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# Development of Sustainable Anticorrosive Coatings Based on Pinus Radiata Bark Wax

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## INTRODUCTION & AIM

Corrosion of metal structures is a major global challenge with significant economic and environmental impacts. According to the OECD, corrosion-related losses can reach up to 3–4% of GDP in developed countries, largely due to the replacement of corroded steel in infrastructure and industrial assets. In Chile, Pinus radiata is the dominant forestry species, covering over 2 million hectares and representing more than 97% of the national sawn wood production, generating a vast amount of bark as an abundant byproduct from forestry and sawmill operations. This high availability of Pinus radiata bark offers a valuable resource for developing sustainable materials, turning forestry waste into value-added products. Critical infrastructure such as bridges and offshore platforms are exposed to highly corrosive environments, worsened by climate change, which accelerates metal degradation. Conventional anticorrosive coatings often contain hazardous substances, including epoxy resins with bisphenol A, lead chromate pigments, volatile organic compounds, and biocides, all of which pose risks to human health and the environment. Despite advances in sustainable coating design, there remains a significant knowledge gap regarding their safety and biocompatibility. This research aims to bridge that gap by developing anticorrosive coatings based on Pinus radiata bark wax, evaluating both their corrosion protection performance and cytotoxicity, thereby contributing to safer, environmentally friendly alternatives that promote circular economy principles and reduce reliance on synthetic materials.

This research aims to develop and evaluate sustainable anticorrosive coatings derived from the wax extracted from Pinus radiata bark, a widely available forestry byproduct. The study seeks to bridge the gap between eco-friendly material design and human safety by formulating a bio-based coating and assessing its performance. Specifically, the project will evaluate the coating's corrosion resistance through electrochemical impedance spectroscopy and determine its biocompatibility using in vitro cytotoxicity assays on HaCaT human keratinocyte cells.

## METHOD

This study follows a four-stage methodology to develop and evaluate sustainable anticorrosive coatings derived from Pinus radiata bark wax.

**Step 1: Bark Collection and Wax Extraction**
Pinus radiata bark was collected from forestry residues and dried to a moisture content below 15%. Wax extraction was performed following the protocol described by Sandoval et al. (2021), using alkaline hydrolysis (1 mol·L⁻¹ NaOH) and petroleum ether under controlled conditions (120 °C, 1.2 atm). The resulting yellow wax was recovered, dried, and stored for formulation.

**Step 2: Coating Formulation**
The extracted wax was blended with film-forming agents and additives to formulate a bio-based anticorrosive coating. The formulation aimed to replicate the consistency and application properties of conventional protective paints.

**Step 3: Coating Application and Cell Culture**
The coatings were applied directly onto sterile culture plates to evaluate their compatibility with human skin cells. HaCaT human keratinocyte cells were seeded onto the coated surfaces and cultured in DMEM (Dulbecco's Modified Eagle Medium) supplemented with 10% fetal bovine serum and antibiotics. Control groups included uncoated plates and plates coated with conventional materials.

**Step 4: Biocompatibility Assessment**
Cell adhesion and morphology were monitored under a microscope to assess the biocompatibility of the coatings. The primary endpoint was the ability of HaCaT cells to adhere and spread on the coated surfaces, indicating non-toxic and cell-friendly behavior. No chemical extraction or metabolic assays were used in this evaluation (Figure 1).

**Step 5: Anticorrosive Performance Evaluation**
To assess corrosion protection, electrochemical impedance spectroscopy (EIS) in Figure 2, was performed on coated metal substrates. The real impedance component (Zreal) was measured in Ω/cm² as an indicator of barrier performance. The following coating conditions were tested:

- Blank (uncoated metal)
- Bio-based coating with pine bark wax
- Commercial coating (standard)
- Commercial coating with trans epoxy resin
- Commercial coating with polyurethane
- Commercial coating with finishing layer

**These comparisons allowed for benchmarking the performance of the developed wax-based coating against conventional alternatives.**

## RESULTS & DISCUSSION

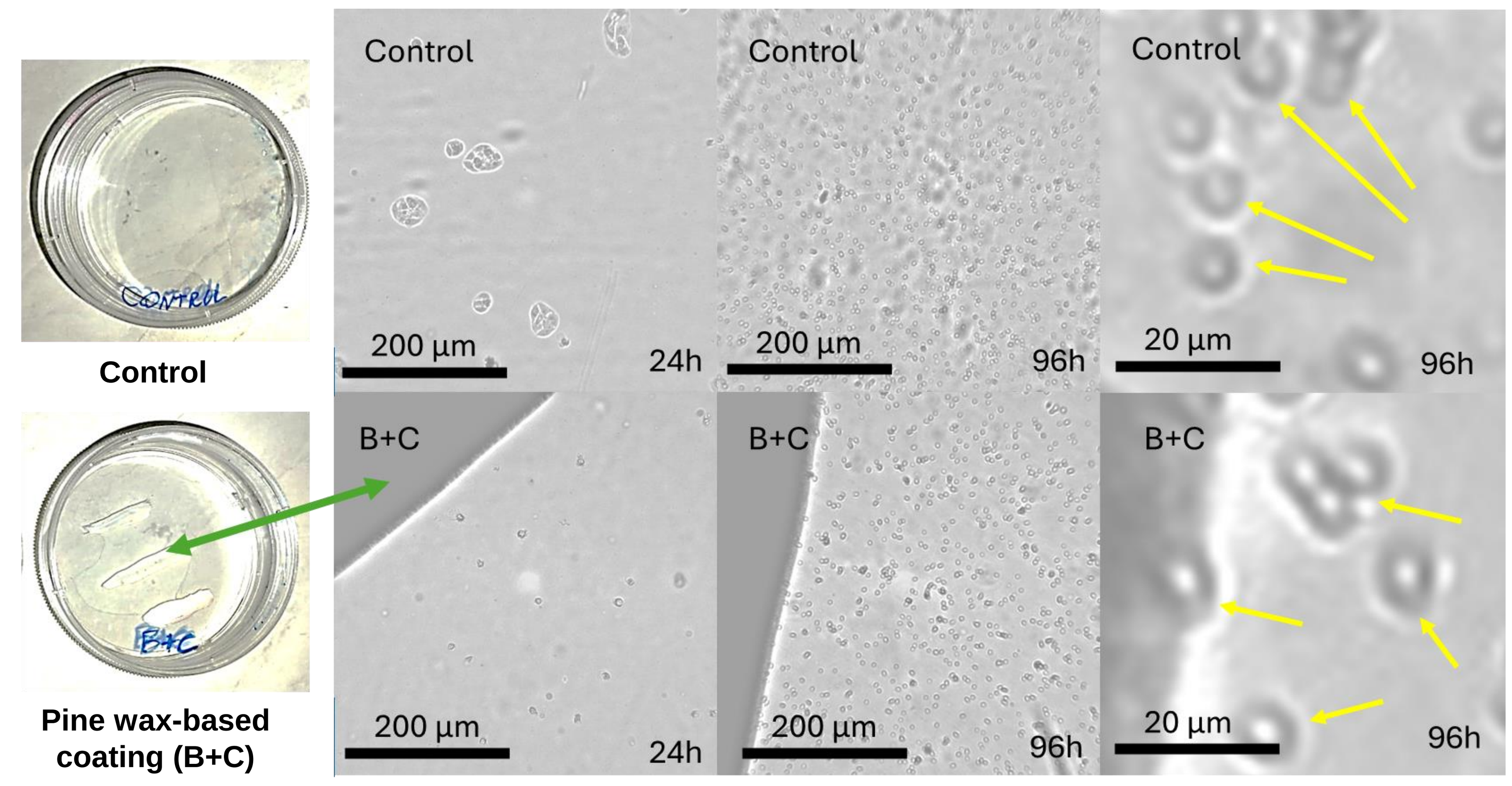


**Figure 1.** Cell culture assays on HaCaT cells demonstrate that **the pine bark wax-based coating (B+C) is biocompatible**, supporting normal cell growth at 24 h and 96 h without observable cytotoxic effects. Cell morphology and confluence in treated samples are comparable to controls. Yellow arrows in the 96 h images indicate rounded cells, which may represent isolated dead or damaged cells, but do not suggest widespread toxicity.

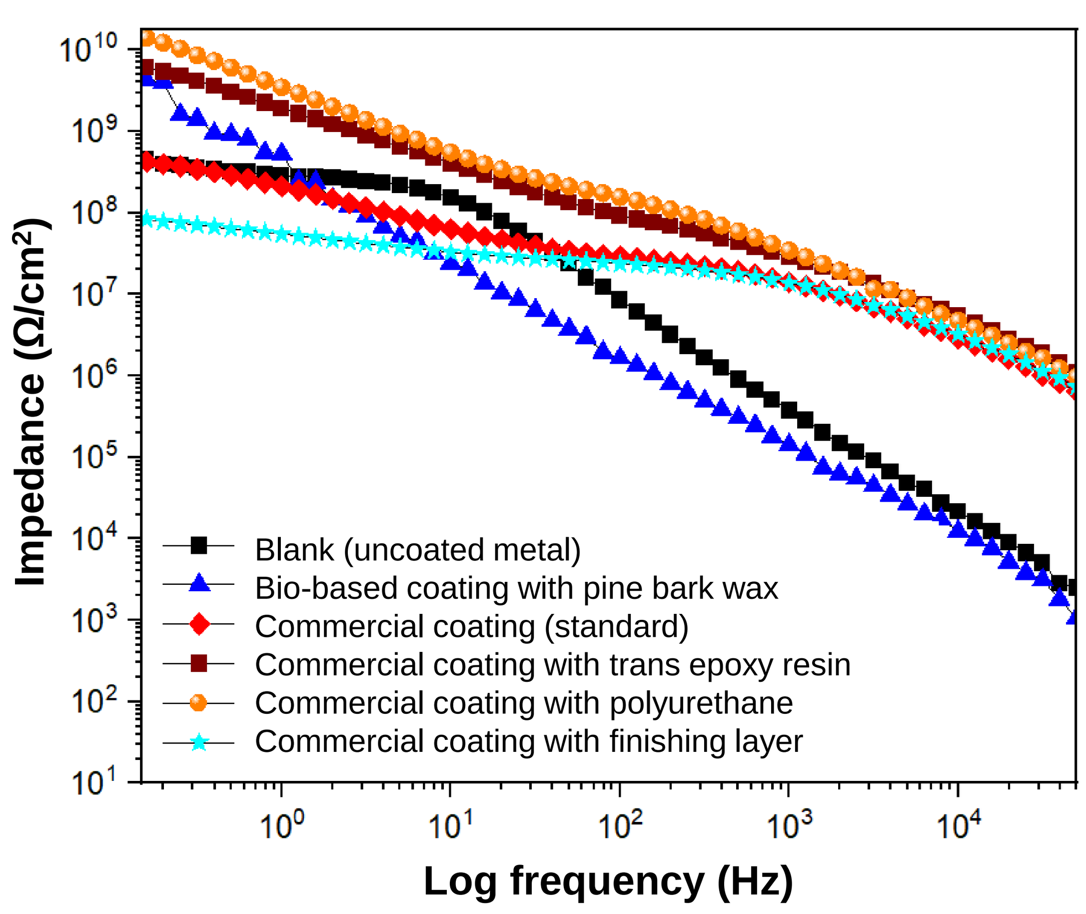


**Figure 2.**
The biobased coating exhibits a **high real impedance** of approximately **$10^{10}$ Ω/cm²** at low frequencies, indicating excellent barrier properties against corrosion. Its impedance remains **stable across the frequency range**, suggesting a dense, uniform structure with low porosity and strong electrochemical resistance. These characteristics position it on par with commercial anticorrosive coatings, confirming its effectiveness as a sustainable, high-performance protective solution.

## CONCLUSION

The pine bark wax-based coating demonstrated excellent anticorrosive performance, with an impedance modulus of $10^{10}$ Ω·cm², comparable to commercial coatings. This indicates a highly effective barrier against corrosive agents. Additionally, cytotoxicity assays using HaCaT cells confirmed the biocompatibility of the coating, as treated cells maintained normal morphology and proliferation over 96 hours, with no significant signs of toxicity. These results support the potential of this biobased formulation as a sustainable and safe alternative for protective coatings in industrial and biomedical applications.

## FUTURE WORK / REFERENCES

Future studies should include detailed physicochemical, mechanical, and electrochemical analyses—such as contact angle measurements, thermal stability (TGA/DSC), adhesion and tensile strength tests, salt spray exposure, and cyclic voltammetry—to fully characterize the coating's performance under various conditions. Additionally, biological evaluations should be expanded to include mitochondrial activity assays (e.g., MTT), apoptosis and necrosis detection, and oxidative stress markers, to better understand the cellular response and ensure long-term biocompatibility. These efforts will strengthen the scientific foundation for the coating's application in industrial and biomedical contexts.

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