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Sustainable Valorization of *Catla Catla* Fish Scales for the Development of Degradable Bioplastics

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Abstract

Plastic pollution from petroleum-based materials poses severe environmental risks. This study develops a biodegradable bioplastic synthesized from fish scales, a rich source of collagen and hydroxyapatite and an abundant seafood industry by-product. Fish scales were processed and combined with a red algae–derived binder and glycerine plasticizer, then molded into sheets. Characterization (FTIR, TGA, XRD, EDS) confirmed key biopolymer structures, thermal stability up to 220 °C, and partial crystallinity. The bioplastic exhibited 85% mechanical strength retention, fully biodegraded within 60 days under composting, and demonstrated suitability for low-heat packaging applications. This approach valorizes marine waste, reduces reliance on fossil-fuel plastics, and aligns with circular economy principles. The findings introduce a scalable, eco-friendly alternative that simultaneously addresses plastic pollution and seafood waste, presenting significant potential for sustainable materials science and industry adoption.

Keywords

fish waste, bioplastic, degradable, byproduct utilization, characterization

1 Introduction

Plastic pollution is one of the most pressing environmental challenges of the 21st century. Global plastic production exceeds 400 million tons annually, with a significant portion discarded into landfills, oceans, and natural ecosystems, where it may persist for centuries. Petroleum-based plastics are inherently non-biodegradable, contributing to soil, air, and marine pollution, and causing severe harm to biodiversity. Growing awareness of these environmental and health hazards has intensified the global demand for sustainable and eco-friendly alternatives [1].

Bioplastics have emerged as a promising solution, offering biodegradability and a reduced carbon footprint. Derived from renewable biological resources including starch, cellulose, plant oils, and proteins they decompose naturally, helping to mitigate waste accumulation. However, conventional plant-based feedstocks such as corn or sugarcane raise ethical and economic concerns by competing with food supplies and requiring substantial agricultural land, water, and fertilizers [2, 3].

To address these limitations, recent research has turned toward underutilized organic waste from agriculture, meat, and seafood processing as sustainable sources for biopolymer production. Among these, fish scales, an abundant by-product of the global seafood industry are particularly promising [4–6]. Millions of tons of fish are processed worldwide each year, generating substantial quantities of unused skin, bones, and scales. Often discarded untreated, these wastes contribute to environmental pollution. Fish scales are rich in type I collagen and hydroxyapatite, along with keratin and trace proteins, making them excellent candidates for biopolymer extraction [7]. Collagen can be hydrolyzed into gelatin, a versatile, film-forming biopolymer extensively used in pharmaceutical, food, and cosmetic applications. When combined with natural plasticizers (e.g., glycerol) or binders (e.g., starch), fish-scale-derived gelatin can be processed into flexible, transparent, biodegradable materials suitable for packaging and other single-use applications [8].

Utilizing fish scales confers multiple advantages: (1) sustainability and year-round availability in fishing regions such as India, Japan, Norway, and Indonesia [9]; (2) low raw material cost [10]; (3) no conflict with food resources [11];

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and (4) alignment with circular economy principles by valorizing waste into value-added products [12]. The resulting bioplastic has been shown to biodegrade within weeks to months under composting conditions, with lower greenhouse gas emissions compared to petroleum-based plastics, as verified by life cycle assessments.

Literature supports the feasibility of fish-scale bioplastics. Studies highlight the strong gelation and film-forming capacity of fish collagen, while previous studies reports rapid degradation in soil and marine environments [10]. Compositional tailoring through cross-linking with tannic acid, blending with starch or cellulose, or applying hydrophobic coatings can improve tensile strength, elasticity, and water resistance, as evident from previous literatures [13]. Recent innovations, including multifunctional reinforced bioplastics (MReB) and noncovalent self-assembly from other organic wastes, underscore a broader trend toward combining waste valorization with performance enhancement to meet packaging industry standards [14, 15].

Despite their potential, moisture sensitivity and moderate thermal limits remain challenges for gelatin-based bioplastics, necessitating further material engineering to expand their application scope. Ensuring regulatory compliance for food-contact and medical uses will also be critical for commercialization [16].

This study aims to develop and evaluate biodegradable bioplastics synthesized from *Catla catla* fish scales, focusing on material formulation, physicochemical characterization, mechanical performance, and biodegradability. By converting seafood waste into high-value materials, the work targets two major environmental issues plastic pollution and organic waste disposal while contributing to the United Nations Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water).

2 Materials and methods

2.1 Materials

Fish scales were procured from local markets and remaining chemicals were procured commercially.

2.2 Experimental

Initially, 50 g of freshly collected fish scales were thoroughly washed under running water to remove surface impurities and organic debris, followed by drying at 60 °C in a hot air oven for 48 h to reduce moisture content. The dried scales were then ground to a fine powder with a particle size corresponding to 625 mesh (~20 μm) to maximize surface area. The fish scale powder was dispersed in distilled water and combined with a gelling agent (red algae powder) and a plasticizer (3% glycerine, w/w relative to total solids). The mixture was maintained at 80 °C under continuous stirring to facilitate dissolution of the gelling agent, gelatinization of collagen, and uniform blending.

Once excess water had evaporated and a viscous mass was obtained, the material was thermoformed into thin sheets under heat and pressure. After curing at controlled conditions, the formed sheets were demolded, and excess flashes were carefully trimmed using a sharp blade. The final dried product had a measured mass of 11.56 g.

Fig. 1 represents the proposed process flowsheet.

2.3 Characterization of bioplastic film

Phase analysis and structural properties were determined using an X-Ray Diffractometer (Rigaku Miniflex 600, Rigaku Corporation, Japan). The elemental composition of magnesium titanate was found using an advanced energy-dispersive X-ray spectroscopy (EDS/EDX) platform equipped with state-of-the-art silicon drift detector (SDD) technology from EDAX Inc., USA. To assess the thermal

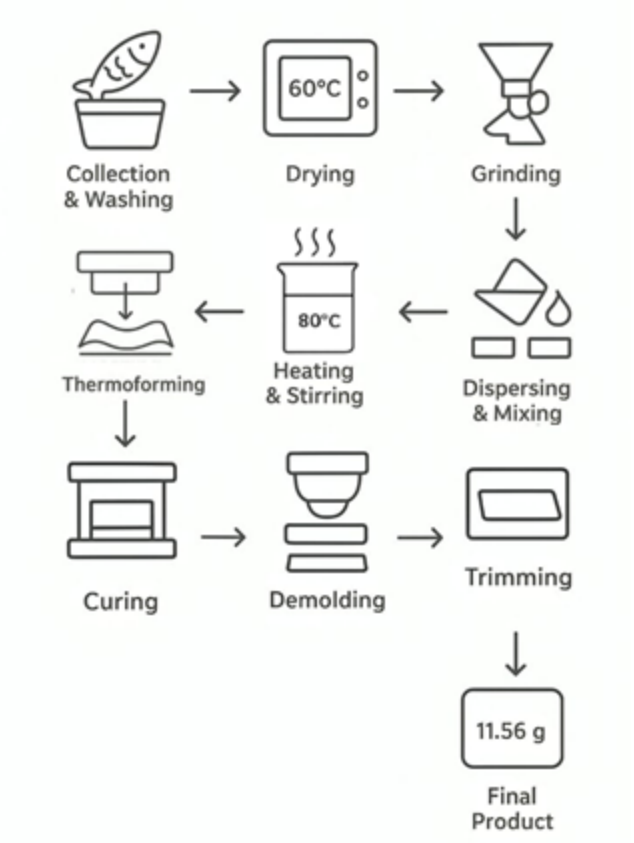


Fig. 1 Process flowsheet to produce bioplastic film

stability of bioplastic film, a simultaneous thermal analyzer (STA 7200, Hitachi HTG, Japan) was employed. Functional configurations of bioplastic film were analyzed using spectrum obtained using FT-IR spectrometer (Cary 630 FTIR with Diamond ATR from Agilent Technologies, USA). Surface morphology examinations were performed using a Scanning Electron Microscope (Vega 3, SBH, TESCAN Brno, S.R.O, Czech Republic). This comprehensive set of analytical techniques provides a thorough understanding of the structural, thermal, functional and morphological characteristics of bioplastic.

2.4 Assessment of bioplastic film

The assessment was performed according to [17].

2.4.1 Moisture content

Measured mass of bioplastic film ($W_{initial}$) was dried in a tray dryer at 105 °C until constant mass is achieved. The mass of the dried sample is W_{dry}. Moisture content is calculated by using Eq. (1).

$$\text{Moisture content}\% = \frac{W_{initial} - W_{dry}}{W_{initial}} \times 100 \quad (1)$$

2.4.2 Thickness

Thickness of the film was measured by using digital screw gauge (Digital Micrometer 0-1", ORTIZA, India).

2.4.3 Hot water solubility

Measured mass of the bioplastic film was immersed in hot distilled water (approximately 90 ºC) with mild stirring at 100 rpm. The percentage of solubility is calculated by using Eq. (2).

$$\text{Hot water solubility}\% = \frac{W_{initial} - W_{final}}{W_{final}} \times 100 \quad (2)$$

2.4.4 Texture, colour and opacity

Texture, color and opacity of the prepared bioplastics were determined manually by sensorial evaluation.

2.4.5 Mechanical strength

The tensile strength of the bioplastic sample, was tested using a UTM (Instron Machine Series 3369, Instron, USA) at room temperature (28 °C).

3 Results and discussions

3.1 Structural characterization

The X-ray diffraction (XRD) pattern of the bioplastic sample reveals a predominantly amorphous nature. The diffraction profile exhibits a broad hump centered around $2\theta \approx 18–22°$, characteristic of disordered molecular structures, and the absence of sharp, well-defined peaks indicates minimal crystalline domains as shown in Fig. 2. This broad amorphous halo suggests that the bioplastic matrix, likely composed of biopolymers such as gelatine, polysaccharides, or other organic constituents, lacks long-range order in its molecular arrangement [18].

The small fluctuations in intensity across the scan are attributed to background noise and minor structural irregularities but do not correspond to distinct crystalline phases. The amorphous structure is consistent with the expected physical properties of bioplastics flexibility, transparency, and ease of processing since crystallinity in polymeric materials often leads to brittleness.

3.2 EDS characterization

The energy dispersive X-ray spectroscopy (EDS) spectrum of the bioplastic synthesized from *Catla catla* fish scales confirms the presence of key elemental constituents, primarily carbon, oxygen, calcium, and phosphorus, as shown in Fig. 3. The dominant peaks of carbon and oxygen indicate the organic nature of the matrix, corresponding to proteinaceous collagen and other biopolymeric components that form the structural backbone of the bioplastic. The presence of calcium and phosphorus in moderate proportions confirms the retention of hydroxyapatite residues derived from the mineralized portion of the fish scales [6]. Quantitative analysis of bioplastic has been depicted in Table 1.

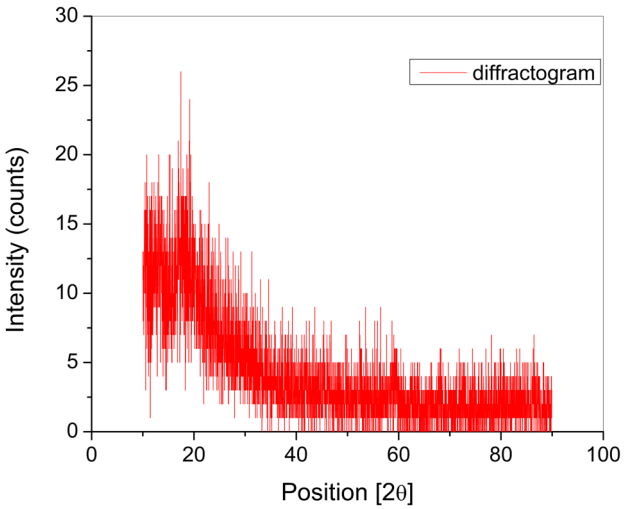


Fig. 2 XRD Graph of bioplastic

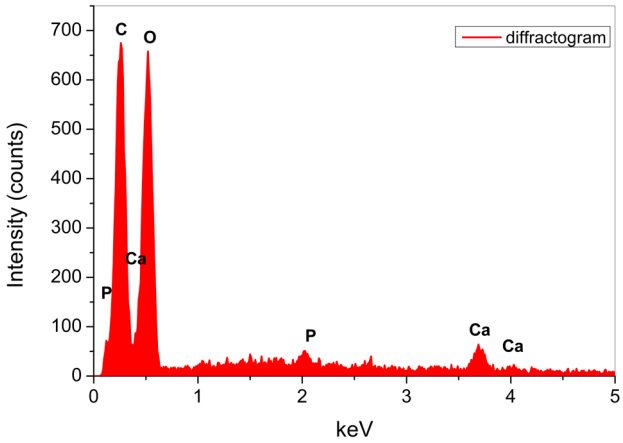


Fig. 3 EDS graph of bioplastic

Table 1 Quantitative analysis of bioplastic

Element	Mass %
C	39.13
O	58.46
P	0.55
Ca	1.85

The strong C and O signals suggest that the matrix is rich in organic functional groups such as hydroxyl, carbonyl, and amide linkages, which contribute to its biodegradability and film-forming characteristics. The Ca and P peaks, on the other hand, reveal partial inorganic reinforcement within the polymeric network, enhancing thermal stability and mechanical rigidity. The absence of any heavy metal or impurity peaks indicates the material's purity and eco-friendly composition. EDS analysis corroborates that the synthesized bioplastic is primarily organic in nature, with bio-derived inorganic phases well integrated into the matrix, contributing to its sustainable and biodegradable character.

3.3 Thermal characterization

The TGA/DTG analysis of the bioplastic shows three distinct mass loss stages as shown in Fig. 4. The analysis is conducted at a heating rate of 10 °C/min in Nitrogen atmosphere with a flow rate of 30 ml/min. The temperature range for the analysis spans from 25 °C (room temperature) to 820 °C. The initial stage (up to ~100 °C) corresponds to ~17% mass loss, attributed to moisture evaporation. The major degradation occurs between ~200–350 °C, with ~82.1% mass loss and a DTG peak at 314 °C, indicating thermal decomposition of the organic polymer matrix (gelatin–polysaccharide components). A minor degradation phase follows up to ~500 °C, after which a gradual

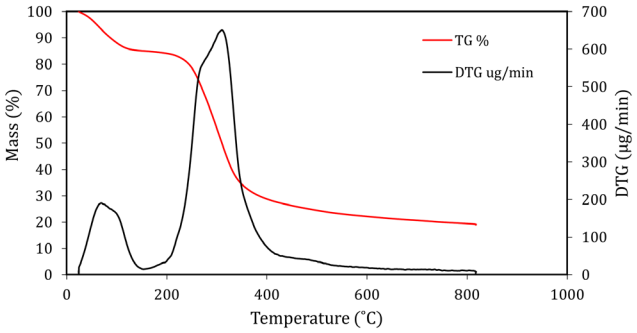


Fig. 4 TG/DTA graphs of bioplastic

mass loss continues until ~800 °C, leaving ~20.4% residual mass, likely due to thermally stable char and inorganic content. These results suggest that the bioplastic maintains stability up to ~150 °C, with rapid degradation occurring in the mid-temperature range typical for biopolymer-based materials. The temperature 150 °C has been experimentally verified by using melting point apparatus [19].

3.4 Functional characterization

The FTIR spectrum of the bioplastic shows characteristic functional groups confirming the presence of both protein and polysaccharide components. A broad band around ~3400 cm^{-1} corresponds to O–H stretching vibrations from hydroxyl groups and intermolecular hydrogen bonding, while a peak near ~3300 cm^{-1} indicates N–H stretching from amide groups in gelatin. The absorption around ~2920 cm^{-1} is assigned to C–H stretching of aliphatic chains. A distinct peak near ~1630–1650 cm^{-1} (C=C) may correspond to amide I vibrations or unsaturated groups. The band around ~1050–1100 cm^{-1} is attributed to C–O stretching vibrations typical of polysaccharides as shown in Fig. 5. These functional groups confirm the incorporation of gelatin-derived peptides and polysaccharide backbones in the bioplastic, suggesting strong intermolecular interactions that contribute to its structural integrity [20].

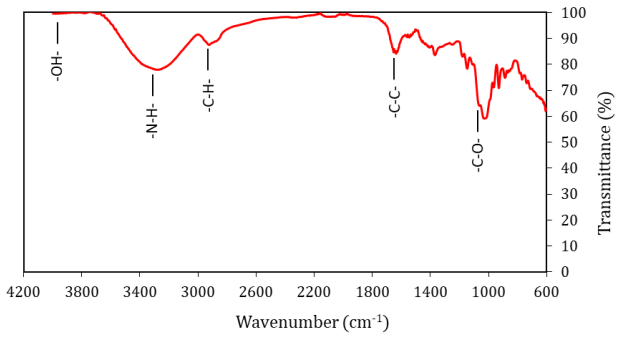
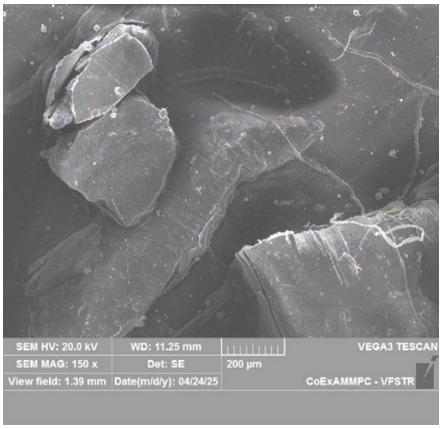


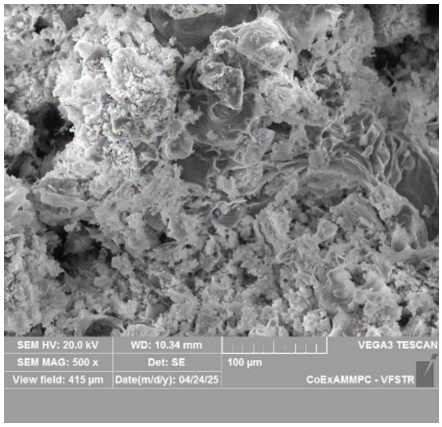
Fig. 5 FTIR graph of bioplastic

3.5 Morphological characterization

The SEM micrographs of the bioplastic at different magnifications reveal a heterogeneous, layered morphology with distinct surface and internal structural features as shown Fig. 6. At lower magnification (Figs. 6(a) and 6(b)), the surface appears rough with irregular flakes and aggregated particles, indicating incomplete homogenization and the presence of polysaccharide–protein domains. Medium magnification images (Figs. 6(c) and 6(d)) show a fibrous and sheet-like structure with compact stacking, suggesting good intermolecular interactions between the biopolymer components. At higher magnification (Fig. 6(e)), the microstructure displays closely packed fibrillar networks and interlinked layers, which can enhance mechanical strength. The observed roughness and layered arrangement may contribute to improved flexibility, while voids and micro-gaps could influence barrier properties by facilitating moisture penetration [21–23]. The morphology confirms effective blending of components with a predominantly continuous matrix, though minor phase separation features are visible.



(a)



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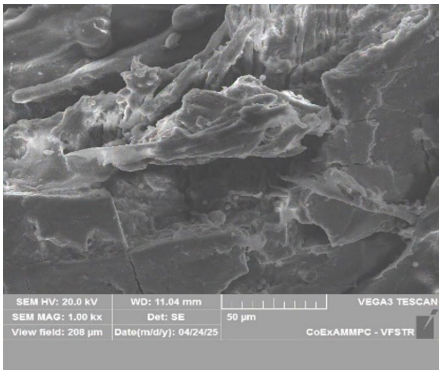

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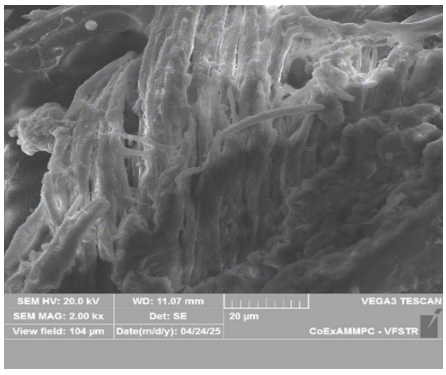
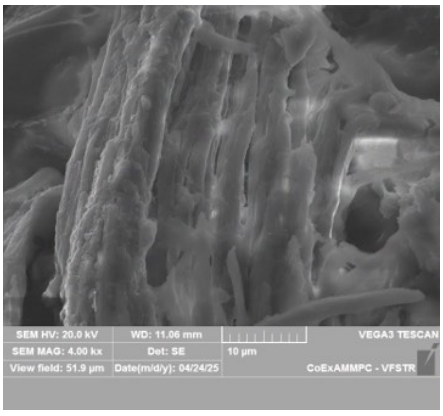


(d)



(e)

Fig. 6 SEM images of the bioplastic in (a) 150 x (b) 500 x (c) 1.00 kx (d) 2.00 kx (e) 4.00 kx magnifications

3.6 Assessment of bioplastic film

Each experimental run was performed five times under identical conditions to ensure reproducibility and reliability of the results. The obtained data exhibited minimal variation among replicates, indicating high consistency, and the average values of these repeated measurements are presented in Table 2.

4 Comparison with other bioplastics

Various types of bioplastics, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based plastics, and cellulose-based films, differ significantly in their mechanical, thermal, and barrier properties. Comparative evaluation of these materials helps in identifying suitable applications and guiding research toward performance enhancement. Table 3 presents a comparative study of selected bioplastics with relevant literature references [13, 24, 25].

5 Conclusions

- The study demonstrates that *Catla catla* fish scale waste, rich in collagen and hydroxyapatite, can be effectively transformed into value-added and biodegradable bioplastic films using eco-friendly processes.
- The resulting bioplastic films exhibit satisfactory mechanical integrity (tensile strength ~15.2 MPa), smooth texture, and flexible handling, making them suitable for low-load packaging and disposable applications.
- With moderate moisture content (8.5%) and hot water solubility (12%), the films maintain structural stability under typical usage but may require further improvements for high-moisture environments.
- The preparation protocol involves simple, scalable steps using readily available biopolymers (red algae binder, glycerine plasticizer) and standard processing equipment, supporting potential for industrial adoption.
- Fish scale-based bioplastics are renewable, compostable, and promote sustainable waste management by reducing both plastic pollution and seafood processing waste.
- The translucency, moderate opacity, and acceptable strength of the films support applications in single-use packaging, agriculture films, and similar fields, with further research needed for broader usage.
- Continued research into enhancing moisture resistance, thermal stability, and incorporating functional additives will broaden the utility and commercial viability of such bioplastics for diverse industries.

Table 2 Assessment of bioplastic film

Property	Value
Moisture content (%)	8.5
Thickness (mm)	0.35
Hot water solubility (%)	12
Texture	Smooth and flexible
Colour	Translucent pale white
Opacity	Moderate
Tensile strength (MPa)	15.2

Acknowledgement

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Table 3 Comparison of various bioplastics

Property	PLA [23]	PHB [24]	Starch-based films [25]	Present work
Tensile strength (TS)	44–82 MPa	30–40 MPa	2–6 MPa	15.2 MPa
Elongation at break	<10%	2–10%	50–150%	50–120%
Glass transition (Tg)	55–65 °C	0–5 °C	Below ambient	Not distinct; soft at RT
Melting point (Tm)	150–170 °C	170–180 °C	No true Tm	150 °C
Water vapor permeability (WVP)	Moderate	Low–moderate	Very high	High
Oxygen barrier	Moderate	Good	Poor	Modest
Thermal stability	Stable up to ~200 °C	Stable up to ~170–180 °C	Degrades at ~200–250 °C	Stable up to ~150 °C
Flexibility / transparency	Moderate	Low	High	Excellent
Biodegradability	Compostable (industrial)	Compostable	Very good	Very good
Typical applications	Rigid packaging, fibers	Packaging, biomedical	Wrapping films	Flexible films, edible coatings

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