

Review

Waterborne Polyurethane for Wind Turbine Blade Corrosion Protection: Synthesis, Modification Strategies, and Performance Advances

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Abstract

Wind turbine blades are exposed to multiple coupled stressors requiring protective coatings with ultra-low volatile organic compound (VOC) content, thick-film capability, and long-term durability. This review critically evaluates waterborne polyurethane (WPU) coatings as a sustainable solution, benchmarking five synthesis routes—prepolymer emulsification, acetone process, melt dispersion, ketimine/ketazine chemistry, and self-emulsification—with prepolymer emulsification identified as the most industrially mature method. Key modification strategies are systematically compared, including nano-reinforcement, surface energy control, self-healing chemistries, and bio-based approaches. Based on a synthesis of laboratory, wind-tunnel, and field studies, three critical bottlenecks—thick-film formation, nanofiller dispersion, and long-term weatherability—are identified. To address these, a layered coating architecture is proposed, integrating a low-surface-energy top-coat, a lamellar-barrier mid-coat, and a post-crosslinked primer. This framework aims to guide the industrial deployment of WPU thick-film blade coatings in offshore and other extreme environments.

Keywords: wind turbine blades; waterborne polyurethane (WPU); corrosion protection coatings; synthesis routes; nano-reinforcement; hybrid modification

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the urgent need to mitigate climate change and ensure energy security. Within this transition, wind power has established itself as a cornerstone technology, with global cumulative installed capacity soaring to approximately 1136 gigawatts (GW) by 2024. This expansion is not merely in scale but also in scope, characterized by a significant shift towards offshore wind farms. These offshore installations benefit from stronger and more consistent wind resources but are simultaneously exposed to a uniquely aggressive marine environment [1–5]. Consequently, the demands placed on wind turbine blades—the critical components that capture wind energy—have escalated dramatically. Their structural integrity and surface condition directly dictate energy capture efficiency, operational uptime, and overall economic feasibility, making the durability of their protective coatings a paramount concern for manufacturers and operators alike [6,7].

The operational reality for a wind turbine blade is one of continuous, multi-axial assault. Aerodynamically, the leading edge bears the brunt of high-velocity impacts from rain droplets, hail, sand, and other airborne particulates, leading to progressive material loss



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known as leading-edge erosion. Mechanically, the blades endure constant cyclic loading, gravitational forces, and vibrational stresses that can induce fatigue cracks. Chemically and physically, the polymeric composite materials and their coatings are degraded by intense ultraviolet (UV) radiation, wide temperature fluctuations, and hygrothermal aging from humidity. In the specific case of offshore turbines, this cocktail is further enriched by the presence of highly corrosive chloride-rich salt spray, which can accelerate galvanic corrosion of any exposed metallic components and weaken fiber-matrix interfaces [1,8–15]. These stressors do not act in isolation but rather synergistically, creating a complex failure cascade. For instance, micro-pits formed by rain erosion can act as stress concentrators for fatigue crack initiation, while UV-induced surface embrittlement can accelerate erosion rates. The consequences of this degradation—increased surface roughness, microcracking, blistering, delamination, and pitting—are severe, leading to reduced aerodynamic performance, increased operation and maintenance (O&M) costs, and potentially premature structural failure requiring costly blade repair or replacement [16–23]. Given that O&M expenditures can represent a significant fraction of the levelized cost of energy, enhancing blade longevity through superior coatings is a critical economic lever [1,8,24].

For decades, the industry has relied on solventborne polyurethane, epoxy, and polyurea coatings to provide this necessary protection. While these systems offer a proven balance of mechanical properties and chemical resistance, their limitations are becoming increasingly untenable. The most pressing issue is their high volatile organic compound (VOC) content, which poses significant environmental and occupational health hazards. Stringent global regulations, such as the EU Directive 2004/42/EC, are aggressively driving the phase-out of high-VOC coatings in favor of more sustainable alternatives [25–28]. Beyond regulatory compliance, solventborne systems face technical hurdles. They often exhibit brittleness, which is poorly suited to accommodate the flexural deformation of modern, highly optimized blade designs. Their long-term weatherability, particularly resistance to UV degradation and hydrolysis, can be insufficient, leading to chalking, loss of gloss, and a decline in barrier properties over time. Furthermore, achieving defect-free, thick-film applications (several hundred micrometers) with solventborne systems is challenging due to the risks of solvent entrapment, mud-cracking, and residual stress, all of which compromise long-term protective performance [29].

In response to these converging pressures, waterborne polyurethane (WPU) has emerged as a front-runner in the next generation of high-performance, sustainable coatings. The fundamental advantage of WPU lies in its use of water as the primary dispersion medium, which dramatically reduces VOC emissions to levels well below regulatory limits, often below 1% [25]. This environmental benefit, however, is complemented by remarkable formulation flexibility. The polyurethane backbone itself is highly tunable: the selection of aliphatic or aromatic isocyanates dictates UV stability [27,30–32]; the choice of polyol (polyether, polyester, polycarbonate) in the soft segment governs hydrolysis resistance and mechanical toughness [33]; and the ratio of soft to hard segments allows for precise control over the coating's flexibility, elasticity, and load-bearing capacity [34,35]. This molecular-level design freedom provides a powerful platform for creating coatings that can be precisely tailored to the specific mechanical and environmental demands of wind turbine blade protection.

Crucially, the performance envelope of WPU can be extended far beyond that of the pristine polymer through advanced modification strategies. While existing reviews have addressed waterborne polyurethane synthesis or coating applications independently, a critical gap remains: no comprehensive review systematically integrates synthesis-process considerations with modification strategies specifically for thick-film wind turbine blade coatings under coupled mechanical–chemical–thermal service stresses. Furthermore, prior

works lack a critical comparison of synthesis routes in terms of industrial scalability, cost implications, and thick-film defect control, nor do they provide actionable engineering frameworks for deployment in offshore environments. This review addresses these gaps by critically evaluating synthesis methods for thick-film applicability, mapping modification strategies to specific failure modes, and synthesizing evidence from laboratory, wind-tunnel, and field studies into a layered coating architecture with quantitative performance metrics. By integrating life-cycle assessment and digital-twin concepts, this review aims to provide not only a comprehensive scientific overview but also an actionable engineering framework to guide the industrial deployment of durable, high-performance WPU thick-film blade coatings in offshore and other extreme environments.

2. Challenges Faced by Wind Turbine Blades and Protective Challenges

2.1. Blade Materials and Environmental Failure Factors

Wind turbine blades are typically made of glass fiber-reinforced epoxy resin composites, which offer high specific strength and fatigue resistance. However, long-term exposure to outdoor environments subjects the blades to a combination of environmental stresses, leading to material degradation and failure [36]. Figure 1 shows the mechanism of leading-edge erosion on the blade, as well as a microscopic photo of a severely eroded blade.

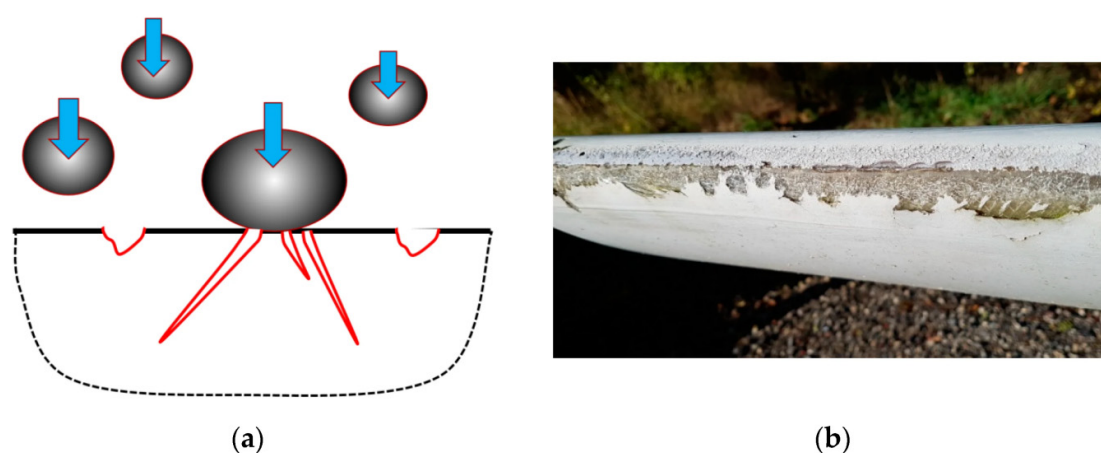


Figure 1. Schema of leading-edge erosion of blades (a) and eroded blade (b) [1]. In (a), corrosive species including chloride ions (Cl^-), oxygen (O_2), and water (H_2O) are shown adsorbing onto the substrate, initiating degradation through electrochemical and hydrolytic mechanisms. The synergistic interaction of these species drives pitting corrosion (Cl^-), hydrolytic chain scission (H_2O), and oxidative degradation (O_2), which collectively lead to interfacial debonding and structural weakening—a cascade that is amplified by mechanical stresses such as rain droplet impact.

The operational degradation of wind turbine blades stems from a combination of continuous environmental and mechanical stressors. Cyclic stresses induced by high wind speeds contribute to material fatigue over time [9]. Simultaneously, the leading edge is subjected to constant erosion from the impact of rainwater and airborne sand or dust particles [10,11]. In marine environments, this is compounded by high humidity and the presence of corrosive chloride-rich salt spray [12]. As illustrated in Figure 1a, the leading-edge region is particularly vulnerable to erosion. Corrosive species—particularly chloride ions (Cl^-), oxygen (O_2), and water (H_2O)—adsorb onto the leading-edge surface and permeate through the coating, driving electrochemical corrosion, hydrolytic chain scission, and oxidative degradation that collectively lead to interfacial debonding and structural weakening. This process is intensified by the high-velocity impact of rain droplets and airborne particles, which accelerates material loss at the leading edge. The blade materials are also challenged by severe temperature fluctuations, which can induce thermal

fatigue, and intense ultraviolet radiation that degrades the polymeric matrix [13,14,17]. In addition to these ongoing factors, sudden stochastic events such as lightning strikes, insect adhesion altering surface aerodynamics, and ice accretion can cause immediate and acute damage [21,22].

2.2. Coating Failure Modes and Consequences

2.2.1. Cracking, Blistering, and Chalk Formation [16–18]

Yang et al. [17] demonstrated that the synergistic effect of ultraviolet (UV) radiation and moisture accelerates the photo-oxidation reactions of resin polymers, significantly leading to coating cracking, blistering, and chalking. In a study conducted at the Horns Rev 1 wind farm, Visbeck et al. [19] found that prolonged rain and sand erosion of the blade leading edge significantly increased surface roughness. This led to a 2.9% reduction in annual energy production per turbine, and an overall 2.7% loss after accounting for wake effects in the wind farm (based on numerical simulations/wind farm modeling results).

2.2.2. Localized Pitting and Corrosion Propagation

In offshore wind environments, neutral chloride salts further accelerate the pitting process on metallic components of the blade surface. According to the study by Dong et al. [20], once defects occur in the coating under salt-spray conditions, the exposed metal substrate may form localized pitting. This corrosion process not only accelerates material aging but also has the potential to propagate to surrounding areas, leading to more severe structural damage.

2.2.3. Interfacial Fatigue Cracks and Delamination

Once the coating fails and is not repaired in time, moisture and oxygen can infiltrate the composite material, causing resin hydrolysis and weakening the fiber/resin interface. In severe cases, this can lead to structural delamination of the laminate and a significant reduction in overall strength [1]. Failure Mode Interactions: The above failure modes often overlap: micro-pits caused by rain erosion can serve as initiators for fatigue cracks, and coating loss accelerates the penetration of environmental agents, creating a vicious cycle of deterioration [23]. As illustrated in Figure 2, damage in wind turbine blades may evolve progressively from leading-edge coating erosion to adhesive-layer debonding/void formation and further to laminate-level interface cracking, matrix cracking, and fiber fracture, reflecting the coupled and multiscale nature of blade degradation.

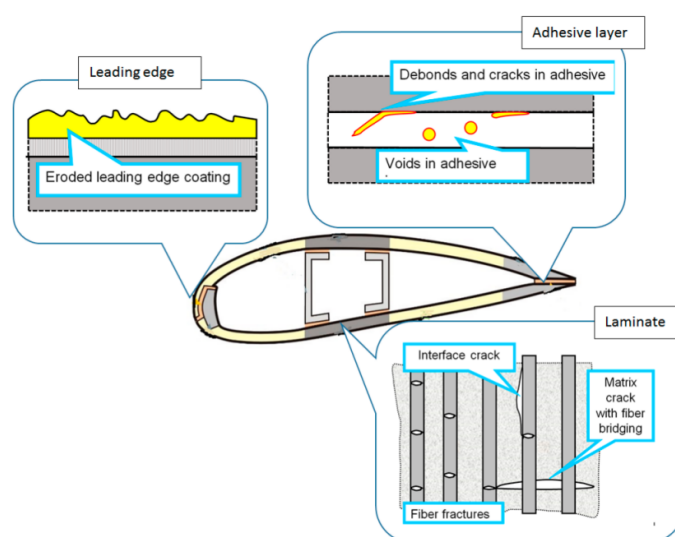


Figure 2. Main structural damage mechanisms of wind turbine blades [37].

2.3. Performance Limitations of Traditional Coatings

Currently, commonly used solvent-borne polyurethane and epoxy coatings for wind turbine blades exhibit several critical shortcomings. These systems are characterized by high volatile organic compound emissions, which increasingly fail to comply with stringent environmental regulations. Technically, they often suffer from high brittleness, making them poorly suited to accommodate the continuous vibration and flexural deformation of modern blades. Furthermore, their long-term durability is often inadequate, leading to premature degradation and failure under the combined assault of ultraviolet radiation, salt spray, and rain erosion. Collectively, these defects severely limit the long-term protective performance of traditional coatings in the wind energy sector.

2.4. Performance Requirements and Outlook for WPU Coatings

To address the multifaceted challenges of the operating environment, an ideal protective coating for wind turbine blades must fulfill several critical functions. It requires excellent weatherability to resist ultraviolet light and thermal aging, thereby suppressing crack formation; outstanding corrosion resistance to block salt spray and moisture, preventing pitting propagation; good mechanical toughness to adapt to structural vibrations and deformation without cracking; and high adhesion coupled with wear resistance to withstand high-velocity particle erosion and prevent localized delamination. Waterborne polyurethane coatings, distinguished by their tunable molecular structure and inherent environmental benefits, present a promising platform for the synergistic optimization of these demanding performance metrics. The following sections will provide a detailed discussion of the structural design and modification advancements that underpin the potential of WPU coatings for this application.

3. Advantages of WPU Coatings for Corrosion Protection of Wind Turbine Blades

Waterborne polyurethane (WPU) coatings have attracted widespread attention in the field of corrosion protection for wind turbine blades. Their environmental friendliness, tunable performance, excellent adhesion, and ease of application make them an ideal alternative to traditional solventborne coatings. Recent studies have further confirmed the substantial potential of WPU coatings in this field:

Chen et al. [38] reviewed rain-erosion protection strategies for wind turbine blades and highlighted polyurethane-based coating systems as promising candidates because they can balance flexibility, adhesion, and erosion resistance. Johansen et al. [39] further showed that graphene oxide (GO)-reinforced polyurethane coatings significantly improved mechanical properties and rain erosion resistance, making them suitable for long-term leading-edge protection. As shown in Figure 3, the nanoengineered graphene-reinforced systems (especially PU + GNP + SG) exhibited a markedly higher number of impacts to material loss than neat PU at comparable impact speeds, demonstrating a substantial extension of leading-edge protection lifetime.

Pathak et al. [40] developed ceramic-oxide-reinforced water-based PU nanocomposite coatings for wind turbine blade protection, and demonstrated significantly reduced solid-particle erosion losses compared with neat PU coatings and GFRP substrates. Liu et al. [41] prepared SiO₂-reinforced WPU nanocomposite coatings, which exhibited significant improvements in mechanical strength and electrochemical impedance, with superior corrosion resistance compared to pure WPU. These studies demonstrate that WPU coatings are not only environmentally friendly but also possess great potential for performance enhancement in corrosion protection, making them a key development direction for wind turbine blade coatings.

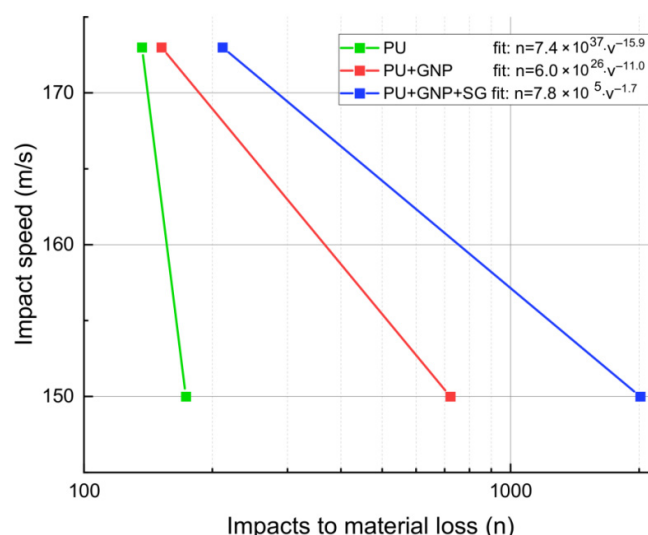


Figure 3. VN curves showing the relationship between impact speed and material loss. The PU + GNP (graphene nanoplatelets) + SG (sol-gel) system exhibits the longest erosion lifetime, attributed to the synergistic effect of graphene nanosheets providing mechanical reinforcement and crack bridging, while the sol-gel network enhances interfacial compatibility and barrier integrity. Quantitatively, this system achieves approximately a 95% increase in ultimate strength and a 124% increase in toughness relative to neat PU, directly translating to extended leading-edge protection under rain erosion conditions. Adapted from Johansen et al. [39].

3.1. Environmental Friendliness

WPU uses water as the dispersion medium, significantly reducing VOC emissions. Measurements have shown that the VOC content in WPU coatings is <1%, while traditional solventborne coatings contain up to 83% VOC, corresponding to approximately 500 g per kg of coating [25]. According to the EU Directive 2004/42/EC, the VOC limit for industrial waterborne coatings is 140 g/L, whereas solventborne coatings can exceed 500 g/L [26], further highlighting the environmental advantages of WPU.

3.2. Structural Tunability

The weatherability, mechanical properties, thermal stability, and corrosion resistance of WPU can be finely tuned by selecting different isocyanates, optimizing the soft/hard segment ratio, and tailoring the soft-segment chemistry. Table 1 summarizes the key formulation parameters and their corresponding effects on coating performance, including UV degradation reduction and corrosion rate, where reported.

Table 1. Influence of structural parameters on the performance of waterborne polyurethane coatings.

Structural Parameter	Variation	Key Performance Enhancement	UV Degradation Reduction	Corrosion Rate (or Protection Efficiency)	References
Isocyanate type	Aliphatic (HDI, IPDI) vs. aromatic	Improved UV stability; reduced yellowing	Significant reduction in photo-oxidation rate	–	[27,30–32]
Soft-segment type	Polycarbonate diol (PCD) vs. polyether/polyester	Enhanced hydrolysis resistance and thermal aging stability	–	Improved long-term corrosion resistance	[33]
Soft/hard segment ratio	Increased hard segment content	Higher rigidity, impact resistance, and storage modulus	–	–	[34,35]

Table 1. Cont.

Structural Parameter	Variation	Key Performance Enhancement	UV Degradation Reduction	Corrosion Rate (or Protection Efficiency)	References
Soft/hard segment ratio	Increased soft segment content	Higher tensile elongation and flexibility; reduced microcracking	–	–	[34,35]
Isocyanate + polyol optimization	Aliphatic isocyanate + polycarbonate polyol	Combined UV stability and hydrolysis resistance	UV degradation rate reduced by >50% (relative to aromatic systems)	Corrosion rate reduced by ~60% in salt-spray tests	[30,33]

Note: Quantitative data on UV degradation reduction and corrosion rate are reported where available from the cited references. Specific values are derived from comparative studies between optimized WPU formulations and conventional or unmodified systems.

3.3. Adhesion and Compatibility with Substrate Corrosion Protection

Waterborne polyurethane (WPU) coatings, due to the abundant urethane groups in their molecular structure, can form hydrogen bonds and other secondary interactions with various substrates, such as glass fiber, metals, and composites. This results in excellent adhesion, thereby enhancing the anticorrosion protection of wind turbine blades made from different materials. Quantitative adhesion studies have demonstrated that WPU coatings achieve pull-off adhesion strengths ranging from 5 to 12 MPa on steel substrates, depending on formulation and surface preparation [42]. Compared to traditional solventborne polyurethanes (typically 4–8 MPa), WPU exhibits comparable or superior adhesion due to its ability to form more uniform interfacial contacts during film formation [43]. The incorporation of functional nanofillers further enhances adhesion: silane-grafted nano-SiO₂/TiO₂ improves adhesion strength by approximately 25%–35% through covalent bonding at the coating–substrate interface [42], while graphene oxide-modified WPU shows a 20%–30% increase in adhesion due to enhanced mechanical interlocking and hydrogen bonding [44]. However, excessive hydrophobicity from fluorine or silicon modification can reduce adhesion by 30%–50%, necessitating a balanced design for topcoat applications [45].

In terms of performance enhancement, the introduction of nanomaterials is a crucial method for improving the overall properties of coatings. Liang et al. grafted graphene oxide (GO) onto the WPU molecular chain, significantly improving the mechanical and surface properties of the coating: tensile strength increased by approximately 65%, abrasion resistance improved by approximately 28%, hardness increased by approximately 16%, and solvent resistance was also enhanced [44]. Additionally, Wen et al. reported that incorporating 0.3 wt. % functionalized graphene oxide nanosheets into WPU markedly reduced water uptake and maintained a low-frequency electrochemical impedance spectroscopy (EIS) impedance modulus above 10⁸ Ω·cm² even after 50 days of immersion in 3.5 wt. % NaCl, indicating substantially enhanced barrier integrity and anticorrosion stability [46].

3.4. Quantitative Corrosion Protection Performance of WPU Systems

Beyond the intrinsic advantages of environmental friendliness and structural tunability, the corrosion protection capability of waterborne polyurethane (WPU) coatings has been systematically evaluated through electrochemical impedance spectroscopy (EIS), salt-spray testing, and long-term immersion studies. Table 2 summarizes representative corrosion performance data for various WPU nanocomposite systems reported in the recent literature.

Table 2. Corrosion protection performance of representative WPU-based coatings.

WPU System	Filler Content (wt. %)	Test Conditions	EIS $ Z $ at 0.01 Hz ($\Omega \cdot \text{cm}^2$)	Corrosion Protection Efficiency	Reference
Pure WPU	–	3.5 wt. % NaCl, 7 d	$\sim 10^5$ – 10^6	–	[46]
GO/WPU (noncovalent)	0.3	3.5 wt. % NaCl, 50 d	$> 10^8$	–	[46]
GO/WPU (covalent)	0.3	3.5 wt. % NaCl, 50 d	$\sim 10^9$	–	[46]
SiO ₂ –GO/WPUA	1.0	3.5 wt. % NaCl, 30 d	9.46×10^8	–	[41]
CeNPs@MXene/WPU	2.0	3.5 wt. % NaCl, 120 d	$\sim 10^8$	–	[47]
fGO/WPU	0.5	3.5 wt. % NaCl, 240 h	1.29×10^7	99.6%	[48]
POSS–GO/WPU	1.0	3.5 wt. % NaCl, 30 d	3.2×10^8	–	[49]

These data demonstrate that well-dispersed nanofillers, particularly two-dimensional materials such as graphene oxide and MXene, can significantly enhance the barrier properties of WPU coatings by creating a tortuous diffusion pathway for corrosive species (H_2O , O_2 , Cl^-). The covalent grafting of nanofillers to the polymer matrix further improves interfacial compatibility and extends the durability of the barrier effect, as evidenced by the sustained high impedance modulus even after extended immersion periods. The corrosion protection efficiency reaches values exceeding 99% in optimized systems, indicating that WPU nanocomposites can achieve performance levels comparable to or exceeding those of conventional solventborne coatings. Bio-inspired self-healing and anti-corrosion WPU coatings based on highly oriented graphene oxide further highlight the ‘barrier + self-healing’ synergy in optimized systems [50]. The barrier enhancement provided by two-dimensional fillers is quantified by the tortuosity factor $\tau = 1 + (\alpha/2)(L/t)\phi$, where τ is the tortuosity factor (dimensionless), α is the orientation factor (0.5 for random orientation, 1.0 for perfect alignment), L/t is the aspect ratio of the nanofiller (length-to-thickness ratio, dimensionless), and ϕ is the filler volume fraction (dimensionless, typically 0.001–0.01 for nanocomposites).

4. WPU Synthesis Processes for Anti-Corrosion Coatings in Wind Turbine Blade Applications

4.1. Comparison of Synthetic Routes and Their Characteristics

Protective coatings for wind turbine blades are applied as thick films (several hundred micrometers). This section critically evaluates five WPU synthesis routes—prepolymer emulsification, the acetone process, melt dispersion, ketimine/ketazine chemistry, and self-emulsification—comparing their industrial maturity, scalability, and suitability for thick-film applications.

4.1.1. Prepolymer Emulsification Method

The prepolymer emulsification method begins with the reaction of a polyol and a diisocyanate to form an NCO-terminated prepolymer, which is subsequently emulsified in water and chain-extended [51]. In anionic aqueous polyurethane dispersions, water dispersibility is achieved by introducing internal ionic centers, such as carboxylate groups from DMPA-type internal emulsifiers, into the polymer backbone—a common strategy in industrial formulations [52]. This approach offers several advantages, including low solvent usage and the production of high-molecular-weight polymers with stable dispersions [52–54]. Typical solids content ranges from 30 to 45%, though optimized formulations can reach 53% or even as high as 66.1%, with further increases possible through organic–inorganic hybridization or filler-assisted strategies [55–58]. However, the process carries inherent risks: the exothermic reaction between NCO groups and water necessitates careful control of water addition and temperature to prevent CO_2 generation and amine formation, which can cause foaming, porosity, and reduced film density [51,59]. Despite its industrial matu-

rity, the prepolymer emulsification method faces inherent limitations for thick-film blade coatings. The exothermic NCO–water reaction becomes increasingly difficult to control at high film thicknesses, where heat accumulation can accelerate CO₂ generation and foam formation. Furthermore, achieving consistent particle size distribution and storage stability at solids contents above 50% remains challenging for many commercial formulations.

4.1.2. Acetone Process

The acetone process operates by introducing acetone during prepolymer formation to reduce viscosity, thereby facilitating neutralization and chain extension. The solvent's miscibility with water and low boiling point allows for its efficient removal after dispersion [51]. Additionally, acetone can form reversible ketimines with amines, which temporarily protect amino groups and delay chain extension, offering enhanced processing control [51,60]. This method is valued for its good batch reproducibility and wide processing window [51]. However, it carries notable disadvantages, including relatively high solvent usage, associated environmental constraints, and the added cost of solvent removal—factors that make residual solvent management particularly critical in thick coating applications [51]. Typical solids content ranges from approximately 25 to 35% [61]. The acetone process offers excellent batch reproducibility and a wide processing window, making it attractive for research applications. However, its scalability is constrained by environmental and economic factors: acetone use increases VOC-related regulatory burden and requires solvent recovery systems. Residual solvent, even at trace levels, can cause pinhole defects in thick-film applications.

For these reasons, the acetone process is better suited for low-volume or laboratory-scale applications rather than high-throughput industrial blade coating. As illustrated in Figure 4, the two methods exhibit fundamentally different particle formation mechanisms. Prepolymer emulsification yields 50–200 nm particles and enables high solids content (up to $\geq 53\%$) but requires careful exotherm management. The acetone process offers finer particles (30–150 nm) and excellent batch reproducibility but risks solvent-bubble defects if residual solvent exceeds 0.1%. These mechanistic differences directly influence thick-film defect control.

4.1.3. Melt Dispersion Method

The melt dispersion method is a solvent-free process in which urea or ammonia is typically reacted with the prepolymer to form urea or biuret groups, thereby enhancing dispersibility. Chain extension and dispersion are subsequently completed under specific conditions, such as through formaldehyde hydroxymethylation [51]. While this approach is environmentally friendly and offers potential for increased solids content with reduced residual solvent, it presents significant challenges. The process demands higher temperatures and shear forces, and the inherently high viscosity of the prepolymer makes dispersion difficult. It also imposes greater demands on heat-sensitive monomers and structures, with the combination of energy consumption and process complexity currently limiting its large-scale adoption [51,62]. While melt dispersion is completely solvent-free, its industrial adoption remains limited due to technical and economic barriers. High processing temperatures can degrade heat-sensitive monomers, and high shear forces impose stringent equipment requirements. The inherently high viscosity of the prepolymer makes uniform dispersion difficult, often resulting in batch-to-batch variability unacceptable for blade manufacturing. Melt dispersion is therefore confined to niche applications where solvent-free processing is mandatory.

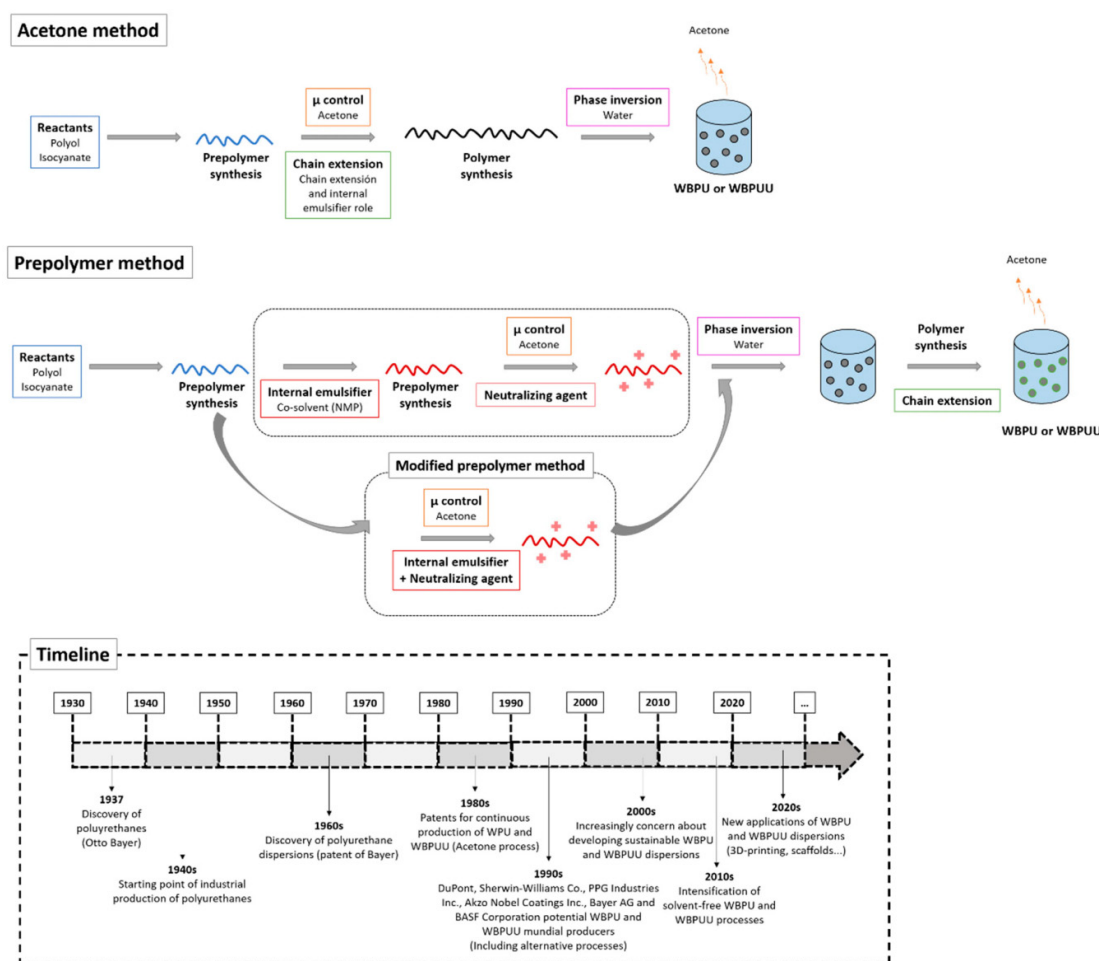


Figure 4. Main steps in the preparation of WBPU by the acetone process and prepolymer emulsification method [34].

4.1.4. Self-Emulsification Method

Definition and features: This method involves introducing ionic/non-ionic hydrophilic monomers into the main chain or side chains, or using block/graft hydrophilic segments to allow the system to disperse self-stably without the need for external emulsifiers [51,52,63]. The process is simple, with low residual surfactants and a relatively low risk of film defects. However, it is more sensitive to the balance between hydrophilic–hydrophobic interactions, particle size distribution, and rheological coupling [51,52].

Self-emulsification eliminates external surfactants, reducing the risk of surfactant migration and film defects—a significant advantage for thick-film applications. However, the balance between hydrophilic and hydrophobic components is inherently delicate: excessive hydrophilicity compromises water resistance, while insufficient hydrophilicity leads to poor dispersion (Table 3). This trade-off imposes tight formulation tolerances that are difficult to maintain under production conditions. In externally emulsified systems, residual surfactants can migrate to the coating surface during film formation, creating hydrophilic domains that increase water sensitivity and reduce barrier performance. These residues may also act as plasticizers, lowering the glass transition temperature and compromising mechanical properties. Furthermore, surfactant migration can lead to dewetting, crater formation, and interlayer adhesion failure—defects particularly problematic in thick-film applications where evaporation rates are slower and surfactant accumulation is more pronounced [51,52]. Self-emulsification avoids these issues by incorporating ionic or nonionic hydrophilic groups directly into the polymer backbone, ensuring that hydrophilic segments

remain covalently bound rather than free to migrate. However, the covalently bound hydrophilic groups themselves can still increase water absorption if not balanced by adequate crosslinking or hydrophobic segments. Optimal film quality, therefore, requires careful control of the hydrophilic monomer content (typically 5–15 wt. %) and crosslinking density to minimize water sensitivity while maintaining dispersion stability [52,63].

Table 3. Synthesis Methods and Key Considerations for Thick-Film Adaptation and Defect Control (Qualitative Review).

Synthesis Route	Solids Content Range	Process and Application Features	Key Considerations for Thick-Film Adaptation	Main Defects and Control Strategies
Prepolymer emulsification	30%–45%, up to $\geq 53\%$, with reports of about 66.1%	Uses a small amount of solvent; moderate process complexity; the most mature and widely used industrial route	Staged water addition, temperature control, antifoaming/defoaming combined with vacuum degassing; match airless spraying and single-pass thickness	NCO–water reaction can generate CO_2 , leading to foaming and porosity; sagging and mud cracking can be mitigated by temperature control and multi-pass application
Acetone process	About 25%–35%	Acetone-containing; moderately high process complexity; technically mature but environmentally constrained	Suitable for rapid preparation and scale-up at medium solids; optimization of residual solvent management and solvent-release profile is required	Prone to pinholes and solvent bubbles; improved by solvent-release control; sagging can be reduced by limiting single-pass thickness
Melt dispersion	Medium to high (system-dependent)	Solvent-free and environmentally friendly, but with high process complexity and energy consumption; mainly used in special application scenarios	Use temperature–shear coupling and online viscosity/torque monitoring; thin-layer multi-pass application is preferred	Susceptible to poor dispersion and mud cracking; requires optimization of temperature–shear program; heat-sensitive components should be used cautiously
Ketimine/ketazine process	Medium to high (high potential)	Solvent-free with high environmental potential, but complex and still mainly at the experimental stage	Suppress foaming through delayed chain extension and control hydrolysis rate	Mainly limited by stability and cost; requires stricter control of intermediate purity and water-release behavior
Self-emulsification	Medium to high (system-dependent)	Solvent-free or with negligible solvent; moderate process complexity; already has industrial applicability	Requires synergistic design of hydrophilic monomers and block segments; high-shear pre-dispersion followed by low-shear application	Air entrapment and coarse particles are common; dispersion, particle size, and formulation balance need to be optimized

Among the five synthesis routes, prepolymer emulsification remains the most industrially mature method due to its high solids content (30%–45% up to $\geq 53\%$) and established process control, though it requires careful exotherm management. The acetone process offers superior batch reproducibility and finer particles (30–150 nm) but faces environmental constraints and risks solvent-bubble defects. Self-emulsification provides a balance between low residual solvent and process simplicity with particle sizes of 30–100 nm, but requires precise formulation control. Melt dispersion (100–500 nm) and ketimine/ketazine chemistry are solvent-free but limited by process complexity and stability issues.

To guide industrial selection, the five synthesis routes can be ranked by application scenario. For OEM high-volume production, prepolymer emulsification is preferred due to its highest solids content and established infrastructure, with self-emulsification as a secondary option. For field maintenance and repair, self-emulsification is recommended for its low residual solvent and simple handling. For R&D and prototyping, the acetone process offers the widest processing window and excellent batch reproducibility. For solvent-free mandatory applications, melt dispersion and ketimine/ketazine chemistry are the only viable options, albeit with higher process complexity and cost. For high-durability thick-film requirements, prepolymer emulsification remains the most reliable choice, with

ketimine/ketazine chemistry offering potential for advanced defect control when process conditions can be tightly managed.

4.1.5. Ketimine/Ketazine Chemistry

This method utilizes ketimine or ketazine compounds as blocked amines that reversibly react with water to release free amine groups, which then react with isocyanates for chain extension. The delayed release of amines allows for controlled reaction kinetics, reducing premature gelation and enabling higher solids content in waterborne systems. While this approach offers potential for solvent-free processing and dense film formation, its industrial adoption remains limited due to complex intermediate synthesis, stringent water-release control, and higher raw material costs compared to conventional methods [51,60]. For thick-film applications, the ketimine/ketazine route shows promise for achieving defect-free coatings with low residual solvent, but requires precise control of hydrolysis rate and processing conditions.

5. Modification Strategies for WPU in Wind Turbine Blade Applications

In Section 4, various WPU synthesis routes and their applicability to thick-film coatings were discussed. However, when subjected to the combined service stresses of rain erosion, UV exposure, temperature fluctuations, microcracks, and icing, a single formulation often cannot meet all the required performance metrics. Current research focuses on five major modification categories: nano-enhancement, functional/polar group incorporation with post-crosslinking, self-healing mechanisms, fluorine/silicon-based surface modification, and bio-based modifications. Given the critical operating conditions involving rain erosion + icing + weathering, this chapter emphasizes nano-enhancement and fluorine/silicon surface modification as the two primary strategies, while the other three serve as complementary techniques.

5.1. Primary Strategy I: Nano-Reinforcement

Multiple studies have shown that nanofillers (typically 2–6 wt. %) improve hardness, wear resistance, and corrosion protection [49,64–72]. However, reported performance varies significantly due to differences in filler type, dispersion quality, and testing methodologies. This section critically evaluates nano-reinforcement strategies in terms of effectiveness, cost, scalability, and limitations.

Taking silicon dioxide (SiO_2) as an example, Malaki et al. [64] observed that the incorporation of nano- SiO_2 into polyurethane acrylate significantly increased adhesion strength and markedly improved microhardness and corrosion resistance. In terms of low filler loading and practical scalability, the quantitative data reported by Wang et al. [67] are representative: a 2 wt. % SiO_2 /PU composite coating exhibited a wear rate and friction coefficient of $1.52 \times 10^{-6} \text{ cm}^3/\text{min}\cdot\text{N}$ and 0.31, respectively, with wear resistance approximately 10 times higher than that of pure PU coatings. For leading-edge erosion, Syamsundar et al. systematically investigated the effects of impact angle and nanoparticle content on the erosion behavior of polyurethane, confirming that both formulation and operational conditions are key determinants of erosion performance [65].

Besides particulate nanofillers such as SiO_2 , graphene-derived nanosheets have also attracted considerable attention because of their excellent lamellar barrier effect in polymer matrices [46]. As illustrated in Figure 5, the dispersed functionalized nanosheets increase the diffusion tortuosity of corrosive species such as H_2O , O_2 , and Cl^- , thereby delaying their penetration to the metal/coating interface and enhancing long-term barrier protection. Further morphological evidence is provided by the work of Rajabimashhadi et al. [73], as shown in Figure 6a,b. The AFM images reveal distinct surface topographies depending on

filler type and dispersion quality. The reduction in Rz (maximum peak-to-valley height) from approximately 120 nm to 60 nm after filler incorporation indicates improved coating compactness, which correlates with enhanced barrier performance. Conversely, increased roughness in poorly dispersed systems reflects filler agglomeration that may serve as stress concentration points, compromising mechanical durability. 2D fillers (GO, MXene) provide superior barrier but cost 10–100× more than 0D fillers (SiO₂). Hybrid systems combining small amounts of 2D with cost-effective 0D fillers offer a pragmatic balance.

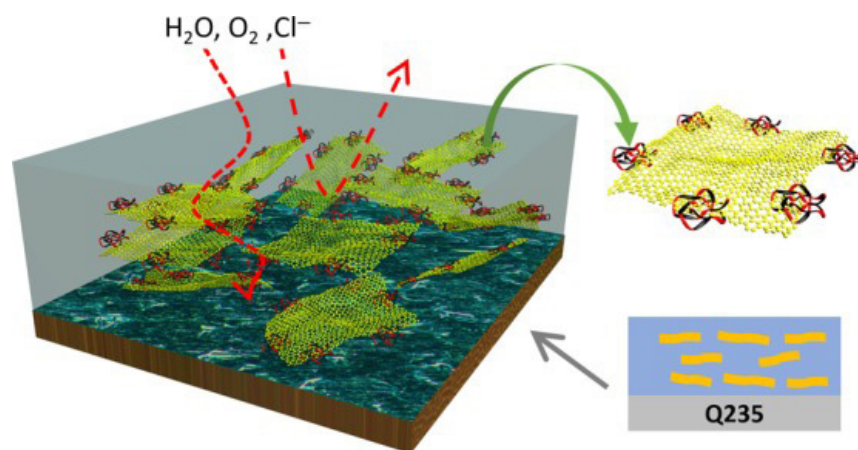


Figure 5. Schematic illustration of the corrosion protection mechanism of IP-GO composite coatings. The dispersed graphene oxide nanosheets create a tortuous diffusion pathway for corrosive species (H₂O, O₂, Cl[−]), quantified by the tortuosity factor $\tau = 1 + (\alpha/2)(L/t)\phi$. For GO with aspect ratio $L/t \approx 500\text{--}1000$ at $\phi = 0.005$, τ increases to 3–5, reducing water permeability by a factor of 3–5 according to Fick’s first law. This barrier effect, combined with strong interfacial bonding, extends the diffusion path and delays corrosive species from reaching the metal substrate [46].

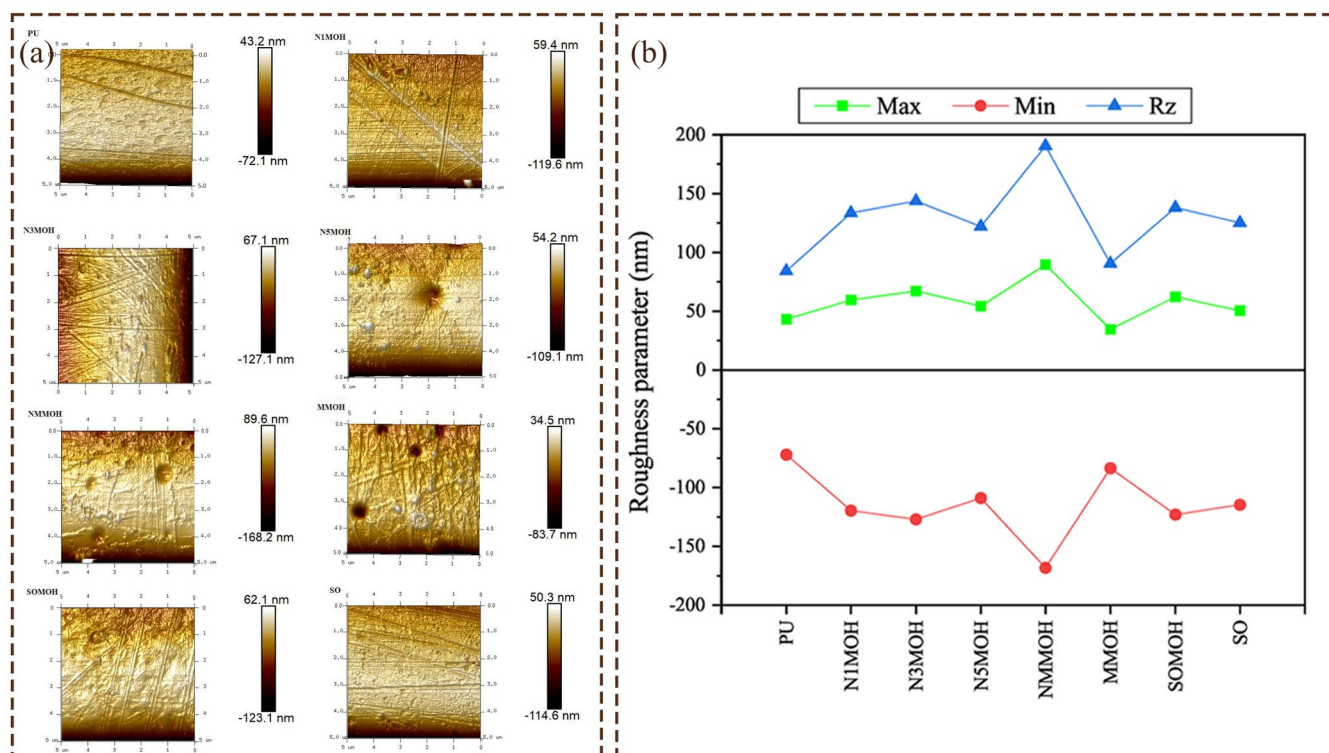


Figure 6. AFM morphology and surface roughness parameter comparison of polyurethane-based composite coatings. (a) AFM images of different nano/micron filler systems. (b) Corresponding

changes in surface roughness parameters: Max (maximum peak height), Min (maximum valley depth), and Rz (average maximum peak-to-valley height). Lower Rz values indicate smoother, more compact coatings, correlating with improved barrier performance [73].

Nanoparticles tend to agglomerate, inducing stress concentration. Surface modification (silane, amine) and high-shear dispersion improve distribution but introduce trade-offs: silane agents can hydrolyze under humidity, amine-functionalized fillers may react with isocyanates, and ultrasonic dispersion is energy-intensive and difficult to scale. The modulus enhancement in nanocomposites follows the Halpin–Tsai equation: $E_c/E_m = (1 + \xi\eta\phi)/(1 - \eta\phi)$, where E_c is the modulus of the nanocomposite (MPa or GPa), E_m is the modulus of the neat polymer matrix (MPa or GPa), ϕ is the filler volume fraction (dimensionless), ξ is a shape factor depending on filler geometry (for two-dimensional fillers, $\xi = 2(L/t)$, where L/t is the aspect ratio), and η is a reduced modulus ratio given by $\eta = (E_f/E_m - 1)/(E_f/E_m + \xi)$, with E_f being the modulus of the filler (MPa or GPa). For graphene oxide in WPU ($E_m \approx 0.1$ GPa), the modulus enhancement reaches 30%–50% at $\phi = 0.005$. The critical filler loading for percolation is $\phi_c = 27\pi/(L/t)$, which for $L/t = 500$ yields $\phi_c \approx 0.0017$.

5.2. Main Line II: Fluorine and Silicon-Based Surface Modification

It is generally agreed that reducing surface energy and constructing stable micro/nano-textures is an effective approach to suppressing icing, contamination, and moisture erosion [45,74,75]. Fluorine-based coatings, due to their low surface energy, can significantly reduce wetting and ice adhesion. When combined with active heating, the overall de-icing energy consumption can be further reduced (wind tunnel experiments show a reduction of over 50%) [74].

Hu et al. summarized the advantages of silicon-based surfaces in terms of low surface energy and environmental friendliness, while also noting the potential weakness of reduced adhesion and mechanical strength, which needs to be balanced during the design process [75]. In specific systems, Wu et al. incorporated PDMS soft segments into waterborne polyurethane, achieving superhydrophobicity (with a maximum water contact angle $> 150^\circ$), which demonstrated significant control over surface wetting [45].

Figure 7 shows the water contact angle (WCA) of WPU composites with different M-PDMS/PTFE contents [76]. The WCA of pure WPU coatings is approximately 83° , but after introducing a small amount of M-PDMS/PTFE, it quickly increases to 107 – 113° . As the content increases (< 8 wt. %), the WCA follows a pattern of initially increasing and then stabilizing, reaching saturation around 8 wt. %. This result suggests that the low-surface-energy characteristics of PTFE and the crosslinked network of M-PDMS work synergistically in the matrix, forming a stable low-surface-energy interface and effectively enhancing hydrophobicity.

Fluorinated raw materials cost 5 – $10\times$ more than conventional precursors. PDMS modifications reduce adhesion by 30%–50% but offer cost-effectiveness. A gradient design—a thin functional topcoat over a robust base layer—is recommended.

Figure 8 presents ATR-FTIR spectra comparing the surface layer and interface layer of the coating. The higher intensity of characteristic peaks (e.g., Si–O–Si at 1000 – 1100 cm^{-1}) at the surface confirms preferential migration of low-surface-energy components toward the air–coating interface. This microphase separation is critical for achieving hydrophobicity but, if uncontrolled, can weaken interlayer adhesion, as indicated by reduced urethane N–H and C=O bands at the interface [77]. Research outlook: It is recommended to quantitatively investigate the synergistic effects of surface energy gradients and microscale roughness on anti-icing and anti-contamination properties, and to conduct in situ observations of surface

evolution and phase separation dynamics under real-service exposure, providing a basis for durability design (Figure 8).

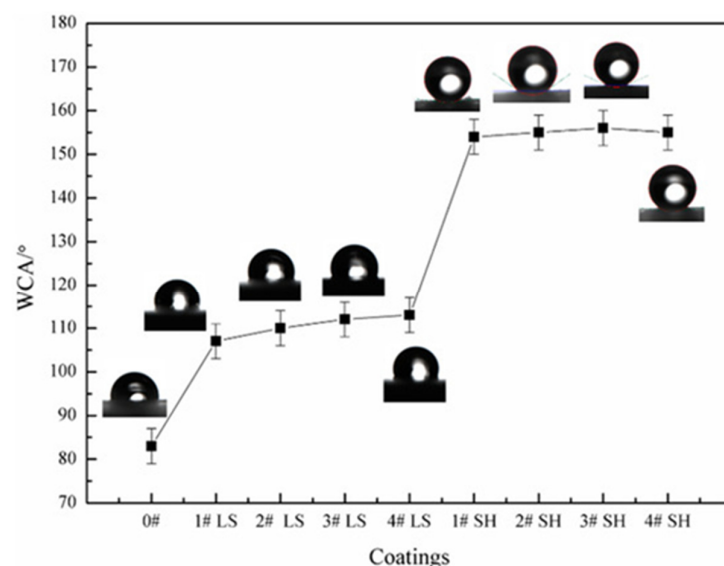


Figure 7. Water contact angle (WCA) of WPU composites as a function of M-PDMS/PTFE content. The WCA increases from approximately 83° (pure WPU) to 107 – 113° at low loadings, reaching saturation around 8 wt. %. This trend indicates surface enrichment of low-surface-energy components, with the saturation point corresponding to complete coverage of the surface by PDMS/PTFE. The plateau suggests that further loading does not enhance hydrophobicity but may introduce bulk property trade-offs, such as reduced adhesion [76].

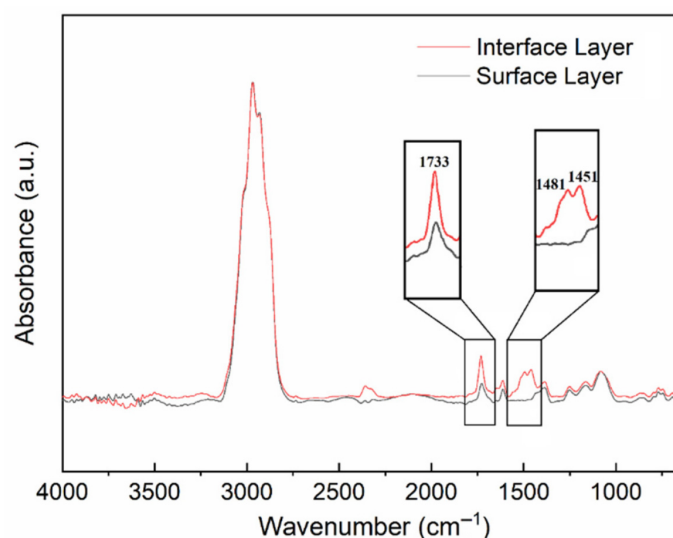


Figure 8. ATR-FTIR spectra of the coating surface layer and interface layer, showing compositional differentiation associated with surface enrichment and interface stabilization. Adapted from Zhou et al. [77].

5.3. Functional/Polar Group Incorporation and Post-Crosslinking

Ionic/polar groups enhance wet adhesion but increase hydrophilicity; excessive content (>4 wt. %) leads to water uptake >10 – 15% . Post-crosslinking restores water resistance but may induce brittleness. Optimal balance requires an ionic group content of 1–4 wt. % with controlled crosslinking density [78–82].

5.4. Self-Healing Functionalization

Self-healing systems demonstrate 80%–95% healing efficiency under ideal conditions but face limitations: activation requires external stimuli not consistently available; contaminants inhibit re-bonding; repeated cycles diminish performance; and self-healing units can reduce tensile strength by 20%–40%. For leading-edge erosion involving continuous material loss rather than discrete cracks, the relevance of self-healing remains questionable [83–89]. Healing efficiency follows $\eta(t) = \eta_{max} [1 - \exp(-kt)]$, with rate constant $k = A \exp(-E_a/RT)$ where $\eta(t)$ is the healing efficiency at time t (dimensionless, 0 to 1), η_{max} is the maximum achievable healing efficiency (dimensionless, typically 0.8–0.95 for dynamic covalent systems), k is the rate constant of the healing process (s^{-1}), and t is time (s). The rate constant follows the Arrhenius equation $k = A \exp(-E_a/RT)$, where A is the pre-exponential factor (s^{-1}), E_a is the activation energy for bond exchange ($\text{kJ}\cdot\text{mol}^{-1}$ or $\text{J}\cdot\text{mol}^{-1}$), R is the universal gas constant ($8.314 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$), and T is the absolute temperature (K). For disulfide-based systems, $E_a \approx 60\text{--}80 \text{ kJ}\cdot\text{mol}^{-1}$, resulting in healing times of 1–2 h at 60 °C compared to 24–48 h at room temperature [90].

5.5. Green Bio-Based Modification

Bio-based WPU reduces petrochemical reliance but introduces challenges: lower reactivity, broader molecular weight distributions, and batch-to-batch variability. Long-term weatherability under UV and hydrolytic exposure requires further validation. A hybrid approach—using bio-based materials in primer layers where UV exposure is limited—offers a viable path to sustainability without compromising durability [91,92] (Table 4).

Table 4. Comparison of Modification Strategies for WPU in Wind Turbine Blade Applications.

Modification Strategy	Representative Mechanisms/Key Points	Performance Improvements (Examples)	Potential Issues	Applicable Scenarios	References
Nano-reinforcement	Reinforcing skeleton and dense barrier; 2D lamellae create tortuous diffusion paths	Improved strength, microhardness, and wear/erosion resistance; enables combined de-icing and erosion protection	Agglomeration-induced stress concentration; dispersion and interfacial compatibility must be optimized	Leading-edge thick-film erosion and corrosion protection; de-icing in cold regions	[49,64–71]
Fluorine-/silicon-based surface modification	Low surface energy, surface enrichment, and controllable microphase separation	Reduced ice adhesion; heating-assisted de-icing lowers energy use; water contact angle up to $\sim 156.5^\circ$	Possible loss of adhesion and mechanical strength; needs coordination with substrate reinforcement	Anti-icing, self-cleaning, and anti-fouling surface layers	[45,74,75]
Functional/polar groups + post-crosslinking	Enhanced wet adhesion; post-crosslinking/dynamic bonds balance dry–wet properties	Tensile strength increased by $\sim 2.7\times$; water absorption/swelling reduced by $\sim 66\%$; supports self-healing network design	Excessive hydrophilicity may cause softening; crosslink density must be carefully controlled	Interfacial adhesion retention under humid and salt-spray conditions	[78–82]
Self-healing functionalization	Dynamic covalent and multiple hydrogen-bond networks; triggered by heat, light, or humidity	High crack-closure efficiency; reversible healing achievable near room temperature	Trade-offs among healing efficiency, weatherability, and mechanical properties; cyclic fatigue remains a concern	Repair of leading-edge microcracks after rain/sand erosion and thermal cycling	[83–88]
Green bio-based modification	Partial substitution with plant oils/lignin; additional UV-shielding functionality	Improved sustainability and weathering potential; reduced solvent use during synthesis	Batch variation and compatibility issues; long-term weathering still needs validation	Green-manufacturing-oriented primer or intermediate coatings	[91,92]

Beyond the barrier effect, the incorporation of nanofillers also exerts a pronounced influence on the mechanical properties of WPU coatings, which is critical for withstanding the cyclic loading, vibration, and impact stresses encountered during wind turbine opera-

tion. Table 5 compiles representative mechanical property data for WPU nanocomposites reported in recent studies. The mechanical reinforcement mechanism varies with filler type. For zero-dimensional nanoparticles such as SiO₂, the enhancement is primarily attributed to uniform stress distribution and the restriction of polymer chain mobility. In contrast, two-dimensional graphene derivatives provide both reinforcement through strong interfacial interactions and toughening via crack deflection and bridging mechanisms. Notably, the combination of graphene nanosheets with a sol–gel network (GNP + SG) has been reported to increase ultimate strength by approximately 95% and toughness by about 124% relative to neat polyurethane, representing a significant improvement in impact resistance relevant to leading-edge protection [71]. A trade-off is often observed between stiffness and flexibility: while increased filler loading typically improves modulus and wear resistance, excessive loading may reduce elongation at break and introduce stress concentration points. Optimization of filler type, loading, and dispersion is therefore essential to achieve a balanced mechanical profile suitable for thick-film blade coatings.

Table 5. Mechanical properties of representative WPU-based nanocomposite coatings.

WPU System	Filler Content (wt. %)	Tensile Strength (MPa)	Elongation at Break (%)	Hardness	Wear Resistance	References
Pure WPU	–	12.5	380	Shore A 85	–	[44]
GO-grafted WPU	0.5	20.6	420	Shore A 98	28% improvement	[44]
Pure PU acrylate	–	–	–	–	Wear rate: $1.52 \times 10^{-5} \text{ cm}^3/\text{min}\cdot\text{N}$	[67]
SiO ₂ /PU	2.0	–	–	–	Wear rate: $1.52 \times 10^{-6} \text{ cm}^3/\text{min}\cdot\text{N}$	[67]
PU + GNP + SG	–	13.5	210	–	Toughness: +124%	[71]
CNC/WPU	1.0	18.9	520	–	–	[88]
PDMS/WPU	10	8.2	560	–	–	[45]
POSS-GO/WPU	1.0	25.3	415	–	–	[49]

5.6. Multifunctional Hybrid Modification

(1). Fluorine-rich/Silicon-rich Outer Layer × Enhanced Barrier Middle Layer Crosslinked/Dynamic Bottom Layer

The outer layer provides low surface energy and micro/nano-texture for anti-icing and contamination resistance [45,74]. The middle layer incorporates graphene–sol–gel or MXene for reinforcement and barrier functions [70,71]. The bottom layer uses post-crosslinking or dynamic bonds to stabilize wet adhesion and enable crack closure [79,80]. Key performance gains include a 50% reduction in de-icing energy consumption [74], superhydrophobicity (WCA > 150°) [45], and a 95% increase in strength and 124% in toughness [71] (Figure 9).

(2). Nano-enhancement × Self-Healing Synergy

Two-dimensional nanosheets or nanocellulose provide mechanical reinforcement and barrier tortuosity, while self-healing units (disulfide bonds, Schiff base, UPy) enable crack closure after micro-damage [49,69–71,83–88]. Figure 10 shows crack closure after healing, with efficiency reaching 80%–95% via thermally activated dynamic bonds ($E_a \approx 60\text{--}80 \text{ kJ}\cdot\text{mol}^{-1}$). Nanofillers maintain mechanical integrity during multiple cycles, though tensile strength may drop 20%–40%—a trade-off remaining for practical application. Synergistic systems demonstrate rapid de-icing (9 V, ~150 s) and multiple healing cycles while maintaining mechanical integrity [69,87,88].

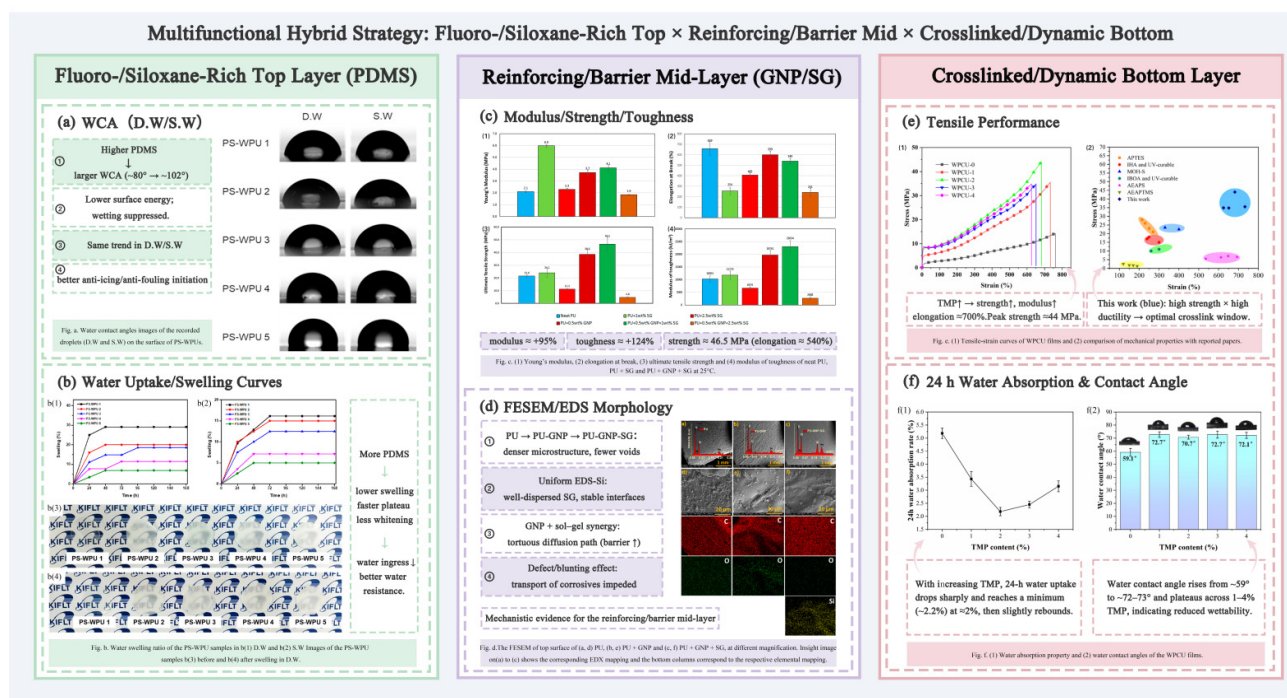


Figure 9. Multifunctional hybrid modification strategy: Fluorine/silicon-rich outer layer × barrier middle layer × dynamic bottom layer and their performance [71,93,94].

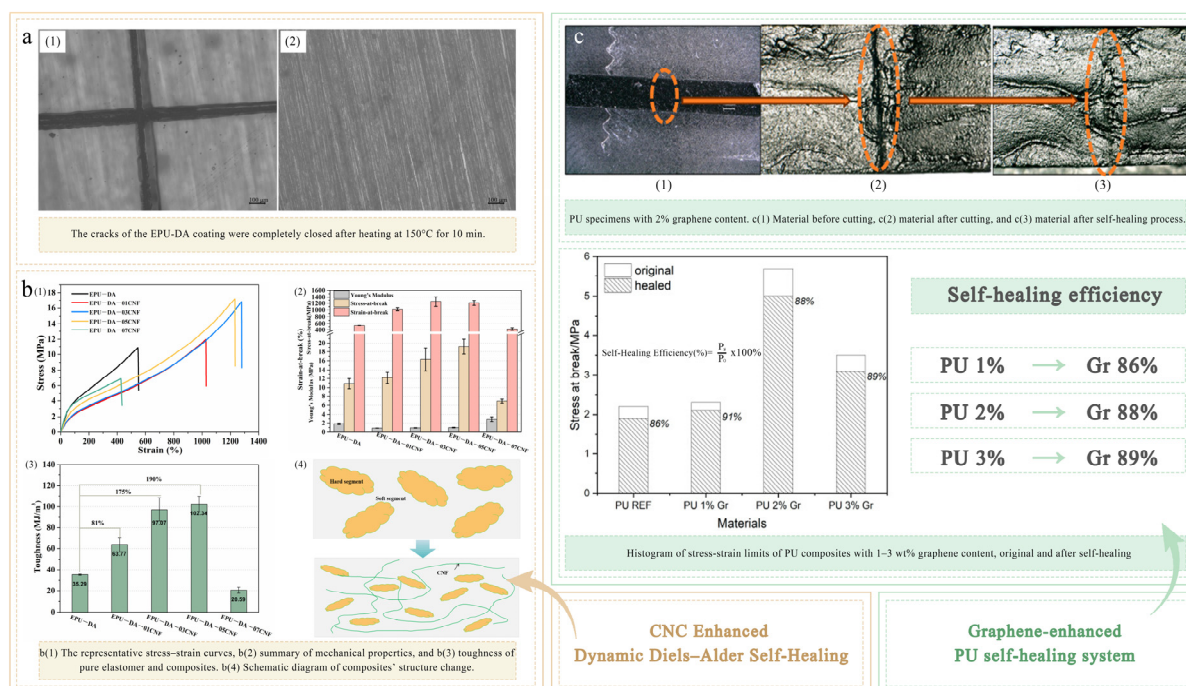


Figure 10. CNC-enhanced Diels–Alder self-healing system and graphene-enhanced polyurethane self-healing system. The images show crack closure before and after healing, with healing efficiency $\eta = (\sigma_{\text{healed}} / \sigma_{\text{original}}) \times 100\%$ reaching 80%–95% under optimized conditions. The underlying mechanism involves reversible dynamic bonds (Diels–Alder adducts or disulfide bonds) that undergo thermally activated exchange, following Arrhenius kinetics with activation energy $E_a \approx 60\text{--}80 \text{ kJ}\cdot\text{mol}^{-1}$. Nanocellulose or graphene reinforcement maintains mechanical integrity during multiple healing cycles [95,96].

(3). Polar/Ionic Groups × Post-Crosslinking/Dynamic Networks

Carboxyl/sulfonic groups enhance wet adhesion, while post-crosslinking suppresses water absorption-induced softening, balancing dry and wet performance [79,80]. This combination can be integrated with fluorine/silicon-rich surfaces to achieve adhesion, water resistance, and anti-wetting simultaneously [45,74,75].

(4). Conductive/Photothermal Functions × Ice-Repellent Surface

Conductive or photothermal units in the middle layer enable rapid de-icing, while the outer layer provides ice-repellent and hydrophobic properties, collectively reducing icing thresholds and de-icing energy consumption [45,69,74,75].

Multi-component systems increase phase separation risks and formulation complexity. A targeted approach focusing on critical failure mechanisms is recommended over uncoordinated “more is better” strategies.

5.7. Summary

For thick-film leading-edge applications, nano-enhancement and fluorine/silicon surface modification are the most cost-effective strategies. Nano-enhancement improves rain erosion and corrosion resistance through reinforcement and barrier effects, while fluorine/silicon modification provides anti-icing and low wettability via low surface energy. When combined with post-crosslinking or dynamic networks, these strategies balance adhesion, water resistance, and self-healing. Functional groups and post-crosslinking address wet adhesion and durability, self-healing units target microcrack repair, and bio-based modifications contribute sustainability and UV shielding. These complementary strategies should be integrated synergistically rather than simply combined.

A layered architecture is recommended: a fluorine/silicon-rich topcoat for anti-icing, a nanofiller-reinforced mid-coat for barrier protection, and a post-crosslinked or dynamic-bond bottom layer for interface stability and crack closure. Evaluation should integrate rain erosion, icing, and aging tests with electrochemical, mechanical, and surface energy metrics, supported by life-cycle assessment and in-service monitoring.

6. Current Status of WPU Coatings in Wind Turbine Blades

6.1. Laboratory Performance Validation

Laboratory studies demonstrate that WPU coatings achieve significant improvements in erosion resistance, corrosion resistance, and weatherability through nano-modification and molecular design [47,97–99]. However, several caveats must be considered: reported EIS $|Z|$ values vary widely (10^5 – $10^9 \Omega \cdot \text{cm}^2$) due to differences in test conditions and sample preparation; most studies use small, defect-free panels under idealized conditions; and accelerated tests do not fully replicate coupled field stresses. Laboratory data should therefore be interpreted as indicators of potential rather than guarantees of field performance.

6.2. Preliminary Field Trials

Several coating companies have initiated field demonstrations of WPU-based leading-edge protection systems [100–103]. DNV-certified WPU blade coatings are commercially available [104–106], and industry adoption of waterborne systems is increasing [107].

6.3. Performance Monitoring and Feedback

Accelerated durability tests are widely used for service-life prediction [108], and field studies confirm coating integrity can be maintained for years under marine conditions [109,110]. Emerging smart monitoring technologies (electrochemical sensors, acoustic emission) offer potential for real-time damage detection [111–113] (Figure 11).

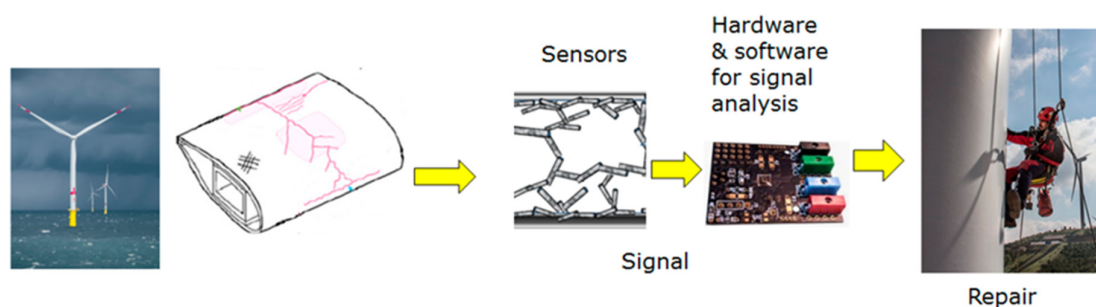


Figure 11. Schematic representation of the monitoring-and-feedback pathway for wind turbine blade damage. The closed-loop system integrates damage detection (via embedded electrochemical, impedance, or acoustic emission sensors), signal processing (with threshold-based algorithms), and autonomous or remote repair (e.g., self-healing coatings or targeted maintenance). This approach enables a transition from scheduled maintenance to condition-based maintenance, potentially reducing operational costs by 20%–40% according to industry estimates. Adapted from [37].

6.4. Challenges and Opportunities for Industrialization

- (1). **Standardization and Consistency:** GB/T 31817 provides foundational guidelines in China [114], while DNV-RP-0171 and DNV-RP-0573 have become de facto standards for rain erosion testing, though harmonization of test methods remains ongoing [115–118].
- (2). **Construction and Process Adaptation:** Thick-film waterborne systems require controlled application conditions and multi-pass processing to suppress defects [34,51,119]. Increasing blade sizes and offshore deployment impose higher demands for leading-edge protection and interface stability.
- (3). **Supply Chain and Compliance:** Low-VOC, zero-NMP, and bio-based materials are becoming key procurement differentiators [120].
- (4). **Opportunities and Recommendations:** Composite modification strategies should be integrated with thick-film processes, supported by engineering validation to establish type approval–field monitoring closed loops [114–116].

6.5. Technology Readiness Levels (TRL) for WPU Blade Coatings

The industrialization status of WPU blade coatings can be assessed using technology readiness levels. Prepolymer emulsification and self-emulsification synthesis routes have achieved TRL 7–9, with commercial products (e.g., Feilv, Xiamen Shuangrui) in operational service [104–106]. Nano-reinforcement with SiO₂ or graphene oxide is at TRL 5–7, with laboratory validation complete and pilot-scale demonstrations ongoing [39,67,71]. Fluorine/silicon surface modification is at TRL 6–8, with field-tested topcoat systems commercially available [45,102]. Self-healing chemistries remain at TRL 3–5, with demonstrated functionality in laboratory settings but limited field validation [83–88]. Bio-based WPU formulations are at TRL 4–6, with sustainability benefits validated but long-term durability data still needed [91,92].

7. Current Challenges and Future Development Directions

7.1. Thick-Film Preparation and Film Formation Stability

Thick-film application (dry film thickness several hundred μm) is challenging for waterborne systems due to defects such as pinholes and bubbling [119]. Key scientific challenges include understanding the kinetics of water evaporation and its coupling with polymer film formation, the mechanisms of defect initiation and propagation during multi-pass application, and the relationship between particle size distribution, rheology, and

defect suppression. Addressing these requires in situ characterization of film formation dynamics and quantitative models linking processing parameters to defect formation.

7.2. Nano-Filler Dispersion and Interface Compatibility

Nanoparticle agglomeration remains a key challenge for nano-reinforcement, causing weakened interfaces and stress concentration [121]. Scientific questions to be addressed include: how do filler geometry, surface chemistry, and processing conditions govern dispersion stability and interfacial adhesion? What are the quantitative relationships between dispersion quality, barrier performance, and mechanical durability under coupled service stresses? How does dispersion evolve during long-term service under UV, humidity, and thermal cycling [122]? Addressing these requires systematic studies linking dispersion parameters to coating performance metrics, combined with advanced characterization techniques such as in situ TEM and AFM under controlled environmental conditions.

7.3. Self-Healing and Smart Monitoring

Self-healing chemistries enable crack closure and barrier recovery [82,85], while smart monitoring technologies offer early damage warning [111–113,123]. Critical scientific challenges include: understanding the kinetics of dynamic bond exchange under service-relevant conditions (temperature, humidity, contamination); establishing quantitative relationships between healing efficiency, network architecture, and mechanical property recovery; and developing reliable sensor integration strategies that do not compromise coating integrity. Furthermore, the relevance of self-healing for erosion-dominated failure (continuous material loss) versus discrete crack propagation requires fundamental investigation. Long-term stability of both healing functionality and sensor systems under coupled environmental-mechanical loading remains an open question.

8. Conclusions

Prepolymer emulsification remains the most industrially mature synthesis route for thick-film WPU coatings, though it requires rigorous process control. Self-emulsification and ketimine/ketazine routes offer low-residual-solvent potential but demand precise formulation control. Nano-reinforcement and fluorine/silicon modification deliver significant performance gains but introduce critical trade-offs: cost and dispersion challenges for nano-reinforcement, and reduced adhesion with high material costs for fluorine/silicon systems. Functional groups with post-crosslinking balance wet adhesion and water resistance, while self-healing and bio-based approaches offer complementary benefits. Laboratory studies demonstrate WPU performance comparable to conventional coatings, but data variability and limited field validation constrain translation to real-world applications. A layered architecture—low-surface-energy topcoat, barrier mid-coat, and post-crosslinked primer—is recommended. Near-term targets include defect-free thick-film processing (pinhole density $\leq 0.05/\text{cm}^2$, $|Z| \geq 10^7 \Omega \cdot \text{cm}^2$). Medium-term goals focus on integrated self-healing and monitoring systems (scratch closure $\geq 80\%$, crack detection $\leq 100 \mu\text{m}$). Achieving these targets will require collaborative investment in process control and long-term field validation.

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