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Environmental Degradation And Protective Performance Of Polyurethane Coatings In Tropical Maritime Environments : A Critical Review For Defence Applications

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Abstract

Polyurethane (PU) coatings are widely used as protective materials due to their flexibility, abrasion resistance, chemical resistance, and weathering performance. However, their protective properties may deteriote under the combined environmental conditions of tropical maritime environments. This study presents a critical review of the environmental degradation mechanisms and protective performance of PU coatings, with particular emphasis on ther implications for defence-related equipment. The review examines existing studies on environmental stressors, including ultraviolet radiation, temperature, humidity, water exposure, marine salts, and, mechanical wear. The reported degradation mechanisms, particularly photo-oxidation, hydrolysis, thermal degradtion, and water-assisted interfacial degradation, are evaluated in relation to changes in coating properties. The findings indicate that enironmental exposure can reduce adhesion, tensile properties, surface integrity, and barrier performance, although the extent of deterioration depends on coating formulation, substrate, and exposure conditions. Therefore, coating durability should be evaluated by considering the specific material system, environmental conditions, and operational requirements.

Keywords : *Polyurethane Coatings, Environmental Degradation, Tropical Maritime Environment, Protective Performance, Defence Equipment.*

Abstrak

Pelapis *polyurethane* (PU) banyak digunakan sebagai material pelindung karena memiliki fleksibilitas, ketahanan terhadap abrasi (*abrasion resistance*), ketahanan terhadap bahan kimia (*chemical resistance*), serta kinerja terhadap pelapukan (*weathering performance*) yang baik. Namun, sifat protektifnya dapat mengalami penurunan akibat kombinasi kondisi lingkungan di wilayah tropis maritim. Penelitian ini menyajikan tinjauan kritis mengenai mekanisme *environmental degradation* dan *protective performance* pelapis PU, dengan penekanan khusus pada implikasinya terhadap peralatan pertahanan. Tinjauan ini mengkaji berbagai penelitian terdahulu mengenai faktor-faktor lingkungan, termasuk radiasi ultraviolet, temperatur, kelembapan, paparan air, garam laut, dan *mechanical wear*. Mekanisme degradasi yang dilaporkan, khususnya *photo-oxidation*, *hydrolysis*, *thermal degradation*, dan *water-assisted interfacial degradation*, dievaluasi berdasarkan kaitannya dengan perubahan sifat pelapis. Hasil kajian menunjukkan bahwa paparan lingkungan dapat menurunkan *adhesion*, sifat tarik (*tensile properties*), integritas permukaan (*surface integrity*), dan kinerja penghalang (*barrier performance*), meskipun tingkat

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Barongko
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penurunannya bergantung pada formulasi pelapis, substrat, dan kondisi paparan. Oleh karena itu, durabilitas pelapis perlu dievaluasi dengan mempertimbangkan sistem material yang digunakan, kondisi lingkungan, dan kebutuhan operasional.

Kata Kunci : Pelapis *Polyurethane*, Degradasi Lingkungan, Lingkungan Tropis Maritim, Kinerja Protektif, Peralatan Pertahanan.

Penulis Korespondensi : Ridha Putri Anandari Nur

I. INTRODUCTION

Protective organic coatings are thin polymer-based layers applied to equipment and structures to separate the underlying material from its service environment. Their main functions are to slow the ingress of water, oxygen, and ions, to remain firmly bonded to the substrate, and to preserve surface appearance. When a coating loses these functions, corrosion of the substrate follows, with direct consequences for maintenence effort and equipment availability. Corrosion represents a significant challenge for the maintenance and long-term durability of engineering assets, particularly in marine environments. Although a comprehensive national estimate of the economic losses caused by corrosion in Indonesia remains difficult to establish, local studies have demonstrated its effects on infrastructure and maritime equipment. Priyotomo (2021) investigated atmospheric corrosion of carbon steel in Pelabuhan Ratu, West Java, and identified chloride deposition and climatic parameters as relevan factors influencing corrosion behavior. These findings emphasize the importance of effective protective systems and appropriate maintenence strategies for engineering assets operating in Indonesia.

Polyurethane (PU) coatings, formed by the reaction of isocyanates with polyols, are among the binders most widely used for demanding protective applications. Their properties can be adjusted through the choice of isocyanate, polyol and crosslink density, and they are valued for combination of abrasion resistance, chemical resistance, flexibility and resistance to weathering (Mayer-Trzaskowska et al., 2025). These characteristics explain their use as topcoats on aircraft, including low-gloss military finishes , and within anticorrosion coating systems for marine structures. Because performance depends strongly on formulation, PU is better regarded as a family of materials than as a single coating.

Tropical maritime environments place several of these functions under stress at the same time. In general terms, such environments are characterised by strong solar ultraviolet (UV) radiation, high air and surface temperatures, persistently high relative humidity, frequent wetting by rain, dew or spray, and the deposition of chloride-bearing marine aerosols. International standard for corrosion of metals and alloys or ISO 9223 treats the temperature-humidity complex, expressed as time of wetness, and airborne salinity as key factors in atmospheric corrosivity, and its extreme category, CX, is associated with marine atmospheric (International Organization For Standardization[ISO],2012). However, the standard classifies environments by the corrosion of bare metals and does not account for UV radiation, which matters for polymers. For coatings, South Florida has long served as the reference severe climate, because its combination of high solar load, humidity and long wet periods drives photo-oxidation, hydrolysis and surface erosion close to their maximum outdoor rates (Oehler et al., 2025). He also caution that results, and even the ranking of coatings, do not necessarily transfer from one site to another, so tropical maritime locations should not be assumed to be identical. Evidence obtained specifically under tropical marine exposure is more limited. Natural exposure at Sanya produced gloss loss and surface damage in marine coating systems with PU topcoats (Zhang et al., 2016), and a year-long exposure of a deliberately scratched PU coating found that relative humidity above 80% was the condition most associated with accelerated degradation

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Barongko
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(Liu et al., 2025). Further field studies have examined PU coatings in tropical marine and South China Sea atmosphere. Abrasion by wind-borne particles, flowing water or handling is a plausible additional stressor, but it is not a focus of the exposure studies cited here.

The scientific problem is that these stressors change the PU network itself, and the changes reduce protection. Chemically, UV radiation in the presence of oxygen causes photo-oxidation and chain scission in aliphatic polyurethanes (Wilhelm & Gardatte, 1998), while water can attack hydrolysable linkages, which is why sea-water ageing is used to assess polyurethanes intended for marine use (Davies & Evrard,2007). These chemical changes alter the coating structure. Under UV irradition in 3.5% NaCl solution, bond scission in an aliphatic PU topcoat increased coating porosity and reduced coating resistance, which is a direct loss of barrier performance (He et al., 2011). Adhesion is also affected assured environmental factors (gao et al.,2019) and to model field degradation from sensor data (liu et al.,2025) show that integration is possible. This review does not claim a new mechanism. Its contribution is to bring environmental stressors, degradation mechanisms and changes in protective properties into one framework, to judge how far laboratory indicators can be relied upon for tropical maritime service, and to draw cautious implications for defence-related equipment.

Accordingly, this review aims to critically evaluate the environmental degradation mechanisms and protective performance of polyurethane (PU) coatings under tropical maritime conditions, with particular emphasis on their implications for defence-related equipment and maintenance. The objectives are to: (1) identify the major environmental stressors affecting PU coatings in tropical maritime environments; (2) explain the degradation mechanisms associated with these stressors; (3) synthesize their effects on adhesion, elasticity, hardness and barrier performance.

II. METHOD

This study employs a critical narrative review approach to examine the environmental degradation mechanisms and protective performance of polyurethane (PU) coatings under tropical maritime conditions. The review focuses on synthesizing and evaluating existing research rather than conducting new experimental investigations. Its scope is organized around three main aspects: environmental stressors affecting PU coatings, the degradation mechanisms associated with these exposures, and the resulting changes in protective properties.

The literature selection was primarily based on previously collected publications relevant to polyurethane coatings and their environmental durability. Studies addressing marine and tropical exposure were prioritized, particularly those investigating the effects of ultraviolet (UV) radiation, temperature, humidity, water, and marine salts. Additional studies were considered when they provided fundamental explanations of PU degradation mechanisms or experimental evidence concerning changes in coating performance. Research conducted outside tropical maritime environments was also included when its findings were relevant to understanding specific degradation processes. However, such findings were interpreted cautiously because differences in exposure conditions and material formulations may limit their direct applicability to tropical maritime service. Publications were selected based on their scientific relevance, the availability of sufficient methodological and experimental information, and their contribution to the objectives of this review. Studies that discussed unrelated coating systems without providing relevant comparisons or explanations of PU behaviour were not considered central to the analysis. The selection was therefore guided by the quality and relevance of the available evidence rather than a predetermined number of publications.

Each selected publication was examined to identify information relevant to the research objectives. The assessment focused on the type of polyurethane material or coating system investigated, the environmental exposure conditions, the degradation mechanisms reported, and the changes observed in material properties. The extracted information was organized into three thematic categories. First, environmental exposure conditions were examined to identify the major stressors affecting PU coatings, including UV radiation, elevated temperature,

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Barongko
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humidity, water exposure, marine salts, and mechanical wear. Second, the reported degradation mechanisms were evaluated, with particular attention to photo-oxidation, hydrolysis, thermal degradation, water absorption, and mechanical damage. Third, the effects of these degradation processes on protective properties were assessed, focusing on adhesion, elasticity, hardness, and barrier performance. Where available, information concerning experimental methods and characterization techniques was also considered to understand how degradation and coating performance were evaluated. Differences in PU formulations, exposure duration, environmental conditions, and testing procedures were recorded because these factors may influence the reported findings and limit direct comparisons between studies.

The collected evidence was analyzed through thematic comparison to establish relationships between environmental stressors, degradation mechanisms, and changes in the protective performance of PU coatings. Rather than describing each publication independently, the findings were compared to identify consistent observations, differences in reported results, and factors that may explain variations between studies. Particular attention was given to the influence of PU formulation and exposure conditions on degradation behaviour. Evidence from laboratory ageing experiments was considered alongside findings from natural outdoor and marine exposure studies to assess the extent to which laboratory observations represent actual environmental conditions. The limitations of transferring results between different climates, exposure environments, and coating systems were also considered. Finally, the synthesized findings were interpreted in relation to the durability and maintenance of equipment operating in tropical maritime environments, including defence-related applications. Where direct evidence from military equipment was limited, the discussion relied on relevant findings from marine and protective coating studies without assuming that laboratory performance directly represents operational service life.

III. RESULTS AND DISCUSSION

Environmental Stressors Affecting PU Coatings

UV radiation is one of the major factors responsible for the chemical and visual degradation of polyurethane (PU) coatings. When exposed to solar radiation, the energy absorbed by the polymer can initiate photo-oxidation and molecular-chain scission, resulting in changes to the coating's chemical structure, surface appearance, and mechanical properties. Wang et al. (2022) demonstrated this effect in a three-layer protective PU coating: after 1200 hours of UV irradiation, the gloss value decreased from 61.1° to 2.8°. The authors also reported reductions in tensile strength and elongation during ageing. A similar degradation mechanism was observed by Liu et al. (2019) during natural exposure in the South China Sea, where ATR-FTIR and XPS analyses indicated the rupture of chemical bonds, particularly C–N bonds, in the PU structure. These findings suggest that prolonged solar exposure can reduce surface quality and gradually weaken the polymer network.

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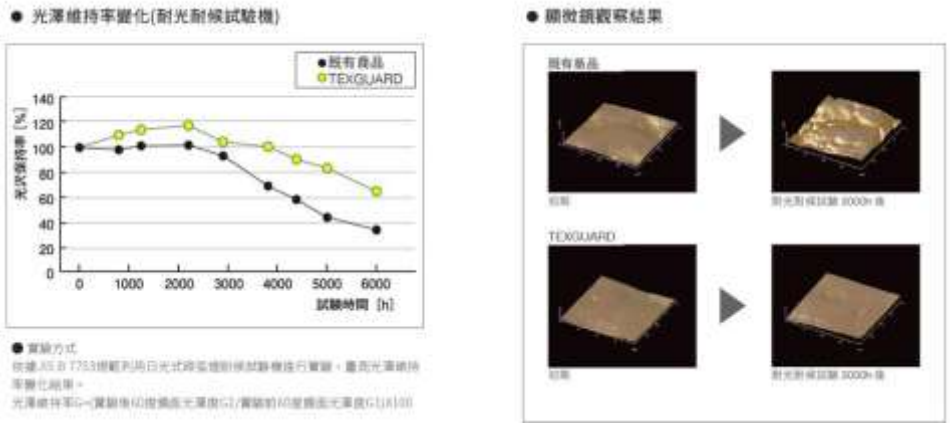


Figure 1 Changes in 60° specular gloss of polyurethane-coated fabrics during 24-month natural ageing

The extent of degradation, however, depends on the coating formulation and exposure conditions. Therefore, results from accelerated UV tests should not be directly interpreted as equivalent to years of natural exposure. (Liu et al., 2019; Wang et al., 2022).

Temperature affects PU coatings through both thermal ageing and repeated expansion–contraction cycles. At elevated temperatures, chemical reactions such as oxidation may accelerate, while repeated temperature changes can generate internal stresses because the coating and substrate may respond differently to heating and cooling. Mushtaq et al. (2025) investigated a PU coating on a glass–epoxy composite under 200 days of cyclic weathering. Their cycle included exposure to −40°C, 70°C, 40°C at 90% relative humidity, and salt fog. Following exposure, the coating's tensile strength decreased from 42 to 29 MPa, while its thermal stability decreased by approximately 11–13°C based on the temperature corresponding to 5% mass loss. In a separate study, Mayer-Trzaskowska et al. (2023) subjected polyurethane/polyurea coatings to 20 temperature cycles consisting of 2 hours at −18°C followed by 1 hour at 60°C. Their findings showed that temperature cycling did not produce the most severe surface changes compared with UV or NaCl exposure, in one tested coating, adhesion actually increased, which the authors associated with possible post-curing or additional cross-linking. This indicates that thermal effects are formulation-dependent and that temperature cycling does not necessarily cause immediate coating failure, although it may contribute to long-term deterioration when combined with other environmental stressors.

Humidity, water, and marine salts can reduce the protective function of PU coatings by promoting water absorption, hydrolysis, and the penetration of corrosive electrolytes toward the coating–substrate interface. Water may interact with susceptible chemical groups in the polymer, while dissolved chloride ions can contribute to the deterioration of the coating system and corrosion processes at the substrate interface. In a natural marine atmospheric exposure study, Liu et al. (2019) reported that the coating resistance decreased 2.575×10^{10} to $7.818 \times 10^{5} \Omega . cm^{2}$ after 24 months, indicating a substantial reduction in its barrier performance.

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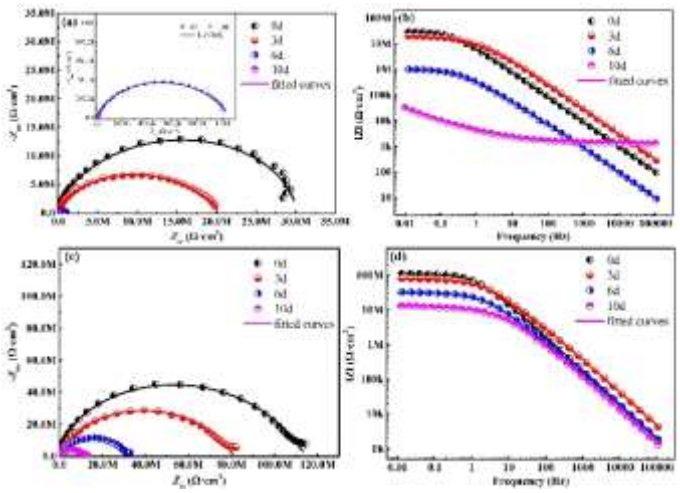


Figure 2 Electrochemical impedance response of two water-based polyurethane coating systems after different accelerated ageing conditions.

Zhang et al. (2021) also compared two water-based PU coating systems under neutral salt spray, UV-condensation, and cyclic salt spray/UV-condensation conditions for 240 days. Their results showed that salt spray produced the greatest reduction in electrochemical impedance, whereas UV-condensation caused the greatest changes in gloss and colour. This distinction is important: visual deterioration does not necessarily indicate the same degree or type of barrier failure. In addition, Mayer-Trzaskowska et al. (2023) found that immersion in a 5% NaCl solution caused the greatest reduction in adhesion among their tested ageing conditions, with pull-off strength decreasing approximately fourfold.

In actual tropical and maritime operating environments, PU coatings are rarely exposed to only one environmental factor. Solar radiation, elevated temperature, high humidity, rainfall, and marine salts may act simultaneously or in repeated sequences, producing degradation patterns that differ from those observed in single-factor laboratory tests. This interaction is illustrated by Wang et al. (2025), who investigated PU-coated fabrics under 24 months of natural exposure in Xishuangbanna, Xiamen, and Jinan.

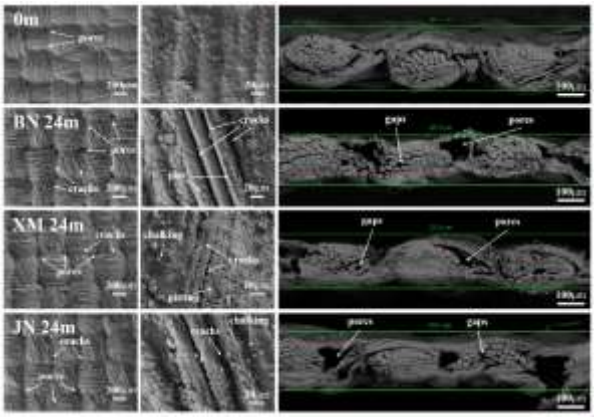


Figure 3 Macroscopic appearance of polyurethane-coated fabrics after natural ageing in different climatic regions.

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Barongko
Jurnal Ilmu Kesehatan

The study reported gloss reductions exceeding 60%, colour differences above 5.8, and tear-strength reductions greater than 50%, the most severe overall degradation occurred in the tropical environment of Xishuangbanna, where high temperature, humidity, and solar radiation acted together. Although this study concerns PU-coated fabrics rather than conventional PU coatings on metal, it provides supporting evidence of the influence of coupled environmental factors on flexible protective materials. Similarly, Mushtaq et al. (2025) reported measurable deterioration after cyclic exposure combining temperature extremes, high humidity, and salt fog. Taken together, these studies indicate that evaluating PU coatings for defence equipment operating in tropical and maritime environments requires consideration of combined exposure conditions, rather than relying solely on individual UV, thermal, or salt-spray tests.

Degradation Mechanisms of PU Coatings

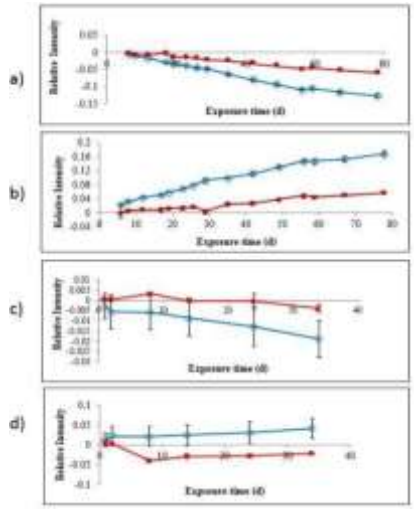


Figure 4 (a) Chain scission (1535 cm−1), and (b) oxidation (1706 cm−1) of neat PU (blue) and PU nanocoating (red) as a function of UV exposure time measured by FTIR-T technique. (c) Chain scission (1535 cm−1) and (d) oxidation (1706 cm−1) of neat PU (blue) and PU (blue) and PU nanocoating (red) as a function of UV exposure time measured by FTIR-ATR technique

Photo-oxidation occurs when ultraviolet (UV) radiation initiates chemical reactions in the polymer, particularly in the presence of oxygen. These reactions can generate reactive species that attack susceptible bonds in the PU structure, resulting in chain scission, oxidation, or additional cross-linking. Jacobs et al. (2016) investigated a commercial nanosilica/PU coating under controlled UV exposure at 50°C. Their FTIR results showed a decrease in the bands associated with amide II at 1535 cm^{-1} and an increase in oxidation-related carbonyl absorption at 1706 cm^{-1}. The authors used these changes to monitor chain scission and oxidation, respectively. Both processes increased with exposure time, although the PU coating containing 5% nanosilica showed a lower degradation rate than the neat PU. Similarly, Cai et al. (2018) found that UVA irradiation accelerated the photo-oxidative degradation of fluorinated polyurethane (FPU), with chemical deterioration extending approximately 20 μm beneath the coating surface after 2,000 hours. In natural marine atmospheric exposure, Liu et al. (2019) also identified C–N bond rupture as the dominant chain-scission pathway in their tested aerospace PU coating. These findings demonstrate that photo-oxidation can alter the polymer structure, although the specific bonds affected and degradation rates depend on the PU formulation and exposure conditions.

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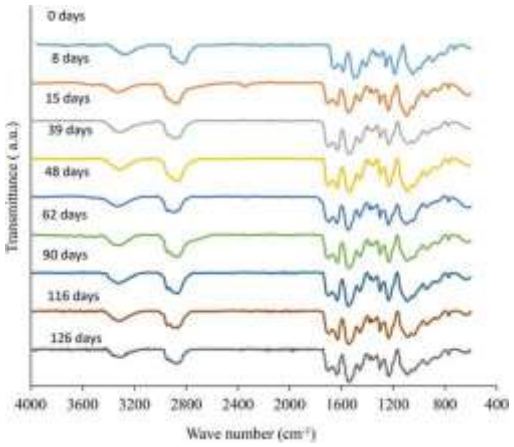


Figure 5 FTIR spectra during UV exposure

Hydrolysis occurs when water reacts with susceptible chemical bonds in a polymer, causing changes in its molecular structure. In PU coatings, urethane and, depending on the formulation, ester linkages may be susceptible to hydrolytic degradation. This process can break polymer chains and generate chemical groups that alter the coating's properties. Ma et al. (2023) investigated a TS55–80 PU coating applied to Q235 carbon steel during 12 months of immersion in real seawater. Their FTIR and XPS analyses indicated chemical changes in the coating, and the authors identified hydrolysis of urethane bonds as the main degradation mechanism. After 12 months, the coating's adhesion had decreased to 0.82 MPa, while its electrochemical impedance decreased to $2.81 \times 10^3 \Omega \cdot cm^2$. These results indicate that prolonged seawater exposure can affect both the chemical structure and protective performance of the tested PU coating. Jacobs et al. (2016) also observed that the presence of humidity accelerated the appearance of surface nanoparticles in their UV-exposed PU nanocoating compared with dry exposure. They proposed that water contributed to the degradation process alongside UV-induced oxidation. Therefore, moisture-assisted degradation should be considered not only as a separate hydrolysis process but also as a factor that can intensify other chemical reactions during environmental ageing.

Thermal degradation refers to changes in polymer structure and properties caused by elevated temperatures, while thermo-oxidative degradation involves reactions between the polymer and oxygen that are accelerated by heat. These processes may affect the thermal stability, molecular structure, and mechanical performance of PU coatings. Liu et al. (2019) reported that natural marine atmospheric exposure significantly reduced the thermal stability of their aerospace PU coating, based on thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). Ma et al. (2023) similarly observed a significant decrease in thermal stability after prolonged seawater immersion, indicating that environmental ageing can alter the thermal response of the coating even when the exposure is not primarily a high-temperature test. In another study, Mushtaq et al. (2025) subjected a PU coating on a composite substrate to cyclic weathering involving −40°C, 70°C, high humidity at 40°C, and salt fog. After 200 days, the temperature corresponding to 5% mass loss decreased by approximately 11–13°C, while tensile strength declined from 42 to 29 MPa. These results indicate that combined environmental ageing can reduce the thermal and mechanical stability of PU coatings. However, the observed changes should not be attributed to heat alone because the cyclic tests also involved moisture and salt fog.

Water absorption can compromise a coating's protective function even before visible cracks or corrosion appear. Water molecules can diffuse through the polymer matrix and interact with its chemical components, potentially causing swelling, plasticization, and reduced adhesion at the coating–substrate interface. Sabet-Bokati and Plucknett (2024) reviewed water-induced failure in polymer coatings and described how water diffusion, swelling, and interfacial weakening can contribute to blistering and delamination. In PU coating systems exposed

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Barongko
Jurnal Ilmu Kesehatan

to seawater, Ma et al. (2023) observed that pigment particle detachment increased the number of pores on the coating surface, allowing corrosive seawater to penetrate more readily. After six months of immersion, bubbles and cracks were already visible, while corrosion products were observed on the coating surface. The authors associated this deterioration with the development of electrochemical reactions at the coating–metal interface. A more recent study by Suo et al. (2026) on polyurethane/epoxy aircraft coating systems further identified the relationship between polymer degradation, electrolyte penetration, corrosion-product accumulation, and adhesion failure under cyclic humid-hot, dry, and acidic salt-spray exposure. Their findings show that interfacial degradation is not simply a consequence of water entering the coating; it can also involve corrosion reactions and internal stresses that eventually promote delamination.

In practical tropical and maritime environments, PU coatings are exposed to several environmental factors simultaneously. Consequently, photo-oxidation, hydrolysis, thermal ageing, and water-assisted interfacial degradation may occur together and influence one another. Wang et al. (2025) proposed a combined degradation mechanism for PU-coated fabrics exposed to different natural climatic regions. Their interpretation distinguishes physical damage associated with thermal stress and moisture intrusion from chemical degradation associated with the combined effects of light, oxygen, and water. The resulting pores and cracks can facilitate further penetration of water and chloride ions, while changes in the polymer structure can weaken the coating and its interface with the substrate. Although this study concerns PU-coated fabrics rather than conventional PU coatings on metal, its proposed mechanism helps explain how multiple environmental factors may act together. More directly relevant to aircraft coating systems, Suo et al. (2026) reported that oxidation- and hydrolysis-induced chain scission increased the hydrophilicity of a polyurethane/epoxy coating system. This facilitated electrolyte transport, corrosion-product accumulation, interfacial stress, and eventual delamination. Taken together, these studies indicate that coating failure in maritime environments is better understood as an interconnected degradation process rather than the result of a single isolated mechanism

Effects of Degradation on Protective Performance

Adhesion is an important indicator of coating durability because it determines whether the protective layer remains attached to its substrate during environmental exposure. In a natural marine-atmosphere study, Liu et al. (2019) reported that the adhesion of an aerospace polyurethane coating on Q235 carbon steel decreased during 24 months of exposure in the South China Sea. The authors also found a correspondence between the reduction in adhesion and the deterioration of the coating's barrier properties. A similar decline was reported by Ma et al. (2023) after 12 months of real seawater immersion, the pull-off adhesion strength decreased to 0.82 MPa, while bubbles, cracks, and corrosion products appeared on the coating surface. These observations indicate that prolonged exposure to moisture and seawater can weaken the coating–metal interface and increase the risk of coating detachment. Regarding flexibility and elasticity, Mushtaq et al. (2025) evaluated tensile properties of PU coating films after cyclic weathering and salt spray exposure. The tensile strength decreased from 42.12 MPa in the unaged condition to 29.95 MPa after 200 days of cyclic weathering, while the maximum elongation decreased from 2.9% to 1.01%. After 1,000 hours of salt spray, the maximum elongation was reduced to 0.7%. The decrease in tensile strength and elongation indicates a reduction in the coating film's ability to withstand deformation before failure. However, these mechanical results came from a PU topcoat applied over an epoxy primer on a glass-fibre-reinforced epoxy composite, rather than a PU coating directly applied to metal.

Surface integrity describes the coating's ability to maintain a continuous, uniform, and defect-free protective layer. Degradation can be observed through the formation of cracks, pores, blisters, scratches, and surface roughness, which may reduce resistance to mechanical damage and facilitate the penetration of environmental agents. Mushtaq et al. (2025) observed that the initially smooth and homogeneous PU surface became rougher after cyclic weathering. After 200 days, small voids and blisters were visible in SEM observations, while scratch resistance decreased by approximately 35% after cyclic weathering and 20% after salt

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Barongko
Jurnal Ilmu Kesehatan

spray exposure. He also reported that wear depth under a 20 N load increased from 45 μm before conditioning to 200 μm after 200 days of cyclic weathering. These results demonstrate that environmental ageing can reduce the coating's resistance to scratching and abrasive contact. Although this study did not directly report a conventional hardness measurement, scratch resistance and wear depth provide related evidence of changes in surface durability; they should not be described as direct hardness values. Similarly, Ma et al. (2023) observed bubbles, cracks, and pigment-particle loss in PU coatings immersed in real seawater, indicating deterioration of the coating's surface continuity.

The barrier performance of PU coatings is commonly evaluated through electrochemical impedance spectroscopy (EIS), particularly the impedance modulus at low frequencies. A decrease in impedance generally indicates increased electrolyte penetration and a reduction in the coating's ability to isolate the substrate from the corrosive environment. Ma et al. (2023) reported that the impedance of a PU coating on Q235 carbon steel decreased to $2.81 \times 10^3 \Omega \cdot cm^2$ after 12 months of real seawater immersion. The authors associated this deterioration with pigment-particle loss and the formation of additional pores, which accelerated seawater penetration and electrochemical reactions at the coating–metal interface. In contrast, Lu et al. (2017) demonstrated that coating formulation also influences corrosion protection. Their acrylic polyurethane coating with an NCO/OH ratio of 1.4 retained an impedance modulus close to $1 \times 10^6 \Omega \cdot cm^2$. after 50 days in 3.5 wt% NaCl solution, whereas coatings with NCO/OH ratios of 0.8 and 1.0 decreased to approximately $1 \times 10^6 \Omega \cdot cm^2$.

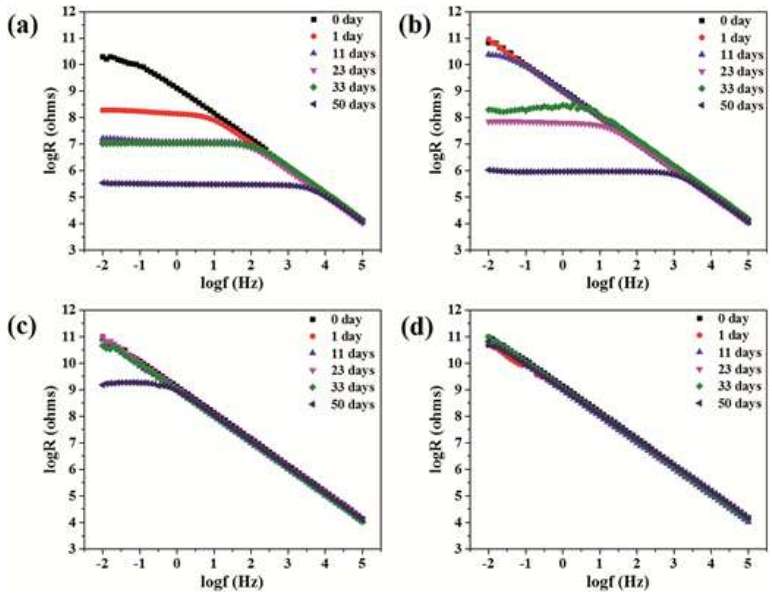


Figure 6 Bode plots of samples in 3.5 wt% NaCl solution after different immersion times: (a) the coating with NCO/OH = 0.8; (b) the coating with NCO/OH = 1.0; (c) the coating with NCO/OH = 1.2; (d) the coating with NCO/OH = 1.4

This comparison shows that corrosion resistance is not determined by environmental exposure alone; the coating formulation and curing ratio also influence its barrier performance. Furthermore, Liu et al. (2019) found that the barrier properties of aerospace PU coatings deteriorated during natural exposure in the South China Sea, with a corresponding decline in adhesion. Together, these findings indicate that once water and dissolved salts penetrate the coating, the protective function progressively weakens and corrosion can develop at the substrate interface.



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Barongko
Jurnal Ilmu Kesehatan

The degradation of adhesion, mechanical properties, surface integrity, and barrier performance has practical implications for defence equipment operating in tropical and maritime environments. Protective coatings on aircraft structures, marine equipment, and other exposed components must withstand environmental exposure while maintaining their ability to resist mechanical damage and prevent corrosion. The natural exposure study by Liu et al. (2019) provides direct evidence from an aerospace PU coating exposed to the South China Sea atmosphere, while Ma et al. (2023) demonstrates the loss of protective performance in a PU coating on steel during real seawater immersion. Mushtaq et al. (2025) further shows that cyclic temperature, humidity, and salt-fog exposure can reduce adhesion, tensile properties, and wear resistance in a PU-coated composite system. These findings support the importance of condition-based coating inspection, particularly for visible cracking, blistering, peeling, loss of adhesion, and localised corrosion. Electrochemical Impedance Spectroscopy, pull-off adhesion, and surface examination can also be used as complementary evaluation methods when assessing coating condition. Nevertheless, the reviewed studies do not establish a universal maintenance interval or service-life threshold for defence equipment. Such decisions require consideration of the specific coating formulation, substrate, exposure conditions, and operational requirements.

IV. CONCLUSION

This review has critically examined the environmental degradation mechanisms and protective performance of polyurethane (PU) coatings under tropical maritime conditions, particularly their implications for defence-related equipment. The findings indicate that UV radiation, elevated temperature, high humidity, water exposure, marine salts, and mechanical wear can affect coating durability through mechanisms such as photo-oxidation, polymer chain scission, hydrolysis, thermal degradation, and water-assisted interfacial degradation. These processes may alter the chemical structure and physical integrity of PU coatings, resulting in reduced adhesion, tensile properties, surface durability, and barrier performance, while water and dissolved salts penetrating coating defects may accelerate corrosion at the coating-substrate interface. The extent of degradation depends on coating formulation, substrate, exposure conditions, and testing methods. Therefore, accelerated laboratory ageing results cannot automatically be considered equivalent to long-term natural exposure. For defence applications, the deterioration of PU coatings may compromise the durability and corrosion protection of aircraft structures, marine equipment, and other exposed components. However, the reviewed literature does not establish a universal maintenance interval or service-life threshold. Consequently, evaluating and maintaining the protective performance of PU coatings requires consideration of the interactions between environmental stressors, material properties, substrate characteristics, and actual operational conditions.

REFERENCES

Cai, G., Wang, H., Jiang, D., & Dong, Z. (2018). Degradation of fluorinated polyurethane coating under UVA and salt spray. Part I: Corrosion resistance and morphology. *Progress in Organic Coatings, 123*, 337–349. https://doi.org/10.1016/j.porgcoat.2018.07.025

Davies, P., & Evrard, G. (2007). Accelerated ageing of polyurethanes for marine applications. *Polymer Degradation and Stability, 92*(8), 1455–1464. https://doi.org/10.1016/j.polymdegradstab.2007.05.016

He, S., Xiong, J., Tang, Y., & Zuo, Y. (2011). The failure behavior of a polyurethane composite coating in 3.5% NaCl solution under ultraviolet irradiation. *Journal of Applied Polymer Science, 120*(4), 1892–1898. https://doi.org/10.1002/app.33301

International Organization for Standardization (ISO). (2012). *ISO 9223:2012: Corrosion of metals and alloys—Corrosivity of atmospheres—Classification, determination and estimation*. Geneva: ISO. https://www.iso.org/standard/53499.html

Jacobs, D. S., Huang, S.-R., Cheng, Y.-L., Rabb, S. A., Gorham, J. M., Yu, L. L., Nguyen, T., & Sung, L.-P. (2016). Surface degradation and nanoparticle release of a commercial nanosilica/polyurethane coating under UV exposure. *Journal of Coatings Technology and Research, 13*(5), 735–751. https://doi.org/10.1007/s11998-016-9796-2

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Liu, J., Li, Z., Zhang, L., Hou, J., Lu, Z., Zhang, P., Wang, B., & Jin, N. (2019). Degradation behavior and mechanism of polyurethane coating for aerospace application under atmospheric conditions in South China Sea. *Progress in Organic Coatings, 136*, 105310. https://doi.org/10.1016/j.porgcoat.2019.105310

Lu, F., Song, B., He, P., Wang, Z., & Wang, J. (2017). Electrochemical impedance spectroscopy (EIS) study on the degradation of acrylic polyurethane coatings. *RSC Advances, 7*, 13742–13748. https://doi.org/10.1039/C6RA26341K

Ma, J., Guo, H., Zhang, X., Li, C., Xie, J., Luo, L., Zhou, K., & Liu, J. (2023). Failure behavior of polyurethane coating immersed in real seawater. *Surface Technology, 52*(1), 178–186. https://doi.org/10.16490/j.cnki.issn.1001-3660.2023.01.018

Mayer-Trzaskowska, P., Robakowska, M., Gierz, Ł., Pach, J., & Mazur, E. (2023). Observation of the effect of aging on the structural changes of polyurethane/polyurea coatings. *Polymers, 16*(1), 23. https://doi.org/10.3390/polym16010023

Mayer-Trzaskowska, P., Ferraris, M., Perero, S., & Robakowska, M. (2025). The influence of the addition of rubber waste on the properties of polyurethane coatings subjected to aging processes. *Coatings, 15*(6), 677. https://doi.org/10.3390/coatings15060677

Mushtaq, M., Gulipalli, P., Adusumalli, R., Suresh, K., & Abraham, A. (2025). Effect of 200 days of cyclic weathering and salt spray on the performance of PU coating applied on a composite substrate. *Science and Engineering of Composite Materials, 32*(1), 20250055. https://doi.org/10.1515/secm-2025-0055

Oehler, H., Wanner, M., Aktas, L., Neumann, M., Lellinger, D., et al. (2025). Site-specific weathering of coatings: II. Comparison of natural weathering and accelerated protocols for Central Europe and Florida. *Journal of Coatings Technology and Research, 22*, 739–761. https://doi.org/10.1007/s11998-024-01005-3

Priyotomo, G., Prifiharni, S., Nuraini, L., Triwardono, J., Royani, A., Sundjono, Purawiardi, I., & Gunawan, H. (2021). A field study of atmospheric corrosion of carbon steel after short exposure in Pelabuhan Ratu, West Java Province, Indonesia. *Walailak Journal of Science and Technology, 18*(17), Article 9667. https://doi.org/10.48048/wjst.2021.9667

Sabet-Bokati, K., & Plucknett, K. (2024). Water-induced failure in polymer coatings: Mechanisms, impacts and mitigation strategies—A comprehensive review. *Polymer Degradation and Stability*. https://doi.org/10.1016/j.polymdegradstab.2024.111058

Suo, H., Akhtar, A., Zhang, Y., Arshad, A., Xin, Y., Lam, R. K. H., Tang, H. P., & Voyle, R. (2026). Degradation kinetics and critical failure transition of polyurethane/epoxy aircraft coatings under accelerated cyclic aging conditions. *Engineering Failure Analysis, 193*, 110878. https://doi.org/10.1016/j.engfailanal.2026.110878

Wang, J., Gu, Z., Zhao, J., Zhang, S., Li, P., Meng, C., Sui, J., Zhang, X., Hu, S., Pan, J., & Li, J. (2022). Aging behavior of the three-proof polyurethane coating under UV radiation. *Polimery, 67*(9), 433–?. https://doi.org/10.14314/polimery.2022.9.4

Wang, S., Wang, D., An, Q., Li, J., Chong, K., Wang, X., Liu, J., Xie, K., Hou, X., Hou, J., & Sun, Y. (2025). Multi-regional natural aging behaviors and degradation mechanisms of polyurethane-coated fabrics under coupled multiple environmental factors. *Polymers, 17*(19), 2634. https://doi.org/10.3390/polym17192634

Wilhelm, C., Rivaton, A., & Gardette, J.-L. (1998). Infrared analysis of the photochemical behaviour of segmented polyurethanes: 3. Aromatic diisocyanate based polymers. *Polymer, 39*(5), 1223–1232. https://doi.org/10.1016/S0032-3861(97)00353-4

Zhang, H., Dun, Y., Tang, Y., Zuo, Y., & Zhao, X. (2016). Correlation between natural exposure and artificial ageing test for typical marine coating systems. *Journal of Applied Polymer Science, 133*(36), 43893. https://doi.org/10.1002/app.43893

Zhang, C., Zhu, Z., & Zhao, J. (2021). Property comparison of two water-based polyurethane coatings in three accelerated aging experiments. *Surface Technology, 50*(10), 330–336. https://doi.org/10.16490/j.cnki.issn.1001-3660.2021.10.034