

# *Hydroxyapatite Recovery from Fish Scales and Its Industrial Applications*

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## **ABSTRACT**

Fish processing industries generate large quantities of waste materials such as scales, bones, skin, and viscera, which often create serious environmental pollution problems when discarded without proper management. Among these by-products, fish scales are considered a valuable natural source of hydroxyapatite, a calcium phosphate biomaterial widely used in biomedical and industrial applications. Hydroxyapatite possesses excellent biocompatibility, bioactivity, and structural similarity to human bone and teeth, making it highly suitable for tissue engineering and regenerative medicine. Recent studies have focused on recovering hydroxyapatite from fish scales using different extraction techniques including acid-alkali treatment, calcination, deep eutectic solvent extraction, and ionic liquid methods. Fish scale-derived hydroxyapatite has demonstrated promising applications in bone tissue engineering, dental materials, wastewater treatment, drug delivery systems, and environmental remediation. In addition, the utilization of fish scale waste supports sustainable waste management and circular bioeconomy concepts by converting low-value biological waste into high-value industrial products. This article highlights the recovery methods, characterization, industrial applications, environmental significance, and prospects of hydroxyapatite obtained from fish scales.

## INTRODUCTION

The rapid expansion of fish processing industries has resulted in the generation of enormous quantities of biological waste, including fish scales, bones, skin, and viscera. Among these by-products, fish scales account for nearly 4-5% of the total body weight of fish and are often discarded without proper utilization, leading to environmental pollution and waste management problems (Patwary *et al.*, 2025). In many developing countries with intensive aquaculture production, disposal of fish scale waste has become a growing environmental concern. Traditionally, these wastes were used only for low-value products such as animal feed or fertilizers, despite containing several valuable biomaterials.

Recent scientific interest has shifted toward converting fish scale waste into high-value industrial products through sustainable waste valorization approaches. Fish scales are naturally rich in collagen, calcium phosphate, and hydroxyapatite, which makes them an attractive raw material for biomedical and industrial applications (Mobarak *et al.*, 2024). Among these compounds, hydroxyapatite (HAp) has gained remarkable attention because of its excellent biocompatibility, bioactivity, and structural similarity to human bone and teeth.

The recovery of hydroxyapatite from fish scales not only reduces environmental burden but also supports the concept of circular bioeconomy by transforming waste into economically valuable products. Today, fish scale-derived hydroxyapatite is being explored for applications in bone tissue engineering, dental materials, wastewater treatment, drug delivery systems, and other advanced industrial sectors (Núñez-Tapia *et al.*, 2026). Therefore, recovery of hydroxyapatite from fish scales represents an ecofriendly and

sustainable strategy with significant industrial potential.

### **Fish Scales as a Valuable Biomaterial Source**

Fish scales are highly mineralized biological structures that serve as protective coverings in fishes. They mainly consist of organic components such as collagen and inorganic minerals including calcium-deficient hydroxyapatite and calcium phosphate (Mobarak *et al.*, 2024). Due to this unique composition, fish scales are increasingly recognized as an important source of biomaterials.

Unlike synthetic raw materials, fish scales are renewable, inexpensive, and abundantly available from fish markets and seafood processing industries. Large quantities of fish scales generated during fish processing are usually discarded into the environment, causing unpleasant odor and microbial contamination. However, scientific studies have demonstrated that these wastes can be converted into valuable products with industrial significance.

Fish scale-derived hydroxyapatite possesses characteristics very similar to the mineral phase of human bones and teeth. In addition, fish scales contain trace minerals such as magnesium, sodium, zinc, and fluoride that may further enhance the biological performance of hydroxyapatite in biomedical applications (Patwary *et al.*, 2025). Because of these advantages, fish scales are now considered an alternative natural source for hydroxyapatite production instead of costly synthetic materials or mammalian bone sources.

## What is Hydroxyapatite?

Hydroxyapatite (HAp) is a naturally occurring calcium phosphate biomaterial with the chemical formula  $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ . It is the primary inorganic constituent of human bone and teeth and is widely used in biomedical engineering due to its excellent biocompatibility and osteoconductive properties (Mobarak *et al.*, 2024).

The calcium-to-phosphorus (Ca/P) ratio of stoichiometric hydroxyapatite is approximately 1.67, which closely resembles that of natural bone mineral. This similarity enables hydroxyapatite to integrate effectively with bone tissues without causing severe immune reactions. Because of this property, hydroxyapatite is extensively used in orthopedic implants, bone grafts, dental restoration materials, and tissue engineering scaffolds.

Apart from biomedical uses, hydroxyapatite also possesses excellent adsorption capacity for heavy metals and toxic pollutants. Its porous structure and ionic properties make it suitable for environmental applications such as wastewater treatment and metal ion removal (Bilal *et al.*, 2024). These multifunctional properties have increased the industrial demand for hydroxyapatite worldwide.

## Recovery of Hydroxyapatite from Fish Scales

The extraction of hydroxyapatite from fish scales generally involves removal of organic components followed by isolation of mineralized materials. Several methods have been developed for efficient hydroxyapatite recovery depending on the desired purity and industrial application.

### Common Extraction Steps

- Collection and washing of fish scales
- Removal of attached tissues and impurities

- Drying of scales
- Acid or alkali treatment
- Calcination at high temperature
- Grinding into fine hydroxyapatite powder

### Major Extraction Methods

#### Acid - Alkali Treatment

In this method, fish scales are treated with hydrochloric acid and sodium hydroxide to remove proteins and organic matter before calcination. Mobarak *et al.* (2024) successfully prepared highly crystalline hydroxyapatite from fish scales using this technique.

#### Calcination Method

Calcination is one of the most widely used and economical methods for hydroxyapatite production. Fish scales are heated at temperatures ranging from 800°C to 1100°C to eliminate organic substances and obtain purified hydroxyapatite crystals (Patwary *et al.*, 2025).

#### Deep Eutectic Solvent Extraction

Liu *et al.* (2021) introduced an environmentally friendly extraction technique using deep eutectic solvents for hydroxyapatite recovery from fish scales. This method showed high extraction efficiency and improved sustainability.

#### Ionic Liquid Extraction

Recent studies have also explored ionic liquid-based extraction methods, where ionic liquids selectively dissolve collagen while leaving hydroxyapatite intact for separation and recovery (Patwary *et al.*, 2025).

### Characterization of Extracted Hydroxyapatite

The quality and purity of fish scale-derived hydroxyapatite are evaluated using different analytical techniques.

## Important Characterization Techniques

- **X-ray Diffraction (XRD):** Determines crystal structure and phase purity
- **Fourier Transform Infrared Spectroscopy (FTIR):** Identifies functional groups
- **Scanning Electron Microscopy (SEM):** Examines particle morphology
- **Energy Dispersive X-ray Analysis (EDX):** Determines elemental composition
- **Thermogravimetric Analysis (TGA):** Evaluates thermal stability

Studies by Bilal *et al.* (2024) and Liu *et al.* (2021) confirmed that fish scale-derived hydroxyapatite possesses good crystallinity, high purity, and suitable structural properties for industrial applications.

## Industrial Applications of Fish Scale-Derived Hydroxyapatite

### Bone Tissue Engineering

One of the most important applications of hydroxyapatite is in bone tissue engineering. Since hydroxyapatite closely resembles the inorganic mineral composition of human bone, it can support bone regeneration and repair. Fish scale-derived hydroxyapatite has demonstrated excellent biocompatibility and cell viability, making it suitable for orthopedic and regenerative medicine applications (Núñez-Tapia *et al.*, 2026).

Hydroxyapatite-based scaffolds are commonly used for treating bone fractures, bone defects, and tissue damage. Studies have shown that fish scale-derived hydroxyapatite promotes osteoblast proliferation and enhances bone healing efficiency. Moreover, naturally derived hydroxyapatite may possess superior biological performance compared to synthetic hydroxyapatite because of the presence of beneficial trace elements.

## Dental Applications

Hydroxyapatite is widely used in dental restoration and oral care products due to its similarity to tooth enamel. Fish scale-derived hydroxyapatite can be utilized in dental fillers, coatings for implants, and remineralization agents in toothpaste formulations. Its bioactive nature helps in strengthening tooth structure and improving implant integration.

### Wastewater Treatment

Hydroxyapatite has gained considerable attention as an adsorbent for removing toxic heavy metals from contaminated water. Bilal *et al.* (2024) demonstrated that fish scale-derived hydroxyapatite effectively adsorbed Pb(II) ions from wastewater. Similarly, Liu *et al.* (2021) reported strong adsorption capacity for lead, copper, zinc, and silver ions.

The adsorption efficiency of hydroxyapatite is mainly due to its porous structure and ionic exchange properties. Therefore, fish scale-derived hydroxyapatite is emerging as a low-cost and ecofriendly material for environmental remediation and water purification technologies.

### Drug Delivery Systems

Nano-sized hydroxyapatite particles are increasingly explored as carriers for controlled drug delivery systems. Their porous surface enables efficient loading and gradual release of therapeutic compounds. Fish scale-derived hydroxyapatite may serve as a biocompatible alternative for pharmaceutical applications.

### Cosmetic and Biomedical Products

Hydroxyapatite is also used in cosmetic formulations and biomedical coatings because of its non-toxic and bioactive nature. It can be incorporated into skincare products, implant coatings, and bioactive composites for medical use.

## Environmental and Economic Significance

Recovery of hydroxyapatite from fish scales contributes significantly to sustainable waste management. Instead of disposing fish processing waste into the environment, industries can convert these materials into valuable industrial products. This approach reduces environmental pollution while generating additional economic benefits.

The valorization of fish scale waste also supports circular economy principles by promoting resource efficiency and sustainable utilization of biological wastes (Patwary *et al.*, 2025). In countries with large aquaculture industries, hydroxyapatite production from fish scales may create new opportunities for waste-based biotechnology industries.

## Advantages of Fish Scale-Derived Hydroxyapatite

- Ecofriendly and sustainable source
- Low-cost raw material
- High biocompatibility
- Similarity to human bone mineral
- Good adsorption properties
- Renewable and abundantly available
- Reduced environmental pollution

## Challenges and Future Perspectives

Despite its advantages, several challenges still limit large-scale commercialization of fish scale-derived hydroxyapatite. Variations in fish species, extraction conditions, and mineral composition may influence the quality of the final product. Standardization of extraction procedures and industrial processing methods remains necessary.

Future research should focus on developing advanced nanostructured hydroxyapatite materials with improved mechanical and biological properties. Further exploration of fish scale-derived hydroxyapatite in

regenerative medicine, environmental engineering, and nanotechnology could expand its industrial importance.

## CONCLUSION

Fish scales, once considered an unwanted waste product of the fish processing industry, are now emerging as an important natural source of hydroxyapatite with enormous industrial potential. The recovery of hydroxyapatite from fish scales provides an ecofriendly and sustainable approach for converting biological waste into high-value biomaterials. Due to its excellent biocompatibility, adsorption capacity, and structural similarity to human bone, fish scale-derived hydroxyapatite has found promising applications in bone tissue engineering, dentistry, wastewater treatment, and biomedical industries.

The growing interest in sustainable biomaterials and circular bioeconomy concepts further highlights the importance of utilizing fish processing wastes efficiently. With continued scientific advancements and industrial development, fish scale-derived hydroxyapatite may become a major biomaterial for future biomedical and environmental applications.

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