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Epoxy coatings for anticorrosion applications: a review

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ABSTRACT
Epoxy resins are among the most commonly used materials for anticorrosion applications due to their excellent adhesion, mechanical strength, and chemical resistance. However, conventional epoxy coatings face significant limitations in providing durable, long-term protection, especially under harsh environmental conditions. As a result, extensive research has been conducted worldwide to enhance the anticorrosion performance of epoxy coatings. This review summarizes the latest advancements in the field, categorizing current developments into three primary approaches: modification of the epoxy resin structure, incorporation of functional fillers, and the development of multifunctional composite coatings. Structural modifications focus on improving the intrinsic properties of epoxy resins to enhance their barrier effect. The inclusion of functional fillers introduces additional protective mechanisms, including self-healing, superhydrophobicity and corrosion inhibition. Multifunctional composite coatings combine the benefits of several approaches, integrating advanced materials and techniques to achieve high performance. By analyzing recent studies and innovations, this review highlights the strengths of each approach, providing insights into future directions for developing high-performance epoxy-based anti-corrosion coatings.

Keywords: composites, epoxy resin, anticorrosive coating, corrosion, corrosion inhibition, anti-corrosion protection.

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Introduction

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A natural process known as corrosion occurs when metal interacts with environmental elements including oxygen, moisture, and chemical agents. This results in structural deterioration, loss of functioning, and eventually large financial losses. A study by the National Association of Corrosion Engineers (NACE) estimates that the yearly cost of corrosion worldwide exceeds $2.5 trillion, or around 3-4% of the world's gross domestic product [1]. Due to the extremely corrosive conditions that are present during the extraction and transportation of hydrocarbons, the oil and gas industry, for example, suffers significant corrosion-related damage to pipes and infrastructure. Likewise, offshore platforms and marine boats are particularly vulnerable to corrosion brought on by saltwater, which speeds up the rate of metal deterioration [2]. Especially in the petroleum industry, corrosion poses a safety risk and results in significant financial losses [3]. The hardened mixture's structure is destroyed by both internal and external forces acting on concrete and the depletion of quality attributes like density, strength, and so forth.

Anticorrosion coatings have been used extensively to address these problems as an affordable way to shield metal surfaces from deterioration, increasing longevity and preserving the structural soundness of important parts. Corrosive substances like oxygen, water, and salts are kept from coming into direct contact with the metal substrate by these coatings, which serve as a physical and chemical barrier. Epoxy resins stand out as one of the most adaptable and efficient choices among the variety of materials used in anticorrosion coatings [3]. Epichlorohydrin reacts with bisphenol-A or other phenolic chemicals to form epoxy resins, which are thermosetting polymers. Epoxy resins, or ERs, are a unique class of organic macromolecules with a wide range of industrial applications. Compared to basic organic corrosion inhibitors, ERs offer superior surface coverage and anticorrosive properties due to their macromolecular nature. During metal-inhibitor interactions, the polar functional groups on the periphery of ERs serve as adsorption sites. Particularly for carbon steel in acidic and sodium chloride (3% and 3.5%) solutions, a few ERs in their pure and cured forms have been employed as anti-corrosive coating materials. Most of the ER's function as mixed-type and interface corrosion inhibitors [4].

The anticorrosive properties and adsorption behaviours of ERs on metallic surfaces have been demonstrated through a variety of computer simulations. Since most ERs are not very soluble, they work best as coating materials for anticorrosive applications. A review of the literature revealed that numerous ER-based coatings are developed and successfully employed for carbon steel and aluminium in brine solution . They are especially good at shielding metal surfaces from corrosion because of their remarkable qualities, which include great mechanical strength, superior adherence to metal surfaces, superior chemical resistance, and thermal stability [5]. They are especially good at shielding metal surfaces from harsh external elements because of their remarkable qualities, which include great mechanical strength, strong chemical resistance, excellent adherence to metal surfaces, and thermal stability [6]. Epoxy coatings are widely used in industrial applications because they form a tight bond with substrates, which lowers the risk of delamination and corrosion undercutting. Their efficacy in reducing corrosion-related damage is further enhanced by their low permeability to oxygen and moisture. Because of their high degree of cross-linking, these resins are stiff and impervious to deterioration in the environment [7].

Benefits of epoxy resins

Epoxy resins, as thermoset polymers, have distinct manufacturing properties such as low pressure, minimal cure shrinkage, and low residual stresses, allowing the creation of precise and durable products. These resins can be used at a wide temperature range by adjusting the cross-linking levels with appropriate curing agents. They are suitable for electrical insulation, surface coatings, engineered composites, and structural adhesives, and are available in both low-viscosity liquid and powder forms. Furthermore, their efficient manufacturing processes contribute to faster production and lower industrial costs, making them highly practical in various industries [8].

In terms of mechanical properties, epoxy resins offer modified fatigue resistance and mechanical strength, as well as superior chemical and heat resistance. These properties are due to their thermosetting polymer nature, which occurs when polyoxides react with hardeners. Their structural integrity allows them to endure severe chemicals, high temperatures, and mechanical strain, making them indispensable for applications that require durable and robust materials. Further, epoxy resins also have excellent chemical resistance, which increases their adaptability to a wide range of industries, including maritime, construction, and automotive. Their ability to form strong protective layers results in excellent bonding with substrates such as concrete, wood, and metals. This makes them ideal for waterproofing, protecting surfaces, and extending the life of materials. Epoxy composites, known for their strength and lightweight characteristics, support advanced manufacturing processes, while epoxy coatings effectively combat corrosion and maintain the integrity of metal surfaces [[9], [10]].

One major advantage of epoxy resins is their ability to improve the mechanical properties of

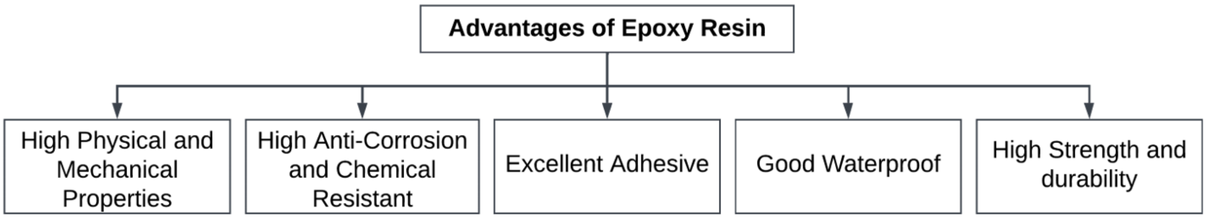

Figure 1 - Advatages of epoxy resins

materials used in industrial manufacturing. Epoxy resins help to produce goods that can withstand harsh industrial conditions by increasing their strength, resilience, and overall performance. Their role includes reinforcing concrete structures, creating high- performance components, and ensuring the dependability and durability of industrial products [[8], [9]]. Another significant advantage of epoxy resins is their ability to address environmental concerns while still providing exceptional performance. These resins have superior mechanical and thermal resistance because they contain cross-linking co-reactants such as polyfunctional amines and acids. Their durability and efficiency make them ideal for applications such as metal coatings and composites. Researchers are developing sustainable alternatives to replace harmful chemicals in epoxy resins, contributing to greener industrial practices [10]. Main advantages of epoxy resins demonstrated in Figure 1.

In recent years, there has been a significant increase in the number of works related to anticorrosive epoxy coatings and composites. The current development of anti-corrosion epoxy coatings can be grouped into 3 main approaches: epoxy composites based on nanofillers, epoxy structure modifications, and multifunctional coatings (Figure 2). Enhancing the corrosion resistance of coatings is achieved by barrier or sacrificial protection or corrosion inhibition [11].

Epoxy composites and systems

One of the common and most affordable methods for improving the anticorrosive properties of epoxy coatings is the introduction of modified mineral nanofillers. Surface modification of the nanoparticles makes them stable and provides a high degree of dispersion, which prevents their aggregation caused by high specific surface area and surface energy [12]. Such nanoparticles are evenly distributed in the coating matrix, reducing its porosity, closing microcracks decreasing coating affinity with corrosion medium, and significantly increasing corrosion resistance. Ou et al. [13] conducted surface modification of TiO_2 nanoparticles by toluene diisocyanate (TDI). The TDI molecules were covalently bonded to the nanoparticle surface, significantly enhancing their dispersibility in toluene. This functionalization approach effectively mitigated the agglomeration tendency of TiO_2 nanoparticles, ensuring a more stable dispersion. In a separate study by Situ et al. [14], polyaniline-titanium nitride (PANI-TiN) nanocomposites were developed through a low-temperature chemical oxidation polymerization process. Adding TiN nanoparticles to PANI nanorods minimized their tendency to aggregate and improved their uniform distribution in the epoxy matrix. The resulting PANI-TiN/epoxy coatings demonstrated significantly enhanced corrosion protection, with impedance modulus values increasing by 115 times compared to pure epoxy coatings after two days of exposure to a 3.5 wt.% NaCl solution. This improvement was primarily due to the combined effects of PANI's passivation properties and creating winding paths by TiN nanoparticles for the electrolyte, slowing down the corrosion process and increasing the durability of the coating. In a study by Jlassi et al. [15], magnetite-clay nanocomposites modified with polyaniline (PANI) and diazonium salts (B-DPA-PANI@Fe_3O_4) were synthesized and integrated into epoxy coatings. The inclusion of 3 wt.% of these fillers significantly enhanced the anticorrosion performance, increasing the charge transfer resistance up to 110 × 10^6 Ω·cm² compared to 0.35 × 10^6 Ω·cm² for pure epoxy. This improvement was attributed to the uniform dispersion of the nanofillers, reduced coating porosity, and the synergistic interaction between the filler and the epoxy matrix, which decreased the penetration of chloride ions in a corrosive environments.

A large number of studies are devoted to the use of graphene to improve coating properties. Graphene, being a two-dimensional nanomaterial, consists of a single layer of atoms and has exceptional barrier properties that prevent the

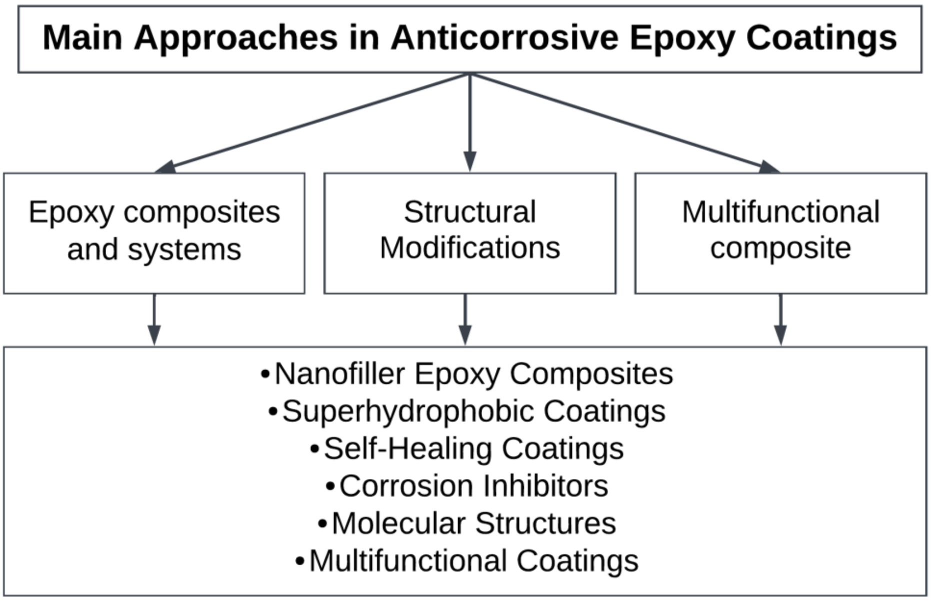

Figure 2 - Main Approaches in Anticorrosive Epoxy Coatings

penetration of almost any molecules or ion. Even small additions of graphene to the coating composition can significantly improve its physical characteristics and enhance protection from aggressive media [16]. In [17], the corrosion behavior of epoxy coatings reinforced with reduced graphene oxide (RGO) on N80 steel was studied under conditions of high salinity (10% NaCl) and a temperature of 80 °C. Coatings with different RGO content (0%, 0.5%, 1%, 2% and 4%) were characterized by SEM, EIS, and Tafel polarization methods. It was found that the addition of RGO reduces the number and size of pores in the coating, improves its adhesion and strength. The coating with 1% RGO showed the best anticorrosive properties, at which the charge transfer resistance (Rct) reached 17×10^6 Ω·cm2, while with an increase in the RGO content above 2%, particle aggregation and deterioration of protective properties were observed. In [18], the effect of an ionic liquid based on 1-butyl-3-methylimidazolium chloride (BMIM-Cl) on the dispersion of graphene oxide (GO) in epoxy resin and the anticorrosive properties of the obtained composites was investigated. The results showed that the adsorption of BMIM-Cl on the GO surface improved the compatibility of nanoparticles with the epoxy matrix, preventing aggregation. Coatings with GO-BMIM demonstrated higher protective properties compared to pure epoxy resin, which was confirmed by EIS, salt spraying and polarization methods. The best barrier effect was achieved with a GO-BMIM content of 0.12%.

It can be functionalized to reduce the aggregation of graphene particles. Ziat et al. [19] dispersed single-layer graphene in pure ethanol, and then created nanocomposites based on epoxy resin with a graphene content of 2 wt.% using the in-situ polymerization method. The functionalized graphene in the coating showed excellent dispersibility. Potentiodynamic polarization and electrochemical impedance spectroscopy have confirmed a significant improvement in the corrosion resistance of the coating on the copper substrate in a NaCl solution with a concentration of 3%. Scanning electron microscopy (SEM) analysis confirmed the effectiveness of the coating as a barrier, and measurements of the wetting angle indicated the hydrophobic properties of the coating, emphasizing its high mechanical strength and barrier characteristics.

Xie et al. [20], in turn, modified graphene oxide (GO) with polyacrylate using radical copolymerization technology. First, the GO surface was treated with silane (KH-570) to create active centers, then polymerization of acrylate monomers was performed in the presence of an initiator (AIBN) at 80 °C. This improved the dispersibility of GO in the epoxy matrix and the interaction at the interface, which was confirmed by scanning electron microscopy. The coatings obtained demonstrated a noticeable increase in anticorrosive properties.

The so-called superhydrophobic surfaces have recently gained particular interest. Such coatings are determined by their ability to minimize interaction with water: the water contact angle (WCA) on their surface exceeds 150°, and the rolling angle (RA) is less than 10°. This gives the coatings unique properties such as self-cleaning, water resistance, and anti-icing, resulting in a wide range of applications potential in various fields [[21], [22]].

Superhydrophobic coatings based on epoxy resins have been developed. A superhydrophobic coating [23] based on hydrophobic silica nanoparticles modified with paraffin wax synthesized by alkaline hydrolysis of silane precursors such as γ-aminopropyltriethoxysilane (APS) and tetraethoxysilane (TEOS) in the presence of paraffin wax was developed. The resulting nanoparticles were incorporated into epoxy matrices, with a 1 wt.% of the modified nanoparticles coating demonstrating improved dispersing of nanoparticles in epoxy coatings and anticorrosive properties, withstanding up to 1,500 hours in a salt mist. In addition, the water-wetting angles reached 100-110° when blended with 3Wt% of nanoparticles, which confirms their hydrophobicity. These results confirm that the modification of silica with paraffin wax increases corrosion resistance, improves mechanical properties, and reduces the wettability of coatings. In another work [24], a superhydrophobic coating based on epoxy resin was created using modified TiO_2 and ZnO nanoparticles synthesized using the "one pot" method. The process involved the preliminary modification of nanoparticles, and then their mixing with epoxy resin cured with HHPA hardener in a ratio of 5:3 by weight. The finished coating had a wetting angle of up to 155.6° and demonstrated high resistance to corrosion and abrasives. Additionally, experiments have shown that the degree of crosslinking of the epoxy matrix and adhesion to the metal substrate plays a key role in increasing the service life of the coating.

In the study [25], a superhydrophobic coating was developed by incorporating modified sepiolite powder into pure epoxy resin. The coating demonstrated improved corrosion resistance compared to pure epoxy, with a contact angle of 154.6° and a sliding angle of 3° when 5 wt% of the modified powder was added. Characterization techniques, including CA, SEM, FT-IR, and XRD, revealed its enhanced wettability and composition. Corrosion tests using EIS, salt-spray, and SKP confirmed that the composite coating effectively restricted corrosion in damaged regions, delaying substrate degradation and significantly enhancing corrosion protection.

In order to increase long-term corrosion protection, self-healing coatings or coatings with corrosion inhibitors can be used. The principle of the first type of coatings is their ability to restore integrity and anti-corrosion properties after damage. This is achieved either by releasing encapsulated active substances that react with the damaged surface and form a protective layer or by reactions triggered by external factors such as temperature or light [[26], [27]]. As for inhibitory protection, its essence lies in the release of inhibitory compounds from the coating matrix into damaged areas, which slows down or prevents corrosion processes [28].

Attaei et al. [29] developed a self-healing epoxy coating with microcapsules containing isophorone diisocyanate (IPDI). Microcapsules were synthesized by interphase polymerization in oil-in-water emulsions, ensuring their thermochemical stability and a diameter of 5-20 microns. Experiments using EIS, SVET, and LEIS have shown that when the capsule coating is damaged, IPDI is released, which forms a polymer layer that effectively suppresses corrosion. The destroyed microcapsules promote polymerization, restoring the protective properties of the coating. A similar study on self-healing coatings by microcapsules is presented in [30]. In another study [31], N-isopropylacrylamide-co-vinyltrimetho-xysilane (NIPAM-VTS) was used as a self-healing agent, with hydrolyzed microgel combined with tetraethoxysilane (TEOS) and 3-aminopropyltriethoxysilane (APTS) to create amino-functionalized smart silica composites and nanoparticles.

The direct addition of corrosion inhibitors to epoxy coatings often results in limited long-term protection and can negatively impact the coating's performance, causing issues such as blistering, reduced corrosion resistance, and weakened mechanical properties [32]. To overcome these drawbacks, an effective alternative approach involves incorporating inhibitors into micro- or nanostructures, which encapsulate or fix the inhibitors within the epoxy resin system, thereby avoiding harm to the coating's overall performance [33].

Structural Modifications of Epoxy Resins

As mentioned above, basic epoxy coatings are not capable of providing long-term corrosion protection. This is due to their limited mechanical and barrier properties, which deteriorate under the influence of aggressive environmental factors. Therefore, the approach discussed below aims to increase the wear resistance and corrosion resistance of epoxy coatings by developing new formulations or synthesizing epoxy resins with different molecular structures. In one study, Dagdag et al. [34] formulated a novel epoxy resin coating (TGEDA-MDA) by curing tetraglycidyl ether of diaminodiphenylmethane (TGEDA) with methylene dianiline (MDA). This coating demonstrated a protective efficiency of approximately 93% in a 3 wt% NaCl solution, as confirmed by potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS). Additionally, computational modeling revealed the strong adhesion of TGEDA-MDA to carbon steel surfaces, forming a stable and effective protective layer. In another study [35], the same group developed a macromolecular epoxy coating (DGEDDS-MDA) based on bisphenol S diglycidyl ether (DGEDDS) cured with methylene dianiline. This molecular structure, rich in hydroxyl and amino groups, enhances adsorption of corrosive substances such as water and chloride ions. Even after 180 days of exposure to ultraviolet radiation, the coating exhibited high durability, with an impedance value of 2.12 kΩ cm^2, indicating sustained protective performance.

Researchers [36] studied the effect of curing agents with different molecular structures—diethylenetriamine (DETA), isophorone diamine (IPDA), and m-phenylenediamine (m-PDA)—on the tribological and anticorrosion properties of epoxy coatings. The molecular structure of these curing agents significantly influenced the cross-linking network and internal structure of the coatings, impacting their performance. Electrochemical tests in 3.5 wt% sodium chloride solution demonstrated that IPDA-cured coatings exhibited the best corrosion resistance due to their compact structure, which effectively blocked corrosive agents. In contrast, m-PDA-cured coatings showed the poorest performance, attributed to a looser internal structure that allowed easier penetration of the corrosive medium.

In recent years, there has been a growing demand for bio-based epoxy resins as sustainable alternatives to petroleum-based counterparts. This shift is driven by concerns over the depletion of fossil fuel resources, greenhouse gas emissions, and the toxicological impacts of conventional materials like bisphenol A (BPA), which is widely used in epoxy resins [37]. The itaconic acid-based epoxy resin (EIA) synthesized by Ma et al. [38] through an esterification reaction between itaconic acid and epichlorohydrin, yielding a resin with a high epoxy value of 0.625 and excellent curing reactivity. When cured with methyl hexahydrophthalic anhydride (MHHPA), EIA demonstrated superior thermal and mechanical properties, including a glass transition temperature of 130.4 °C and a tensile strength of 87.5 MPa, comparable to or exceeding traditional diglycidyl ether of bisphenol A (DGEBA) resins. Furthermore, the properties of EIA were enhanced by incorporating comonomers such as divinyl benzene (DVB) and acrylated epoxidized soybean oil (AESO), underscoring its potential as a sustainable replacement for petroleum-based thermosetting resins.

A bio-based epoxy resin synthesized from cashew nutshell liquid was developed for a one-component anticorrosive coating using a solvent-free process with in situ generated performic acid [39]. The curing behavior of the epoxy-phenol system with 1-methylimidazole (1-MIM) as an accelerator demonstrated efficient catalysis with only 5% by weight of 1-MIM, achieving a curing temperature of 150 °C. The coating exhibited high crosslink density, thermal stability (decomposition at 200 °C), and a glass transition temperature of 30 °C. Electrochemical impedance spectroscopy, along with adhesion and visual assessments, confirmed its excellent anticorrosive performance under salt spray and immersion in 3.5% NaCl solution. The material also maintained high adhesive strength and low delamination during humidity exposure tests. These results highlight the potential of this bio-based epoxy coating for corrosion protection applications.

Multifunctional composite coating

Epoxy resin coatings relying on a single anticorrosion approach often fall short in addressing the challenges posed by complex real-world conditions. The development of materials that integrate multiple protective approaches offers innovative opportunities to enhance the effectiveness and durability of epoxy coatings in practical applications. Dagdag et al. [40] developed an anticorrosive epoxy coating by synthesizing DGEDDS with epichlorohydrin, 4,4′-dihydroxy diphenyl sulfone, and sodium hydroxide, using 4,4′-methylene dianiline (MDA) as a hardener and zinc phosphate tetrahydrate (ZPH) as an anticorrosion pigment, resulting in a highly stable and corrosion-resistant coating. Liang et al. [41] developed nanocomposite epoxy coatings by incorporating 5% nano-Al through a two-stage process, ensuring high concentration and low viscosity. The nano-Al particles initially corrode to protect the substrate and subsequently form aluminum oxide and hydroxide, which act as barriers to prevent the penetration of corrosive liquids. Characterization through immersion, salt spray tests, and EIS confirmed a significant improvement in the coating's corrosion resistance. In the study by Lakouraj et al. [42], a high-performance epoxy resin was developed by curing diglycidyl ether of bisphenol-A (DGEBA) with diaminoxanthone (DAX) and incorporating functionalized Fe_3O_4 nanoparticles. Corrosion resistance tests, including potentiodynamic polarization and immersion in HCl solution, showed that the addition of 10% Fe_3O_4 nanoparticles significantly enhanced the anticorrosion performance compared to the neat DGEBA/DAX system.

In one study [43], α-Fe_2O_3@TA@GO composites were prepared by modifying mica iron oxide with tannic acid and graphene oxide and then incorporating them into an epoxy-acrylic resin. This hybrid system significantly improved corrosion resistance, achieving a low corrosion current density of 1.459 $\mu A/cm^2$ and a high charge transfer resistance of 14,350 $\Omega \cdot cm^2$. The addition of 5 wt% of the composite provided optimal performance, showcasing excellent compatibility and improved dispersion stability. In another study [44], epoxy resins were combined with functionalized materials, and similar processes involving surface modifications and composite incorporation were employed. The results indicated enhanced mechanical strength, thermal stability, and anticorrosion properties, demonstrating the potential of hybrid systems to overcome the inherent limitations of pure epoxy coatings.

Advancement of epoxy resin as anticorrosion coatings

Over the years, the field of epoxy resins has continuously evolved due to their unique properties such as high mechanical strength, temperature and solvent resistance, and strong adhesion to metals and composites. These developments have made epoxy resins crucial across aerospace, automotive, construction, and biomedical applications. Supplementing these commercial coatings are some of the newer developments such as the incorporation of nanomaterials into epoxy-based nanocomposite coatings to design coatings with a combination of unique properties of both epoxy and nanomaterials, providing a new range of advanced coatings with enhanced functionalities.

The development of superhydrophobic epoxy-based nanocomposite coatings; however, is a game-changer in this aspect, as they exhibit exceptional wetting resistance, chemical stability, and mechanical robustness. Incorporation of nanomaterials, such as silica nanoparticles, carbon nanotubes, and graphene, further enhances the properties of these coatings, resulting in high-performance coatings for applications such as anti-corrosion and self-cleaning surface [[45], [46]]. As epoxy is comparatively strong, durable and can bond with any material such as metal and glass, it is being used as a matrix material in these nanocomposites. These coatings show super hydrophobicity with water contact angles over 150° and very high corrosion and mechanical stress resistance and are very effective in extreme environments such as aerospace and marine industries [47]. In addition to performance enhancements, the establishment of superhydrophobic coatings matches sustainability objectives. Researchers are developing eco-friendly formulations to replace volatile organic compounds (VOCs), substances that have a negative environmental impact. This trend is part of a larger paradigm shift in materials science, to create smart materials that are high- performing but responsible at the same time [48].

Furthermore, the introduction of nanomaterials such as silica nanoparticles and graphene into epoxy resins has made considerable contributions to their corrosion resistance, hydrophobicity, and mechanical properties. By mimicking the arrangement of hydrophobic structures found in nature (e.g. lotus leaves), such nanocomposites repel water as well as prevent the buildup of corrosive agents on the composite surface, while also enabling other properties for example self-cleaning ability [[48], [49]]. These advanced coatings are usually made by spray coating, drop-coating and 3D bioprinting [45], while spray coating has received the most attention for large-scale usage. Additionally, continuous developments in environmentally friendly formulations are rendering these coatings sustainable, maintaining high performance and low environmental impacts [50]. These developments not only enhance the durability and effectiveness of epoxy coatings but also establish them as a cornerstone in modern industrial applications, ensuring long-term protection and sustainability.

The molecular weight of epoxy oligomers has a noticeable effect on the anti-corrosion properties of coatings [[51], [52], [53], [54], [55], [56]]. Low molecular-weight epoxy resins provide a higher density of crosslinks, thereby reducing free volume and segmental mobility, which makes it more difficult for corrosive molecules to penetrate the coating. However, excessive crosslink density can lead to the formation of microcracks and pores in the coating, compromising its protective performance [[52], [55], [56], [57], [58], [59]]. In contrast, high molecular-weight epoxy resins, with their higher hydroxyl functionality, offer improved wetting and adhesion to metal substrates but result in coatings with lower crosslink density. This reduces hardness and chemical resistance while enhancing flexibility and impact resistance. Therefore, optimizing the molecular weight of epoxy resins requires balancing the desired protective properties with mechanical and structural integrity.

Conclusions

In summary, epoxy resin coatings have established themselves as a reliable method of preventing corrosion in a wide range of sectors, such as the infrastructure, marine, and oil and gas industries. They are extremely effective at protecting metal surfaces from the damaging effects of oxygen, water, and salts as the main causes of corrosion due to their exceptional mechanical strength, chemical resistance, and superior adhesion. The performance of epoxy- based coatings has been greatly improved by developments, especially the addition of nanomaterials like carbon nanotubes, graphene, and silica nanoparticles. Even in the harshest conditions, these developments have increased the coatings' lifespan in addition to improving their hydrophobicity and durability. Epoxy resins cross-linked molecular structure adds to their durability by making them resistant to physical and chemical stresses like impact and abrasion. Additionally, a major advancement in water repellence and maintenance ease has been the development of superhydrophobic qualities. The continuous transition to more environmentally friendly formulations, which seek to lessen the environmental impact while preserving peak performance levels, complements this development. The future of protective coatings is being reshaped by epoxy-based anticorrosion coatings, particularly those enhanced with nanocomposites, in a variety of demanding industries, including automotive and aerospace. These coatings provide an economical and environmentally friendly way to combat corrosion, greatly lowering maintenance expenses while boosting the dependability and safety of vital infrastructure. Epoxy coatings are expected to become even more important in maintaining the longevity and integrity of industrial assets for many years to come because of ongoing advances in material science.

Conflicts of interest. Authors declare no conflict of interest.

CRediT author statement: **L.Bekbayeva:** performed the methodology and writing the original draft preparation; **R.Zhanibekov, R.Sharipov and G.Meldybayev:** performed the data collection and part of the methodology; **E-S.Negim**: supervised the study and revising manuscript; **D. Puzikova** and **N. Kenzin:** performed data interpretation for application of epoxy and revising the final draft of manuscript; **A.Maridan:** performed the introduction writing.

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ТҮЙІНДЕМЕ
Эпоксидті шайырлар тамаша адгезиясы, механикалық беріктігі және химиялық төзімділігі арқасында коррозияға қарсы қолдануда ең көп пайдаланылатын материалдардың бірі болып табылады. Алайда, дәстүрлі эпоксидті жабындар агрессивті орта жағдайларында ұзақ мерзімді және сенімді қорғауды қамтамасыз етуде айтарлықтай шектеулерге ие. Осыған байланысты, бүкіл әлемде эпоксидті жабындардың коррозияға қарсы қасиеттерін жақсартуға бағытталған ауқымды зерттеулер жүргізілуде. Бұл шолуда осы саладағы соңғы жетістіктер жинақталып, үш негізгі бағытқа бөлінді: эпоксидті шайыр құрылымын өзгерту, функционалды толтырғыштарды қосу және көпфункционалды композиттік жабындарды әзірлеу. Құрылымды өзгерту эпоксидті шайырлардың тосқауылдық әсерін жақсарту үшін олардың ішкі қасиеттерін жетілдіруге бағытталған. Функционалды толтырғыштарды қолдану өзін-өзі қалпына келтіру, супергидрофобтық қасиеттер және коррозияны тежеу сияқты қосымша қорғаныс механизмдерін қамтамасыз етеді. Көпфункционалды композиттік жабындар бірнеше тәсілдердің артықшылықтарын біріктіріп, жоғары тиімділікке қол жеткізу үшін алдыңғы қатарлы материалдар мен технологияларды біріктіреді. Соңғы зерттеулер мен инновацияларды талдау арқылы бұл шолу әрбір тәсілдің артықшылықтары мен кемшіліктерін көрсетіп, жоғары тиімді эпоксидті коррозияға қарсы жабындарды әзірлеудің болашақ бағыттары туралы түсінік береді.

Түйін сөздер: Композиттер, эпоксидті шайыр, коррозияға қарсы жабын, коррозия, коррозияны тежеу, коррозияға қарсы қорғаныс.

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Эпоксидные покрытия для защиты от коррозии: обзор

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АННОТАЦИЯ
Эпоксидные смолы являются одними из самых широко используемых материалов для антикоррозионного применения благодаря их отличной адгезии, механической прочности и химической стойкости. Однако традиционные эпоксидные покрытия имеют существенные ограничения в обеспечении долговечной и надежной защиты, особенно в условиях агрессивной окружающей среды. В связи с этим во всем мире ведутся масштабные исследования, направленные на улучшение антикоррозионных свойств эпоксидных покрытий. В данном обзоре обобщены последние достижения в этой области, которые можно разделить на три основные направления: модификация структуры эпоксидной смолы, внедрение функциональных наполнителей и разработка многофункциональных

композитных покрытий. Модификация структуры направлена на улучшение внутренних свойств эпоксидных смол для повышения их барьерного эффекта. Использование функциональных наполнителей обеспечивает дополнительные защитные механизмы, включая самовосстановление, супергидрофобность и ингибирование коррозии. Многофункциональные композитные покрытия объединяют преимущества нескольких подходов, интегрируя передовые материалы и технологии для достижения высокой эффективности. Анализируя недавние исследования и инновации, данный обзор подчеркивает сильные стороны каждого подхода, а также дает представление о перспективах разработки высокоэффективных эпоксидных антикоррозионных покрытий.

Ключевые слова: Композиты, эпоксидная смола, антикоррозионное покрытие, коррозия, ингибирование коррозии, антикоррозионная защита.

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References

[1] Ma X, Li Y, Zhang J, Wang P. Epoxy coatings with enhanced anticorrosion performance: Recent advancements and applications. Metals. 2023; 13(2):272. https://doi.org/10.3390/met13020272

[2] NACE International. International Measures of Prevention, Application, and Economics of Corrosion Technology (IMPACT) Report. 2016. Retrieved from https://www.nace.org

[3] Zhang W, Zhang H, Zhou X, Li X. Preparation and properties of self-healing epoxy coatings for anticorrosion applications. Reactive and Functional Polymers. 2020; 151:104741. https://doi.org/10.1016/j.reactfunctpolym.2020.104741

[4] Verma C, Olasunkanmi LO, Akpan ED, Quraishi MA, Dagdag O, El Gouri M, Sherif ESM, Ebenso EE. Epoxy resins as anticorrosive polymeric materials: A review. Reactive and Functional Polymers. 2020; 150:104741. https://doi.org/10.1016/j.reactfunctpolym.2020.104741

[5] Singh D, Jain S. Epoxy coatings: A comprehensive review of applications in anticorrosion protection. Materials Science Forum. 2020; 1023:81-102.

[6] Donnet JB, Bansal RC. Polymer and Surface Coatings Chemistry. CRC Press; 1998.

[7] Neville A, et al. Epoxy resins in corrosion protection: Mechanisms and applications. Progress in Organic Coatings. 2017; 112:283-295.

[8] MDPI. The IUPAC nomenclature for an epoxy resin and its influence on material properties. Polymers. 2023; 16(4):548. https://doi.org/10.3390/polym16040548

[9] De Gruyter. Epoxy resins: Classification, applications, and benefits. Engineering Review. 2021; 2021(0078). https://doi.org/10.1515/eng-2021-0078

[10] Saba N, Jawaid M, Alothman OY, Tahir PM. Recent advances in epoxy resin, natural fiber reinforced epoxy composites and its applications. Journal of Reinforced Plastics and Composites. 2015; 34(12):1–18. https://doi.org/10.1177/0731684415618459

[11] Ou B, Wang Y, Lu Y. A Review on Fundamentals and Strategy of Epoxy-Resin-Based Anticorrosive Coating Materials. Polymer-Plastics Technology and Materials 2020. https://doi.org/10.1080/25740881.2020.1819317.

[12] Salimian S, Malfait WJ, Zadhoush A, Talebi Z, Naeimirad M. Fabrication and Evaluation of Silica Aerogel-Epoxy Nanocomposites: Fracture and Toughening Mechanisms. Theoretical and Applied Fracture Mechanics. 2018; 97:156–164. https://doi.org/10.1016/j.tafmec.2018.08.007

[13] Ou B, Li D, Liu Q, Zhou Z, Liao B. Functionalized TiO2 Nanoparticle Containing Isocyanate Groups. Materials Chemistry and Physics. 2012; 135:1104–1107. https://doi.org/10.1016/j.matchemphys.2012.06.027

[14] Situ Y, Ji W, Liu C, Xu J, Huang H. Synergistic Effect of Homogeneously Dispersed PA I-TiN Nanocomposites Towards Long-Term Anticorrosive Performance of Epoxy Coatings. Progress in Organic Coatings. 2019; 130:158-167. https://doi.org/10.1016/j.porgcoat.2019.01.034

[15] Jlassi K, Radwan AB, Sadasivuni KK, et al. Anti-Corrosive and Oil Sensitive Coatings Based on Epoxy/Polyaniline/Magnetite-Clay Composites Through Diazonium Interfacial Chemistry. Scientific Reports. 2018; 8:13369. https://doi.org/10.1038/s41598-018-31508-0

[16] Xu X, Yi D, Wang Z, et al. Greatly Enhanced Anticorrosion of Cu by Commensurate Graphene Coating. Advanced Materials. 2018; 30:1702944. https://doi.org/10.1002/adma.201702944

[17] Zhu L, Feng C, Cao Y. Corrosion Behavior of Epoxy Composite Coatings Reinforced with Reduced Graphene Oxide Nanosheets in High Salinity Environments. Applied Surface Science. 2019; 493:889–896. https://doi.org/10.1016/j.apsusc.2019.06.271

[18] Khalili Dermani A, Kowsari E, Ramezanzadeh B, Amini R. Utilizing Imidazole-Based Ionic Liquid as an Environmentally Friendly Process for Enhancement of the Epoxy Coating/Graphene Oxide Composite Corrosion Resistance. Journal of Industrial and Engineering Chemistry. 2019; 79:353-363. https://doi.org/10.1016/j.jiec.2019.07.010

[19] Ziat Y, Hammi M, Zarhri Z, Laghlimi C. Epoxy Coating Modified with Graphene: A Promising Composite Against Corrosion Behavior of Copper Surface in Marine Media. Journal of Alloys and Compounds. 2020; 820:153380. https://doi.org/10.1016/j.jallcom.2019.153380

[20] Xie Y, Liu C, Liu W, et al. A Novel Approach to Fabricate Polyacrylate Modified Graphene Oxide for Improving the Corrosion Resistance of Epoxy Coatings. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2020; 593:124627. https://doi.org/10.1016/j.colsurfa.2020.124627

[21] Barati Darband G, Aliofkhazraei M, Khorsand S, Sokhanvar S, Kaboli A. Science and Engineering of Superhydrophobic Surfaces: Review of Corrosion Resistance, Chemical and Mechanical Stability. Arabian Journal of Chemistry. 2020; 13:1763–1802. https://doi.org/10.1016/j.arabjc.2018.01.013

[22] Piscitelli F, Chiariello A, Dabkowski D, et al. Superhydrophobic Coatings as Anti-Icing Systems for Small Aircraft. Aerospace. 2020; 7:1-18. https://doi.org/10.3390/aerospace7010002

[23] Atta AM, Mohamed NH, Rostom M, et al. New Hydrophobic Silica Nanoparticles Capped with Petroleum Paraffin Wax Embedded in Epoxy Networks as Multifunctional Steel Epoxy Coatings. Progress in Organic Coatings. 2019; 128:99–111. https://doi.org/10.1016/j.porgcoat.2018.12.018

[24] Li M, Liu N, Chen J, et al. Simple Construction Based on Epoxy-Bonded Super-Hydrophobic Anti-Corrosion Coating. Journal of the Taiwan Institute of Chemical Engineers. 2019; 95:682–691. https://doi.org/10.1016/j.jtice.2018.10.016

[25] Yuan S, Zhao X, Jin Z, et al. Fabrication of an Environment-Friendly Epoxy Coating with Flexible Superhydrophobicity and Anti-Corrosion Performance. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2022; 633:127545. https://doi.org/10.1016/j.colsurfa.2021.127545

[26] Attaei M, Calado LM, Taryba MG, et al. Autonomous Self-Healing in Epoxy Coatings Provided by High-Efficiency Isophorone Diisocyanate (IPDI) Microcapsules for Protection of Carbon Steel. Progress in Organic Coatings. 2020; 139:105445. https://doi.org/10.1016/j.porgcoat.2019.105445

[27] Qian B, Song Z, Hao L, et al. Self-Healing Epoxy Coatings Based on Nanocontainers for Corrosion Protection of Mild Steel. Journal of The Electrochemical Society. 2017; 164:54-60. https://doi.org/10.1149/2.1251702jes

[28] Montemor MF. Functional and Smart Coatings for Corrosion Protection: A Review of Recent Advances. Surface and Coatings Technology. 2014; 258:17-37. https://doi.org/10.1016/j.surfcoat.2014.06.031

[29] Attaei M, Calado LM, Taryba MG, Morozov Y, Shakoor RA, Kahraman R, Marques AC, Montemor MF. Autonomous Self-Healing in Epoxy Coatings Provided by High-Efficiency Isophorone Diisocyanate (IPDI) Microcapsules for Protection of Carbon Steel. Progress in Organic Coatings. 2020; 139:105445. https://doi.org/10.1016/j.porgcoat.2019.105445

[30] Tezel Ö, Beyler Çiğil A, Kahraman MV. Design and Development of Self-Healing Coating Based on Thiol–Epoxy Reactions. Reactive and Functional Polymers. 2019; 142:69-76. https://doi.org/10.1016/j.reactfunctpolym.2019.06.004

[31] Atta AM, Ezzat AO, El-Saeed AM, Tawfeek AM, Sabeela NI. Self-healing of chemically bonded hybrid silica/epoxy for steel coating. Progress in Organic Coatings. 2020; 141:105549. https://doi.org/10.1016/j.porgcoat.2020.105549

[32] Yang M, Wu J, Fang D, Li B, Yang Y. Corrosion Protection of Waterborne Epoxy Coatings Containing Mussel-Inspired Adhesive Polymers Based on Polyaspartamide Derivatives on Carbon Steel. Journal of Materials Science & Technology. 2018; 34:2464-2471. https://doi.org/10.1016/j.jmst.2018.05.009

[33] Mohammadi I, Izadi M, Shahrabi T, Fathi D, Fateh A. Enhanced Epoxy Coating Based on Cerium Loaded Na-Montmorillonite as Active Anti-Corrosive Nanoreservoirs for Corrosion Protection of Mild Steel: Synthesis, Characterization, and Electrochemical Behavior. Progress in Organic Coatings. 2019; 131:119–130. https://doi.org/10.1016/j.porgcoat.2019.02.016

[34] Dagdag O, Hsissou R, El Harfi A, Berisha A, Safi Z, Verma C, Ebenso EE, Touhami ME, El Gouri M. Fabrication of Polymer-Based Epoxy Resin as Effective Anti-Corrosive Coating for Steel: Computational Modeling Reinforced Experimental Studies. Surfaces and Interfaces. 2020; 18:100454. https://doi.org/10.1016/j.surfin.2020.100454

[35] Dagdag O, Berisha A, Safi Z, et al. Highly Durable Macromolecular Epoxy Resin as Anticorrosive Coating Material for Carbon Steel in 3% NaCl: Computational Supported Experimental Studies. Journal of Applied Polymer Science. 2020; 137:e49003. https://doi.org/10.1002/app.49003

[36] Liu D, Zhao W, Wu F, Cen Q, Zeng Z, Wu X, Xue Q. Effect of Curing Agent Molecular Structures on the Tribological and Corrosion Behaviors of Epoxy Resin Coatings. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2015; 472:85-91. https://doi.org/10.1016/j.colsurfa.2015.02.036

[37] Sreehari H, Sethulekshmi AS, Saritha A. Bio Epoxy Coatings: An Emergent Green Anticorrosive Coating for the Future. Macromolecular Materials and Engineering. 2022; 307:2200004. https://doi.org/10.1002/mame.202200004

[38] Ma S, Liu X, Jiang Y, Tang Z, Zhang C, Zhu J. Bio-Based Epoxy Resin from Itaconic Acid and Its Thermosets Cured with Anhydride and Comonomers. Green Chemistry. 2013; 15:245 -254. https://doi.org/10.1039/C2GC36715G

[39] Da Silva LR, Carvalho BA, Pereira RC, Diogenes OB, Pereira UC, Da Silva KT, Araujo WS, Mazzetto SE, Lomonaco D. Bio-Based One-Component Epoxy Resin: Novel High-Performance Anticorrosive Coating from Agro-Industrial Byproduct. Progress in Organic Coatings. 2022; 167:106861. https://doi.org/10.1016/j.porgcoat.2022.106861

[40] Dagdag O, El Harfi A, Essamri A, et al. Anticorrosive Performance of New Epoxy-Amine Coatings Based on Zinc Phosphate Tetrahydrate as a Nontoxic Pigment for Carbon Steel in NaCl Medium. Arabian Journal for Science and Engineering. 2018; 43:5977-5987. https://doi.org/10.1007/s13369-018-3160-z

[41] Liang Y, Liu F-C, Nie M, Zhao S, Lin J, Han E-H. Influence of Nano-Al Concentrates on the Corrosion Resistance of Epoxy Coatings. Journal of Materials Science & Technology. 2013; 29:353–358. https://doi.org/10.1016/j.jmst.2013.01.014

[42] Lakouraj MM, Rahpaima G, Zare EN. Effect of Functionalized Magnetite Nanoparticles and Diaminoxanthone on the Curing, Thermal Degradation Kinetic, and Corrosion Property of Diglycidyl Ether of Bisphenol A-Based Epoxy Resin. Chinese Journal of Polymer Science. 2014; 32:1489-1499. https://doi.org/10.1007/s10118-014-1535-5

[43] Chen Y, Wen S, Wang J, Wang G, Wang C, Wang Y, Li S, Zhang J. Preparation of α-Fe2O3@TA@GO Composite Material and Its Anticorrosion Performance in Epoxy-Modified Acrylic Resin Coatings. Progress in Organic Coatings. 2021; 154:105987. https://doi.org/10.1016/j.porgcoat.2020.105987

[44] Tian W, Wang S, Wang C, Xu H, Zhao Y, Jin H, Tian L. An Epoxy-Modified Polyurethane Composite Coating with Repetitive Self-Healing Function for Anti-Cavitation, Anticorrosion, and Antifouling Applications. Chemical Engineering Journal. 2023; 477:146849. https://doi.org/10.1016/j.cej.2023.146849

[45] Sabergaliyev M, Yeligbayeva G, Khassanov D, Muradova S, Orazalin Z, Ainakulova D, Sharipov R, & Negim E-S. Modified bitumen-polymer mastic to protect metal coatings from corrosion. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2023; 331(4):12-20. https://doi.org/10.31643/2024/6445.35

[46] Sutar P, Raju KR, Pattanayak S. Superhydrophobic coatings: A review. Surface and Coatings Technology. 2014; 258:169-182. https://doi.org/10.1016/j.surfcoat.2014.04.024

[47] Wang L, Chen S, Zhang Z. Development of superhydrophobic polymer-based nanocomposites for advanced applications. Journal of Materials Science & Technology. 2020; 39:1-18. https://doi.org/10.1016/j.jmst.2020.01.025

[48] Zhang M, Li X, Li Q. Epoxy-based superhydrophobic coatings for corrosion protection. Corrosion Science. 2019; 153:1-11. https://doi.org/10.1016/j.corsci.2019.02.018

[49] Ainakulova D, Muradova S, Khaldun M A A, Bekbayeva L, Megat-Yusoff P, Mukatayeva Z, Ganjian E, & Negim E-S. Analytical Review of Conductive Coatings, Cathodic Protection, and Concrete. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2023; 329(2):92-102. https://doi.org/10.31643/2024/6445.20

[50] Peng Y, Zhang Y, Xu X. Eco-friendly superhydrophobic coatings for corrosion resistance. Materials Chemistry and Physics. 2019; 232:19-27. https://doi.org/10.1016/j.matchemphys.2019.03.051

[51] Ghashghaee M, Fathi M, Heidari A. Corrosion-resistant coatings based on epoxy resin and nanomaterials: A review. Corrosion Science. 2020; 177:108533. https://doi.org/10.1016/j.corsci.2020.108533

[52] Ghaffari M, Shahrabi T. Application of epoxy-based nanocomposites for anticorrosion protection in marine environments. Journal of Applied Polymer Science. 2021; 138(15):49716. https://doi.org/10.1002/app.49716

[53] Sørensen PA, Kiil S, Dam-Johansen K, Weinell CE. Anticorrosive Coatings: A Review. Journal of Coatings Technology and Research; 2009; 6:135-176. https://doi.org/10.1007/s11998-008-9144-2

[54] Levita G, De Petris S, Marchetti A, Lazzeri A. Crosslink Density and Fracture Toughness of Epoxy Resins. Journal of Materials Science. 1991; 26:2348-2355. https://doi.org/10.1007/BF00544129

[55] Makhmetova A, Negim E-S, Ainakulova D, Yeligbayeva G, & Khatib J. An Overview of Epoxy Resins as coating to protect metals from corrosion. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2023; 328(1):20-32. https://doi.org/10.31643/2024/6445.03

[56] Vecera M, Mleziva J. The Influence of the Molecular Structure on the Chemical Resistivity of Solventless and High-Solid Epoxy Resins. Progress in Organic Coatings. 1995; 26:251-259. https://doi.org/10.1016/0300-9440(95)00553-R

[57] Di Benedetto M. Multifunctional Epoxy Resins Come of Age. Journal of Coatings Technology. 1980; 52:65-68.

[58] Atta AM, Mansour R, Abdou MI, Sayed AM. Epoxy Resins from Rosin Acids: Synthesis and Characterization. Polymers for Advanced Technologies. 2004; 15:514-522. https://doi.org/10.1002/pat.523

[59] Rouw AC. Model Epoxy Powder Coatings and Their Adhesion to Steel. Progress in Organic Coatings. 1998; 34:181-189. https://doi.org/10.1016/S0300-9440(98)00020-4