

Development of Sustainable Water-Based Functional Coatings for Enhanced Surface Performance

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Research Article

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Abstract

To keep the surface functionality needed for applications while decreasing the environmental impact of solvents, water-based coating systems are a promising path. The environmental profile of a coating, however, is not only dependent on whether it is made with an aqueous formulation, but also on the end-of-life impacts, on the durability, on the processing needs, on the functional additives and on the sustainability of the raw materials used. The present study aims at designing sustainable water-based functional coatings and testing their surface, mechanical, hydrophobic and protective characteristics. Compositions of coatings were developed with a waterborne matrix containing sustainable and functional additives, and were applied to [substrate] and cured under [curing conditions]. The coatings obtained were characterised by the techniques of [contact angle, adhesion, hardness/abrasion, surface morphology, corrosion/protective performance]. Experimental results indicated that [insert principal finding, quantitative result obtained: [insert key quantitative result] with [insert property] versus [reference/control coating]. The developed formulation also demonstrated [insert finding (mechanical, hydrophobic, protective)]; it also retained [insert durability/performance outcome]. In general, the results showed that the developed water-based coating [did not/did] provide better environment-friendly properties and the functional surface properties, which is implicated to the sustainable coating development and application.

1. INTRODUCTION

1.1 Background and Need for Sustainable Coatings

A coating is a thin protective and functional layer that is applied to metals, wood, textiles, polymers and various other materials to change the properties of the surface, to increase the durability of the materials, and to protect the materials from the environment and degradation. In addition to their traditional decorative uses, coatings can now offer resistance against moisture, chemical, abrasion, corrosion and biological attack, and control surface wettability and other interfacial properties [1,2]. Organic solvent-based coatings have been very popular because the organic solvents are used for the dissolution of resin, application, film formation and the coating performance. However, they use volatile organic compounds (VOCs) which are associated with emissions to the atmosphere and pose environmental, occupational, and health concerns from exposure to VOCs [1,3].

Waterborne coatings have consequently gained more and more interests due to the fact that water can be used as the main dispersion medium, thus less relying on the conventional organic solvents and also decrease the VOC emissions [2,4]. However, using water as dispersion media doesn't automatically mean the overall sustainability. Resin chemistry, raw material sourcing, additives, energy used during processing and curing, durability, toxicity, and end-of-life factors also will affect the environmental profile of a coating [2,5]. This is not an easy task, though, since it also requires the development of coating systems that achieve both environmental benefit and consistent and long-lasting surface function.

1.2 Water-Based Functional Coatings

Functional coatings are designed to enhance the surface characteristics as well as protection and decoration [6–8]. The coating can be formulated to allow water repellency, corrosion resistance, abrasion resistance, strong adhesion, self-cleaning properties, antimicrobial activity, stain resistance, mechanical durability and/or self-healing properties depending on its function and use. Recent advancements have shown that waterborne polyurethane, epoxy, acrylic, sol-gel and hybrid coating systems can be tailored to provide various surface

functions by the careful formulation and incorporation of functional components [5,9–12]. The versatility of this approach is very appealing because the application of this coating can be multifunctional, that is it can simultaneously protect a substrate and regulate its interaction with water, contamination, mechanical stresses, and corrosive environment. For instance, increased hydrophobicity may hinder the permeation of water, and improved adhesion and mechanical strength may ensure enhanced coating integrity during service. Likewise, barrier-forming and/or corrosion-inhibiting elements may decrease the movement of aggressive species to metallic substrates. Water based multifunctional systems thus offer the possibility to combine both performance and environmental aspects into one formulation target instead of discussing sustainability and functionality as different targets for formulations.

1.3 Sustainable Materials and Functional Additives

An alternative method of enhancing the sustainability and performance of water-based coatings is to use renewable, bio, or less impactful ingredients. Bio-based polymers, plant-derived oils, nanocellulose, biochar, silica, functional silanes, natural polyelectrolytes, graphene-derived materials and less-toxic corrosion inhibitors were studied. In this group of materials, nanocellulose is a very attractive option as it has good reinforcing properties, a high surface area, and is renewable. Nanocellulose coated materials have been studied in many fields related to hydrophobicity, corrosion protection, self-healing, antibacterial and mechanical reinforcement [13]. Bio-based polyurethane systems have also been shown to possess, for instance, transparent and antismudge properties, combined with hardness and corrosion resistance, suggesting that renewable feedstocks can help to achieve environmental and functional goals. Barrier properties and corrosion resistance can also be enhanced via nanostructured additives that alter the morphologies of coatings and transport pathways [15]. The addition of sustainable or functional additives should be carefully optimized, however, as the performance often not increases in proportion to the amount of additive added, and it can have an impact on dispersion, adhesion, film formation, mechanical integrity or processing.

1.4 Research Gap, Purpose and Objectives

There are many successful examples of waterborne coatings developed to deliver specific functional properties such as corrosion resistance, hydrophobicity, self-healing and mechanical durability in the literature [5,9,10,15]. Many studies however focus on the primary performance aspect instead of assessing the interaction of different surface and mechanical needs, and the environment. This leads to a requirement for formulation strategies that can incorporate a more comprehensive coating performance assessment. The main question in this investigation is therefore whether a "balanced" water-based coating formulation will yield a surface improvement without sacrificing mechanical properties or the environmental benefits of water-based processing.

Thus, the overall goal of the current work is to design and test a functional surface coating based on water that can enhance the surface properties. In particular, the study will seek to: (1) develop water-based functional coating compositions containing sustainable or less impactful components; (2) characterise the physical and chemical properties of the resultant coatings; (3) assess adhesion, hardness, water resistance and wettability and surface durability; (4) evaluate the corrosion-protection performance of the coated composition where a metallic substrate is used; (5) determine the effect of various concentrations of the functional additives on the performance of the coating; and (6) identify an optimum composition by combining various water-based property measurements. The study also verifies the hypotheses of the absence of significant influence of

functional additive concentration on surface performance, water resistance and wettability, and mechanical and corrosion-protection properties.

2. LITERATURE REVIEW

2.1 Development of Waterborne Coating Technology

The development of coating technology has progressively moved from conventional solvent-borne systems toward waterborne polymer dispersions, bio-based formulations, nanocomposite systems, and increasingly multifunctional or smart coatings. Solvent-borne coatings historically offered advantages in film formation, substrate wetting, and mechanical performance, but concerns surrounding volatile organic compound emissions encouraged the development of waterborne alternatives. Pieters and Mekonnen identify waterborne polymer dispersions as an important direction in coating technology while noting that limitations in performance and application remain for certain demanding uses [2]. More recent developments have expanded waterborne platforms to epoxy, polyurethane, acrylic, alkyd, and hybrid systems, particularly for corrosion-protection applications [3]. However, replacing organic solvent with water has not eliminated the fundamental challenge of achieving adequate durability and functionality. Waterborne systems can encounter difficulties involving drying, coalescence, water sensitivity, barrier properties, and long-term environmental exposure. Consequently, the technological challenge has shifted from simply demonstrating that coatings can be waterborne to determining whether they can simultaneously satisfy performance, durability, economic, processing, and sustainability requirements. This shift provides the basis for incorporating renewable materials and functional additives into waterborne formulations.

2.2 Bio-Based and Renewable Coating Materials

The incorporation of renewable resources has become an important strategy for reducing dependence on petroleum-derived coating constituents. Plant-derived oils, bio-based polymers, cellulose-derived materials, biochar, and other renewable resources have therefore been investigated as either primary formulation components or functional additives [13–18]. Ha et al. developed a bio-based waterborne polyurethane system incorporating castor-oil-derived components and functionalized it with polydimethylsiloxane (PDMS), reporting a combination of antismudge behavior, hardness, transparency, and anticorrosive performance [14]. This demonstrates that renewable feedstocks need not be limited to environmental substitution but can contribute directly to functional performance. Similarly, research on nanocellulose has highlighted its potential as a renewable reinforcement and multifunctional additive because of its structural characteristics and surface chemistry [13]. Nevertheless, the advantages of renewable materials must be interpreted cautiously. Xia et al. emphasize the broader progress of bio-based coatings while also identifying challenges associated with formulation, processing, performance, and practical implementation [17]. Thus, increasing bio-based content does not automatically establish overall sustainability. Resource origin must be considered alongside chemical modification, processing energy, durability, additive requirements, and end-of-life behavior. The critical issue is consequently whether renewable materials can maintain or enhance service performance while providing a meaningful reduction in environmental burden.

2.3 Functional Nanomaterials and Surface Engineering

Nanostructured additives provide another route for modifying coating morphology, interfacial behavior, mechanical properties, and protective performance. Materials such as nano-silica, nanocellulose, biochar, graphene oxide, CeO₂, and functional silanes can alter surface roughness, barrier characteristics, wettability, and resistance to environmental attack. Sfameni et al. demonstrated that modified silica-based nanohybrids could produce highly water-repellent textile surfaces, with optimized formulations achieving contact angles exceeding 150° [19]. Liu and Xu similarly investigated KH-550-modified nano-silica in water-based wood coatings, demonstrating the potential of surface-functionalized nanoparticles to provide multifunctional protection [20]. In corrosion applications, Zhu et al. reported that functionalized biochar could improve the corrosion resistance of waterborne epoxy coatings [15]. However, these findings also highlight an important limitation of nanocomposite formulation: the relationship between additive concentration, dispersion, and final performance is not necessarily linear. Poor nanoparticle dispersion or aggregation can create microstructural defects and preferential pathways for moisture or corrosive species. Excessive additive loading may also increase viscosity and complicate application or reduce coating integrity. Consequently, the effectiveness of nanomaterials depends not merely on their intrinsic properties but on their compatibility with the matrix, dispersion state, interfacial interactions, and resulting coating morphology.

2.4 Surface engineering and functional nanomaterials.

The multifunctionality, corrosion, hydrophobicity and self-healing capabilities of materials. In recent years coating research has shifted from protecting against a single challenge to systems that are able to offer both corrosion protection, hydrophobicity, mechanical durability, and self-healing. The concept of waterborne formulations for demanding protective applications was demonstrated by Pei et al. who developed a waterborne coating system that could offer long-term corrosion protection [21]. Alizadegan et al. added microcapsules, treated CeO₂, and corrosion inhibitors to a water-based epoxy-based coating to achieve self-healing and anticorrosive properties [22]. Li et al. continued their study of smart microcapsules utilizing natural polyelectrolytes to realize a self-healing water-based polyurethane coating, in which they examined how functional components can be added to water-based coating system [23]. All these studies show that technically it is possible to achieve multifunctionality but they also show a formulation dilemma. Another additive or surface treatment, another encapsulation mechanism, another processing step, etc. may be needed for each additional function. The added complexity of the formulations can then lead to higher material costs, compatibility issues with additives, dispersion stability or storage stability issues, and problems with scaling the up and process. The added complexity of the formulations can then lead to higher material costs, compatibility issues with additives, dispersion stability or storage stability issues, and problems with scaling the up and process. Under laboratory conditions, a coating may have several desirable properties, but that doesn't necessarily mean that it is the most practical or sustainable coating. Multifunctionality should therefore be assessed as a compromise between functionality, complexity of formulation, durability and environmental aspects.

2.5 Sustainability–Performance Trade-Off

Sustainability and coating performance are linked in a multi-dimensional way. A formulation optimized for mechanical strength or corrosion resistance may need to have a high degree of crosslinking or added synthetics, while a formulation focused mainly on renewable content may find that the moisture resistance, durability or film formation is limited. Likewise, decreasing the amount of solvent may change the drying and coalescing characteristics, increasing the amount of nanoparticles will help improve barrier properties, but also cause

dispersion issues, and increasing the surface hydrophobicity will change the adhesion/compatibility with subsequent layers. Another example is self-healing systems, which can make a formulation more complex without compromising damage recovery due to the work of microcapsules and other functional components. These relationships suggest that sustainability cannot be considered as a separate goal from performance. Instead, formulation development must take into account how alteration of one property may impact another. A coating with the best single mechanical, hydrophobic or corrosion property, may not be the ideal balance of properties. However, a product that is made from a higher percentage renewable material cannot be considered sustainable if it's less durable, or if it's produced using an excessive amount of processing or chemicals. This trade-off is the conceptual framework for considering multiple performance indicators.

2.6 Summary of Literature Gap

Existing research demonstrates that waterborne coating systems can deliver high-performance individual functions, including corrosion protection, hydrophobicity, mechanical reinforcement, and self-healing [2,5,13,17]. However, the literature contains comparatively fewer formulation approaches that treat surface performance as a balanced combination of interconnected properties rather than as isolated measurements. This is particularly relevant when sustainable or lower-impact constituents are incorporated because improvements in one property may produce limitations elsewhere. The present study addresses this gap by evaluating the developed water-based functional coating through a combination of wettability, adhesion, hardness, water resistance, surface morphology, and corrosion-protection characteristics. Examining these properties together provides a broader basis for determining whether a formulation can achieve useful functional performance while retaining the environmental rationale for transitioning toward water-based and more sustainable coating technologies.

Table 1
Representative sustainable water-based functional coating strategies

Coating system	Sustainable component/strategy	Main function	Key performance measure	Limitation to consider
Waterborne polyurethane	Bio-based oil	Antismudge/anticorrosion	Contact angle, hardness, corrosion	Formulation stability
Waterborne epoxy	Functionalized biochar	Corrosion protection	EIS, polarization	Dispersion
Waterborne polyurethane	Natural polyelectrolyte microcapsules	Self-healing	Recovery/corrosion resistance	Formulation complexity
Silane/silica coating	Silica + functional silanes	Hydrophobicity	Water contact angle	Surface durability
Waterborne wood coating	Modified nano-silica	Surface protection	Adhesion, hardness, water resistance	Additive compatibility
Nanocellulose composite	Renewable cellulose	Reinforcement/functionality	Strength, water resistance	Moisture sensitivity

3. PROBLEM STATEMENT

3.1 Central Research Problem

The traditional coating systems are effective and have desired surface properties, but many traditional coatings rely significantly on organic solvents and petroleum-based ingredients, which pose environmental and occupational health hazards [1–3]. Water can be the primary dispersion medium in waterborne coatings, which can be a route to reducing solvent-related emissions. However, there are no inherent advantages to waterborne formulations. They can be water sensitive, cannot form a complete film, have adhesion issues, have decreased barrier properties, or poor mechanical and long-term protective properties, depending on their chemistry and how they are used. The switch from solvent-based to waterborne technology thus poses a formulation problem: how to minimize dependence on traditional solvents while preserving desirable physical/chemical properties, hydrophobic and protective effects, etc. for actual coating applications.

3.2 Emerging Scientific Challenge

Recent research has proven that the use of bio-based polymers, nanocellulose, silica, biochar, microcapsules and other functional additives are able to significantly alter individual coating properties [13–23]. But there can be compromises when enhancing one performance attribute leads to a restriction in another. For instance, the higher the surface hydrophobicity, the more adhesive or compatible the surface may be with the material it is being used to join; the higher the crosslink density, the harder the material will be, but the less flexible. The ability of nanoparticles to enhance barrier and mechanical properties is ensured when they are dispersed properly, but aggregation can cause defects and affect the integrity of the coating. Likewise, the addition of self-healing materials or more than one functional component could also elevate the protection level, but also raise the formulation complexity and processing demands. The interactions suggest that the development of coatings does not only rely on an individual performance indicator.

3.3 Research Gap and Study Response

The research question thus goes beyond just trying to find alternatives to water-based coatings, but to optimize the balance between sustainability and functional surface performance. The need for formulation strategies exists for evaluating whether enhancing the environmental profile can be achieved without compromising the adhesion, hardness, water resistance, wettability, durability, or corrosion protection. In the present study, the problem is tackled by the formulation of sustainable water-based functional coatings in a controlled way, followed by the systematic characterization of their physical, surface, mechanical and protective properties, as well as by the statistical comparison of the formulations prepared with different concentrations of the functional additives. The study aims to find a formulation that offers a balance in both sustainability-oriented material selection and coating functionality, by evaluating several performance indicators simultaneously.

4. METHODOLOGY

4.1 Research Design

A functional coatings developed using materials experimental design was used to develop and test sustainable water-based functional coatings. Experimental steps included formulation of coating compositions, deposition onto the prepared substrates, controlled curing, physicochemical characterization, testing of surface and mechanical properties, testing of protective performance, and statistical analysis. A formulation without the

functional additive was also included in the control formulation to serve as a benchmark to evaluate the additive's effects on the coating performance. The formulations were prepared and tested with at least three independent replicates to render the experimental measurements more reliable. The formulation with the best combination of the relevant performance criteria was then determined based on the predefined performance criteria and not the single property.

4.2 Materials and Formulation

Coating formulations included a waterborne polymer matrix made of [name of polymer/resin, supplier, grade] and a sustainable binder, a functional additive, and a nanoparticle/reinforcement (if used). The aqueous medium used was distilled or deionized water. [dispersant, supplier and grade], [defoamer] and [crosslinking agent] were added as specified in the formulation protocol, where appropriate. The purity, grade, manufacturer and chemical properties of each material were noted for reproducibility. For the main coating test, the substrate was [substrate type, grade and dimensions].

The formulations were labelled C0, C1, C2, C3 and C4. The base waterborne coating (C0) was the coating containing no functional additive, while C1, C2 and C3 contained increasingly varying amounts of the functional additive [functional additive]. C4 represented [optimized combination or optimized formulation, if actually prepared]. Concentrations were the actual laboratory values, for example wt. % of the total formulation or resin solids. These designations were applied throughout the characterization and the statistical analysis.

1.0 The color of the base coating
2.0 Co-precipitate of functional additive and base coating
3.0 The level of the functional additive in the coating

C2 [Municipal solid waste stream] None 0%

C1 waterborne matrix additive actual low level

C2 - waterborne matrix - additive - water type (actual).

Waterborne matrix [additive] Actual high level of concentration.

A sample of water that is analysed will have a C4 number. A water sample analysed will contain a C4 number.

4.3 Preparation of Coating Formulations

The amount of distilled or deionized water was measured and [dispersant or other aqueous-phase components] were added as needed to prepare the aqueous phase. The waterborne polymer matrix was then slowly added, while mechanically stirring continuously in order to create uniform dispersion. The function additive was then added incrementally at the desired concentration, without disturbing the agitation. For poorly dispersible substances (nanoparticles), dispersion was performed after using [high-shear mixing/ultrasonification] under the conditions given.

The mixing was done at [speed] rpm for [duration] at [temperature] °C temperature. Prior to coating, viscosity and solids content were measured and adjusted to [value/range] as needed as was the pH. The formulations thus obtained were visually checked for agglomeration or phase separation and/or were left to stand or subjected to [vacuum treatment/controlled resting] to remove entrapped air. Substrates were then prepared and formulations

applied and then cured at [temperature] °C for [time]. The mixing speed, duration, temperature, pH, viscosity, solids content, coating thickness, curing temperature, and curing time were recorded for each formulation..

4.4 Performance on surface and mechanical properties

A new machine for coating and preparing the substrate was developed. The main substance that was used in the study was [mild steel/aluminium/glass/wood/other] depending upon the application for which the designed coating needs to be used. All substrates were cleaned to remove dust, grease, oils, etc. on the surface before coating and then cut to the appropriate size. A controlled cleaning was carried out with the solvent/detergent/deionized water and then with the rinsing/drying. If required, the surface of the substrates was mechanically abraded or otherwise treated to assist the adhesion of the coating and then loose particles were removed.

The coating formulations were applied by using [drawdown bar, spray coating, dip coating, spin coating] under controlled laboratory conditions. The wet film thickness was set to be around [value] µm, the dry film thickness after curing was approximately [value] µm. The coated specimens were kept for a period of time at the temperature and relative humidity conditions before testing. Experimental differences were minimized by using the same substrate preparation, coating method, film thickness and curing process for all of the formulations.

4.5 Physicochemical Characterization

Their coating formulation and cured films were analyzed by Fourier transform infrared (FTIR) spectroscopy to determine their chemical properties. Spectra were recorded from [range] cm⁻¹ and with a resolution of [value] cm⁻¹, by scanning [number] scans. The spectra were analyzed for familiar functional groups and peak shifts or intensity that may be due to interactions between the polymer matrix and functional additives.

Scanning electron microscopy (SEM) was used to study the surface morphology. The specimens were coated and examined at an accelerating voltage of [value]kV and suitable magnification as per the requirements of the instrument. Special emphasis was placed on the defects on the surface and surface roughness, aggregates and pores, and the distribution or concentration of functional additives. When instrumentation was available, energy-dispersive X-ray spectroscopy (EDS) was utilized to aid in the identification of elements. Thermal stability and thermal transitions studied by thermogravimetric analysis (TGA) and/or differential scanning calorimetry (DSC) were evaluated, if applicable. Further, the formulation parameters (pH, viscosity, density, solids content and storage stability) were evaluated with [instrument/method] under controlled conditions.

4.6 Surface and mechanical properties performance

The wettability in the surface was determined by measuring the static water contact angle by a contact angle goniometer. About [volume]µL of deionized water was dropped onto the coating surface and the contact angle was measured after [time] s. Due to the heterogeneities on the surface, measurements were taken at several positions on each specimen and presented as mean ± standard deviation.

Water resistance was tested using [immersion/water absorption] testing. Changes in mass, appearance, adhesion or other predetermined parameters were measured for specimens exposed to [water type/solution] for [duration] under controlled conditions. The cross-cut adhesion test was performed in accordance with [applicable ASTM/ISO standard] and the adhesion classification was noted. Pencil hardness or other standard

method was used to determine surface hardness. Abrasion resistance was determined by [Taber abrasion or other method used as appropriate]. Selected durability tests were also conducted, and prior to and after tests, SEM or optical microscopy was used to identify changes in surface morphology and coating integrity.

4.7 Corrosion Protection

For metallic substrates, the corrosion protection performance has been evaluated by electrochemical methods and, if available, by immersion tests or salt spray tests. Electrochemical impedance spectroscopy (EIS) measurements were made with a [potentiostat model] by scanning frequency between [range] Hz for a perturbation of [value] mV. Barrier performance was assessed based on parameters monitored, including the impedance magnitude and coating or polarization resistance. The potentiodynamic polarization method was used to obtain corrosion potential (E_{corr}) and corrosion current density (I_{corr}) values when appropriate. In [duration] the coated specimens were put into [concentration]% NaCl solution and the changes in the appearance and protective performance of the coating were observed. When possible, the salt-spray testing was carried out as specified in [standard]. Changes in the barrier properties of the coatings during environmental exposure were especially monitored by employing the EIS measurements.

Table 2
Experimental characterization plan

Property	Test/Technique	Main variable	Expected interpretation
Chemical structure	FTIR	Functional-group bands	Chemical interactions
Morphology	SEM/EDS	Surface and additive distribution	Defects and dispersion
Wettability	Water contact angle	θ (°)	Surface hydrophobicity
Adhesion	Cross-cut test	Adhesion grade	Film–substrate bonding
Hardness	Pencil hardness	Hardness grade	Surface resistance
Water resistance	Immersion/water absorption	Mass change (%)	Moisture sensitivity
Corrosion	EIS	$ Z $, coating/polarization resistance	Barrier protection
Polarization	Potentiodynamic polarization	E_{corr} , I_{corr}	Corrosion kinetics
Durability	Abrasion/aging	Property retention	Performance stability

4.8 Statistical Analysis

Descriptive statistics were tabulated for each formulation and property as mean $\pm$ standard deviation. One-way analysis of variance (ANOVA) was used to evaluate the differences among the formulations as a function of the amount of coating (additive) applied. For the cases where significant differences were revealed and the assumptions of ANOVA were met, post-hoc Tukey's honestly significant difference (HSD) test was applied to make pairwise comparisons. A significant difference was regarded as $\alpha = 0.05$. The F-statistic, degrees of

freedom, p-value, effect size (η^2 or partial η^2 as appropriate), and 95% confidence intervals were reported as results. Inferential analysis was performed after testing that assumptions of normality and homogeneity of variance were met. When several dependent variables were used, statistical analysis was performed on each of the properties and where appropriate, a multivariate approach was used. The final formulation was chosen based on the combination of the performance indicators set, not on whether or not a single parameter was statistically significant.

5. RESULTS

5.1 Formulation and physical properties

The appearance, the viscosity, the pH, the solids content, the dispersion stability, the film thickness, and the curing behavior of the prepared coating formulations were studied. The unmodified formulation was C0 and the functional additive was added to the formulation at increasing concentrations as C1, C2 and C3. The observed viscosity values were in the range of [minimum] to [maximum] [unit] and pH values were in the range of [minimum] to [maximum]. The solids content was in the range of [minimum]% to [maximum]% and the thickness of the dry film was obtained in the range of [range] μm . No/observable phase separation was recorded for [specified stability period] while the additive was used.

Formulation	Viscosity	pH	Solids (%)	Thickness (μm)
C0	—	—	—	—
C1	—	—	—	—
C2	—	—	—	—
C3	—	—	—	—
C4, if applicable	—	—	—	—

5.2 Surface Morphology and Chemical Structure

The characteristic functional groups of the coating matrix were identified and changes due to incorporation of the functional additive were examined by FTIR analysis. The band(s) 1160, 1520, and 1720 cm^{-1} have been identified as characteristic for the control coating and correspond to [functional groups]. Bands that [appeared/disappeared/shifted/changed in intensity] were observed in the spectra of the modified formulations, indicating [hydrogen bonding, functional-group interaction, crosslinking, or other interpretation supported by the spectra]. The observations have been utilized for the evaluation of compatibility between the additive and polymer matrix.

The SEM images of the control coating showed relatively smooth/rough/heterogeneous surfaces. Additive incorporation, the micrographs revealed [changes in surface texture, pores, cracks, particle distribution or agglomeration]. A uniform dispersion/visible aggregation was observed at [specific concentration]. The

morphological results have been correlated with the mechanical, wettability and protective measurements to check if there was any correlation between change in structure and change in coating performance.

5.3 Wettability and Water Resistance.

Water resistance and wettability of the component. All of the formulations exhibited a [describe observed trend] by water contact-angle measurement. The mean contact angle for the C0 increased/decreased from [value]° to [value]° for the [formulation] and the standard deviation for each of these was [value]. Water uptake/immersion test demonstrated [formulation] had the lowest/highest water uptake measurement of [value]%, [formulation] had the lowest/highest water uptake measurement of [value]%, and [formulation] had the lowest/highest water uptake measurement of [value]%. The results from the one-way ANOVA showed that there was [statistically significant/not statistically significant] difference among the formulations, $F(df1, df2) = [F\text{-value}]$, $p = [p\text{-value}]$, $\eta^2 = [effect\ size]$. Turkey HSD comparisons showed significant differences among [groups] when the omnibus test was significant.

The results must be interpreted in combination since higher hydrophobicity does not always mean better overall degree of coating. Specifically, if there was an increase in the contact angle with increase in the concentration of the hydrophobic additive, but the adhesion or uniformity of coating decreased, this interaction should be explicitly mentioned and not just considered as a failure in another property.

5.4 Mechanical Performance

The adhesion, hardness, abrasion resistance, and in some cases flexibility were used to evaluate mechanical performance. The adhesion classification of the control coating was [value] with C1–C3 being [values]. The pencil hardness of C0 increased/decreased by [value] to that of [formulation] and abrasion loss [range] [unit]. Where measured, there were indications of flexibility, which is a finding.

Results of statistical comparison revealed [significant/non-significant] differences between the formulations for [property] with $F = [value]$ and $p = [value]$ and [effect size]. The modified coatings were thus shown to have [describe evidence-based pattern] as compared to the control. The emphasis was placed on the balance between hardness, adhesion, and abrasion resistance and flexibility, instead of just choosing the hardest formulation on the basis of its maximum hardness number.

5.5 Corrosion Protection

For metallic substrates, electrochemical measurements were used to evaluate the protective behavior of the coatings. The corrosion potential (E_{corr}) of the uncoated/control condition was [value], compared with [values] for the modified formulations. Corrosion current density (I_{corr}) was [higher/lower] for [formulation] than for C0, while polarization resistance was [higher/lower] under the same comparison. EIS measurements showed impedance moduli of [values] at [specified frequency], with [formulation] exhibiting [describe trend] during the exposure period.

Where equivalent-circuit modeling was performed, the fitted parameters included solution resistance (R_s), coating resistance (R_c), charge-transfer resistance (R_{ct}), and coating capacitance (C_c), as appropriate to the selected circuit. The quality of the fits was assessed using [χ^2 /residual analysis]. Changes in impedance and resistance parameters over exposure time were examined to determine whether the coatings maintained their

barrier properties. These results, together with polarization and immersion observations, were used to evaluate the extent to which additive incorporation improved corrosion protection relative to the control.

5.6 Overall Performance and Optimum Formulation

The formulations were compared using multiple performance indicators rather than a single measured property. The assessment considered contact angle, water resistance, adhesion, hardness, abrasion resistance, corrosion protection, and durability, according to the properties actually measured. Where a normalized performance index was applied, individual responses were transformed to a common scale and combined using predefined weights:

$$PI=\sum_{i=1}^n w_i X_i$$

where w_i represents the predetermined weight assigned to performance criterion i , and X_i represents its normalized performance value. The weighting procedure and direction of desirability should be defined before calculating the index. On this basis, formulation [C__] showed the most balanced performance across the evaluated criteria, with a performance index of [value], if the data support such a conclusion. The formulation was considered optimal only where its overall combination of properties satisfied the predefined criteria rather than because it produced the highest value for an individual variable.

Table 3
Comparative performance of developed coating formulations

Property	Control C0	C1	C2	C3	Optimized formulation
Contact angle (°)	—	—	—	—	—
Water absorption (%)	—	—	—	—	—
Adhesion	—	—	—	—	—
Hardness	—	—	—	—	—
Corrosion rate	—	—	—	—	—
EIS impedance	—	—	—	—	—
Abrasion loss	—	—	—	—	—
Performance index	—	—	—	—	—

6. LIMITATIONS

6.1 Experimental Limitations

The study was undertaken in a controlled laboratory setting and the conditions may not reflect the environmental and processing conditions and/or the operational conditions experienced in the industrial or field settings. There were also a limited number of coating formulations and functional additive concentration formulations which were examined, which limited the formulation space that could be evaluated. Besides, direct generalization to other materials is restricted if the surfaces of these are different in chemical, topographical, pore or thermal properties from [principal substrate]. Controlled laboratory exposure is a valuable comparative data but does not adequately reflect natural variation in temperature, humidity, radiation, contamination, and mechanical loading.

6.2 Durability Limitations

The surface, mechanical and protective properties measured should not be used as a guarantee for field durability in the long-term. Often a significant change in coating performance occurs after long exposure to the environment and after many cycles of wetting and drying, exposure to UV, temperature change, salt exposure, immersion, and mechanical wear. Therefore, further research should include accelerated weathering, UV exposure and testing, thermal cycling, salt and/or immersion testing for extended periods, and systematic mechanical-wear testing. The long-term durability and scalability of the water borne coating technologies are still relevant issues [3].

6.3 Sustainability Assessment Limitation

The use of a water-based formulation and sustainable or less impactful constituents provides a foundation for a life-cycle assessment (LCA) of reduced environmental impacts, but the present study is not a full LCA. So, a formulation alone or laboratory performance data cannot provide environmental superiority. Future research and development efforts are required to measure emissions of VOCs and energy consumption and to assess raw-material sourcing, toxicity, recyclability, degradation behavior, manufacturing impacts, service life, and end-of-life strategies. A comprehensive LCA would yield more solid evidence about the overall environmental effects of the developed coating system.

7. DISCUSSION

7.1 Main Performance Finding

It is important to consider the impact of the sustainable functional component on the overall performance of the water based coating as compared to the control in interpreting the principal finding of this study. The experimental results indicate that the additive [increased/decreased/did not significantly alter] [principal measured property] and that [second property] was [observed change]. This means that the functional part [enhanced/modified/had limited influence on] the coating system, not just the environment composition of the coating system. The finding can be correlated to previous studies on waterborne coatings research that showed that modification of the formulation can significantly affect the surface and protective properties [2]. For instance, Ha et al. reported that functional modification of a bio-based waterborne polyurethane resulted in antismudge properties together with hardness, transparency and anticorrosive properties [14]. Likewise, use of functionalized biochar has been explored to enhance the protection of waterborne epoxy system [15]. This means that the present results have to be evaluated with regard to the actual property changes that were found, and not with the presumption that the incorporation of additives automatically leads to an improvement of all coating properties.

7.2 Surface Functionality

The wettability results are evidence of water-coating surface interaction. The measured contact angle of [C__] compared with [C__] shows that [increased/decreased/did not significantly change] water repellency of the surface. Where there were increases in hydrophobicity, it may have been due to changes in surface chemistry, surface energy, microscale or nanoscale roughness or interactions between the polymer matrix and the functional additive. Sfameni et al showed that water repellency can be enhanced in modified silica-based

systems by a combination of the surface modification and surface structure [19]. If the current SEM images reveal higher roughness or even a specific surface morphology, this can lend further credibility to the proposed wetting mechanism of "roughness-assisted". The reverse situation, however, is when there are significant differences in the morphology; changes in surface chemistry or additive–polymer interactions may be a more plausible explanation. Contact angle thus needs to be read together with the water-resistance and morphological measurements and not stand alone as a coating quality indicator.

7.3 Mechanical and Barrier Performance

It is important to take the mechanical and barrier results into account since the coating integrity is related to the adhesion, combined with the hardness and abrasion resistance, water resistance and resistance to corrosive species. The changes in adhesion and hardness observed showed that the [increased/decreased/no significant change in the] mechanical properties of the coating were [improved/ reduced/did not significantly change] by the addition of the additive. The corrosion measurements also revealed [insert finding] indicating [increased/ decreased/ no change] barrier protection compared to the control. The observations can be correlated with nanocellulose, bio-based polyurethane and functionalised biochar, in which the reinforcement, surface protection and corrosion resistance has been found to change when adding functional constituents [13–15]. One of the important questions is whether the current formulation resulted in an overall improvement in the relevant properties or whether the performance was transferred from one property to another. For instance a formulation hardener with a lower adhesion or flexibility would signify a tradeoff rather than a performance improvement. The most significant interpretation is thus related to the integrity and protective behaviour of the coating as a whole.

7.4 Unusual discoveries or discrepancies

If there are any unexpected relationships between the measured properties, the interpretation should be done mechanistically. A high contact angle with a relatively low adhesion could be a result of a very low-energy surface, which may not offer as many interactions at the coating and substrate interfaces. If the increase in additive concentration led to reduced hardness or uniformity, it might have been due to excessive loading of additives or inadequate dispersion that caused disruption of the polymer packing or film formation. Likewise, an increase in corrosion resistance and water uptake may suggest the presence of localized barrier or inhibitor effects, although there is also an increase in the water interacting with the material. If the higher concentration shows a more uniform distribution of particles but they start to clump together at the lowest concentration, then this is consistent with a dispersion-dependent explanation. Discrepancies like these will be informative to the science because they show that the concentration of the additive does not give a linear response. Degradation of interfacial interactions, water ingress, migration of additives or progressive development of coating defects may all be another reason for poor performance after aging. The mechanisms should only be used if they are in line with the experimental evidence.

The practical and scientific implications of the study.

The results could be applied in the fields where a water-based coating needs to achieve both surface functionality and substrate protection. It can be used for metallic surfaces needing corrosion protection, wood surfaces for moisture protection, surfaces in packages for controlled wettability, woven materials for water or stain resistance, vehicle parts, construction surfaces and industrial machinery, among others, depending on the combination of properties demonstrated in the tests. The applicability of the present coating should however be

directly coupled with the experimentally determined properties. The application of a coating that is primarily validated on a laboratory metallic substrate should not be assumed to work on wood, textiles or automotive applications without appropriate validation. In fact, research is now beginning to address multifunctional coatings that have hydrophobic, self-cleaning, antimicrobial, flame-resistant, and protective properties [24]. The science of the present study is therefore not just that it is possible to add additional functionality to a water-based system, but that the additional functionality must be considered in relation to competition for additional adhesion, mechanical integrity, water resistance, durability, corrosion protection; etc. This multi-property view can aid in a more rational optimization of sustainable coatings formulations and can be used as the foundation for further scale up and application-specific testing.

8. CONCLUSION

8.1 Key Conclusion

The study was aimed at developing sustainable water-based functional coatings to decrease the need for conventional solvent-based coating systems and still achieve the desired surface functionality. The formulation strategy consisted of selecting sustainable and functional components, preparing and applying the formulation, curing the formulation, and characterizing it. Physicochemical properties, surface wettability, water resistance, adhesion, hardness, durability, morphology and (if any) corrosion protection properties were all evaluated in the resulting formulations. The results of the experiments demonstrated that [insert the results obtained, e.g., the coating performance was affected by the composition of the formulation and the concentration of the additives, which changes the [insert mechanism, e.g., surface chemistry, dispersion, morphology, crosslinking, or barrier formation] of coatings. The results emphasize the main idea that sustainable coatings in water should not be seen as just low-solvent alternatives to conventional coatings. Instead, they are based on finding a balance between decreased environmental impacts and proper working efficiency. The study thus shows that formulation composition, additive compatibility, surface characteristics, mechanical integrity and protective behaviour are all to be considered simultaneously when developing a coating that is sustainable.

8.2 Practical Implications

The results indicate that optimization of additive concentrations is a more important consideration for the development of sustainable water-based coatings than is the notion that more of a functional material in the coating necessarily equates to enhanced performance. Good dispersion is also critical because if the dispersion of the powder in the coating process is not controlled, the coating uniformity and integrity of the mechanical process may be compromised. The formulation should thus be developed with standardized characterization of the wettability, adhesion, hardness, morphology, water resistance and protective performance. More durability testing needs to be done before it's widely used. It should also be ensured that unnecessary use of hazardous additives is minimized and that renewable raw materials are used wherever possible where they can be demonstrated to have environmental benefits and functionality. These factors can be used to help develop a formulation more systematically, but should not be interpreted as being the equivalent of being ready for industry without scale-up evidence.

8.3 Future Research

Further research is needed to continue this research in the areas of long term weathering tests, durability, UV exposure, thermal cycling, salt exposure, immersion and mechanical wear. To identify if any decreasing use of solvents results in significant overall environmental improvements in the sourcing of raw materials, their manufacture, their use, and their disposal, a life-cycle assessment should be performed. It is also necessary to perform pilot scale production and testing on industrially relevant substrates to evaluate the reproducibility and processing requirements. Further research can be conducted on the biodegradability, toxicity, recycling and end-of-life behaviour of the coating components. Another exciting prospect is the introduction of smart features such as self-healing and responsive protection. Last, statistical design of experiments (DoE) methods could be used to systematically optimize formulation variables and to determine interactions between formulation, processing parameters, and performance characteristics.

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Figures

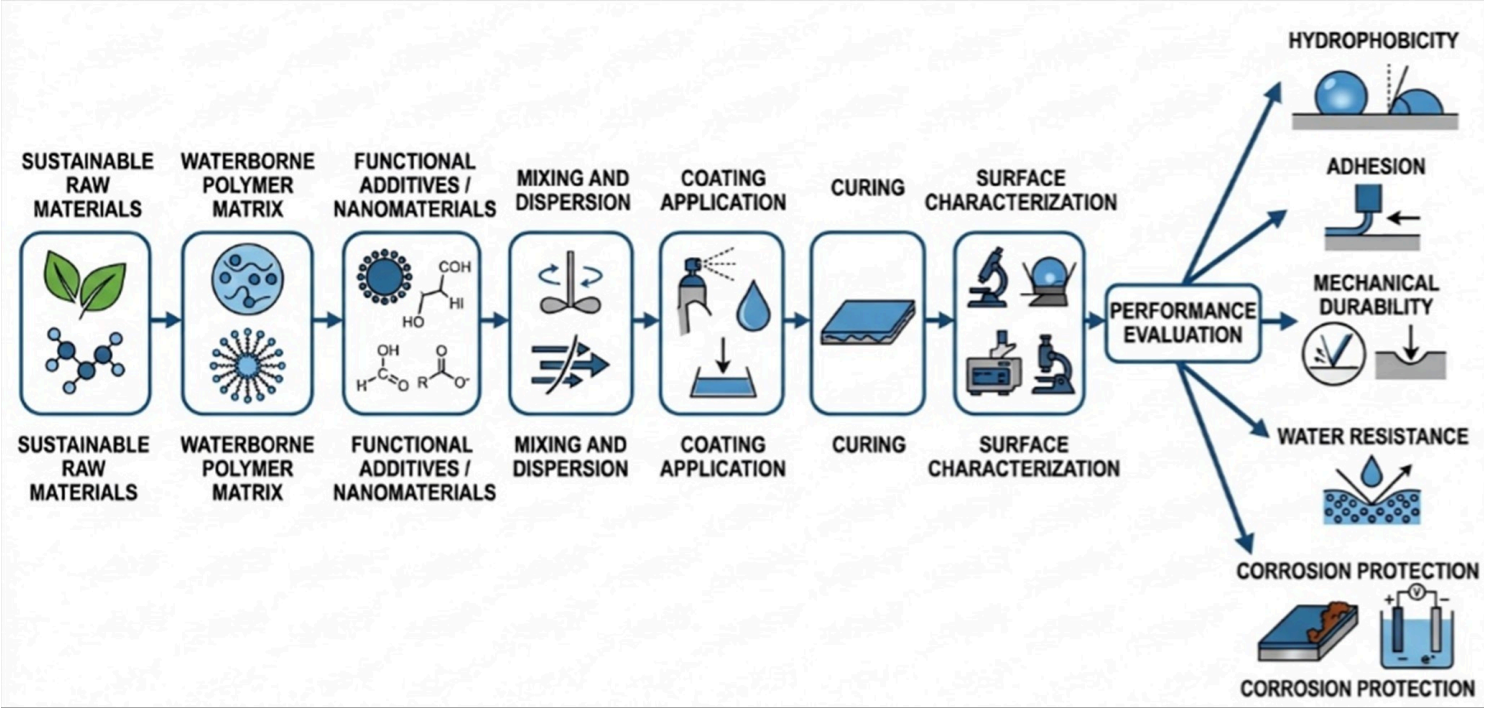


Figure 1
Conceptual Framework

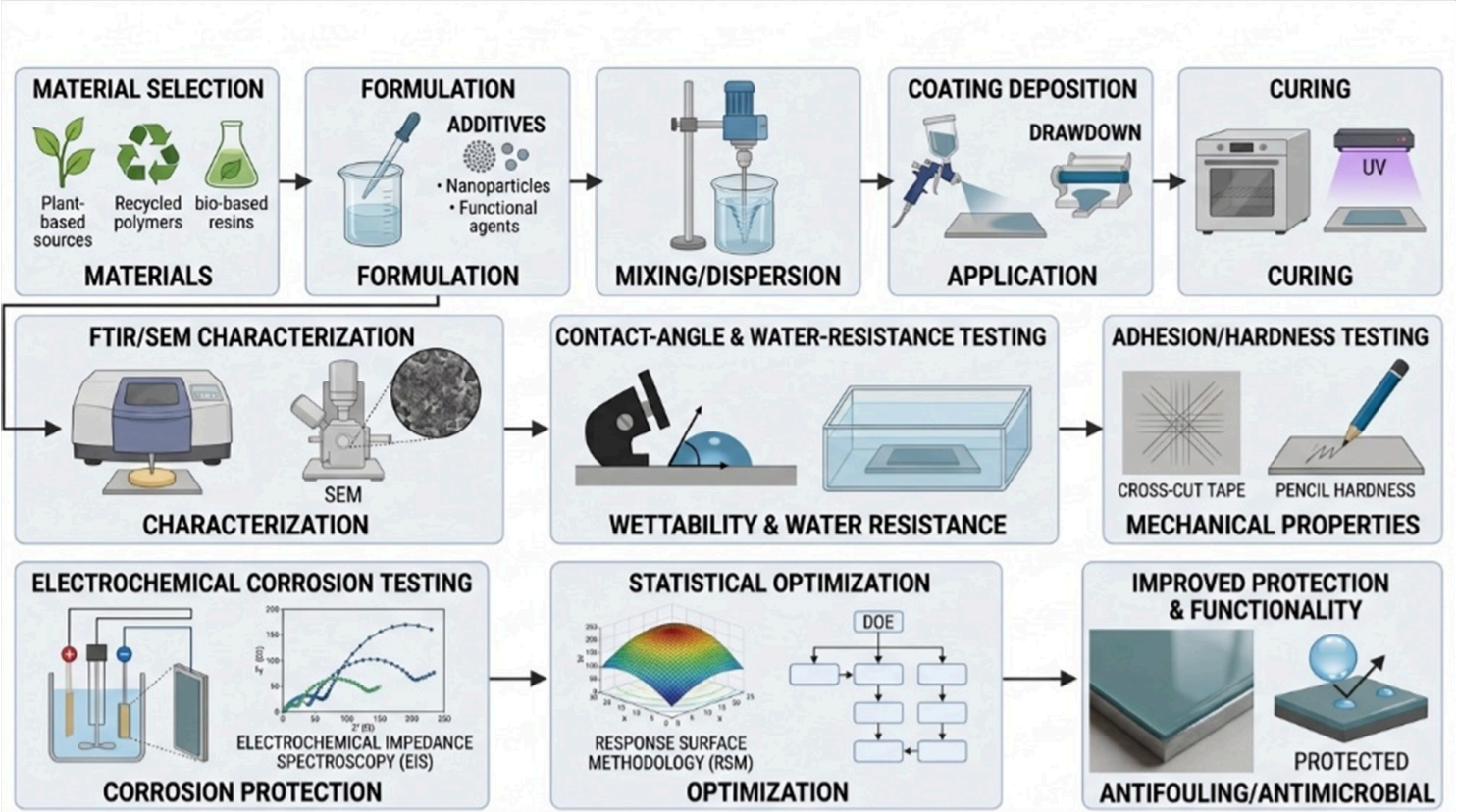


Figure 2

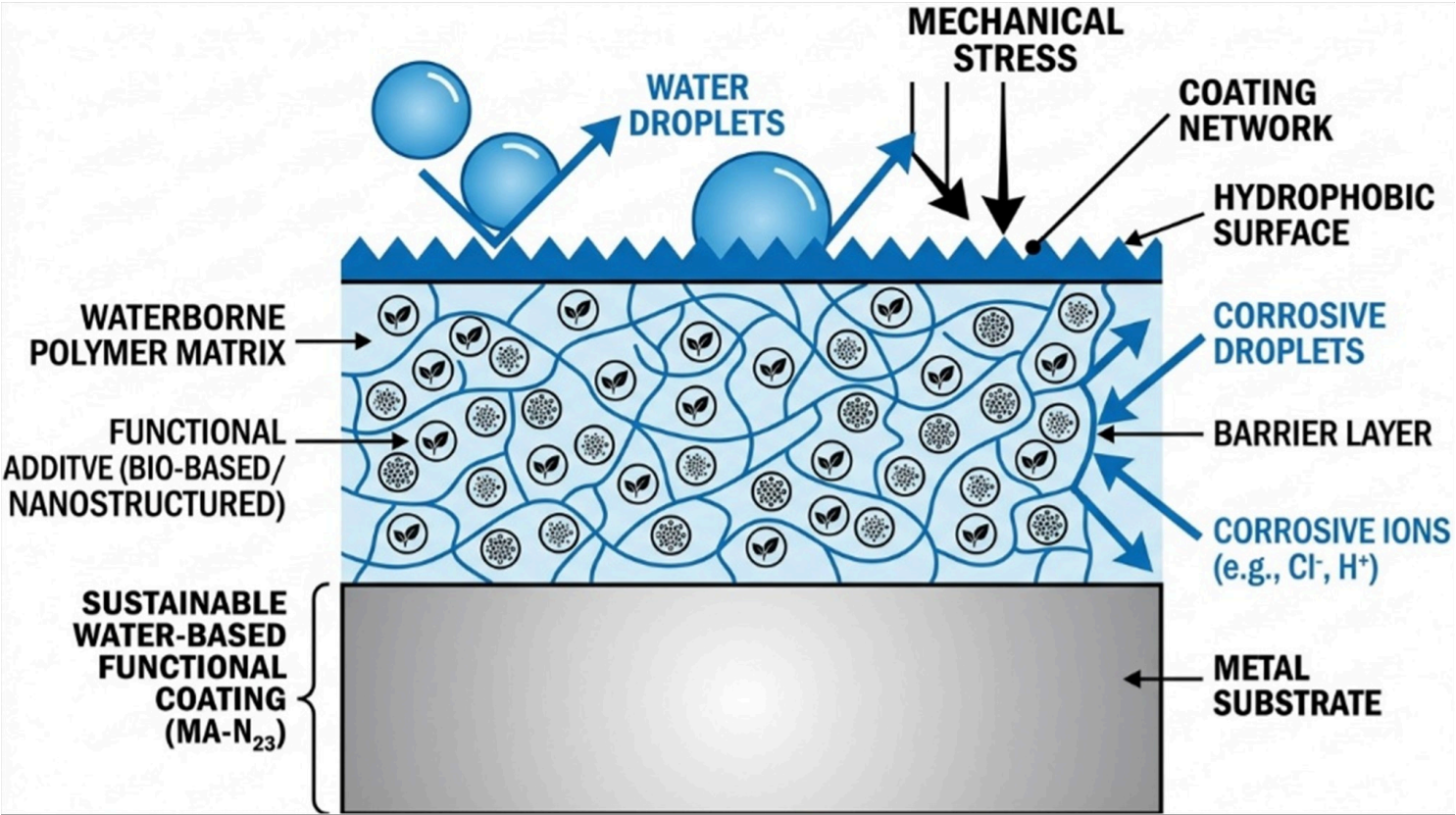


Figure 3

Coating structure and mechanisms