*EduChemia*
*Jurnal Kimia dan Pendidikan*

Vol.10, No.1, 2025, p. 149-162
e-ISSN 2502-4787

# *SMART-COATING* CORROSION INHIBITOR FOR CARBON STEEL USING LDH MODIFIED WITH LAUNDRY DETERGENT WASTE

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Received: 08 November 2024. Accepted: 20 Mei 2025. Published: 8 Agustus 2025

DOI: 10.30870/educhemia.v10i1.29560

**Abstract:** This research was conducted with the aim of reducing environmentally harmful detergent waste while utilizing its anionic surfactant content for the development of Zn-Al LDH composites with benzimidazole as a smart corrosion inhibitor for low-carbon steel, providing dual protection. The samples used in this research included detergent waste collected from commercial laundry services in the Ketintang area of Surabaya, commercial detergent, dodecylbenzenesulfonate, and pure Zn-Al LDH. The methodology involves the synthesis of Zn-Al LDH followed by characterization using FTIR, XRD, and TGA. The results indicate that the thermal decomposition profiles of Zn-Al LDH intercalated with commercial detergent, detergent waste, and dodecylbenzenesulfonate confirm that Zn-Al LDH can be modified with laundry waste. Additionally, interactions between Zn-Al LDH and benzimidazole enhance the crystalline structure of Zn-Al LDH, improving its quality as an anticorrosion material. Quantitative corrosion rate analysis using the weight loss method revealed that the Zn-Al LDH–dodecylbenzenesulfonate–benzimidazole sample exhibited the highest corrosion resistance, followed by the Zn-Al LDH–commercial detergent–benzimidazole, Zn-Al LDH–pure–benzimidazole, and Zn-Al LDH–detergent waste–benzimidazole samples. Overall, these findings support the feasibility of repurposing detergent waste as a functional additive for Zn-Al LDH-based corrosion inhibitors. Although not as effective as pure commercial surfactants, detergent waste provides environmental and functional benefits, reducing environmentally harmful and sustainable smart coatings for corrosion protection.

**Keywords:** Smart coating, Zn-Al LDH, Laundry detergent waste

**Abstrak:** Penelitian ini bertujuan untuk memanfaatkan limbah deterjen dalam teknologi smart-coating yang mengandung senyawa inhibitor korosi dengan menggunakan layered double hydroxide (LDH) Zn-Al. Sampel yang diambil dalam penelitian ini adalah limbah detergen pencuci pakaian yang berasal dari jasa laundry di sekitar Ketintang Surabaya, detergen komersial, Dodecylbenzenesulfonate dan Zn-Al LDH murni. Metode yang digunakan adalah sintesis Zn-Al LDH kemudian karakterisasi menggunakan FTIR, XRD dan TGA. Dengan hasil bahwa profil penguraian LDH yang diselingi oleh Detergen Komersial, Limbah Detergen, dan Dodecylbenzenesulfonate menunjukkan bahwa Zn-Al LDH dapat dimodifikasi dengan limbah cuci baju dan interaksi antara Zn-Al LDH dengan benzimidazole dapat meningkatkan struktur kristal Zn-Al LDH untuk meningkatkan kualitas Zn-Al LDH yang dihasilkan sebagai anti korosi, Melalui uji kuantitatif laju korosi dengan metode *weight loss* didapatkan hasil bahwa sampel Zn-Al LDH-Dodecylbenzenesulfonate-benzimidazol mempunyai kemampuan korosi paling baik, kemudian diikuti oleh sampel Zn-Al LDH-Detergen-benzimidazol, selanjutnya Zn-Al LDH-Al LDH-murni-benzimidazol dan LDH-limbah-benzimidazol. Secara keseluruhan, temuan ini mendukung kelayakan pemanfaatan limbah deterjen sebagai aditif fungsional dalam pengembangan inhibitor korosi berbasis Zn-Al LDH. Meskipun efektivitasnya tidak setinggi surfaktan komersial murni, limbah deterjen memberikan manfaat, baik dari sisi lingkungan maupun fungsi, yaitu mengurangi pencemaran dan mendukung pengembangan pelapis pintar berkelanjutan untuk perlindungan terhadap korosi.

**Kata kunci:** *Smart coating, Zn-Al LDH*, limbah detergen laundry

## INTRODUCTION

In an effort to maximize productivity and time efficiency, modern society increasingly seeks convenience and practicality in various aspects of life, including the growing accessibility and affordability of laundry services. Unfortunately, many laundry businesses remain environmentally unfriendly, as detergent wastewater is often discharged directly into rivers without prior treatment, leading to potential water pollution (Zahro, 2017).

Detergents contain approximately 25 different chemical compounds, which can generally be categorized into three main groups: (1) anionic surfactants, (2) supporting agents, and (3) additives such as bleaching agents. Anionic surfactants constitute approximately 20–30% of the total composition, whereas supporting agents account for approximately 70–80% (Sembodo et al., 2021). Anionic surfactants derived from sulfates are the result of reactions between long-chain alcohols and sulfuric acid, which produce sulfate alcohols that have surface-active properties (surface-active agent: surfactant) (Larasati et al., 2021). Surfactants serve as the primary active component in detergents and are characterized by long chemical chains that are resistant to natural degradation. The presence of surfactants in aquatic systems hinders the diffusion of oxygen from the atmosphere into the water, reducing dissolved oxygen levels and subsequently disrupting aquatic ecosystems (Tanjung et al., 2019). This process contributes to eutrophication, a condition characterized by excessive accumulation. This phenomenon is marked by an increase in phytoplankton populations and excessive growth of aquatic plants (algal blooming) (Simbolon, 2016).

Anionic surfactant pollution remains relatively high and can be utilized as an intercalating agent in the synthesis of layered double hydroxides (Zn-Al LDH). For example, nitrate-intercalated Zn-Al LDH can serve as a precursor for the preparation of Zn-Al LDH intercalated with corrosion-inhibiting ions, which are applied for multifunctional metal corrosion protection (Zheng et al., 2021). The utilization of detergent wastewater as an intercalating agent in Zn-Al layered double hydroxide (LDH) composites presents an effective solution for mitigating water pollution. Layered double hydroxides (Zn-Al LDH) possess a high surface area and remarkable adsorption capacity. Recent studies have integrated the modified characteristics of Zn-Al LDH using anionic surfactants as long-term corrosion inhibitors through the intercalation of anionic-type inhibitor species (Hardiyanti, 2018). Zn-Al LDH is a synthetic inorganic compound composed of metal ion layers with a structure similar to that of natural minerals (Mishra et al., 2018). It can be modified through intercalation, allowing the incorporation of various ions and compounds within its layered structure. Modified Zn–Al LDH is categorized as an advanced material with versatile applications, including its use as a smart coating or corrosion-resistant coating for metals. Smart coatings are intelligent layers designed to provide active protection and responsiveness to specific stimuli originating from either intrinsic or extrinsic factors (Tejero-Martin et al., 2019). Several researchers have developed Zn-Al LDH modified with positively charged ions (Carneiro et al., 2015) and negatively charged organic corrosion inhibitors (Serdechnova et al., 2016), which have demonstrated effectiveness in inhibiting corrosion in aluminum alloys. Corrosion inhibitors are synthetic or natural substances that are added in small amounts to protect metals from corrosion by forming a film on the metal surface. However, to date, no Zn-Al LDH has been developed using neutral corrosion inhibitors or neutrally charged species. One organic corrosion inhibitor that has potential is the compound benzimidazole (Wajdi et al., 2018). Recent studies have reported the use of benzimidazoles and their derivatives as corrosion inhibitors (CIs) in relation to their spatial molecular structure, surface charge density, electronic parameters and affinity for metal surfaces (Guttierez et al., 2016; Mousavi et al., 2012). Benzimidazoles have a suitable structure for coordinating metals;

therefore, they have the ability to control the corrosion of steel or metal. Several papers have proposed various mechanisms of action by which benzimidazoles are absorbed on metal surfaces (Guttierez et al., 2016; Vinutha & Venkatesha., 2016). Therefore, in this study, we modified Zn-Al LDH with a neutral corrosion inhibitor, benzimidazole, as a smart coating for low-carbon steel. Zn-Al LDH intercalated with detergent wastewater was used as a precursor, as detergent waste was chosen because of its high anionic surfactant content.

Carbon steel was selected as the research object because it is a crucial metal used in construction and machinery. Carbon steel containing 0.25% to 0.3% C is commonly found in bolts, rivets, and other structural applications. The lower the carbon content is, the less resistant the steel becomes to corrosion (low-carbon steel) (Nasution, 2018). Zn-Al LDH modified with anionic surfactants and benzimidazole is expected to function as a smart protective coating, providing dual protection against corrosion of low-carbon steel.

Based on these considerations, this research was conducted with the aim of reducing environmentally harmful detergent waste while utilizing its anionic surfactant content for the development of Zn-Al LDH composites with benzimidazole as a smart coating corrosion inhibitor for low-carbon steel, providing dual protection.

## METHOD

This study employed the synthesis of Zn-Al LDH followed by characterization using various analytical methods, including FTIR, XRD, and TGA. The data were obtained from quantitative corrosion rate measurements using the weight loss method. The materials used in this research included benzimidazole, $ZnCl_2$, sodium dodecylbenzene, ethanol, nitrogen gas, $AlCl_3 \cdot 6H_2O$, distilled water, NaOH, diethyl ether, epoxy resin and hardener, carbon steel, and detergent waste. The equipment utilized in this study consisted of beakers, graduated cylinders, an analytical balance, watch glasses, pipettes, spatulas, filters, an oven, a microwave, a hotplate with a magnetic stirrer, sandpaper, a Teflon vessel, pH indicators, a centrifuge, thermogravimetric analysis (TGA), Fourier transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD).

### *Synthesis of Zn-Al LDH (Zn-Al LDH-Pure)*

The synthesis of pristine Zn-Al LDH (denoted as Zn-Al LDH-pure) was carried out as a reference material for comparison with the modified Zn-Al LDH. In the initial stage, Zn-Al LDH was synthesized using 7.98 g of $ZnCl_2$ p.a. and 4.71 g of $AlCl_3 \cdot 6H_2O$ as precursor salts. The metal salt solution was prepared by dissolving the reagents in 200 mL of deionized water in an Erlenmeyer flask under continuous stirring. While stirring, a 1 M NaOH solution was gradually added dropwise to maintain a constant pH of 8.5. The reaction mixture was then stirred for 24 hours at an ambient temperature using a magnetic stirrer on a hot plate to facilitate the formation of Zn-Al LDH. The resulting suspension was subjected to centrifugation, followed by two consecutive washes with deionized water to remove residual impurities. The obtained solid was subsequently dried in an oven at 60°C for 24 hours, yielding the final Zn-Al LDH product (Cursino et al., 2013).

***Synthesis of Zn-Al LDH-Detergent Waste***

This procedure was conducted separately, but all the experimental parameters remained consistent throughout the trials. The synthesis of Zn-Al LDH modified with laundry detergent waste collected from commercial laundry services in the Ketintang area of Surabaya followed a similar procedure for the synthesis of Zn-Al LDH, with the key difference being the addition of 200 mL of detergent waste as an intercalating agent. In this synthesis, 7.98 g of $ZnCl_2$ p.a. and 4.71 g of $AlCl_3 \cdot 6H_2O$ were dissolved in detergent waste solution under continuous stirring. While stirring, a 1 M NaOH solution gradually added dropwise until the pH reached a constant value of 8.5. The reaction mixture was then stirred for 24 hours at an ambient temperature using a magnetic stirrer on a hot plate. Following synthesis, the resulting suspension was subjected to centrifugation and washed twice with deionized water to remove impurities. The obtained solid product was subsequently dried in an oven at 60°C for 24 hours to yield the modified Zn–Al LDH composite (Cursino et al., 2013).

***Synthesis of Zn-Al LDH-Commercial detergent***

This procedure was also conducted as a separate experiment, maintaining identical parameters across all trials. The synthesis of Zn-Al LDH modified with a commercial detergent (same brand as the detergent waste) followed a similar procedure as the synthesis of Zn-Al LDH, with modifications in the reagent composition. In this synthesis, 27.18 g of commercial detergent was first added, followed by 7.98 g of $ZnCl_2$ p.a. and 4.71 g of $AlCl_3 \cdot 6H_2O$, which were then dissolved in 200 mL of deionized water under continuous stirring. While stirring, a 1 M NaOH solution gradually added dropwise until the pH reached a constant value of 8.5. The reaction mixture was then stirred for 24 hours at an ambient temperature using a magnetic stirrer on a hot plate. After synthesis, the resulting suspension underwent centrifugation and was washed twice with deionized water to remove residual impurities. The obtained solid product was subsequently dried in an oven at 60°C for 24 hours, yielding the modified Zn–Al LDH composite (Cursino et al., 2013).

***Synthesis of Zn-Al LDH-dodecylbenzenesulfonate***

This procedure was also conducted as a separate experiment, ensuring that all experimental parameters remained consistent across trials. The synthesis of Zn-Al LDH modified with dodecylbenzenesulfonate (DBS) followed a similar approach to that of Procedure 1, with modifications in the reagent composition. In this synthesis, 27.18 g of DBS was first introduced, followed by the addition of 7.98 g of $ZnCl_2$ p.a. and 4.71 g of $AlCl_3 \cdot 6H_2O$, which were dissolved in 200 mL of deionized water under continuous stirring. While stirring, a 1 M NaOH solution was gradually added dropwise until the pH stabilized at 8.5. The reaction mixture was then stirred for 24 hours at an ambient temperature using a magnetic stirrer on a hot plate. Following synthesis, the resulting suspension underwent centrifugation and was washed twice with deionized water to remove residual impurities. The obtained solid product was subsequently dried in an oven at 60°C for 24 hours, yielding the DBS-modified Zn-Al LDH composite (Cursino et al., 2013).

***Incorporation of benzimidazole into modified Zn-Al LDH***

The corrosion inhibitor utilized in this experiment was benzimidazole, a neutral organic compound that was incorporated into the previously synthesized modified Zn-Al LDH. The role of the modified Zn-Al LDH composite was to serve as a smart coating material for corrosion protection. For each sample, 0.55 g of modified Zn-Al LDH was combined with 0.47 g of benzimidazole. Subsequently, 20 mL of deionized water was added, and the mixture was stirred for 5 minutes to achieve homogeneity. The resulting suspension was then transferred into a Teflon vessel containing an additional 20 mL of deionized water. The Teflon vessel was placed in a microwave reactor and heated at a high temperature for 2 minutes. After cooling, the product was transferred into a centrifuge tube and washed twice with diethyl ether to remove unreacted residues. The final drying process was carried out in an oven at 60–80°C until a completely dry product was obtained.

### *Combining a Modified Zn-Al LDH with Epoxy Resin*

The product obtained after incorporation of benzimidazole into the modified Zn-Al LDH was mixed with epoxy resin and sonicated at 30 kHz for 5 minutes to achieve a homogeneous solution. A hardener was then added to the mixture to function as a curing agent. The theoretical ratio of epoxy resin to curing agent was maintained at 2:1 (Rodriguez et al., 2020). Before application, the carbon steel sheets were sanded and cleaned with ethanol to ensure a contaminant-free surface. The epoxy resin, which incorporates Zn-Al LDH modified with benzimidazole from various samples, was then applied onto the steel sheets. The coated samples were left to cure at room temperature for 6 days, followed by drying at 50°C for 16 hours. Once fully dried, the coated carbon steel sheets were immersed in 0.1 M HCl for 1 week to evaluate their corrosion resistance. Corrosion characterization was then conducted through further observations and analyses.

The characterization of all the produced samples was carried out using several analytical methods, namely, FTIR, TGA, and XRD.

## RESULTS AND DISCUSSION

### 1. TGA analysis of pure and modified LDH

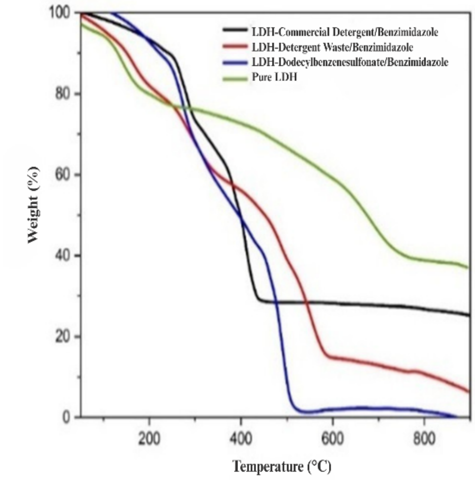


**Figure 1.** TGA analysis of Zn-Al LDH-commercial detergent-benzimidazole, Zn-Al LDH-liquid detergent waste-benzimidazole, and Zn-Al LDH-dodecylbenzenesulfonate-benzimidazole.

The thermal decomposition profiles of Zn-Al LDH intercalated with commercial detergent, laundry detergent waste, and dodecylbenzenesulfonate-benzimidazole exhibit distinct differences, as shown in the figure above.

The Zn-Al LDH-commercial detergent-benzimidazole curve (black curve) demonstrated a sharp weight loss at approximately 300°C, followed by a gradual weight decrease up to 800°C. These findings indicate that commercial detergents undergo rapid decomposition at approximately 300°C and continue to degrade at a slower rate up to 800°C.

Compared with those of the other curves, the Zn–Al LDH–liquid detergent waste–benzimidazole curve (red curve) exhibited more gradual weight loss over the entire temperature range. These findings suggest that laundry detergent waste is more thermally stable than commercial detergent. This can be attributed to the lower content of organic compounds (anionic surfactants) in laundry detergent waste than in pure commercial detergent. The Zn–Al LDH–dodecylbenzenesulfonate–benzimidazole curve (blue curve) shows a gradual weight loss that falls between the Zn–Al LDH–commercial detergent and Zn–Al LDH–liquid detergent waste curves. This finding indicates that dodecylbenzenesulfonate has a moderate decomposition rate, with its organic compound or anionic surfactant content being lower than that of the Zn-Al LDH commercial detergent but higher than that of the Zn-Al LDH laundry detergent waste.

Overall, the decomposition profiles of Zn-Al LDH intercalated with commercial detergent, laundry detergent waste, and dodecylbenzenesulfonate indicate that laundry detergent waste contains the lowest number of anionic surfactants.

## 2. XRD analysis of pure and modified Zn-Al LDH

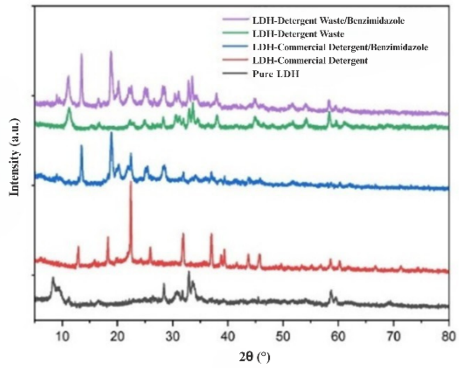


**Figure 2.** XRD Analysis of Zn-Al LDH-Commercial Detergent, Zn-Al LDH-Laundry Detergent Waste, and Zn-Al LDH-Dodecylbenzenesulfonate

As shown in the figure, the XRD diffraction pattern of Zn-Al LDH changes after intercalation with commercial detergent, laundry detergent waste, and the subsequent addition of benzimidazole.

Zn-Al LDH-Laundry detergent waste/benzimidazole (purple) exhibited the highest diffraction peaks among the samples. This indicates that this sample has a better crystalline structure, which may be attributed to interactions between the Zn-Al LDH and the benzimidazole contained in the laundry detergent waste. Moreover, Zn-Al LDH-Laundry detergent waste (green) presented lower diffraction peaks than did Zn-Al LDH-Laundry detergent waste/

benzimidazole, suggesting a poorer crystalline structure, possibly due to impurities in the detergent waste.

Zn-Al LDH-Commercial detergent/ benzimidazole (blue) exhibited diffraction peaks like those of Zn-Al LDH-Laundry detergent waste/benzimidazole, indicating a well-ordered crystalline structure. These findings suggest that laundry detergent waste was successfully intercalated into the Zn-Al LDH interlayer, confirming the feasibility of modifying Zn-Al LDH with detergent waste. The Zn-Al LDH-Commercial Detergent (red) sample shows diffraction peaks comparable to those of the Zn-Al LDH-Laundry detergent waste but slightly greater than those of the other samples, which may be due to the higher purity of surfactants in the commercial detergent than in the detergent waste. Based on this analysis, the interaction between Zn-Al LDH and benzimidazole enhances the crystalline structure of Zn-Al LDH, which can be beneficial for improving its performance as an anticorrosion material. Further analysis indicates that the obtained diffraction patterns still retain the primary characteristics of the Zn-Al LDH structure, albeit with minor crystalline defects likely caused by synthesis conditions such as pH, temperature, and reaction time.

## 3. FTIR analysis of pure and modified Zn-Al LDH

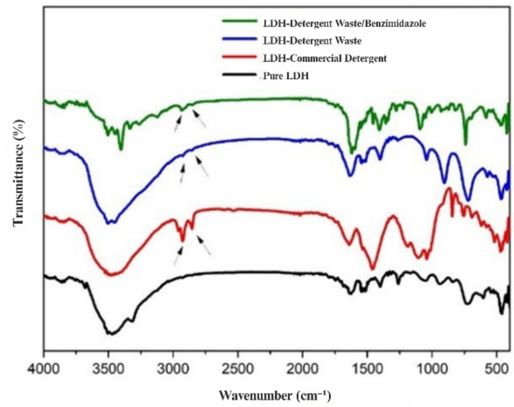


**Figure 3.** FTIR Analysis of Zn-Al LDH-Commercial Detergent, Zn-Al LDH-Laundry Detergent Waste, and Zn-Al LDH-Dodecylbenzenesulfonate

The red curve in the above spectrum indicates the intercalation of anionic surfactants from commercial detergents into the Zn-Al LDH interlayer. This is evidenced by the appearance of asymmetric and symmetric C–H functional groups at wavenumbers of approximately 2900 and 2850 $cm^{-1}$.

The blue curve, representing Zn-Al LDH modified with detergent waste, also indicates the intercalation of anionic surfactants. However, the signals at wavenumbers 2900 and 2850 $cm^{-1}$ are not as pronounced. This is due to the reduced or impure content of anionic surfactants in detergent waste. Nevertheless, the anionic surfactants intercalated within the Zn-Al LDH interlayer are still capable of binding benzimidazole, as evidenced by the shift in the O-H functional group at approximately 3500 $cm^{-1}$. This confirms that the incorporation of benzimidazole within the Zn-Al LDH interlayer can serve as an effective corrosion inhibitor. The desorption of Cs by cationic surfactants through an ion-exchange mechanism is demonstrated by the presence of asymmetric and symmetric C–H functional groups in MMTK10/Cs at approximately 2900 and 2850 $cm^{-1}$ after treatment with BDAB and DTAB.

## 4. Corrosion Rate Analysis Using the Weight Loss Method

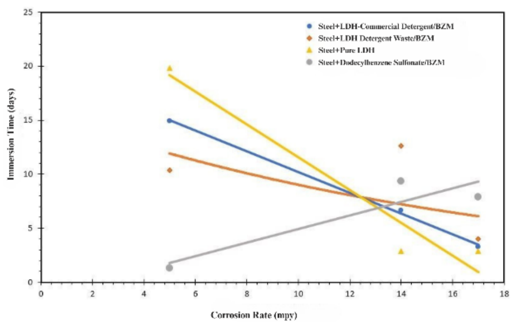


**Figure 4.** Corrosion Rate Analysis Using the Weight Loss Method for Zn-Al LDH-Commercial Detergent, Zn-Al LDH-Detergent Waste, and Zn-Al LDH-Dodecylbenzenesulfonate

As shown in Figure 4, the corrosion rates of carbon steel coated with pure Zn-Al LDH and Zn-Al LDH intercalated with commercial detergent, detergent waste, and dodecylbenzenesulfonate (DBS) are significantly different. The data indicate that each variation influences the corrosion rate of carbon steel over immersion periods of 5 days, 14 days, and 17 days.

As shown in Figure 4, the corrosion rates of carbon steel coated with pure Zn-Al LDH and Zn-Al LDH intercalated with commercial detergent, detergent waste, and dodecylbenzenesulfonate (DBS) are significantly different. The data indicate that each variation influences the corrosion rate of carbon steel over immersion periods of 5 days, 14 days, and 17 days. The lowest average corrosion rate was observed for carbon steel coated with Zn-Al LDH intercalated with dodecylbenzenesulfonate (DBS), as shown by the Zn-Al LDH-DBS curve (gray curve), which had the lowest average corrosion rate of 6.1672 mpy. This is attributed to the presence of pure anionic surfactants in DBS, which effectively act as corrosion inhibitors for carbon steel. Similarly, the Zn-Al LDH-Commercial Detergent-Benzimidazole curve (blue curve) exhibited an average corrosion rate of 8.2824 mpy, indicating that the relatively high purity of anionic surfactants in commercial detergents provides notable corrosion resistance. On the other hand, Zn-Al LDH-Pure (yellow curve) demonstrated a faster corrosion process than Zn-Al LDH-DBS-Benzimidazole and Zn-Al LDH-DBS-Detergent did, with an average corrosion rate of 8.5228 mpy. This is due to the absence of benzimidazole in pure Zn-Al

LDH synthesis, allowing iron to corrode more rapidly. In this case, the higher concentration of free hydrogen ions ($H^+$) interacting with the Zn-Al LDH layer facilitates the formation of $H_3PO_4$, accelerating the corrosion reaction rate.

Furthermore, the final curve, Zn-Al LDH-Waste detergent-benzimidazole (orange curve), exhibited an average corrosion rate of 8.9948 mpy, indicating a relatively rapid corrosion process. This is attributed to the impurities present in the anionic surfactants contained in detergent waste.

Based on the results and the graph above, a preliminary conclusion can be drawn that the variation in carbon steel coatings using pure Zn-Al LDH and Zn-Al LDH intercalated with commercial detergent, detergent waste, and dodecylbenzenesulfonate (DBS) results in different average corrosion rates owing to differences in anionic surfactant content. Additionally, immersion duration affects the corrosion rate of carbon steel. Among all the variations, the lowest average corrosion rate was observed for the carbon steel coated with Zn-Al LDH intercalated with DBS.

## CONCLUSION

This study investigated the potential of utilizing environmentally harmful detergent waste as a source of anionic surfactants for the synthesis of Zn–Al layered double hydroxide (LDH) composites intercalated with benzimidazole to develop smart anticorrosion coatings for low-carbon steel. TGA, XRD, FTIR, and corrosion rate analyses were conducted on Zn-Al LDH modified with commercial detergent, detergent waste, and pure dodecylbenzenesulfonate (DBS).

TGA revealed that, compared with its commercial counterpart, detergent waste-modified LDH has improved thermal stability, likely due to its lower organic content. The XRD results indicated that benzimidazole enhances the crystallinity of LDH composites, particularly when intercalated with detergent waste, confirming successful interlayer intercalation and structure retention. FTIR analysis confirmed the presence of anionic surfactants and successful benzimidazole incorporation through characteristic functional group shifts, even in detergent waste-modified LDH.

Corrosion tests demonstrated that while Zn-Al LDH intercalated with pure DBS offered the best corrosion protection (lowest corrosion rate), the detergent waste-modified Zn-Al LDH also showed measurable corrosion inhibition, although it was slightly less effective because of the lower purity and presence of impurities. Nonetheless, its performance remained superior to that of unmodified Zn-Al LDH.

Overall, these findings support the feasibility of repurposing detergent waste as a functional additive for Zn-Al LDH-based corrosion inhibitors. Although not as effective as pure commercial surfactants, detergent waste provides environmental and functional benefits, reducing environmentally harmful and sustainable smart coatings for corrosion protection.

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