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Synergistic applications of polypyrrole coatings in aluminum food cans: From corrosion protection to VOC sensing

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INTRODUCTION & AIM

Aluminum is widely used in food packaging due to its light weight, excellent barrier properties, and recyclability. However, its susceptibility to corrosion and interaction with volatile organic compounds (VOCs) poses significant challenges for food safety and shelf-life. To address these issues, multifunctional coatings are emerging as innovative solutions.

This study explores the synergistic application of **polypyrrole (PPy)** and **fractal copper nanoparticles (CuNPs)** as composite coatings for aluminum food cans. Polypyrrole is a conductive polymer known for its corrosion resistance and environmental responsiveness, while fractal copper nanoparticles offer high surface area and sensitivity to VOCs.

The main aims of this work are:

- To fabricate and characterize PPy/CuNPs composite coatings on aluminum substrates.
- To evaluate their effectiveness in **corrosion protection** under food packaging conditions.
- To investigate their potential for **VOC detection**, contributing to intelligent packaging systems.

By combining corrosion inhibition with VOC sensing, this multifunctional approach paves the way for **next-generation smart food packaging materials** that enhance safety, extend shelf life, and support real-time freshness monitoring.

METHOD

In this study, the electropolymerization of pyrrole was conducted using a <u>**conventional three-electrode setup**</u>. The working electrode, a 5 × 2 cm^2 section of industrial **aluminum**, was obtained from a commercially available can. Before each experiment, the exposed surface was meticulously polished with 400–1200 grit emery paper to achieve a mirror-like appearance, followed by ultrasonic cleaning with distilled water, degreasing with acetone, and air drying. After pretreatment, the electrode was immediately placed into a custom-made, one-compartment electrochemical cell. A **platinum plate** served as the auxiliary electrode, while a **silver wire coated with silver chloride** was employed as the reference electrode.

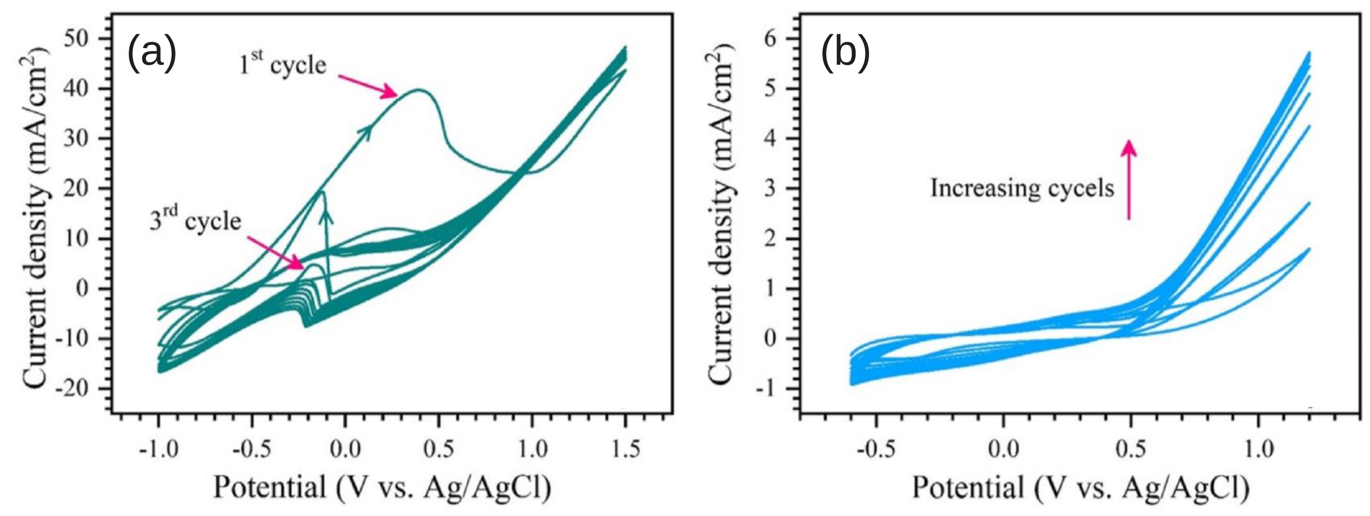
Oxalic acid and sodium salicylate were employed as **supporting electrolytes** in the electrodeposition process. **Several electrochemical techniques** were utilized for the electropolymerization process, each of which significantly influences the electropolymerization reaction and the quality of the resulting coating in terms of morphology, homogeneity, and adhesion. In this context, a comprehensive investigation was performed to study the effects of **potentiodynamic**, **potentiostatic**, and **galvanostatic** techniques on the electropolymerization of the monomer.

Following electrosynthesis, both films were exposed to a 0.1 M copper chloride solution where an applied potential of −1.2 V vs. Ag/AgCl was used. This potential facilitated the **electrochemical reduction of Cu ions**, resulting in the formation of **Cu metallic particles** within the polymer matrix.

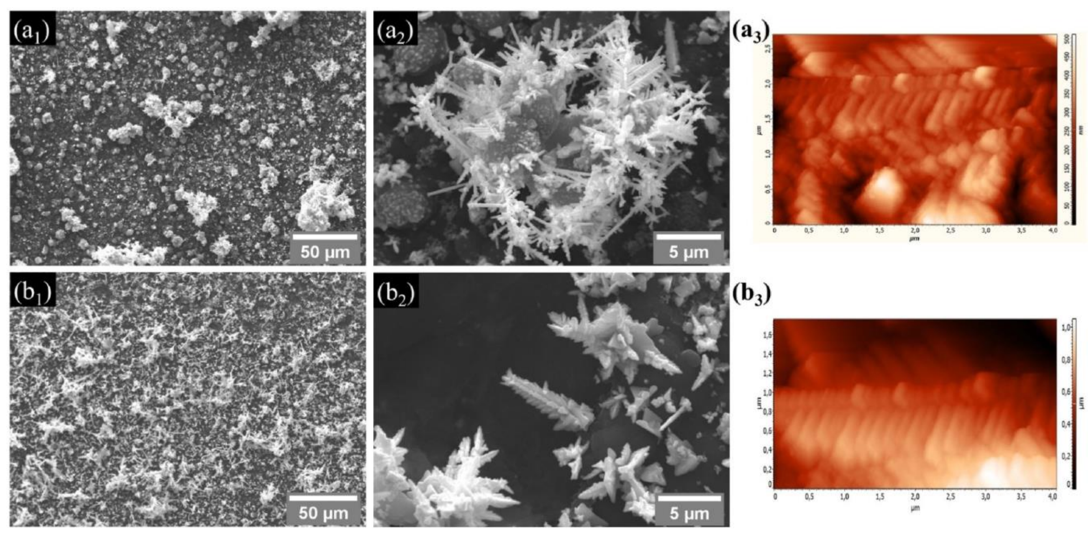
CONCLUSION

This study demonstrated the **successful design** and application of **PPy**-based coatings embedded with fractal **Cu crystals**, tailored for corrosion protection and ammonia detection in food packaging. Electrochemical analyses underscored the coatings' substantial **corrosion protection**, with Rp values reaching 1.74 kΩ cm^2 and 1.32 kΩ cm^2 for PPy@OxAc and PPy@NaSa, respectively, and **inhibitory efficiencies exceeding 96 %** in saline conditions. Ammonia sensitivity testing revealed that exposure to NH_3 led to a reversible resistance shift, attributed to either proton transfer in the PPy@OxAc or electron transfer in the PPy@NaSa, signaling the composite's **capability to detect spoilage indicators** through a robust and repeatable response.

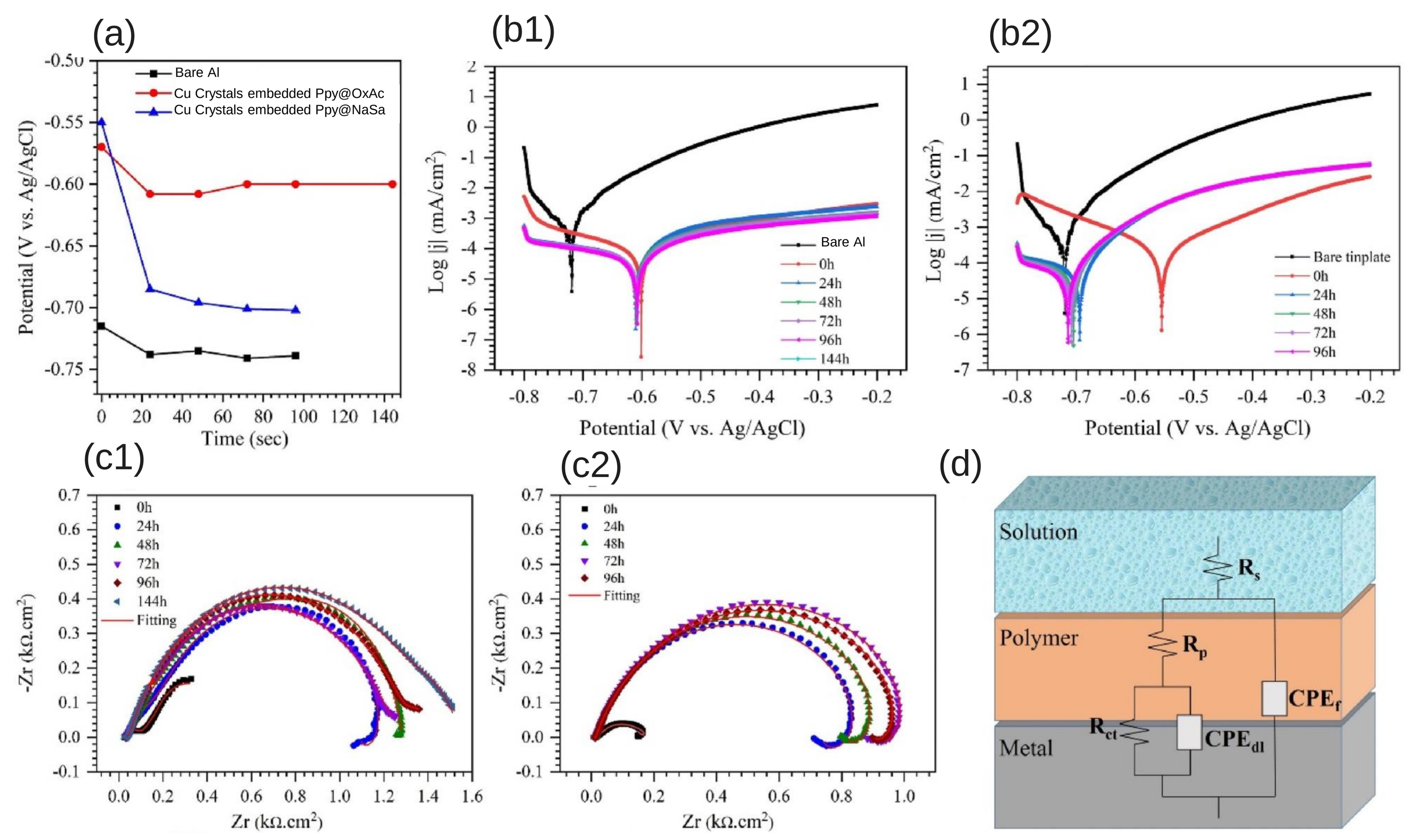
RESULTS & DISCUSSION



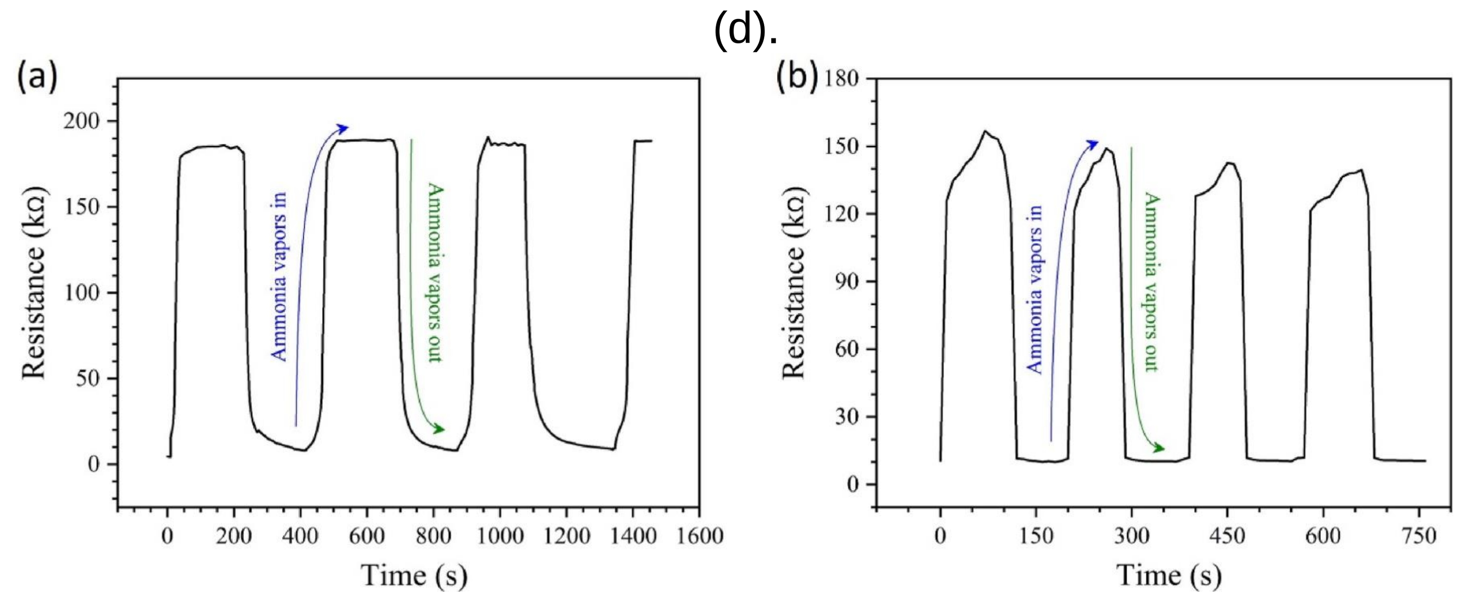
j-E voltammetric plots attained in an aqueous medium of 0.1 M **OxAc** (a) and 0.5 M **NaSa** (b) in the existence of 0.3 M pyrrole on Al electrodes. <u>*Scan rate: v = 100 mV/s*</u>.



SEM and **AFM** micrographs of copper fractal crystal embedded PPy films obtained in 0.1 M AcOx (a1, a2, a3) and 0.5 M SaNa (b1, b2, b3).



Duration dependency of the **OCP** in 3 % NaCl of Al electrodes covered by PPy coatings (a). **Potentiodynamic polarization** curves for Cu–PPy@OxAc (b1) and Cu–PPy@NaSa (b2). **Nyquist plots** for Cu–PPy@OxAc (c1) and Cu–PPy@NaSa (c2) obtained in 3 % NaCl solution (experimental records (dots) and fitted data (line)). A representative diagram of the composite/solution and metal/composite interfaces with an **equivalent circuit** used to fit the EIS data (d).



Resistance response over time for Cu–PPy@OxAc (a) and Cu–PPy@NaSa (b).

FUTURE WORK / REFERENCES

[1] El Guerraf, Abdelqader, et al. "Smart conducting polymer innovations for sustainable and safe food packaging technologies." *Comprehensive Reviews in Food Science and Food Safety* 23.6 (2024): e70045.

[2] El Guerraf, Abdelqader, et al. "Antibacterial activity and volatile organic compounds sensing property of polypyrrole-coated cellulosic paper for food packaging purpose." *Polymer Bulletin* 79.12 (2022): 11543-11566.