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Nature-Friendly Water-Based Resin Paints with SiO_2 Nanoparticles for Electrostatic Spraying

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ABSTRACT
This study presents an environment-friendly and less toxic approach to electrostatic spraying using novel water-based resin paints enhanced with SiO_2 nanoparticles. Addressing the environmental and health concerns of traditional toxic solvent-based coatings, our research emphasizes the development and application of these paints on anodized aluminum substrates. Our experimental procedure involves formulating water-based paints; applying them via electrostatic spraying; and analyzing their stability, coverage, and adhesion properties. The findings demonstrated that the paints maintained stability and showed improved adhesion and uniformity without using a toxic solvent-based resin, particularly on substrates with extended anodizing treatment. This study highlights the potential of using water-based resin paints in industrial applications, offering a sustainable, efficient, and high-performance alternative to conventional coatings, paving the way for future research into their broader application and environmental impact.

摘要
本研究提出了一种环保、低毒的静电喷涂方法，使用新型的SiO2纳米粒子增强的水性树脂涂料. 为了解决传统有毒溶剂型涂料的环境和健康问题，我们的研究强调了这些涂料在阳极氧化铝基材上的开发和应用. 我们的实验程序涉及配制水性涂料; 通过静电喷涂施加它们; 并分析其稳定性、覆盖率和粘附性能. 研究结果表明，在不使用有毒溶剂基树脂的情况下，涂料保持了稳定性，并显示出更好的附着力和均匀性，特别是在经过长时间阳极氧化处理的基材上. 这项研究强调了在工业应用中使用水性树脂涂料的潜力，为传统涂料提供了一种可持续、高效和高性能的替代品，为未来研究其更广泛的应用和环境影响铺平了道路.

KEYWORDS
SiO2; electrostatic spraying; resin; paint; nanoparticle; nanoscience

关键词
SiO2; 静电喷涂; 树脂; 油漆; 纳米粒子; 纳米科学

Introduction

The sustainable development goals (SDGs) provide a comprehensive framework for addressing global challenges such as climate change, environmental degradation, and resource scarcity (Bashir, Iftikhar, and Majeed 2024; Iftikhar et al. 2024; Majeed and Iftikhar 2024; Majeed, Iftikhar, and Abbas 2024; Majeed, Iftikhar, and Abid 2024a, 2024b; Majeed, Iftikhar, and Abbas 2024; Majeed, Iftikhar, and

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Maqsood 2024a, 2024b; Majeed, Iftikhar, and Mukhtar 2024; Majeed, Iftikhar, and Siddique 2024; Majeed, Iftikhar, and Zohaib 2024; Phiri et al. 2023). Particularly, SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production) emphasize the need for sustainable industrial practices and innovations that minimize environmental impact. Developing eco-friendly materials is crucial to achieving these goals, particularly in the manufacturing and construction sectors where traditional practices often lead to significant pollution and resource depletion. In this context, the creation of nature-friendly water-based resin paints is crucial for achieving SDG.

Electrostatic spraying has emerged as a significant advancement in surface coating techniques, marked by its efficiency and precision (Edward Law 2001; H. Kim, Qaiser, and Hwang 2023; G. Lee et al. 2023; Milić, Marinković, and Ćojbašić 2023, 2023; Rivero et al. 2020; Wang et al. 2021; Y. Zhang et al. 2021). This method uses a high-voltage electrostatic field to induce negatively charged paint particles to migrate toward a positively grounded workpiece, resulting in a uniform coating. The process involves connecting the paint source to a negative electrode and grounding the workpiece. The electrostatic force exerted on the paint particles, influenced by the field voltage and charge of the particles, is inversely proportional to the distance between the spray gun and the workpiece. Notably, high voltages create an air ionization zone near the spray gun tip, which charges the atomized paint particles, directing them uniformly toward the workpiece surface.

Traditionally, electrostatic spraying has relied on liquid coatings containing organic solvents, which pose environmental and health risks due to vaporization during application (Jayaprakash et al. 2023; Purwar et al. 2022; Zhao et al. 2024). These coatings also present challenges in transportation and storage and contribute to environmental pollution by paint wastage and inefficient application processes (Chen et al. 2020; Ha, Müller, et al. 2023; Ha, Qaiser, et al. 2023; Viguri et al. 2005; S. Zhang et al. 2023; Zhou et al. 2021). In response to these issues, and driven by increasing environmental consciousness, there has been a shift toward more sustainable practices in surface coating applications. One such practice is anodizing, an electrochemical process that enhances the surface properties of metals, particularly aluminum (Choi, Qaiser, and Hwang 2024; Hwang, Han, and Matteini 2022; W. Lee and Park 2014; Montero-Moreno, Sarret, and Müller 2007; Paz Martínez-Viademonte et al. 2020; Thames and Theradiyil Sukumaran 2020; Tsangaraki-Kaplanoglou et al. 2006; Wu et al. 2023). Anodizing involves immersing aluminum in an acid electrolyte bath and passing an electric current through it, which results in the formation of a protective oxide layer on the aluminum surface. This layer not only provides corrosion resistance and increased durability but also serves as an ideal base for electrostatically applied coatings, improving adhesion and longevity (Li et al. 2024; Liu et al. 2021; Suryaprabha et al. 2023).

While the development of water-based resin paints and their application via electrostatic spraying have been explored in previous studies, our research introduces several innovative aspects that address existing gaps. Firstly, the incorporation of SiO_2 nanoparticles into water-based resin paints is novel, as it significantly enhances the stability, adhesion, and uniformity of the coatings without relying on toxic solvents. Secondly, our study provides a detailed comparative analysis of traditional and electrostatic spraying techniques, demonstrating the superior performance of the latter in terms of coverage and droplet distribution. Additionally, the exploration of anodizing treatments on aluminum substrates and their impact on the adhesion and durability of the coatings is a unique aspect of our research. These innovations collectively advance the field by offering a sustainable, high-performance alternative to conventional coatings, paving the way for broader industrial applications.

Experimental details

Preparation of water-based paints

In the experimental procedure, the initial step involved the blending of 100 g of styrene-acrylic emulsion (BASF Joncryl 2136) with 50 g of water. This amalgamation was achieved by mechanical stirring at 500 rpm for a duration of 10 min. Subsequently, 5–10 g of silicon dioxide (SiO_2) nanoparticles, characterized by a diameter of 30 nm, were introduced into the aforementioned mixture. The stirring speed was then elevated to 2000 rpm, and this mechanical agitation continued for 1 h. To impart color to the coating, pigments such as blue, red, or yellow, with a concentration of 1 wt%, were incorporated into the mixture. This addition was followed by stirring at 1000 rpm for 10 min. Then, following the nanoparticle and color pigments dispersion process,1 g of a defoaming agent (BASF Foamstar 2213) was incorporated into the mixture, along with 1 g each of a wetting agent (BASF Hydropalat 3475) and a smooth leveling agent (BASF Hydropalat 3682). Mechanical stirring was employed to homogenize these components for 15 min. Subsequently, the mixture was allowed to stand for a minimum duration of 20–30 min to facilitate the defoaming process.

Appendix: Material Data Sheet (MDS) and Safety Data Sheet (SDS)

Material Data Sheet (MDS):

Styrene-Acrylic Emulsion (BASF Joncryl 2136): Chemical Composition: Styrene-Acrylic Copolymer, Physical State: Liquid, Color: Milky white, pH: 8.0–9.0, Viscosity: 100–200 mPa.s, Solids Content: 35–40%.

Silicon Dioxide (SiO_2) Nanoparticles: Particle Size: 30 nm, Purity: >99.5%, Surface Area: 200 m^2/g, Density: 2.65 g/cm^3.

Pigments (Blue, Red, Yellow): Chemical Composition: Varies by color, Physical State: Powder, Color: Varies (Blue, Red, Yellow), pH: 6.0–7.5, Solubility: Insoluble in water.

Additives (Defoaming Agent, Wetting Agent, Smooth Leveling Agent): Chemical Composition: Proprietary blends, Physical State: Liquid, Color: Clear to slightly hazy, pH: 7.0–8.5, Viscosity: 50–150 mPa.s.

Safety Data Sheet (SDS):

Styrene-Acrylic Emulsion (BASF Joncryl 2136): Hazard Identification: Not classified as hazardous, First Aid Measures: In case of contact with eyes, rinse immediately with plenty of water and seek medical advice. Handling and Storage: Store in a cool, well-ventilated area. Keep container tightly closed.

Silicon Dioxide (SiO_2) Nanoparticles: Hazard Identification: May cause respiratory irritation, First Aid Measures: In case of inhalation, move to fresh air and seek medical attention if symptoms persist. Handling and Storage: Avoid generating dust. Store in a cool, dry place.

Pigments (Blue, Red, Yellow): Hazard Identification: Not classified as hazardous, First Aid Measures: In case of contact with skin or eyes, wash with plenty of water. Handling and Storage: Store in a dry place. Keep containers tightly closed.

Additives (Defoaming Agent, Wetting Agent, Smooth Leveling Agent): Hazard Identification: Not classified as hazardous, First Aid Measures: In case of contact with eyes, rinse immediately with plenty of water and seek medical advice. Handling and Storage: Store in a cool, well-ventilated area. Keep container tightly closed.

Electrostatic spraying process

The electrostatic spraying of the prepared water-based paint involved a series of critical steps:

(1) Workpiece pretreatment: Each workpiece was first anodized, followed by degreasing by dip and wash procedures. The workpieces were then rinsed, dried, and cooled below 35°C, preparing them for the spraying process.
(2) Equipment inspection: Before spraying, we comprehensively inspected the paint supply system, recovery system, spray gun, electrostatic controller, and auxiliary systems (including air conditioning and dehumidification) to ensure optimal operation.
(3) Spraying preparation: The pre-treated workpieces were transported to the powder-spraying room via a conveying chain. Dry compressed air was used to clean any accumulated material from the spray gun and the feeding system.

(4) Curing process: After spraying, the workpieces were cured by heating to 200°C and maintaining this temperature for 15 min, which was crucial for the final properties of the paint.

As shown in Figure 1, during electrostatic spraying, the spray gun-to-metal shell distance is controlled within the range of 150–300 mm. The electrostatic spraying voltage is set in the range of 20–90 kV, with an electrostatic current of 10–60 μA. The flow rate pressure ranges from 0.30 to 0.55 MPa, the atomization pressure is maintained at 0.30–0.45 MPa, and the cleaning gun pressure is 0.5 MPa. The fluidized pressure within the ink supply barrel ranges from 0.04 to 0.10 MPa. The conveying chain operates at a speed of 4.5–5.5 m/min, resulting in a paint film thickness of 55–90 μm on the metal shell surface.

Characterization

Field-emission scanning electron microscopy (SUPRA 40VP, Carl Zeiss, Germany) was used to analyze the morphologies of the printed samples at the Jeonbuk National University Center for University-wide Research Facilities (CURF, Jeonju, Korea). A Brookfield digital rotational viscometer (Model DVNXRVCJG, Brookfield Engineering Laboratories, Middleboro, MA, USA) was used to measure the rheological properties of the as-prepared inks with shear rates of 0.1–1000 s^{-1}.

Results and discussion

Figure 2 presents the optical photographs of the as-prepared water-based paints after standing for one month. This visual evidence is crucial in demonstrating the long-term stability of the paint formulation. A key observation from Figure 2 is the absence of particle sedimentation within the polymer matrix solution. The SiO_2 nanoparticles remained uniformly dispersed over an extended period, indicating a high degree of stability. This stability is particularly significant given the common challenges in conventional composites, where nanoparticle settling over time is a recurrent issue. The sustained suspension of nanoparticles within the polymer matrix not only enhances the consistency of the paint but also implies extended shelf life and reliability for industrial applications. Furthermore, Table 1 provides a detailed breakdown of the pH measurements for the water-based paints, both in their pristine form and with varying concentrations of SiO_2 nanoparticles. The pH values ranged from 7.86 to 7.91, as detailed in Table 1. These pH measurements indicate a weakly

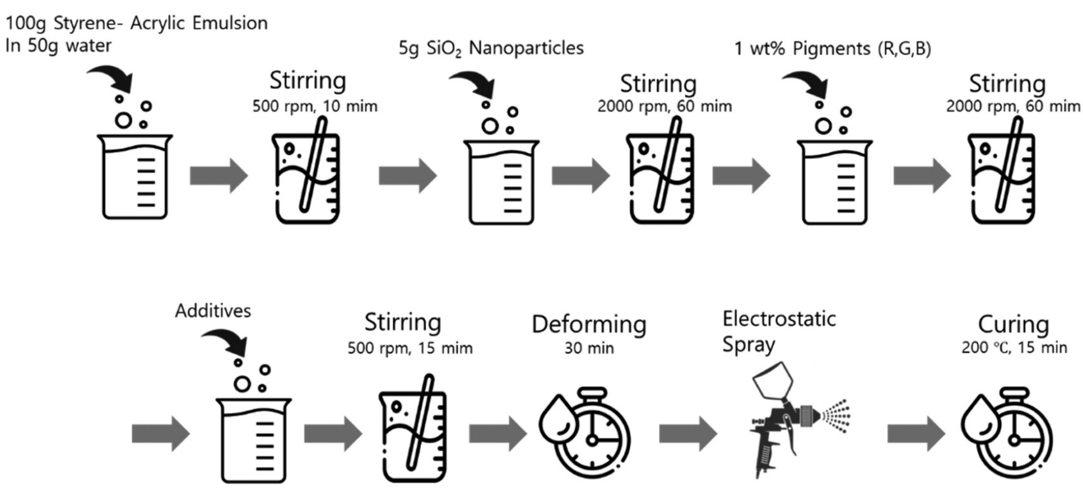

Figure 1. Schematic diagram of the electrostatic spraying process.

Figure 2. Optical photos of as-prepared water-based paints after keeping them standing for one month.

Table 1. The pH of the as-prepared water-based paints.

Sample details	pH
Pristine	7.86
+5% SiO_2	7.89
+10% SiO_2	7.91

alkaline nature of the paints, which is beneficial for prolonged storage. Notably, as the SiO_2 content increased, there was a slight elevation in the pH value. This correlation suggests that the nanoparticle content subtly alters the chemical properties of the paint, potentially affecting its long-term stability and application characteristics. Together, these results validate the effectiveness of our formulation approach in creating a water-based paint that is not only environmentally friendly but also stable and reliable for various industrial applications.

In our experimental process, a significant step was the incorporation of different color pigments into the prepared water-based coatings. We successfully mixed pigments to achieve three distinct paint colors – red, yellow, and blue – as illustrated in Figure 3. This step was crucial in demonstrating the versatility and compatibility of our water-based coatings with various pigments. It revealed excellent compatibility, indicating that these coatings could be tailored to a wide range of aesthetic requirements without compromising their environmental friendliness or performance characteristics. This versatility in color mixing provides a strong foundation for further applications in electrostatic spraying, where color variety and consistency are essential. The successful integration of diverse pigments into

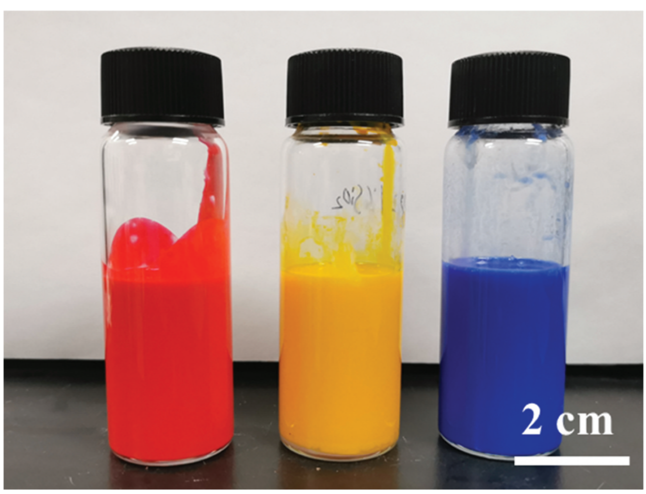

Figure 3. Optical image of as-prepared water-based paints mixed with different colored pigments.

our coatings not only broadens the potential application spectrum but also highlights the practical adaptability of our formulation for various industrial uses.

In our research, we aimed to explore the potential of composite paints with enhanced rheological properties to revolutionize the precision and quality of printed patterns. To achieve a comprehensive understanding of these advancements, we focused on the role of SiO_2 nanoparticle concentration in modifying the rheological behavior of the paints. The primary tool for this investigation was a plate – plate rheometer, which allowed us to measure the viscosity of our paint formulations under various shear rates. These measurements were crucial in assessing the performance of the paints during the printing process. Our findings depicted in Figure 4 reveal a notable trend across all specimens: a decrease in ink viscosity with an increase in shear rate, which is a characteristic behavior of pseudo-plastic fluids. Interestingly, we observed that paints with higher concentrations of SiO_2 nanoparticles exhibited increased viscosities at the same shear rates compared to those with lower nanoparticle contents. This trend was consistent across the different formulations tested, indicating a direct correlation between SiO_2 concentration and viscosity behavior. The rheological behavior observed in our composite paints has profound implications for their application in printing technology. The elevated viscosities at higher SiO_2 concentrations even under varying shear rates suggest that these paints have an enhanced ability to maintain their structural integrity during the printing process. This characteristic is crucial in achieving optimal ink distribution across the substrate surface, which in turn ensures superior leveling in the unprinted areas. Therefore, the incorporation of SiO_2 nanoparticles in the paint formulations not only improves their environmental friendliness but also significantly enhances their printing properties, making them highly suitable for applications requiring high precision and quality in pattern reproduction.

Our experimental approach involved a side-by-side comparison of traditional and electrostatic spraying techniques to evaluate their respective coverage effects and droplet distribution uniformity. Figures 5a,b provide a visual representation of the outcomes obtained under these controlled experimental conditions. The most salient observation from the data is the superior coverage effect achieved by electrostatic spraying compared to traditional spraying. This is evidenced by the more uniform droplet distribution observed in the electrostatically sprayed samples. By contrast, samples obtained from conventional spraying methods exhibited a tendency for droplet coalescence, leading to the formation of larger, uneven droplets. Moreover, Figures 5c,d reveal a distinctive pattern in the water-based paints applied by electrostatic spraying, characterized by a uniform pattern resembling small squares. This unique appearance is a direct consequence of the polarization effects induced by the high voltage applied during electrostatic spraying. The observed polarization effect during electrostatic

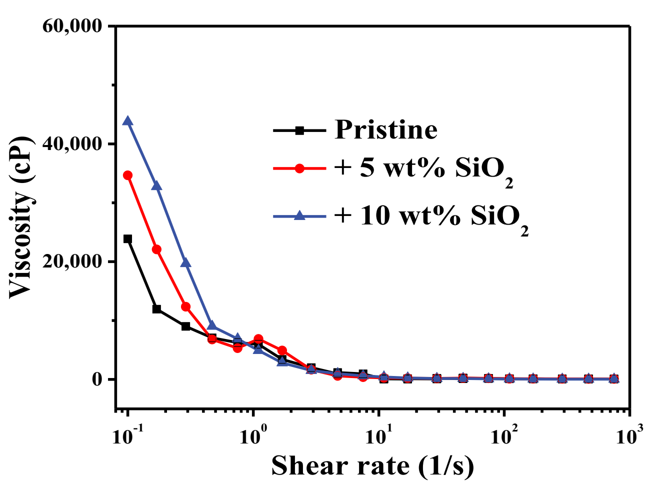

Figure 4. Viscosity of the as-prepared water-based paints.

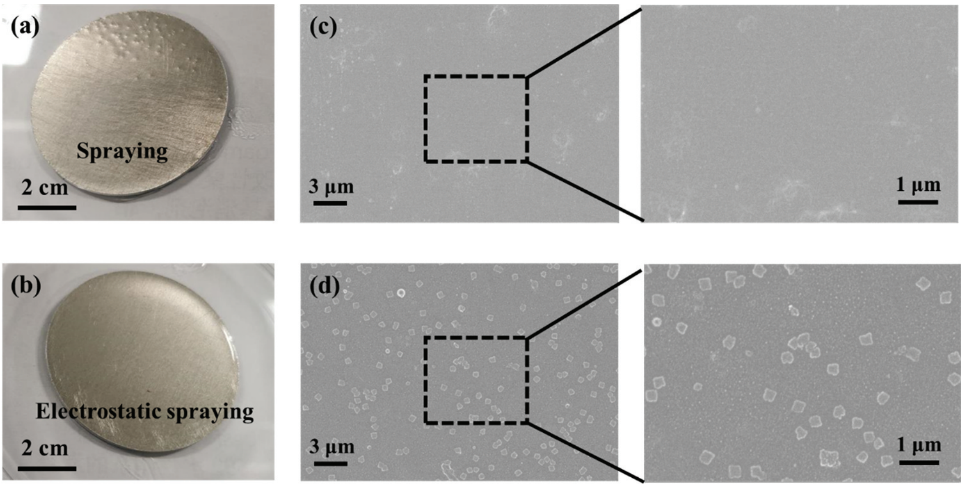

Figure 5. Optical image of samples prepared by (a) traditional spraying and (b) electrostatic spraying. Scanning electron microscopy (SEM) images of the samples prepared by (c) traditional spraying and (d) electrostatic spraying.

spraying leads to the formation of a consistent crystal phase within the coating. The presence of this structured and uniform crystal phase has significant implications for the performance of the coating. Notably, it contributes to improved adhesion properties of the dry film. The cohesive nature of this crystalline structure enhances the adherence of the coating to the substrate, resulting in a more robust and reliable bond (Hakki et al. 2018; H.-S. Kim et al. 2007; G. Zhang et al. 2007). This contrasts sharply with the outcomes of traditional spraying methods, where the lack of such a structured phase can lead to inferior adhesion and less durable coatings.

Anodization, as an electrochemical process, transforms the surface of metallic aluminum into a durable oxide layer with decorative qualities. This is achieved by immersing aluminum in an acid electrolyte and applying an electric current, causing the aluminum atoms at the surface to bond with oxygen, forming an anodic coating. This anodized layer acts as a protective barrier that surpasses the hardness of bare aluminum and offers exceptional resistance to corrosion and weathering. The thickness of the anodized aluminum surface typically ranges from 0.000508 to 0.00254 cm depending on the specific anodizing process employed. Despite its enhanced properties, anodized aluminum maintains the metallic appearance of aluminum, albeit with a glossy, glass-like finish that resists peeling or flaking. To introduce color and further protect the porous oxide layer from wear, various dyes and sealants are applied by companies. Our experimental analysis, visually represented in Figure 6a, focused on the effects of different anodizing treatment durations on aluminum substrates. The results indicated that increasing the duration of the anodizing process led to noticeable changes in the surface properties of aluminum. Longer treatment times were found to create surface irregularities, making the aluminum substrates less smooth. Further elucidation is provided by the scanning electron microscopy (SEM) images in Figures 6b–d, which depict the aluminum substrates subjected to varying anodizing treatment durations. With extended treatment, the aluminum substrates underwent a structural transformation, revealing a more intricate and subtle porous network. These SEM images effectively demonstrate the progressive impact of prolonged anodizing treatment on the surface morphology and microstructure of the aluminum substrates. This observable transformation in the structure of aluminum due to different anodizing durations has significant implications. The emergence of a more complex porous network with the increase in treatment duration suggests that the anodization process can be finely tuned to achieve desired surface characteristics.

Figure 7 displays the water contact angle (CA) of Al substrates treated under varying anodizing treatment durations, revealing that anodizing treatment enhances the hydrophobicity of Al substrates, with the hydrophobicity increasing with treatment time. To provide a comprehensive understanding

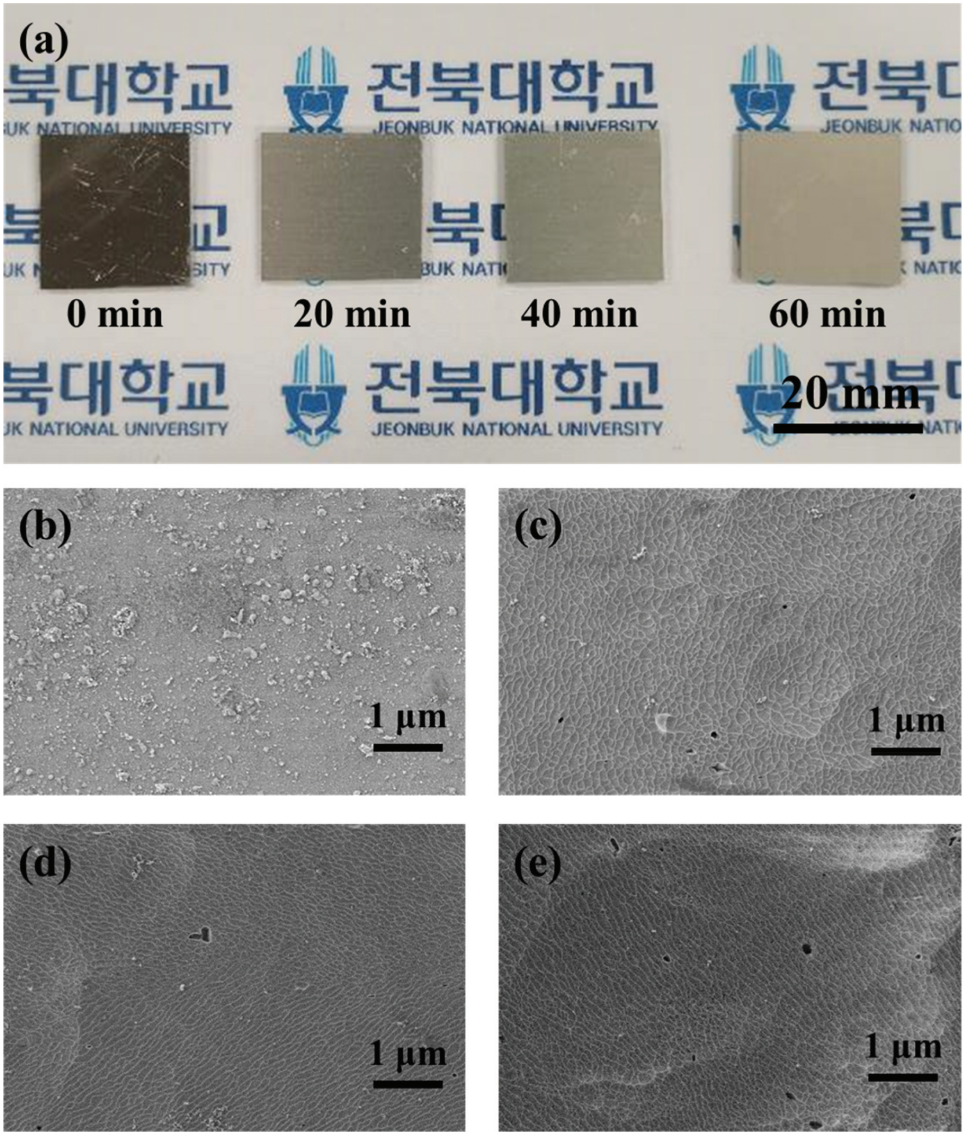

Figure 6. (a) Optical image of the Al substrates treated under varying anodizing treatment durations. SEM image of the Al substrates treated for (b) 0, (c) 20, (d) 40, and (e) 60 min.

of the surface properties, we determined the surface energies of the anodized Al substrates using the Owens – Wendt technique; the corresponding results are summarized in Table 2. Notably, the pristine Al substrate exhibited a surface energy of 49.85 mN m^{-1}. However, as the anodizing treatment duration was extended, the Al substrate showed a lower surface energy. This decrease in surface energy is attributed to the increase in surface holes resulting from the prolonged anodizing treatment. These findings underscore the significant impact of anodizing treatment on the surface properties and hydrophobic behavior of the Al substrates.

Figures 8a–d demonstrate the application of electrostatic spraying to the prepared paints on Al substrates, which have been subjected to different durations of anodizing treatment. These images reveal a consistent and satisfactory coverage effect across all the samples, underscoring the effectiveness of electrostatic spraying in achieving uniform and comprehensive coating application. Furthermore, an examination of the SEM images depicted in Figures 8e–h reveals that SiO_2

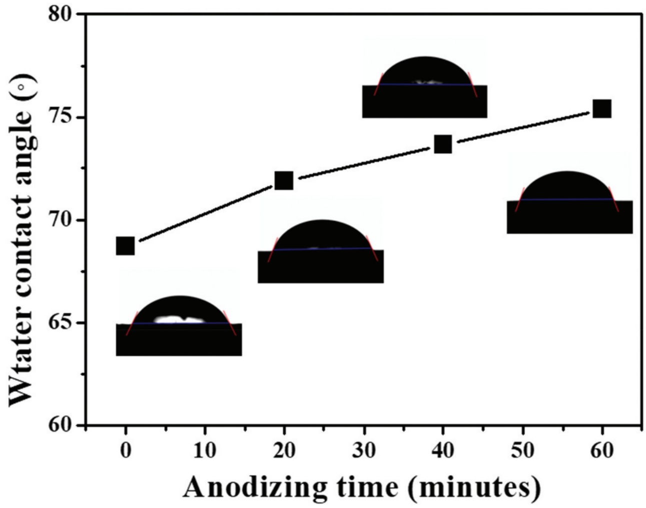

Figure 7. Water CA of Al substrates treated under varying anodizing-treatment durations.

Table 2. Surface energies of Al substrates treated under varying anodizing-treatment durations.

Sample details	Water CA(°)	Diiodomethane CA (°)	Surface energy (mN m^{-1})	Dispersive surface energy (mN m^{-1})	Polar surface energy (mN m^{-1})
Pristine	69.24	31.65	49.85	31.25	17.31
Anodized 20 min	70.98	32.15	46.21	32.98	15.24
Anodized 40 min	72.39	34.02	45.96	34.16	13.12
Anodized 60 min	76.24	35.54	44.32	36.75	12.25

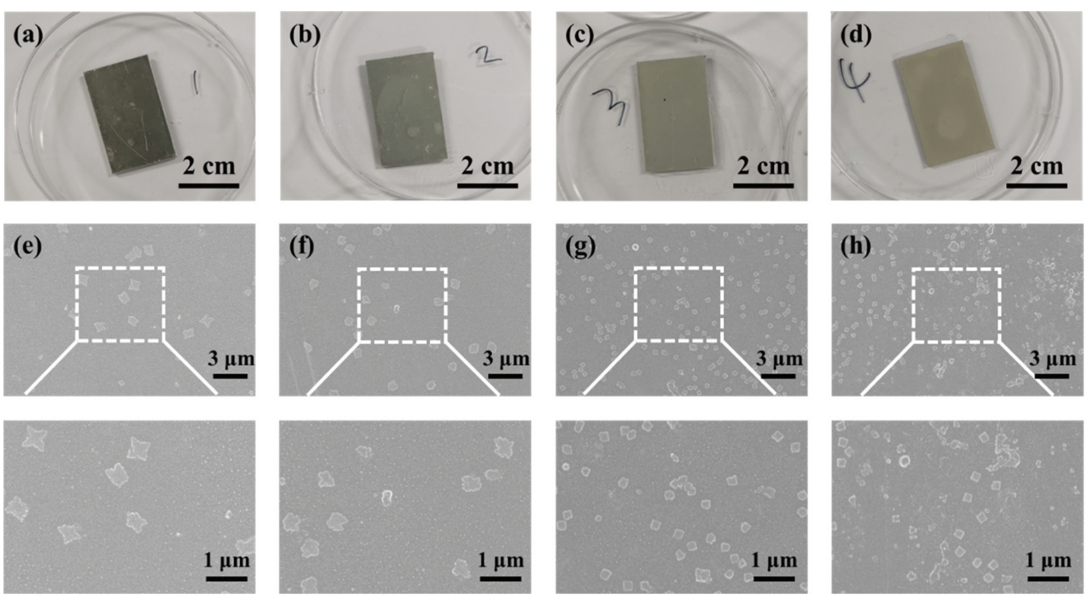

Figure 8. Optical image of electrostatically sprayed Al substrates subjected to anodizing treatment for (a) 0, (b) 20, (c) 40, and (d) 60 min. SEM image of electrostatically sprayed Al substrates subjected to anodizing treatment for (e) 0, (f) 20, (g) 40, and (h) 60 min.

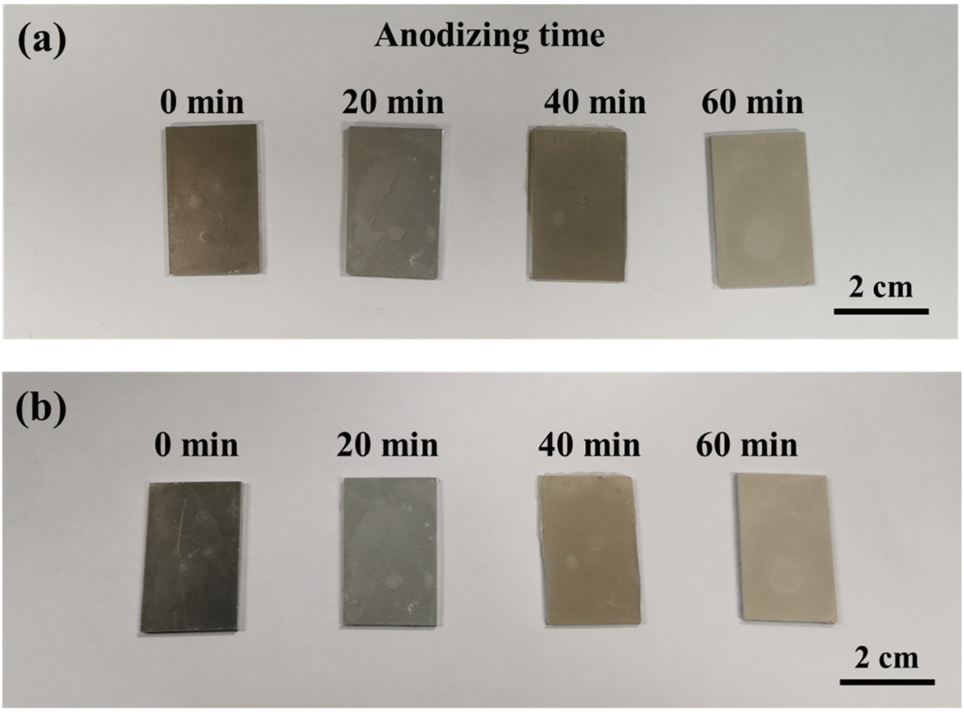

Figure 9. Optical images (a) before and (b) after the peel test.

nanoparticles are evenly dispersed within the paints. This uniform dispersion of nanoparticles is a critical observation, as it highlights the successful incorporation of SiO_2 nanoparticles into the coating matrix. Such a uniform dispersion can contribute significantly to the performance and properties of the coatings, ensuring consistent and desirable characteristics across the coated surfaces.

To further evaluate the influence of the anodizing treatment on the coated substrates, we conducted a peel test. Figure 9 presents the results of this test, revealing a clear correlation between anodizing treatment duration and the adhesion strength of the paint film. The Al substrate that had not undergone anodization exhibited poor adhesion, with the paint film easily peeled off. Conversely, as the duration of anodizing treatment increased, the adhesion of the paint film to the substrate progressively improved and became more resistant to detachment. This trend can be attributed to the effects of the anodizing treatment on the Al substrates. Anodization enhances the availability of adhesion sites while reducing the surface energy of the substrates. Consequently, the interface forces between the paint film and the Al substrate are strengthened, leading to an increased bond and greater resistance to peeling. These results highlight the significant effect of anodizing treatment in enhancing the adhesion properties of the paint film to the Al substrate, which is critical for the durability and longevity of coated materials in practical applications.

Conclusion

This investigation on environment-friendly paints for electrostatic spraying has revealed transformative potential in the area of coatings. Our study demonstrated that utilizing high-voltage electrostatic fields in the application of specially formulated water-based paints significantly enhances the efficiency and quality of the coating process. This method not only optimizes material utilization but also aligns with the increasing environmental consciousness in the industry by minimizing the negative impact traditionally associated with solvent-based coatings. The introduction of our novel water-based resin paints for electrostatic spraying marks a significant step forward in addressing the environmental and safety concerns prevalent with traditional oil-based paints. The experimental results, including the stability of the paint formulation, effectiveness of electrostatic spraying on anodized substrates, and improved adhesion properties, highlight the superiority of our paint in terms of coverage, durability, and environmental safety. The successful incorporation of SiO2 nanoparticles leading to enhanced paint properties such as uniformity, adhesion, and hydrophobicity is particularly noteworthy. Furthermore, the exploration of anodizing treatments on aluminum substrates has shown that such treatments can significantly improve the adhesion and durability of the applied coatings. The findings of the peel tests reinforce the practical applicability of these coatings in various industrial contexts, ensuring both longevity and environmental compliance.

Long-term environmental impact and cost analysis

The use of water-based resin paints with SiO_2 nanoparticles significantly reduces VOC emissions, contributing to improved air quality and reduced health risks. The production process of water-based paints is more energy-efficient and involves fewer hazardous chemicals, resulting in a lower carbon footprint. The enhanced stability and adhesion properties lead to less frequent reapplication, reducing material consumption and waste generation. Electrostatic spraying ensures efficient paint usage with minimal overspray, further reducing environmental contamination.

While the initial production costs may be higher, the long-term economic benefits include reduced maintenance costs, lower waste and material usage, improved health and safety, and regulatory compliance. These factors make water-based resin paints with SiO_2 nanoparticles a cost-effective and sustainable choice for industrial applications.

In conclusion, our research presents a compelling case for adopting water-based resin paints in electrostatic spraying applications across multiple industries. By offering a balance of environmental friendliness, cost-effectiveness, and high performance, this innovation stands to revolutionize the coating industry. Future studies may delve into further optimizing the paint formulation for specific industrial applications, exploring long-term environmental impacts, and assessing the scalability of this approach for broader commercial use.

Commercialization potential

The commercialization plan includes addressing initial investment, production costs, operational feasibility, and market analysis. Despite higher initial costs, long-term economic benefits include reduced maintenance costs, lower waste and material usage, improved health and safety, and regulatory compliance. The SWOT analysis highlights the strengths, weaknesses, opportunities, and threats associated with our water-based resin paints, providing a comprehensive understanding of the commercialization landscape.

In conclusion, our research presents a compelling case for adopting water-based resin paints in electrostatic spraying applications across multiple industries. By offering a balance of environmental friendliness, cost-effectiveness, and high performance, this innovation stands to revolutionize the coating industry. Future studies may delve into further optimizing the paint formulation for specific industrial applications, exploring long-term environmental impacts, and assessing the scalability of this approach for broader commercial use.

Highlights

- An environment-friendly and less toxic approach to electrostatic spraying using novel water-based resin paints enhanced with SiO_2 nanoparticles was demonstrated.

- The incorporation of SiO_2 nanoparticles into water-based resin paints significantly enhances the stability, adhesion, and uniformity of the coatings without relying on toxic solvents.
- A detailed comparative analysis of traditional and electrostatic spraying techniques demonstrated the superior performance of coverage and droplet distribution.
- Anodizing treatments on aluminum substrates further enhanced the adhesion and durability of the coatings.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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