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# Radar absorbing Films Based on Chitosan–Polyvinyl Alcohol Incorporated with Hydroxyapatite from Yellowfin Tuna Bone Waste

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**Abstract**

Radar absorbing films (RAF) play a crucial role in stealth technology by reducing radar reflections and thereby lowering the detectability of objects. Conventional inorganic absorbers such as ferrite and carbon are effective but present limitations due to their high density, cost, and limited environmental compatibility. These challenges have driven interest in developing lightweight, sustainable, and polymer-based alternatives. Yellowfin tuna bone waste, containing approximately 60–70% minerals predominantly composed of hydroxyapatite, offers a promising source for enhancing electromagnetic absorption while simultaneously supporting waste valorization. This study aimed to evaluate the mechanical and electromagnetic properties of RAF from chitosan, polyvinyl alcohol (PVA), and hydroxyapatite derived from yellowfin tuna bone waste. The films were produced with varying chitosan concentrations (0%, 0.5%, 1%, 1.5%, 2%) and characterized for tensile strength, elongation, stiffness, and electromagnetic absorption across the 5–10 GHz frequency range. The tensile strength increased from 0.105 MPa in the control to 0.151 MPa at 2% chitosan, while elongation declined from 39% at 0.5% chitosan to 21% at 1.5% chitosan. The optimal absorption was observed at 1.5% chitosan, exhibiting a reflection loss of 14 dB at 8 GHz, which corresponds to approximately 96% absorption with only 4% reflection. Overall, the films demonstrated a favorable balance between mechanical integrity and electromagnetic wave absorption, highlighting their potential as lightweight, flexible, and environmentally sustainable radar absorbing materials.

**Keywords:** Chitosan; Mechanical Properties; Hydroxyapatite; Radar absorbing material; Yellowfin Tuna.

## INTRODUCTION

Radar absorbing films (RAF) are essential in stealth technology because they reduce the radar cross section of objects, thereby making them more difficult to detect. These films functioned by absorbing incident electromagnetic waves and converting them into heat or other harmless forms of energy, which decreases the intensity of the signal reflected back to the radar. Traditionally, many RAF have been fabricated from inorganic materials such as ferrite, carbon, and silicon carbide. Although these materials demonstrate excellent radar wave absorption, their high density, cost, and limited environmental compatibility restrict their broader applications (Chen et al. 2021).

To address these limitations, recent research has focused on polymers and naturally derived materials that are lightweight, flexible, and environmentally sustainable. Among these, fishery by-products represent a promising source. Tuna is one of the most widely processed fish globally, yet its industry generates considerable waste. Only about 50–60% of the total body weight is utilized as edible meat, while the remainder, including the head, skin, and bones, is often discarded. Tuna bones constitute the largest fraction of this waste and, if unmanaged, can contribute to environmental burdens. Importantly, these bones contain a significant amount of minerals. Previous studies have shown that 60–70% of the dry weight of bones is mineral, predominantly in the form of calcium phosphate. In yellowfin tuna bones, calcination yields a mineral composition of approximately 62.31% calcium oxide (CaO) and 37.46% phosphorus pentoxide (P2O5), confirming hydroxyapatite as the principal component (Mutmainnah et al. 2017).

Hydroxyapatite (Ca10(PO4)6(OH)2), the main inorganic constituent of bones and teeth, possesses dielectric and magnetic properties that make it valuable for electromagnetic wave absorption and for enhancing the structural stability of composites. Incorporating hydroxyapatite into polymer films can improve absorption by facilitating stronger wave interactions and increasing polarization effects. Previous studies have demonstrated that hydroxyapatite-based composites can achieve reflection loss values below −10 dB in the microwave frequency range, corresponding to more than 90% absorption of incident energy. Furthermore, the presence of hydroxyapatite particles promotes interfacial polarization, a key mechanism in effective radar wave attenuation. Thus, utilizing hydroxyapatite derived from yellowfin tuna bone waste not only improves the functional performance of RAF but also contributes to waste valorization and environmental sustainability (He et al. 2023).

Chitosan, a biodegradable natural polymer derived from chitin in fishery waste, exhibits dielectric properties that support electromagnetic wave absorption. However, its mechanical strength and absorption capacity are often insufficient when used alone. Polyvinyl alcohol (PVA), a synthetic polymer, offers strong mechanical properties, excellent film-forming ability, and good compatibility with fillers (Yang et al. 2024). When blended with chitosan, PVA enhances both mechanical strength and flexibility (He et al. 2024). By integrating chitosan, PVA, and hydroxyapatite sourced from yellowfin tuna bone waste, it is possible to develop RAF that are lightweight, flexible, mechanically robust, and eco-friendly.

The present study focuses on the fabrication of RAF composed of chitosan, PVA, and hydroxyapatite derived from yellowfin tuna bone waste. The films were evaluated for their magnetic properties to determine their radar wave absorption capacity and for their mechanical properties to assess strength and flexibility. This study aimed to evaluate the mechanical and electromagnetic properties of RAF from chitosan, polyvinyl alcohol (PVA), and hydroxyapatite derived from yellowfin tuna bone waste. The findings are expected to contribute to the development of sustainable, high-performance materials for future stealth technology applications.

## MATERIALS AND METHOD

### Material and equipment

Yellowfin tuna bone waste was collected from the fisheries industry in Jakarta. Chitosan powder (deacetylation degree of 93%) and PVA (88.2% hydrolized) were purchased from local chemical store. Other chemicals such as acetone, distilled water, $H_3PO_4$, and, NaOH were used from the lab stock. The equipment consisted of an oven and a hot plate with a magnetic stirrer for drying and mixing solutions, glass molds for film casting, a micrometer for thickness measurements, a Universal Testing Machine for evaluating mechanical properties, and a Vector Network Analyzer (VNA) for characterizing electromagnetic properties in the 5–10 GHz frequency range. Basic laboratory apparatus, including beakers, pipettes, and filtration devices, were also employed.

### Synthesis hydroxyapatite

Hydroxyapatite was synthesized from yellowfin tuna bones using the precipitation method. The bones were first cleaned by boiling, drying, and soaking in acetone for three days to remove oils and organic residues. After drying, they were heated at 105 °C and subsequently calcined at 900 °C for five hours to produce calcium oxide (CaO). The CaO was dissolved in distilled water, followed by the dropwise addition of 0.6 M $H_3PO_4$ solution under continuous stirring at 90 °C, with the pH adjusted to 10 using NaOH. The resulting hydroxyapatite precipitate was allowed to settle, filtered, washed, dried, and finally calcined again at 900 °C for five hours to obtain pure hydroxyapatite powder (Mutmainnah et al. 2017).

### Preparation of RAF

RAF were prepared using the solution casting method following Pugar et al. (2024). Chitosan solution was prepared by dissolving 2.5% (b/v) chitosan in 0.1 M acetic acid and stirring for 24 hours until homogeneous. The chitosan concentration in the films was varied at 0%, 0.5%, 1%, 1.5%, and 2%. Separately, a PVA solution was prepared by dissolving 5% (b/v) PVA in distilled water at 80–90 °C for two hours. Both solutions were then mixed and stirred with a magnetic stirrer at room temperature for four hours. Subsequently, 0.1 g of hydroxyapatite was added, and the mixture was stirred until uniform. The final solution was poured into glass molds, dried at room temperature for approximately 72 hours, and further dried in an oven at 60 °C for 24 hours. The fully dried films were carefully peeled from the molds and subjected to characterization.

### Mechanical properties measurement

The mechanical properties of the films were evaluated according to ASTM D882 using a Universal Testing Machine (Toyoseiki Strograph MI, 50 kgf capacity). Film thickness was measured at five different points with a micrometer to ensure accuracy. Tensile testing was then conducted at a crosshead speed of 50 mm/min at room temperature. From these tests, tensile strength, Young's modulus, and elongation at break were obtained to assess the strength and flexibility of the films (Amalia et al. 2018).

### Electromagnetic properties test

The electromagnetic properties were analyzed using a Vector Network Analyzer (VNA, Agilent N5230C PNA-L) with the waveguide method in the 5–10 GHz frequency range. The films were cut to match the waveguide dimensions and placed in the sample holder for measurement. Reflection loss (RL) was calculated from the obtained data to evaluate the radar absorption performance of the films in the microwave range (Jahan et al. 2019).

### Data analysis

Data were analyzed descriptively. Mechanical properties were interpreted based on tensile strength, elongation, and Young's modulus to determine the strength, flexibility, and rigidity of the films. Radar absorption performance was evaluated from reflection loss values in the 5–10 GHz range, covering both the C-band (4–8 GHz) and X-band (8–12 GHz). Reflection, absorption, and dielectric constant values were also calculated to examine the films' interaction with electromagnetic waves. The analysis focused on identifying the lowest RL values, absorption rates, and their correlation with mechanical properties.

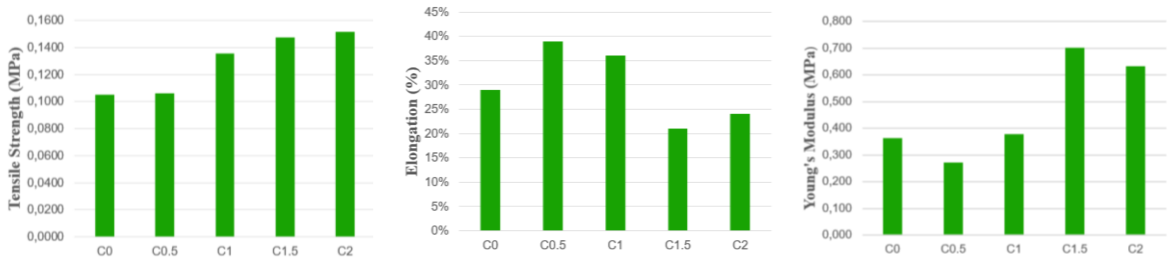
## RESULTS AND DISCUSSION

### Mechanical properties

The tensile strength of the chitosan–PVA–hydroxyapatite films increased with the addition of chitosan (Figure 1a). The control sample without chitosan exhibited the lowest value at approximately 0.105 MPa, whereas the highest tensile strength was observed in the film containing 2% chitosan, reaching about 0.151 MPa. This improvement suggests that chitosan strengthens the polymer network by forming interactions with PVA and facilitating a more uniform distribution of hydroxyapatite particles, resulting in a more compact and stable structure. Similar findings were reported in chitosan–PVA hydrogels with hydroxyapatite mineralization, which demonstrated higher tensile strength compared to the control (Bi et al. 2019). The incorporation of hydroxyapatite into chitosan-based composites has also been shown to enhance tensile strength and stiffness, although it can compromise flexibility (Alanis-Gómez et al. 2022). Overall, the present results confirm that increasing chitosan content enhances the strength and stability of the films, which is crucial for applications requiring reliable mechanical durability.

In contrast, the elongation at break displayed an opposite trend to tensile strength (Figure 1b). The highest elongation was recorded in the film with 0.5% chitosan at approximately 39%, while the lowest value was observed in the film with 1.5% chitosan at around 21%. A small amount of chitosan appears to enhance flexibility by allowing greater mobility of polymer chains, whereas higher concentrations lead to a denser and more rigid network, thereby reducing elasticity. This trend is consistent with previous reports indicating that the addition of hydroxyapatite to chitosan-based composites increases strength and stiffness but decreases plastic deformation (Alanis-Gómez et al. 2022). These findings suggest that films with lower chitosan content are more flexible, whereas higher chitosan concentrations yield stronger but less elastic films.

Young's modulus also increased with the addition of chitosan (Figure 1c). The control film exhibited the lowest modulus at approximately 0.363 MPa, while the highest value was recorded in the film with 1.5% chitosan, reaching about 0.701 MPa. Although the modulus slightly decreased at 2% chitosan, it remained higher than that of the control. This indicates that the incorporation of chitosan enhances film stiffness, likely due to the formation of a tighter and more robust network through interactions among chitosan, PVA, and hydroxyapatite. A similar stiffening effect has been reported in chitosan–PVA hydrogels mineralized with hydroxyapatite, which exhibited increased rigidity as a result of their denser structure (Bi et al. 2019). Other studies on chitosan composites have also confirmed that hydroxyapatite addition improves stiffness and strength at the expense of elasticity (Alanis-Gómez et al. 2022). Collectively, these results demonstrate that increasing chitosan content produces films with greater rigidity and mechanical stability. Films with low chitosan content (0.5%) are more flexible, whereas those with higher concentrations (1.5–2%) are stronger and stiffer but less elastic.




(a) (b) (c)

**Figure 1.** Mechanical properties of RAF (a) tensile strength, (b) elongation, and (c) Young's modulus

Note: C0= Chitosan 0%, PVA 5%, Hydroxyapatite 0.1 gram
C0.5= Chitosan 0.5%, PVA 5%, Hydroxyapatite 0,1 gram
C1= Chitosan 1%, PVA 5%, Hydroxyapatite 0.1 gram
C1.5= Chitosan 1.5%, PVA 5%, Hydroxyapatite 0.1 gram
C2= Chitosan 2%, PVA 5%, Hydroxyapatite 0.1 gram

### Electromagnetic properties

Reflection loss (RL) is a key parameter to evaluate how effectively the films absorb electromagnetic waves. A material is generally considered a good absorber when the RL value is below –10 dB, corresponding to more than 90% wave energy absorption (Du, 2022). From the data, several chitosan-PVA-hydroxyapatite film formulations achieved RL values below –10 dB within the 5–10 GHz frequency range (Figure 2a). At 1.5% chitosan concentration, the RL value reached around –12 dB at 8 GHz, indicating that only about 3.7% of the incident energy was reflected, while approximately 96.3% was absorbed. At certain compositions, absorption performance was even stronger, with RL values approaching –31 dB, consistent with previous reports that chitosan incorporation enhances electromagnetic absorption (Sofyan et al., 2017).

The absorption percentage analysis confirms this trend (Figure 2b). The composite films exhibited varying absorption levels depending on frequency, with a significant increase at 1.5% chitosan, reaching above 90% absorption near 8 GHz. This observation aligns with the RL criteria, where values below –10 dB correspond to high absorption efficiency. The enhanced absorption is attributed to interfacial polarization between chitosan, PVA, and hydroxyapatite, which strengthens the wave attenuation mechanism.

Meanwhile, the low reflection percentage further demonstrates the films' effectiveness (Figure 2c). The reduced reflectivity is linked to homogeneous filler distribution and favorable interfacial interactions, minimizing backward scattering of electromagnetic waves. Similar behavior has been reported in other chitosan-based composites, where optimized filler dispersion lowers reflection while enhancing absorption efficiency (Sofyan et al., 2017).

The dielectric properties provide further insight into the absorption mechanism. The real part of the dielectric constant (ε′) reflects the material's capacity to store electrical energy, while the imaginary part (ε″) represents energy dissipation as heat. An effective absorber requires a balanced combination of both. In this study, increasing chitosan concentration influenced both ε′ and ε″, with the 1.5% formulation exhibiting high ε′ for energy storage and elevated ε″ for energy loss (Figure 2d). This balance explains the optimal RL and absorption performance observed. Previous studies (Li et al., 2017; Zhang et al., 2017; Mishra et al., 2020; Vaganathan et al., 2022) have similarly emphasized that interfacial polarization, conductivity, and uniform filler distribution contribute to enhanced dielectric response and wave attenuation.

Overall, the results demonstrate that chitosan-PVA-hydroxyapatite composite films possess strong electromagnetic absorption capability, characterized by RL values below –10 dB, absorption above 90%, low reflection, and balanced dielectric properties. The formulation with 1.5% chitosan shows the most promising performance, making these films suitable candidates for radar absorbing materials in microwave frequency applications.

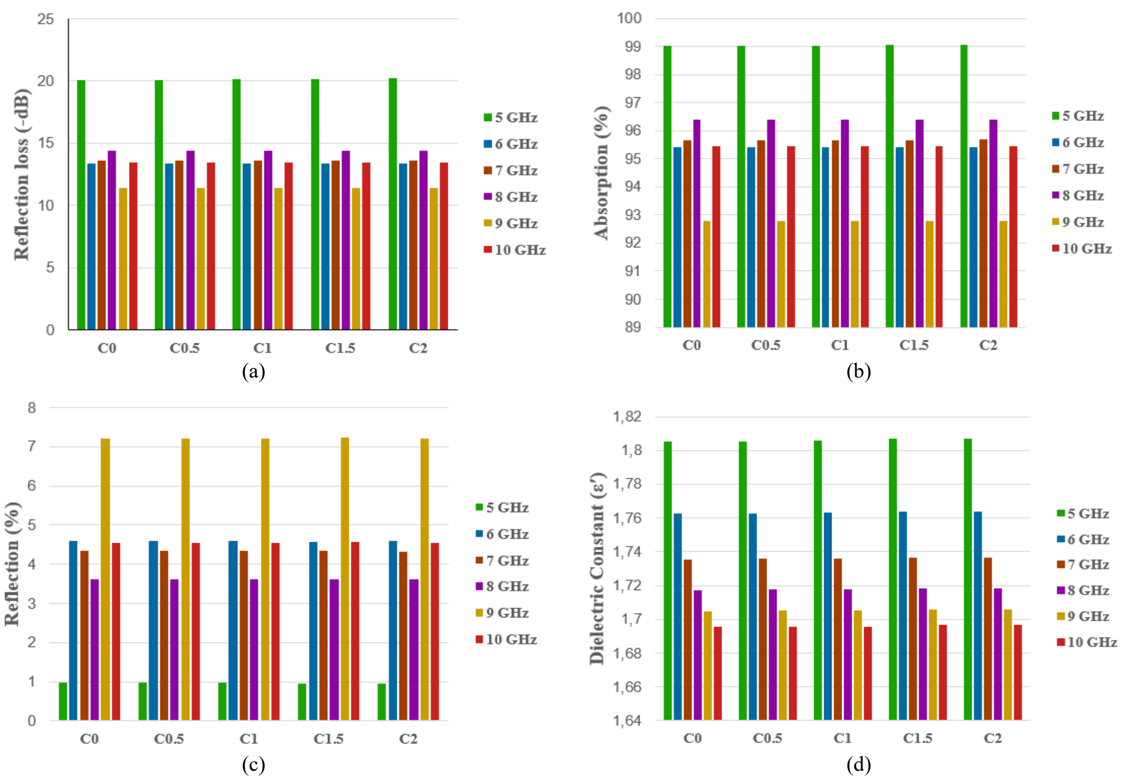



**Figure 2.** Electromagnetic properties RAF (a) reflection loss, (b) absorption, (c) reflection, and (d) dielectric constant
Note: C0= Chitosan 0%, PVA 5%, Hydroxyapatite 0.1 gram
C0.5= Chitosan 0.5%, PVA 5%, Hydroxyapatite 0,1 gram
C1= Chitosan 1%, PVA 5%, Hydroxyapatite 0.1 gram
C1.5= Chitosan 1.5%, PVA 5%, Hydroxyapatite 0.1 gram
C2= Chitosan 2%, PVA 5%, Hydroxyapatite 0.1 gram

**Mechanical–Electromagnetic Properties Correlation**

The interdependence between mechanical reinforcement and electromagnetic absorption in chitosan PVA hydroxyapatite films can be explained through microstructural densification and dielectric polarization theory. The incremental addition of chitosan enhances tensile strength and Young's modulus because of stronger intermolecular interactions and filler–matrix bonding, while elongation decreases as a result of reduced free volume and chain mobility (Hadi & Farhan, 2025; Ramesan et al. 2024). This densification promotes an increase in contact area among phases, which is crucial for interfacial polarization. Interfacial polarization is a key mechanism that drives dielectric loss at microwave frequencies by facilitating space charge relaxation (Kruzelak et al., 2021).

Consequently, the formulation at 1.5% chitosan achieves the optimal electromagnetic response, with reflection loss around –12 dB at 8 GHz (corresponding to approximately 96% absorption), due to a finely tuned balance between ε′ (energy storage) and ε″ (energy dissipation). At lower chitosan content (e.g., 0.5 %), the network remains loose, limiting interfacial polarization and dissipative mechanisms; ε′ may remain moderate, but ε″ is insufficient to ensure strong absorption (Kruzelak et al., 2021). Conversely, at higher chitosan content (e.g., 2 %), excessive stiffness and increased solution viscosity during casting may induce filler agglomeration and hamper dipole relaxation dynamics; this disrupts impedance matching and reduces absorption efficiency despite increased mechanical strength (Soares et al., 2021).

In essence, moderate mechanical stiffening optimizes the dielectric landscape by maximizing interfacial area and minimizing structural defects that lead to reflection. Excessive stiffening, however, constrains polarization dynamics and impairs impedance matching. The convergence of an intermediate-high modulus, adequate tensile strength, and residual ductility at 1.5 % chitosan yields the most favorable synergy of low reflection loss, high absorption, and sufficient mechanical robustness for practical applications.

## CONCLUSIONS

This study demonstrated that the incorporation of chitosan into PVA–hydroxyapatite composite films significantly influenced both mechanical and electromagnetic properties. Increasing chitosan content enhanced tensile strength and Young's modulus, indicating stronger and stiffer films, although elongation at break decreased due to reduced flexibility. Electromagnetic characterization showed that the films effectively absorbed microwave radiation in the 5–10 GHz range, with reflection loss (RL) values below –10 dB, corresponding to more than 90% absorption. The optimal performance was obtained at 1.5% chitosan, where mechanical rigidity and dielectric properties (ε′ and ε″) reached a balanced state, resulting in strong absorption (~96.3%) and low reflection. These findings highlight the interdependence of mechanical reinforcement and electromagnetic absorption, where controlled chitosan concentration governs both structural compactness and interfacial polarization mechanisms. Overall, the chitosan–PVA–hydroxyapatite films show strong potential as radar-absorbing materials with adequate mechanical durability, making them promising candidates for stealth and microwave shielding applications.

***Authors' Contributions:*** Esa Ghanim Fadhallah designed the study. Fran Denis Sitohang and Muhammad Hibban Fadlurrohman Ayyasy carried out the laboratory work. Esa Ghanim Fadhallah analyzed the data. Fran Denis Sitohang and Muhammad Hibban Fadlurrohman Ayyasy wrote the manuscript. All authors read and approved the final version of the manuscript.

***Competing Interests:*** The authors declare that there are no competing interests.

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