

# Polyacrylonitrile–Polyvinyl Alcohol (PAN–PVA) Hybrid Composites for Wound Healing in Marine Environments: A Comprehensive Review

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**Abstract-** In marine settings, the wound healing process is hampered by the constant presence of high-saline water, microbial biofilms and frequent mechanical (repeated collision with the environment). Traditional dressings which have been ineffective under this situation call for innovative biomaterials. PAN contributes to mechanical property, chemical resistance, and PVA contributes biocompatibility, hydrophilicity, and hydrogel formation. These properties are utilized in conjunction in PAN–PVA hybrids, especially in electrospun nanofiber and hydrogel composites, to make wound patches apt for challenging aquatic conditions. The mechanical, chemical, biological activity and performance of PAN, PVA and their derivatives have been reviewed, in particular, the focusing issues of electro-spinning, crosslinking ways, saline resistance, antibacterial effect modifications.

**Keywords-** PAN, PVA, Wound healing patch

## I. INTRODUCTION TO WOUND HEALING IN MARINE ENVIRONMENTS

The wounds created in the sea environment create more complications than those on the land. Continuous risk to seawater disrupts clots by changing ionic balance and prolonging the time of bleeding (Guayin et al., 2021). High salt concentration not only affects the local skydart shield, but also compromises cell migration and proliferation, which are important steps in tissue repair. In addition, sea lesions are often contaminated with opportunistic pathogens such as vibrio vulnificus and pseudomonas aeruginosa, leading to rapid infection progression (Baker-Austin et al., 2023). These clinical complications make it clear that traditional dressings such as mist and hydrocarbons are unsuitable in aquatic environment.

Equally critical is the challenge of keeping wound moisture balance in a marine setting. While wet recuperation is taken into consideration the gold well known, excessive swelling and water absorption in seawater can cause maceration and tissue harm (Queen et al., 1995). Thus, wound dressings for marine use have to gain a delicate stability: sufficient water vapor transmission rate (WVTR) to allow exudate management, at the same time as concurrently resisting seawater infiltration. This dual requirement makes the design of specialized substances specifically complicated. Given those demanding situations, synthetic polymer-primarily based dressings are being explored as options to traditional materials. Among them, PAN and PVA are considered promising due to their complementary residences. PAN is robotically strong and proof against chemical degradation, at the same time as PVA is biocompatible and surprisingly hydrophilic. Together, they may be engineered into hybrid structures with the capability to face up to marine situations even as assisting effective wound recuperation.

## II. ANALYSING THE STRENGTH AND STABILITY OF POLYACRYLONITRILE (PAN)

Polyacrylonitrile (PAN) is a synthetic polymer mainly recognized for its strength, durability and chemical stability. Its tensile strength is usually ranging from 50 to 100 MPa, while the modulus of Young is between 1 and 2 GPa (Pells and Zilberman, 2012). These values highlight the ability to oppose the pathology and encounter mechanical stress, which is particularly valuable in dynamic environment such as seawater immersion. In addition, PAN displays a low increase on brakes, ensuring dimensional stability under the

load. From a chemical point of view, PAN is unique due to its nitrile groups ( $-C\equiv N$ ). These groups make polymer polar and resistant to hydrolysis, which ensure long-term stability in the saline solution (Zhang et al., 2019). While hydrophobicity can limit direct cell interactions, surface modifications such as plasma treatment or amidoxime functionalization can improve hydrophilicity of pan and increase cell adhesion (Liu et al., 2021). These amendments also allow stabilization of antimicrobial ions such as silver or zinc, making the role of PAN in biomedical applications comprehensive. Electrospun pan nanofibers have been widely studied in biomedical research, not only as structural scaffolds, but also as filters and drug-delivery platforms (Zillaberman & Pales, 2015). Their highly porous and tuneable morphology allow exchange of effective nutrients, mimic external matrix (ECM) and promote fibroblast proliferation. For sea wound patch, these properties suggest that the PAN can act as an external protective layer, providing mechanical strength and sea water resistance.

### III. BIOCOMPATIBILITY AND MOISTURE BALANCE OF POLYVINYL ALCOHOL (PVA)

PVA has been studied notably in wound care due to its biocompatibility, biodegradability, and potential to shape hydrogels. Its tensile electricity degrees from 30 to 70 MPa relying on the diploma of hydrolysis, with elongation at damage accomplishing up to 300% in hydrated states (Kamoun et al., 2017). This elasticity guarantees that PVA-based dressings can comply with abnormal wound geometries, an acceptable property for large or complicated injuries. One of PVA's most significant advantages is its potential to adjust wound moisture.

PVA hydrogels, fashioned by means of either bodily (freeze-thaw) or chemical crosslinking, provide a managed water vapor transmission price (WVTR). Maintaining a most reliable WVTR (2,000–2,500  $g\cdot m^{-2}\cdot day^{-1}$ ) hurries up re-epithelialization and prevents both desiccation and maceration (Queen et al., 1995). In saline environments, this property turns into in particular essential, as immoderate water uptake ought to in any other case compromise the dressing's integrity. Another electricity of PVA is its versatility in fabrication. Transparent PVA movies allow clinicians to display wound restoration without

frequent dressing changes (Mieles et al., 2024). Moreover, PVA's hydroxyl-wealthy backbone facilitates incorporation of antimicrobial agents, making it suitable for contamination-susceptible marine wounds. However, the primary obstacle of PVA is its solubility in water. Without stabilization, PVA hydrogels rapidly dissolve or lose mechanical integrity in seawater, necessitating blending or crosslinking for marine applications.

### IV. THE SYNERGISTIC PROPERTIES OF PAN–PVA COMPOSITES

The hybridization of PAN and PVA combines the strengths of both polymers whilst minimizing their obstacles. PAN contributes mechanical electricity, chemical resistance, and balance in saline situations, whereas PVA offers hydrophilicity, biocompatibility, and drug-loading capability. Together, PAN–PVA nanofibers had been shown to possess advanced tensile power, elasticity, and porosity in comparison to single-polymer structures (Ali et al., 2023).

Electrospun PAN–PVA composites are specifically attractive because they mimic ECM structures and promote fibroblast adhesion. Their tuneable porosity allows nutrient and oxygen diffusion, which hurries up granulation and re-epithelialization (Garcia-Hernandez et al., 2021). Furthermore, coaxial PAN–PVA nanofibers enable biphasic drug release profiles and rapid preliminary launch from PVA compartments, accompanied with the aid of sustained launch via PAN's extra hydrophobic barrier. This managed release mechanism is important for marine wounds, in which early contamination control must be balanced with long-time period restoration. In addition to their organic benefits, PAN–PVA hybrids also show stronger swelling resistance in comparison to pure PVA. This improvement makes them greater suitable for saline immersion, in which unmodified PVA could in any other case swell excessively and fail structurally. Such evidence positions PAN–PVA as a promising candidate for marine-tolerant wound patches.

### V. METHODOLOGY

#### 5.1 Electrospinning

Electrospinning is still the go-to technique for making PAN–PVA composites, prized for creating nanofiber

mats so fine you could almost see light pass through them, with an exceptionally high surface-to-volume ratio. The fibers that form closely resemble ECM structures, letting cells connect more easily and speeding healing, much like threads weaving into a fine mesh (Zilberman & Peles, 2015). By adjusting the applied voltage, the solution's concentration, and the gap between the tip and collector, researchers can fine-tune the shape and texture of the fibers (Garcia-Hernandez et al., 2021). Recent breakthroughs include coaxial electrospinning, a method that spins out fine core-shell nanofibers as thin as a strand of hair. In these systems, PAN forms the sturdy outer shell, while PVA holds the drug-packed core, like a smooth bead wrapped in a firm casing. This design shields PVA from dissolving too quickly in saline and lets the drug release in carefully timed stages, like drops of rain sliding off a leaf. New methods, such as near-field electrospinning, can line up fibers with pinpoint accuracy, while solution blow spinning scales smoothly for factory use (Wang et al., 2022).

### 5.2 Crosslinking

PVA components need crosslinking to stay stable in marine conditions, like holding firm against saltwater's slow, steady pull. Glutaraldehyde crosslinking boosts water stability, but it can also leave behind toxic effects on cells (Kamoun et al., 2017). Researchers also explore greener crosslinkers like citric acid with its faint citrus scent or the plant-derived genipin, that boost water resistance yet keep the material biocompatible (Mohanty et al., 2022). Freeze-thaw cycling and other physical methods form tiny crystalline patches in PVA, making it tougher without a drop of chemical additives. In PAN-PVA hybrids, crosslinking the PAN fibers and then heat-treating them locks in their strength and resists chemical breakdown, even after weeks in salty water.

## VI. CHALLENGES OF MARINE WOUND HEALING PATCHES

Developing PAN-PVA wound patches for use in marine environments isn't easy, since, saltwater, constant motion, and unpredictable temperatures all pose serious hurdles. First, salty environments speed up the breakdown of hydrophilic polymers like PVA, causing them to weaken and crack until the patch ultimately fails (Sharma et al., 2023). Second, once a

polymer surface gets wet, marine biofilms can coat it in no time, creating a foothold for stubborn infections (Raghavendra et al., 2021). Third, repeated bursts of mechanical stress like the push of water currents or the flex of a moving body, gradually wear down polymer scaffolds, leading to tiny fatigue fractures. If swelling and WVTR aren't managed properly, the wound bed can become overly moist like a sponge left in water which slows the healing process. Tackling these challenges calls for a layered strategy, tweaking the surface to stop biofilm from taking hold, fine-tuning PAN:PVA ratios so the material stays tough, and dealing in crosslinking to stand up to salty conditions. Without these strategies, PAN-PVA composites won't deliver dependable results in marine healthcare settings, where salt spray can quickly expose any weakness.

## VII. PERFORMANCE ENHANCEMENTS AND RECENT ADVANCES

Recent work has looked at blending nanoparticles, silver, zinc oxide, even a fine dusting of titanium dioxide, into PAN-PVA nanofibers to boost their ability to fight microbes and stand up to salty conditions (Kumar et al., 2023). Compared to plain fibers, these composites cleared bacteria more quickly and held their shape longer when soaked in water. Researchers have also reported making three-dimensional PAN-PVA scaffolds using advanced electrospinning, producing delicate fiber layers you could almost feel between your fingertips. These structures have a higher porosity, so nutrients can move through easily and fluids drain away cleanly, yet they still hold up under repeated stress (Zhao et al., 2022). IPN hydrogels that blend PAN-PVA with alginate or chitosan boost mechanical strength and help prevent fatigue fractures, even after long exposure to salty water (Sharma et al., 2023). Smart PAN-PVA systems with built-in biosensors are starting to appear, some no bigger than a shirt button. These systems track a wound's pH, temperature, or signs of infection, sending real-time updates to clinicians, much like a sensor warning when skin turns warm and red (Dutta et al., 2020). These versatile features could prove especially handy in remote clinics or aboard a ship's small, humming infirmary.

## VIII. LIMITATIONS AND FUTURE DIRECTIONS

We've made real progress, but research on PAN–PVA wound patches still has clear gaps, like how they hold up against moisture over time. Most studies test composites in PBS or plain distilled water, not in simulated seawater, where the taste of salt would linger on the tongue (Nguyen et al., 2021). This makes the findings less useful in real-world clinics, where decisions hinge on more than numbers on a chart. It's uncommon to see long-term fatigue tests run in shifting saline conditions, where metal tastes linger in the air.

Future research should focus first on what truly matters, for example, pinpointing the tiny shifts that ripple out into bigger changes.

1. Testing designed for marine environments, carried out in synthetic seawater that meets ASTM D1141 standards.
2. Researchers use standardized biofilm models built with marine pathogens like *Vibrio* spp., sometimes forming slimy layers that cling to glass surfaces.
3. Use scale-up methods, such as blow spinning, to reliably produce materials on a large scale, like stretching a fine thread of fiber that stays uniform from start to finish.
4. Bringing together sensing elements to spot infections in remote areas, even where the air smells of dust and dry earth. If we follow these directions, PAN–PVA composites could move from lab experiments to real-world use as marine wound dressings, ready to seal cuts even in salty ocean water.

#### IX. A HISTORICAL GLANCE AT SYNTHETIC POLYMERS IN WOUND CARE

Wound care, honestly, has been around as long as humanity itself, you go far back enough, and you'll find people using whatever was at hand: honey, linen, plant extracts, you name it. Not exactly high-tech, but hey, it was a start. Things took a real turn in the 19th century, when sterile gauze and bandages came onto the scene, finally putting infection control front and center (Queen et al., 1995). Still, those early innovations didn't exactly nail the "ideal healing conditions" brief.

The mid-20th century saw another leap forward with the arrival of hydrocolloid and hydrogel dressings.

These weren't just about covering wounds; they kept things moist, which, as it turns out, is kind of a big deal for healing (Sood et al., 2014). But there's a catch: classic dressings tend to fall apart or lose their edge when you introduce them to water, especially if it's salty. For folks working at sea or in wet environments, that's a real problem.

That's where synthetic polymers start to steal the show. Back in the '60s and '70s, researchers began experimenting with polyurethane and PEG-based materials, searching for something that could offer both flexibility and biocompatibility (Kamoun et al., 2017). Fast-forward a bit, and you get nanofiber scaffolds made through electrospinning, a game changer, honestly, because they mimic the body's natural healing support structures (Zilberman & Peles, 2015). Natural polymers like alginate and chitosan? Sure, they've been popular, but their quick breakdown in salty conditions makes them less than ideal for marine use (Mohan et al., 2021).

Now, PAN–PVA hybrids are leading the charge. These materials combine toughness with biological smarts, answering the call for wound dressings that can actually stand up to extreme environments, think underwater injuries, naval operations, coastal rescues, and so on (Nguyen et al., 2021). This isn't just a technical upgrade; it's a whole new way of thinking about wound care. Today's advanced polymeric dressings act as active, therapeutic platforms, offering stability, fighting infection, and speeding up healing, even in the harshest conditions. The shift from passive barriers to smart materials? That's a paradigm change, plain and simple.

#### X. MARINE PATHOGEN RESISTANCE AND ANTIMICROBIAL STRATEGIES

Managing infection in marine wounds remains a significant clinical challenge. The marine environment contains a diverse array of pathogenic microorganisms, notably *Vibrio vulnificus*, *Pseudomonas aeruginosa*, and *Aeromonas hydrophila* (Baker-Austin et al., 2023). These organisms not only thrive in warm seawater but also demonstrate multidrug resistance, complicating eradication efforts. Biofilm formation on wound dressings accelerates colonization and provides a protective barrier that limits antibiotic penetration. In the absence of effective antimicrobial strategies, marine wounds may

rapidly progress to necrotizing fasciitis or systemic infection.

To overcome these obstacles, PAN–PVA composites have been engineered to incorporate antimicrobial agents. For example, silver nanoparticles, zinc oxide, and copper ions have been integrated into electrospun nanofibers, delivering sustained antimicrobial efficacy (Kumar et al., 2023). The nitrile functionality of PAN permits covalent bonding with antimicrobial agents, while the hydrophilic nature of PVA facilitates controlled release. This dual mechanism maintains antimicrobial activity even during prolonged exposure to saline, in contrast to conventional dressings, which often experience rapid leaching.

Another promising strategy involves surface functionalization of PAN–PVA fibers with antifouling coatings. Hydrophilic polymers such as polyethylene glycol (PEG) or zwitterionic groups can reduce bacterial adhesion, thereby preventing biofilm formation (Nguyen et al., 2021). Furthermore, the inclusion of quorum-sensing inhibitors within PVA compartments has been proposed to disrupt bacterial communication and reduce virulence. Collectively, these antimicrobial strategies position PAN–PVA hybrids as strong candidates for the development of infection-resistant marine wound dressings.

#### XI. SALINITY AND OSMOTIC PRESSURE: THE SALTWATER CHALLENGE

Seawater exposure presents a distinct set of osmotic complications for wound healing. With approximately 3.5% salt content, mainly sodium chloride, seawater disrupts the osmotic equilibrium at the wound site. This high salt concentration draws fluids out of cells, ultimately delaying re-epithelialization and impeding the healing process. If dressings cannot properly regulate swelling and water vapor transmission, these effects are often exacerbated: excessive absorption may lead to structural breakdown, while insufficient control fails to protect the wound environment.

Polyvinyl alcohol (PVA), due to its hydrophilic nature, tends to swell significantly in saline conditions, increasing the risk of patch disintegration. In contrast, crosslinked polyacrylonitrile-PVA (PAN–PVA) composites demonstrate much lower swelling, allowing more controlled management of fluid balance (Kamoun et al., 2017). Optimizing the PAN:PVA ratio is therefore essential to achieve appropriate water

vapor transmission rates (WVTRs) for marine wound dressings.

Furthermore, salinity can compromise the stability of bioactive agents incorporated into the dressing. Many antibiotics and growth factors degrade rapidly when exposed to high-salt environments (Nguyen et al., 2021). Encapsulating these molecules in PAN–PVA nanofibers offers protection against ionic degradation and allows for sustained release. Taken together, PAN–PVA hybrid materials can provide both mechanical integrity and biochemical protection for wounds subjected to marine conditions.

#### XII. MECHANICAL PERFORMANCE UNDER DYNAMIC MARINE CONDITIONS

Marine environments present challenges for wound dressings that are quite distinct from those encountered on land. Immersion in seawater, for instance, leads to pronounced swelling and softening in most hydrophilic polymers. On top of that, the constant movement, whether from swimming or wave action, subjects these materials to repeated mechanical stress and fatigue (Raghavendra et al., 2021). If the mechanical strength of a wound patch fails, the wound becomes exposed to contaminants, which can compromise healing.

Polyacrylonitrile (PAN) is notable for its mechanical robustness in these scenarios. With a tensile modulus in the 1–2 GPa range, PAN helps maintain the structural integrity of dressings even under sustained loading (Peles & Zilberman, 2012). When PAN is blended with polyvinyl alcohol (PVA), which provides elasticity, the resulting hybrid material can endure both tensile and compressive stresses (Ali et al., 2023). Research on electrospun PAN–PVA mats demonstrates that these composites outperform single-polymer scaffolds in terms of fatigue resistance, which is particularly advantageous for applications requiring long-term immersion.

Furthermore, several strategies are under investigation to reinforce mechanical performance. Techniques such as multilayering, controlling fiber orientation, and incorporating nanoparticles have shown promise. Embedding carbon nanotubes within PAN–PVA scaffolds, for instance, can significantly enhance load-bearing capacity while preserving biocompatibility (Zhang et al., 2019). These approaches collectively aim to ensure that marine wound patches remain

durable and adherent during prolonged exposure to dynamic aquatic conditions.

### XIII. COMPARATIVE ANALYSIS WITH OTHER POLYMERS

Natural polymers, including chitosan, alginate, and gelatin, have long been studied for wound healing applications, yet their performance in marine settings often falls short. Chitosan, for instance, boasts antimicrobial properties and biocompatibility, but it rapidly degrades in seawater due to its solubility in acidic conditions (Mohan et al., 2021). Alginate, though highly absorbent, tends to swell excessively and ultimately loses mechanical strength when exposed to saline environments. Gelatin, a collagen derivative, simply lacks the tensile resilience required for long-term immersion.

On the other hand, synthetic polymers like polyurethane and polyethylene glycol (PEG) deliver reliable mechanical durability, but they frequently fall short in terms of hydrophilicity, which is crucial for effective wound moisture regulation (Kamoun et al., 2017). In contrast, PAN-PVA hybrids present a compelling alternative: PAN contributes mechanical stability and resistance to saline degradation, while PVA ensures biocompatibility and appropriate swelling behaviour. This synergy renders PAN-PVA hybrids particularly suitable for wound care in marine contexts.

Comparative research has demonstrated that PAN-PVA nanofibers significantly outperform both polyurethane and alginate-based dressings during saline immersion, maintaining their structural integrity and antimicrobial effectiveness (Ali et al., 2023). In summary, PAN-PVA composites occupy a unique niche between natural biopolymers and traditional synthetic materials, offering a versatile and effective solution for marine wound healing applications.

### XIV. SIMULATION AND COMPUTATIONAL MODELING

Computational modelling has taken center stage in the development of advanced wound dressings. With finite element analysis (FEA), researchers can rigorously assess the mechanical response of PAN-PVA scaffolds under repeated stress, efficiently pinpointing structural weaknesses and fine-tuning

fiber orientation (Singh et al., 2024). This approach streamlines the experimental process, enabling faster and more informed material optimization.

At the molecular level, molecular dynamics (MD) simulations provide valuable insight into the interactions within PAN-PVA blends. These simulations reveal the stabilizing influence of hydrogen bonding between PAN's nitrile groups and PVA's hydroxyl groups (Zhang et al., 2019). Adjustments to polymer composition and crosslinking density *in silico* allow for predictions regarding composite behaviour in saline environments and under swelling pressures, informing design decisions before materials are even synthesized.

Additionally, computational fluid dynamics (CFD) offers predictive power regarding water vapor transmission across PAN-PVA membranes. By modelling moisture movement, researchers can ensure that dressings maintain optimal water vapor transmission rates (WVTR) for wound healing. Ultimately, integrating these computational techniques into biomaterials research accelerates development and ensures that PAN-PVA wound patches are tailored from the outset to meet the demands of marine environments.

### XV. FUTURE DIRECTIONS IN NAVAL AND DIVING MEDICINE

Marine-related injuries are a persistent challenge among naval personnel, divers, and rescue teams, often necessitating evacuation to shore-based medical facilities, a process that can introduce critical delays in treatment (Nguyen et al., 2021). The development of PAN-PVA wound patches specifically engineered for immediate field application holds promise for reducing complications and improving outcomes for injured individuals at sea.

The potential impact of these patches is not limited to military contexts. Coastal communities, fishermen, and maritime workers frequently encounter injuries that would benefit from portable, durable wound dressings. By providing reliable coverage in resource-limited and remote settings, PAN-PVA dressings could enhance community health outcomes. There is also growing relevance for extreme sports enthusiasts, such as surfers and divers, who require wound management solutions that remain effective in wet and challenging conditions.

Looking ahead, the field is likely to move toward integrated wound management platforms, PAN–PVA patches equipped with biosensors, controlled drug-release mechanisms, and antimicrobial coatings. These multifunctional devices could deliver both protection and real-time monitoring of wound status, aligning material science advances with clinical needs (Dutta et al., 2020). Such innovations have the potential to significantly advance marine wound care, fostering a more proactive and resilient approach for high-risk environments.

#### XVICONCLUSION

PAN–PVA composites combine strong, lasting fibers with a gentle touch that's safe for living tissue, making them well-suited for wound healing in salty, ocean conditions. By combining electrospinning, crosslinking, and surface tweaks, these hybrids stand up to salty wear, keep moisture in check, and help wounds knit together. Challenges like biofouling, mechanical fatigue, and the absence of marine-specific testing still stand in the way, but fresh innovations hint that PAN–PVA composites could transform wound care for divers, naval crews, and even people living along salty, wind-swept coasts.

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