy*, *120B*(2), 91–106. https://doi.org/10.3318/bioe.2020.13

[57] Faria, C. L., Martins, M. S., Matos, T., Lima, R., Miranda, J. M., & Gonçalves, L. M. (2022). Underwater energy harvesting to extend operation time of submersible sensors. *Sensors*, *22*(4), 1341. https://doi.org/10.3390/s22041341

[58] Kallweit, J., Pätzel, M., Pursche, F., Jabban, J., Morobeid, M., & Gries, T. (2021). An overview on methods for producing side-emitting polymer optical fibers. *Textiles*, *1*(2), 337–360. https://doi.org/10.3390/textiles1020017

[59] Tow, K. H., Chow, D. M., Vollrath, F., Dicaire, I., Gheysens, T., & Thévenaz, L. (2018). Exploring the use of native spider silk as an optical fiber for chemical sensing. *Journal of Lightwave Technology*, *36*(4), 1138–1144. https://doi.org/10.1109/JLT.2017.2756095

[60] Hou, Z., Liu, J., Liao, Y., Gong, J., Li, C., Li, M., . . . , & Huang, Q. (2026). Design and application of flexible wearable sensors based on optical fibers. *Talanta*, *297*, 128576. https://doi.org/10.1016/j.talanta.2025.128576

[61] Li, Y., Zhang, L., Wang, K., Xu, L., & Gulliver, T. A. (2025). Underwater acoustic intelligent spectrum sensing with multimodal data fusion: An Mul-YOLO approach. *Future*

Generation Computer Systems, *173*, 107880. https://doi.org/10.1016/j.future.2025.107880

[62] Dong, Y., Li, Q., Zhao, Z., Gong, J., Li, Z., & Zhang, J. (2022). A wearable pressure sensor based on ionogel/textile for human motion monitoring. *Fibers and Polymers*, *23*(8), 2351–2363. https://doi.org/10.1007/s12221-022-4839-z

[63] Zhang, Y., Tan, W., Hu, X., Pan, W., Xu, T., Wang, L., & Liu, C. (2026). Integrated smart diaper for self-pumping urine drainage and comfortable on-site electroanalysis. *Sensors and Actuators B: Chemical*, *446*, 138627. https://doi.org/10.1016/j.snb.2025.138627

How to Cite: Yap, C. K., Tiamiyu, M. A., Aguol, K. A., Ong, M. C., Syazwan, W. M., Azrizal-Wahid, N., . . . , & Leow, C. S. (2026). Integrating Marine Mussel Distribution and Carbon Sequestration with Smart Wearable Technology: A Novel Intersection for Blue Carbon Monitoring and Environmental, Social, and Governance Innovation. *Smart Wearable Technology*, *2*, A16. https://doi.org/10.47852/bonviewSWT52026516