

Chicken Feather-Derived Keratin-Based Bioplastic as a Corrosion Inhibitor for Mild Steel in 0.1 M HCl: Electrochemical, Gravimetric and Adsorption Studies

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Abstract

Background

Chicken feather waste is a protein-rich biomass that can be converted into keratin-based materials with potential applications in corrosion protection. This study evaluated a keratin-based bioplastic (KBP) prepared from waste chicken feathers as a corrosion inhibitor for mild steel in 0.1 M hydrochloric acid.

Methods

Keratin was obtained by alkaline hydrolysis followed by acid precipitation and incorporated with glycerol and microcrystalline cellulose to form a bioplastic film. The material was characterized using FTIR, SEM, EDX, XRD and DSC. Corrosion behaviour was assessed by gravimetric and electrochemical methods over 303–333 K and at KBP concentrations of 0–0.8 g/L for the temperature-dependent electrochemical dataset. Potentiodynamic polarization was performed in a three-electrode cell after 30 min open-circuit stabilization. Adsorption behavior was evaluated using Langmuir, Freundlich and Temkin models.

Results

Increasing KBP concentration reduced corrosion current density and corrosion rate while increasing polarization resistance, surface coverage and inhibition efficiency. At 303 K, corrosion rate decreased from 37.56 mm year⁻¹ in the uninhibited system to 21.79 mm year⁻¹ at 0.8 g/L, corresponding to 41.99% inhibition efficiency. Polarization data indicated mixed type inhibition behavior while the highest inhibition efficiency in the temperature series was 54.00% at 0.8 g/L and 323 K, after which efficiency declined to 32.49% at 333 K. The Langmuir model showed the highest linear-fit coefficients ($R^2 = 0.9994\text{--}0.9997$) among the evaluated models, although the high fits of the other models indicate that model fit alone does not establish a unique adsorption mechanism. Activation energies increased from 15.26 kJ mol⁻¹ in the uninhibited system to 17.80 kJ mol⁻¹ at 0.8 g/L KBP.

Conclusion

The chicken feather-derived KBP reduced mild-steel corrosion under the tested acidic conditions, with performance dependent on concentration and temperature. The results are consistent with adsorption-mediated inhibition and surface modification. The adsorption and thermodynamic results should be interpreted as mechanistic evidence rather than definitive proof of a single adsorption mode.

Introduction

Corrosion of metallic materials in acidic environments is a persistent materials and industrial problem because acidic media can accelerate electrochemical metal dissolution, shorten service life and

increase maintenance requirements. Mild steel is widely used because of its favorable mechanical properties, availability and relatively low cost, but its use in acidic processing and cleaning environments is limited by its susceptibility to corrosion. Corrosion inhibitors are therefore commonly introduced into aggressive electrolytes to reduce the rate of anodic metal dissolution and/or cathodic reactions. Conventional organic inhibitors can be effective, but interest in bio-derived and polymeric inhibitor systems has increased because renewable feed stocks may provide functional groups capable of interacting with metal surfaces while also offering opportunities for waste valorisation (1, 11–13).

Protein-based materials are of particular interest in corrosion-control research because their structures contain heteroatom-bearing and polar functional groups that can interact with metallic interfaces. Keratin is a structural protein characterized by a highly cross-linked structure and is abundant in feathers, hair, wool and related biological materials. Chicken feathers are therefore an attractive source of keratin for material recovery. Their conversion into useful products can simultaneously address a waste-management problem and provide a feedstock for the development of functional biomaterials (1, 2).

The physicochemical properties of keratin depend strongly on the extraction and processing route. Alkaline hydrolysis can disrupt the structural organization of feather keratin and produce a material that can subsequently be formulated into films. Previous studies have demonstrated that extracted chicken-feather keratin can be converted into bioplastic films using glycerol as a plasticizer and that the resulting materials can be characterized by FTIR, SEM, DSC and XRD (2, 3). These studies demonstrate the potential of extracted feather keratin for conversion into functional bioplastic films.

Further modification of keratin films can be achieved through incorporation of polysaccharide-based reinforcing materials. In particular, microcrystalline cellulose has been investigated as a component of keratin-based bioplastic films, with reported effects on the structural and physicochemical properties of the resulting material (4). The combination of keratin, glycerol and microcrystalline cellulose provides a composite material containing proteinaceous and hydroxyl-containing components that may contribute to interfacial interactions during corrosion inhibition.

Corrosion inhibition by organic and polymeric materials is commonly interpreted in terms of interfacial adsorption. Depending on the chemical structure of the inhibitor and the experimental environment, adsorption can reduce the number of electrochemically active sites available for metal dissolution and can impede charge-transfer processes. Adsorption isotherms are frequently used to describe the relationship between inhibitor concentration and surface coverage, with Langmuir, Freundlich and Temkin models among the commonly evaluated approaches (6, 16). However, the quality of a linearized fit should not by itself be treated as definitive proof of a particular molecular adsorption mechanism, especially when the inhibitor is a heterogeneous biological material rather than a single defined compound (6, 16).

Temperature is also an important variable in corrosion inhibition because it affects both the underlying corrosion reactions and the interactions between inhibitor constituents and the metal surface. Previous corrosion studies have shown that inhibitor performance may increase or decrease with temperature

depending on the chemical system and the balance between adsorption, desorption and reaction kinetics (8–10). Electrochemical techniques such as potentiodynamic polarization provide complementary information by allowing changes in corrosion current density, corrosion potential and polarization resistance to be evaluated. These measurements can help distinguish changes in overall corrosion rate from changes in the relative influence of anodic and cathodic processes (7, 13, 17).

Despite the increasing interest in feather-derived biomaterials, the corrosion inhibition performance of chicken feather-derived keratin bioplastic formulation in hydrochloric acid has not been sufficiently evaluated. In the present study, KBP was introduced into the corrosive electrolyte as a soluble inhibitor rather than applied as a performed coating. The resulting corrosion response was therefore evaluated in terms of concentration-dependent electrochemical and gravimetric protection and the associated surface modification.

The present study therefore investigated a keratin-based bioplastic (KBP) prepared from waste chicken feathers as a corrosion inhibitor for mild steel in 0.1 M HCl. The material was characterized using FTIR, SEM, EDX, XRD and DSC, while corrosion behavior was evaluated using gravimetric and electrochemical approaches. The electrochemical study examined KBP concentrations of 0–0.8 g/L at 303–333 K, and adsorption behavior was evaluated using Langmuir, Freundlich and Temkin models. The study aimed to evaluate whether the prepared KBP could reduce corrosion under the tested conditions and to describe the concentration- and temperature-dependent behavior without assigning a definitive molecular adsorption mechanism that was not directly demonstrated by the available surface analyses.

Methods

Collection and Pretreatment of Chicken Feathers

Waste chicken feathers used as the precursor for keratin production were obtained from a chicken-processing plant in Ikere-Ekiti, Ekiti State, Nigeria. The collected feathers were initially washed with detergent to remove adhering dirt and other contaminants and subsequently rinsed several times with running tap water to remove residual detergent. The feathers were further rinsed with deionized water and dried at room temperature for 7 days.

The dried feathers were degreased using petroleum ether for 24 h (overnight) and subsequently washed with distilled water. The cleaned and degreased feathers were conditioned at 20°C and 65% relative humidity for 24 h. The feathers were then treated with cetyltrimethylammonium bromide (CTAB) at a concentration of 1 g L⁻¹ for 3 h to reduce microbial contamination. Following treatment, the feathers were washed thoroughly with distilled water, cut into smaller pieces and dried before storage at 4°C until further use.

Extraction and Precipitation of Keratin from Chicken Feathers

Keratin was extracted from the pretreated chicken feathers using an alkaline hydrolysis and acid precipitation procedure adapted from Elemile et al. (5). Briefly, 1000 g of clean, dry chicken feathers was weighed into a suitable plastic container and 2 L of 1 M NaOH solution was added. The mixture was allowed to hydrolyse for 24 h with intermittent stirring at approximately 1 h intervals to ensure adequate contact between the feathers and alkaline solution.

Following hydrolysis, the hydrolyzed and unhydrolyzed fractions were separated by filtration through a 1-mm plastic sieve. Keratin was subsequently precipitated from the hydrolyzed fraction by gradual addition of 10% (w/w) of 35% hydrochloric acid solution with gentle stirring to ensure homogeneous mixing. The resulting slurry was allowed to stand for 30 min to facilitate precipitation. The precipitated material was washed repeatedly with distilled water to remove residual acid and soluble impurities. The material was subsequently separated using muslin cloth and dried at room temperature to constant mass. The dried material obtained was regarded as the extracted chicken-feather keratin.

Determination of Keratin Extraction Yield

The extraction yield of keratin was determined gravimetrically using the ratio of the mass of the dried extracted keratin to the initial dry mass of chicken feathers:

Extraction yield (%) = (weight of extracted keratin/ Initial weight of chicken feather) x 100

The protein content of the extracted keratin was determined using the Bradford protein assay, with bovine serum albumin (BSA) used as the standard.

Preparation of Keratin-Based Bioplastic Film

Keratin-based bioplastic film was prepared according to the procedure reported by Sharma and Gupta (2016), with modifications where applicable. 250 mg of dried extracted keratin was dissolved in 5 mL of 2 M NaOH under vigorous agitation at 300 rpm and 45°C. The resulting keratin solution was mixed with the film-forming components comprising glycerol and microcrystalline cellulose.

Glycerol at 3.5% and microcrystalline cellulose at 0.2% were incorporated into the formulation to improve the flexibility and film-forming characteristics of the keratin matrix. The resulting mixture was poured into a 10-cm-diameter Petri dish previously treated with the appropriate release/ greasing agent. The cast solution was dried in an oven at 60°C for 48 h to obtain the keratinbased bioplastic film.

After drying, the film was carefully removed from the Petri dish and stored under suitable conditions until characterization and corrosion-inhibition studies. The thickness of the prepared film was measured using a micrometer.

Characterization of the Extracted Keratin and Keratin-Based Bioplastic

Fourier Transform Infrared Spectroscopy

Fourier transform infrared (FTIR) spectroscopy was employed to identify the principal functional groups present in the extracted keratin and keratin-based bioplastic film. The spectra were recorded over the range of 4000–400 cm^{-1} . The characteristic absorption bands were used to identify functional groups associated with the keratin structure and to assess changes arising from film formation.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used to examine the surface morphology of the extracted keratin and prepared keratin-based bioplastic film. The technique was used to assess surface texture, morphology, homogeneity and structural changes associated with incorporation of the film-forming components.

Optical Microscopy

Optical microscopy was used to examine the surface condition of mild-steel specimens before and after exposure to the acidic medium. The technique was used to compare the morphology of uninhibited and keratin-bioplastic-protected mild steel and to assess the extent of surface deterioration and protective-film formation.

Energy-Dispersive X-ray Spectroscopy

Energy-dispersive X-ray spectroscopy (EDX) was employed to determine the elemental composition of the extracted keratin and keratin-based bioplastic film. The analysis provided information on the elements present in the samples and their relative distribution.

X-ray Diffraction

X-ray diffraction (XRD) analysis was performed to investigate the structural characteristics and degree of crystallinity of the extracted keratin and keratin-based bioplastic film. The diffraction patterns were used to assess changes in structural organization resulting from film formation.

Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) was used to investigate the thermal transitions of the extracted keratin and keratin-based bioplastic film. The analysis was used to determine relevant thermal characteristics, including glass-transition and other thermal transition temperatures where identifiable.

Preparation of Mild-Steel Specimens

Mild-steel specimens were prepared for gravimetric and electrochemical corrosion studies. The specimens were mechanically polished using progressively finer abrasive papers to obtain a clean and relatively uniform surface. The specimens were subsequently washed with distilled/ deionized water and degreased with acetone before use.

For electrochemical measurements, a mild-steel working electrode with an exposed surface area of 1 cm² was employed. The remaining surface of the electrode was isolated from the electrolyte to ensure that corrosion occurred only on the defined exposed area.

Preparation and Application of Keratin-Based Bioplastic Inhibitor

The prepared keratin-based bioplastic was used as the corrosion-inhibiting material for mild steel in 0.1 M HCl. Different concentrations of the inhibitor were investigated to establish the concentration-dependent inhibition behavior.

For the gravimetric and electrochemical experiments, inhibitor concentrations of 0.01, 0.1, 0.2, 0.3, 0.4 and 0.5 mM were investigated, as stated in the thesis.

Preparation of Corrosive Medium

A 0.1 M hydrochloric acid solution was used as the corrosive medium. The required quantity of concentrated hydrochloric acid was diluted appropriately with distilled/deionized water to prepare the working solution. The prepared solution was allowed to equilibrate to the required experimental temperature (303, 313, 323 and 333K) before each corrosion test.

Gravimetric (Weight-Loss) Corrosion Measurement

The corrosion inhibition performance of the keratin-based bioplastic was initially evaluated using the gravimetric weight-loss method. Cleaned and weighed mild-steel specimens were immersed in 0.1 M HCl in the absence and presence of the specified concentrations of keratin-based bioplastic.

The specimens were exposed for 1, 5, 10, 24, 48 and 72 h. At the end of each exposure period, the specimens were removed from the corrosive medium, thoroughly cleaned to remove corrosion products, rinsed, dried and reweighed. The mass loss was determined from the difference between the initial and final masses.

Each experiment was performed in triplicate and the mean values were reported.

The corrosion rate was calculated from the measured mass loss using the appropriate relationship incorporating the exposed surface area, exposure time and density of the mild steel.

The inhibition efficiency was calculated as:

$$IE (\%) = (W_o - W_i) / W_o$$

W_o = weight loss of mild steel in the uninhibited 0.1 M HCl solution

W_i = weight loss in the presence of the keratin-based bioplastic

The degree of surface coverage was calculated from:

$$\Theta = (W_o - W_i) / W_o$$

Effect of Temperature

The effect of temperature on the corrosion inhibition performance of the keratin-based bioplastic was investigated at the optimum inhibitor concentration and exposure time. The temperature of the corrosive medium was varied over the experimentally investigated range of 303 to 333 K.

The effect of temperature was evaluated using gravimetric and where experimentally performed, electrochemical measurements.

Electrochemical Measurements

Electrochemical measurements were performed using a conventional three-electrode electrochemical cell. The mild-steel specimen served as the working electrode, a platinum rod served as the counter electrode, and an Ag/AgCl reference electrode saturated with 3 M KCl served as the reference electrode.

The exposed area of the mild-steel working electrode was 1 cm². Prior to each measurement, the electrode surface was prepared as described above and immersed in 0.1 M HCl in the absence or presence of the specified concentration of keratin-based bioplastic.

The electrochemical system was allowed to stabilize for 30 min before measurements were commenced in order to establish a reasonably stable open-circuit potential.

All electrochemical measurements were conducted in triplicate, and the mean values were used for interpretation.

Open-Circuit Potential

The open-circuit potential (OCP) of the mild-steel electrode was monitored after immersion in the 0.1 M HCl solution until a relatively stable potential was obtained. OCP measurements were conducted for both uninhibited and inhibitor-containing solutions.

The stabilized OCP served as the reference potential for subsequent electrochemical measurements.

Potentiodynamic Polarization

Potentiodynamic polarization measurements were performed to evaluate the effect of the keratin-based bioplastic on the anodic and cathodic corrosion reactions of mild steel.

Polarization scans were conducted over a potential range of + 250 to – 250 mV relative to the stabilized OCP at a scan rate of 0.1 mV s⁻¹.

The polarization curves were used to determine the corrosion potential E_{corr} and corrosion current density (I_{corr}) by Tafel extrapolation. The corrosion rate and inhibition efficiency were subsequently determined

from the electrochemical parameters.

The inhibition efficiency based on corrosion current density was calculated as:

$$IE (\%) = ((I_{corr, 0} - I_{corr, i}) / I_{corr, 0}) \times 100$$

$I_{corr, 0}$ is the corrosion current density of mild steel in the uninhibited 0.1 M HCl solution and

$I_{corr, i}$ is the corrosion current density in the presence of the keratin-based bioplastic.

The surface coverage was calculated from:

$$\Theta = ((I_{corr, 0} - I_{corr, i}) / I_{corr, 0}) \times 100$$

Together with changes in the anodic and cathodic branches of the polarization curves, were used to assess the influence of the keratin-based bioplastic on the corrosion reactions.

Effect of Keratin-Based Bioplastic Concentration

The concentration dependence of corrosion inhibition was investigated by exposing mild-steel specimens to 0.1 M HCl containing different concentrations of the keratin-based bioplastic.

The effect of inhibitor concentration was evaluated using weight-loss measurements and electrochemical measurements. The corrosion rate, inhibition efficiency, surface coverage and electrochemical parameters were compared with those obtained from the uninhibited control.

Adsorption Isotherm Studies

The adsorption behavior of the keratin-based bioplastic on the mild-steel surface was investigated using the surface-coverage data obtained from the gravimetric and electrochemical measurements.

The experimental surface coverage values were fitted to Langmuir, Freundlich and Temkin adsorption models to determine the model that best described the interaction between the inhibitor molecules and the mild-steel surface.

Data Analysis and Reproducibility

All gravimetric and electrochemical corrosion experiments were performed in triplicate. The results were expressed as mean values, and appropriate statistical treatment was applied to assess reproducibility and differences between experimental conditions.

The inhibition performance of the keratin-based bioplastic was evaluated by comparing the uninhibited mild-steel system with the corresponding inhibitor-containing systems using corrosion rate, mass loss, inhibition efficiency, surface coverage and electrochemical parameters.

Results

Chemical and morphological characteristics of KBP

FTIR spectra of the extracted keratin and KBP retained characteristic protein-associated bands. The spectra included a broad N–H/O–H stretching region around 3292 cm⁻¹, aliphatic C–H stretching in the 2959–2878 cm⁻¹ region, a carbonyl band around 1745 cm⁻¹, and amide I, II and III-associated bands near 1635, 1541 and 1231 cm⁻¹, respectively. The presence of these bands is consistent with retention of protein functional groups after processing. The film also showed changes in band intensity and broadening in regions associated with hydroxyl and carbonyl-containing groups, consistent with interactions among the components of the composite (Table 1).

Table 1
FTIR functional groups of the keratin and bioplastic film Keratin Spectrum Interpretation

Wavenumber (cm ⁻¹)	Functional Group / Vibration	Interpretation
Keratin		
3292.54	N–H or O–H stretching	Hydrogen bonding, typical of proteins
2959.34–2877.60	C–H stretching	Aliphatic chains (CH ₃ , CH ₂)
1744.91	C = O stretching	Carbonyl group (possibly from amide or ester)
1635.43	Amide I (C = O stretching)	Protein backbone (α-helix or β-sheet)
1541.23	Amide II (N–H bending, C–N stretching)	Confirms protein structure
1231.41	Amide III	Complex protein vibrations
772.84–355.47	Fingerprint region	Unique to keratin structure
Bioplastic		
3292.54	N–H or O–H stretching	Hydrogen bonding, typical of proteins
2959.34–2877.60	C–H stretching	Aliphatic chains (CH ₃ , CH ₂)
1744.91	C = O stretching	Carbonyl group (possibly from amide or ester)
1635.43	Amide I (C = O stretching)	Protein backbone (α-helix or β-sheet)
1541.23	Amide II (N–H bending, C–N stretching)	Confirms protein structure
1231.41	Amide III	Complex protein vibrations
772.84–355.47	Fingerprint region	Unique to keratin structure

SEM examination showed a change from the more irregular/agglomerated morphology of extracted keratin to a more continuous morphology in the prepared film (Fig. 1). These observation support the formation of a keratin-based composite but do not by themselves establish the exact molecular structure or interfacial corrosion mechanism.

EDX (Fig. 2) detected carbon and oxygen as major constituents of the material, together with smaller amounts of other elements including sulfur and inorganic elements.

DSC (Fig. 3) showed thermal transitions for both materials, with the film exhibiting a transition around 190°C.

XRD (Fig. 4) patterns showed broadening and reduced sharpness after film formation, consistent with a reduction in the degree of structural order relative to the extracted keratin.

Surface appearance of inhibited mild steel

Optical micrographs of mild steel exposed to 0.8 g/L KBP at 303–333 K (Fig. 5) showed visible differences in surface appearance relative to the untreated surface. These observations are considered qualitative evidence of surface modification/coverage during exposure. They are not interpreted as proof of a mechanically adherent cured coating.

Effect of KBP concentration and temperature on electrochemical corrosion

Increasing KBP concentration consistently decreased j_{corr} and corrosion rate and increased polarization resistance and calculated surface coverage across the four temperatures. At 303 K, j_{corr} decreased from $3.24 \times 10^{-3} \text{ A cm}^{-2}$ in the blank to $1.88 \times 10^{-3} \text{ A cm}^{-2}$ at 0.8 g/L KBP. Correspondingly, corrosion rate decreased from 37.56 to 21.79 mm year⁻¹ and calculated inhibition efficiency increased to 41.99%.

At 313 K, corrosion rate decreased from 54.39 mm year⁻¹ in the blank to 28.28 mm year⁻¹ at 0.8 g/L, with an inhibition efficiency of 48.01%. At 323 K, the corresponding decrease was from 58.61 to 26.96 mm year⁻¹, with an inhibition efficiency of 54.00%. At 333 K, corrosion rate decreased from 66.95 to 45.20 mm year⁻¹, with an inhibition efficiency of 32.49% at 0.8 g/L. Thus, the highest inhibition efficiency in the temperature series occurred at 323 K rather than at the lowest temperature.

Across the tested temperatures, j_{corr} and corrosion rate decreased with increasing KBP concentration, while R_p and calculated inhibition efficiency increased. At 333 K, the inhibition efficiency values were lower than those observed at 303–323 K (Table 2).

Table 2

Electrochemical corrosion parameters for mild steel in 0.1 M HCl at different KBP concentrations and temperatures. Values are the reported study averages from the present study table; the data table did not retain standard deviations.

T (K)	KBP (g/L)	E_{corr} (V)	j_{corr} (A/cm ²)	CR (mm/y)	R_p (Ω)	θ	IE (%)
303	0	-0.368	3.24×10^{-3}	37.56	8.16	0	0
303	0.2	-0.303	2.83×10^{-3}	32.78	9.40	0.127	12.73
303	0.4	-0.258	2.47×10^{-3}	28.61	11.05	0.238	23.83
303	0.6	-0.411	2.15×10^{-3}	24.97	12.41	0.335	33.52
303	0.8	-0.393	1.88×10^{-3}	21.79	14.36	0.420	41.99
313	0	-0.398	4.69×10^{-3}	54.39	5.81	0	0
313	0.2	-0.406	3.98×10^{-3}	46.19	6.88	0.151	15.08
313	0.4	-0.403	3.38×10^{-3}	39.22	8.30	0.279	27.89
313	0.6	-0.395	2.87×10^{-3}	33.31	9.59	0.388	38.76
313	0.8	-0.416	2.44×10^{-3}	28.28	11.40	0.480	48.01
323	0	-0.368	5.05×10^{-3}	58.61	5.56	0	0
323	0.2	-0.396	4.16×10^{-3}	48.27	6.78	0.176	17.64
323	0.4	-0.383	3.43×10^{-3}	39.75	8.43	0.322	32.18
323	0.6	-0.398	2.82×10^{-3}	32.74	10.05	0.441	44.14
323	0.8	-0.408	2.32×10^{-3}	26.96	12.31	0.540	54.00
333	0	-0.368	5.77×10^{-3}	66.95	5.02	0	0
333	0.2	-0.387	5.23×10^{-3}	60.69	5.56	0.094	9.35
333	0.4	-0.390	4.74×10^{-3}	55.01	6.28	0.178	17.83
333	0.6	-0.396	4.30×10^{-3}	49.86	6.80	0.255	25.53
333	0.8	-0.402	3.90×10^{-3}	45.20	7.57	0.325	32.49

Potentiodynamic polarization behavior

The polarization data (Fig. 6) showed a concentration-dependent reduction in j_{corr} without a uniform, large displacement of E_{corr} . At 303 K, E_{corr} shifted anodically at 0.2 and 0.4 g/L and cathodically at 0.6 and 0.8 g/L. At 313–333 K, the inhibitor generally produced cathodic shifts relative to the blank. These shifts varied with concentration and temperature, so the overall behavior is best described as mixed-type

inhibition with a variable relative influence on anodic and cathodic processes rather than as a purely anodic or purely cathodic inhibitor.

Gravimetric corrosion behavior

The present study reports independent weight-loss measurements in 0.1 M HCl, with triplicate specimens and assessment across contact times of 1–72 h. For the temperature/concentration dataset reproduced in the study, the reported mass-loss values are shown in Table 3. Unlike the electrochemical current-density results, the mass-loss values do not show a uniform monotonic decrease with increasing KBP concentration at every temperature; for example, at 303 K the reported mass loss was 0.0032 g in the blank, 0.0020 g at 0.2 g/L, 0.0052 g at 0.4 g/L, 0.0053 g at 0.6 g/L and 0.0009 g at 0.8 g/L.

Table 3

Mass loss of mild-steel specimens reported for the temperature/concentration corrosion dataset.

KBP concentration (g/L)	303 K mass loss (g)	313 K mass loss (g)	323 K mass loss (g)	333 K mass loss (g)
0	0.0032	0.0032	0.0019	0.0030
0.2	0.0020	0.0010	0.0018	0.0014
0.4	0.0052	0.0025	0.0015	0.0021
0.6	0.0053	0.0029	0.0019	0.0020
0.8	0.0009	0.0019	0.0014	0.0013

Adsorption behavior

The Langmuir, Freundlich and Temkin models were evaluated at 303, 313, 323 and 333 K (Table 4). The linearized Langmuir fits produced R^2 values of 0.9994–0.9997, while Freundlich R^2 values ranged from 0.9981 to 0.9995 and Temkin R^2 values from 0.9751 to 0.9838. Although the Langmuir model had the highest R^2 at each temperature, the close fit of the Freundlich model indicates that the data do not uniquely establish an ideal homogeneous monolayer. The appropriate conclusion is therefore that the experimental data showed the closest linear fit to Langmuir-type behavior under the studied conditions.

Table 4

Adsorption isotherm parameters for KBP on mild steel.

Temperature (K)	Langmuir K_{ads}	R^2	Freundlich K_{ads}	R^2	Temkin K	R^2
303	0.6858	0.9997	0.5170	0.9991	8.7067	0.9809
313	0.8262	0.9995	0.5895	0.9987	9.0242	0.9838
323	0.9857	0.9994	0.6608	0.9981	9.4132	0.9788
333	0.4928	0.9997	0.4019	0.9995	8.2968	0.9751

The Langmuir K_{ads} parameter increased from 303 to 323 K and then decreased at 333 K. The decrease coincided with the reduction in inhibition efficiency at 333 K. However, because KBP is a heterogeneous composite and concentration was expressed in g/L, the K_{ads} values are best treated as model-specific empirical parameters rather than conventional molecular equilibrium constants with a rigorously defined molar basis.

Overall, the electrochemical results showed concentration-associated reductions in j_{corr} and corrosion rate together with increases in R_p and calculated inhibition efficiency. The maximum calculated inhibition efficiency was 54.00% at 0.8 g/L and 323 K. The adsorption models and temperature-dependent parameters are presented separately below.

Temperature-dependent activation energy

Table 5
Temperature-dependent activation-energy and thermodynamic parameters for the KBP/mild-steel/HCl system.

KBP concentration (g/L)	E _a (kJ mol ⁻¹)	ΔH° (kJ mol ⁻¹)	ΔG° at 303 K (kJ mol ⁻¹)
0	15.2641	12.6244	71.1239
0.2	15.8815	13.2418	71.5249
0.4	16.5180	13.8783	71.9263
0.6	17.2228	14.5831	72.3339
0.8	17.8013	15.1616	72.7317

The apparent activation energies and thermodynamic parameters obtained across the tested KBP concentrations are summarized in Table 5. Note, the positive ΔG° values are reported as calculated values and are not interpreted here as evidence of spontaneous adsorption.

Discussion

The present study evaluated chicken feather-derived keratin-based bioplastic (KBP) as a corrosion inhibitor for mild steel in 0.1 M HCl using electrochemical, gravimetric, adsorption and material-characterization approaches. The principal finding is that KBP produced a measurable concentration-associated reduction in electrochemical corrosion, while the magnitude of protection varied with temperature. At 0.8 g/L, inhibition efficiencies were 41.99%, 48.01%, 54.00% and 32.49% at 303, 313, 323 and 333 K, respectively. The maximum value of 54.00% at 323 K indicates moderate inhibition under the conditions studied rather than exceptionally high protection. Such concentration-dependent inhibition is consistent with the general behavior reported for organic and bio-derived corrosion inhibitors, in which adsorption of inhibitor constituents at the metal/electrolyte interface can reduce active corrosion sites (6, 12, 18, 19).

The concentration response is most clearly demonstrated by the electrochemical data. At 303 K, j_{corr} decreased from $3.24 \times 10^{-3} \text{ A cm}^{-2}$ in the uninhibited solution to $1.88 \times 10^{-3} \text{ A cm}^{-2}$ at 0.8 g/L, while R_p increased from 8.16 to 14.36 Ω . Comparable changes occurred at the other temperatures. The simultaneous decrease in corrosion current density and increase in polarization resistance are consistent with reduced electrochemical activity at the exposed steel surface. Similar combinations of lower corrosion current and higher interfacial resistance have been reported for organic and protein-derived inhibitors in acidic media (18, 20). The present data therefore support an inhibitive interfacial effect, although they do not by themselves identify the molecular species responsible for that effect.

Temperature produced a non-monotonic response. Inhibition improved from 303 K to 323 K but decreased at 333 K. This behavior indicates that temperature affected the balance between corrosion kinetics and retention of inhibitor constituents at the steel/electrolyte interface. In corrosion-inhibition systems, increasing temperature can accelerate both metal dissolution and inhibitor transport, adsorption and desorption; consequently, the net effect is system-dependent (8–11). The decline from 54.00% at 323 K to 32.49% at 333 K should therefore not be interpreted as evidence for a single temperature-controlled adsorption mechanism. It is more appropriately regarded as evidence that the protective effect of the present KBP formulation was less stable or less effective at the highest temperature tested.

The potentiodynamic polarization results further indicate that KBP affected both anodic and cathodic components of the corrosion process. At 303 K, E_{corr} shifted in the anodic direction at 0.2 and 0.4 g/L and in the cathodic direction at 0.6 and 0.8 g/L, whereas more negative shifts were generally observed at the higher temperatures. Because the direction of E_{corr} displacement changed with concentration and temperature, classification as a mixed-type inhibitor is more appropriate than assigning KBP exclusively to anodic or cathodic inhibition. Mixed-type behavior has also been reported for organic and bio-derived inhibitors studied in acidic environments (13, 14, 18, 20). The present polarization data do not justify describing KBP as predominantly anodic or predominantly cathodic across all conditions.

The increase in R_p with inhibitor concentration provides additional evidence for modification of the metal/electrolyte interface. At 303 K, R_p increased from 8.16 Ω for the blank to 14.36 Ω at 0.8 g/L, and at 323 K it increased from 5.56 to 12.31 Ω . Increased polarization or charge-transfer resistance is commonly interpreted as evidence that inhibitor-derived species impede electrochemical charge-transfer processes at the metal surface (17, 18, 20). In the present study, this interpretation should remain qualitative because the retained dataset does not include the full replicate-level electrochemical output or detailed impedance spectra needed to establish a more specific interfacial model.

The gravimetric measurements provide complementary evidence but are more variable than the electrochemical concentration-response data. The reported mass-loss values do not decrease uniformly with increasing KBP concentration at every temperature. For example, at 303 K the mass loss was 0.0032 g in the blank, 0.0020 g at 0.2 g/L, 0.0052 g at 0.4 g/L, 0.0053 g at 0.6 g/L and 0.0009 g at 0.8 g/L. Accordingly, the gravimetric results should be regarded as supportive evidence of corrosion

modification rather than as a simple monotonic concentration-response relationship. Differences between weight-loss and electrochemical trends are not inherently contradictory because the methods assess corrosion through different measurement principles and exposure conditions (11, 18).

The adsorption analysis showed that the Langmuir model produced the highest R^2 at each temperature, with values of 0.9994–0.9997. However, the Freundlich and Temkin models also produced high coefficients of determination. The relative superiority of the Langmuir fit therefore supports a Langmuir-type empirical description of the present concentration–surface-coverage relationship, but it does not establish that the real steel surface is homogeneous or that adsorption occurs as an ideal one-molecule-per-site monolayer. High linear-fit coefficients among several adsorption models are a recognized limitation of relying on linearized isotherms alone (6, 16, 21). This is particularly relevant for KBP because it is a heterogeneous composite rather than a single chemically defined inhibitor molecule.

For the same reason, the K_{ads} values should be interpreted as model-dependent empirical parameters rather than rigorous molecular equilibrium constants. KBP concentration was expressed in g/L, and the composite contains keratin together with glycerol and microcrystalline cellulose; therefore, a single molecular mass cannot appropriately represent the inhibiting material as a whole. The increase in K_{ads} from 303 to 323 K followed by a decrease at 333 K broadly parallels the temperature pattern in inhibition efficiency, but this association should not be taken as proof of a particular adsorption mechanism. Nonlinear isotherm fitting combined with direct surface-sensitive techniques would provide stronger evidence in future work (6, 16, 21).

The characterization results provide a plausible material basis for the observed interfacial effect. FTIR identified protein-associated N–H/O–H, carbonyl and amide bands, while the composite formulation also contained cellulose and glycerol. Keratin-based materials contain polar and heteroatom-containing functional groups that can participate in interactions at aqueous metal interfaces (1–4). Nevertheless, the present FTIR, SEM and EDX results characterize the material rather than directly identifying the chemical species adsorbed onto the steel surface. The optical surface observations therefore support qualitative surface modification, but they should not be presented as direct proof of a chemically characterized protective film.

Taken together, the results support an adsorption-mediated inhibition model in which constituents of the heterogeneous KBP formulation interact with the exposed steel/electrolyte interface and reduce corrosion activity. The strongest evidence is the concentration-associated decrease in j_{corr} and corrosion rate together with the increase in R_p . The adsorption-model results and material characterization are consistent with this interpretation, but they do not establish a unique molecular mechanism. The maximum inhibition efficiency of 54.00% places the present formulation in the moderate-performance range under the tested conditions. Its main significance is the demonstration that chicken feather-derived keratin can be converted into a functional bio-based material capable of modifying mild-steel corrosion in hydrochloric acid, rather than a claim of superiority over established corrosion inhibitors (12, 18, 19).

Limitations

Several limitations should be recognized. First, KBP is a heterogeneous composite, so assigning a single molecular adsorption constant is inherently approximate. Second, standard deviations were not retained for the reported electrochemical averages, limiting formal statistical comparison. Third, the gravimetric mass-loss values in the combined temperature/concentration table are variable and do not show a uniform monotonic concentration response at every temperature. Fourth, direct surface-chemical analyses such as XPS or post-exposure FTIR were not available to establish the chemical nature of the adsorbed layer. Fifth, the study evaluated KBP primarily as a soluble inhibitor in the electrolyte rather than as a mechanically adhered coating; therefore, coating adhesion or durability should not be inferred from the present experiments. Sixth, although XRD analysis was performed and its qualitative outcome is described in the text, the corresponding diffractogram is not reproduced as a figure in this manuscript; this finding should therefore be treated as a preliminary description pending inclusion of the supporting data. Finally, environmental safety and biodegradation of the specific KBP formulation were not independently tested in the corrosion study and should not be claimed as experimentally demonstrated properties.

Conclusion

A keratin-based bioplastic (KBP) was prepared from waste chicken feathers and evaluated as a corrosion inhibitor for mild steel in 0.1 M HCl. The prepared material exhibited characteristic protein functional groups and composite morphology, based on FTIR, SEM, EDX, XRD, TGA and DSC characterization, together with measurable thermal and structural properties. Electrochemical measurements showed concentration-dependent decreases in corrosion current density and corrosion rate and increases in polarization resistance and surface coverage. At 0.8 g/L KBP, inhibition efficiency reached 41.99% at 303 K and a maximum of 54.00% at 323 K, before decreasing to 32.49% at 333 K. The polarization behaviour was consistent with mixed-type inhibition. Langmuir-type behaviour provided the highest linear fit among the tested adsorption models, but the close fits of the Freundlich and Temkin models mean that a unique adsorption mechanism cannot be established from R^2 values alone. Overall, the findings support chicken-feather-derived KBP as a potentially useful biomass-derived corrosion inhibitor and illustrate a possible route for converting poultry waste into a functional materials application. Further work should focus on optimizing the formulation, quantifying replicate variability, applying nonlinear adsorption analysis and directly characterizing the steel/KBP interface after exposure.

Abbreviations

KBP

Keratin-based bioplastic

MS

Mild steel

FTIR

Fourier-transform infrared spectroscopy

SEM

Scanning electron microscopy

EDX

Energy-dispersive X-ray spectroscopy

XRD

X-ray diffraction

TGA

Thermogravimetric analysis

DSC

Differential scanning calorimetry

OCP

Open-circuit potential

 E_{corr}

Corrosion potential

 J_{corr}

Corrosion current density

 R_p

Polarization resistance

CR

Corrosion rate

IE

Inhibition efficiency

 K_{ads}

Adsorption equilibrium constant

 E_a

Activation energy

 ΔH

Enthalpy change

 ΔG

Gibbs free-energy change

HCl

Hydrochloric acid

NaOH

Sodium hydroxide

Ag/AgCl

Silver/silver chloride

Pt

Platinum

Declarations

Ethics approval and consent to participate

Not applicable. The study did not involve human participants or live animals.

Consent for publication

Not applicable.

Funding

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Author Contribution

TOA conceptualized the study, conducted the literature review, participated in laboratory work, analyzed the data, and prepared the first manuscript draft. EA supervised the study, analyzed data and contributed to manuscript development. OTO co-supervised the study, contributed to data analysis and manuscript development. AAO, FDA, OTI, and CAF assisted with laboratory procedures. All authors reviewed and approved the final manuscript.

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JIDEX CHICKEN PLANT, IKERE, EKITI STATE

Data Availability

The datasets and materials used and analyzed during this study are included in this published article.

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Figures

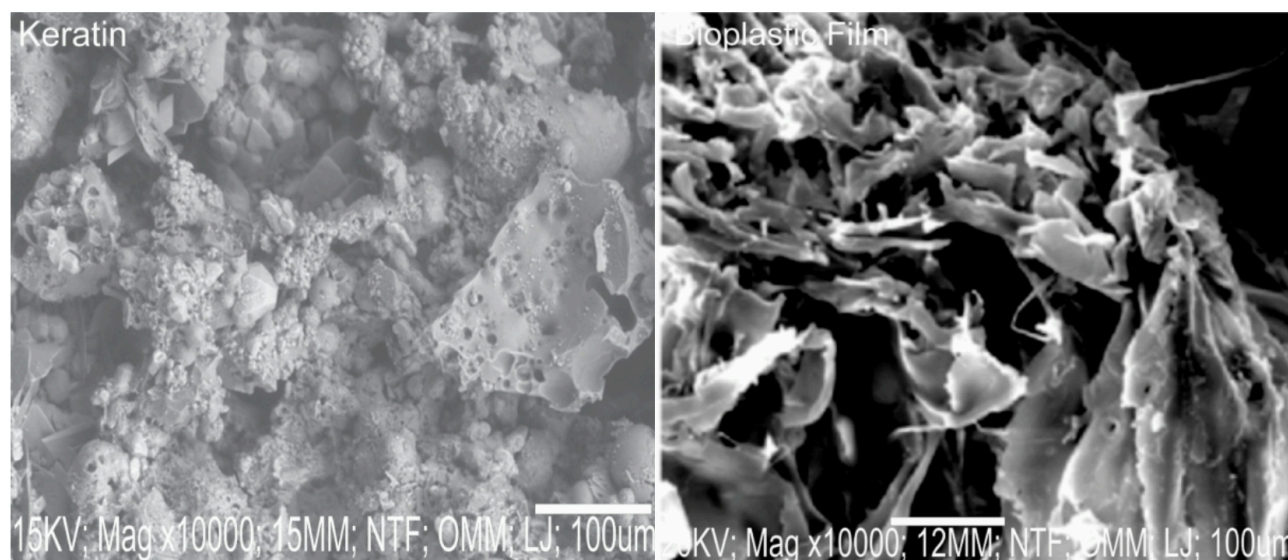


Figure 1

Scanning electron microscope image (SEM) of (a) keratin at 10,000 magnification and (b) bioplastic film at 10,000

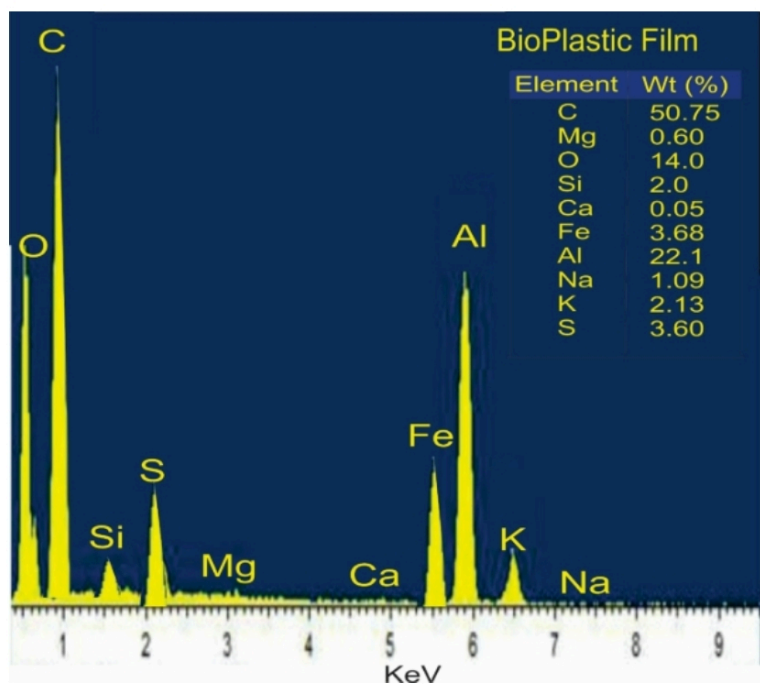
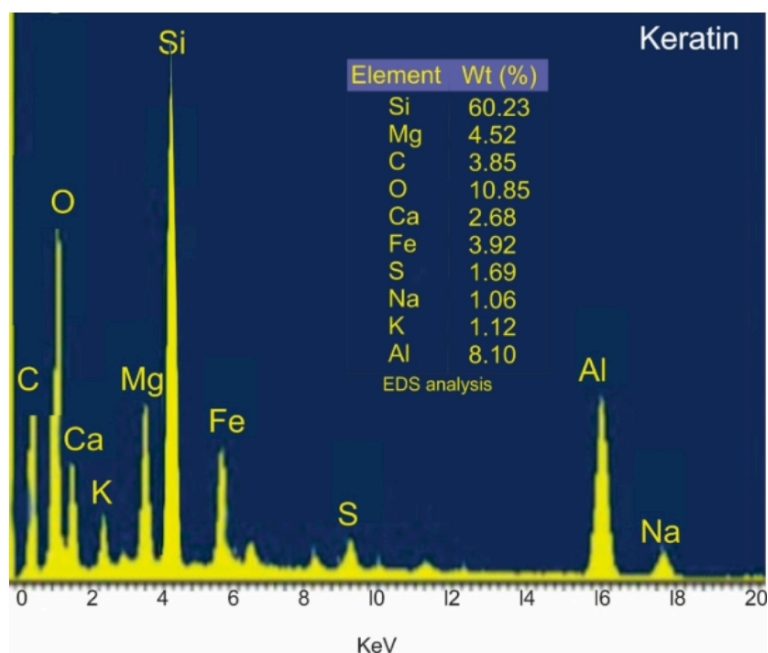


Figure 2

EDX spectra of extracted keratin and keratin-based bioplastic film.

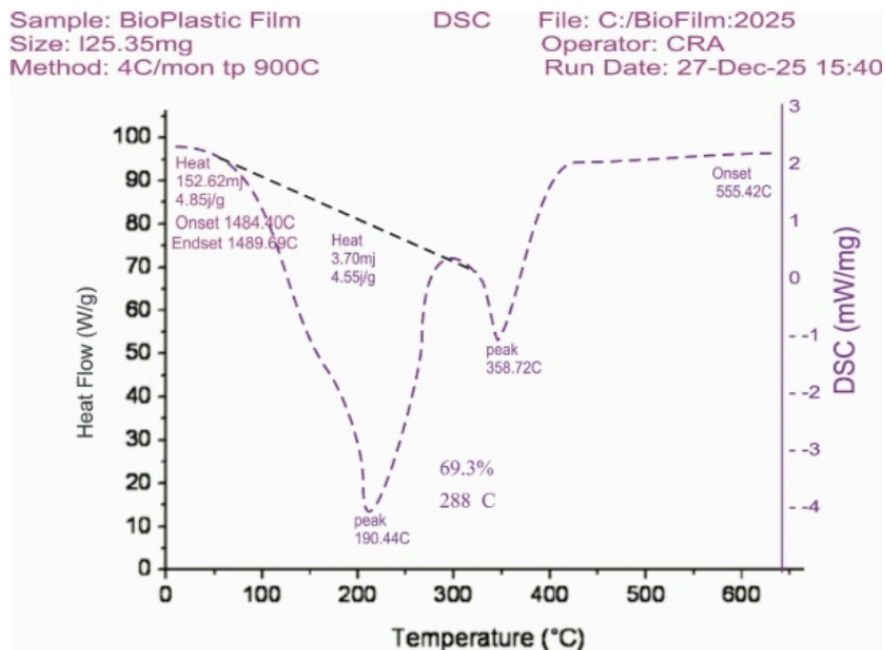
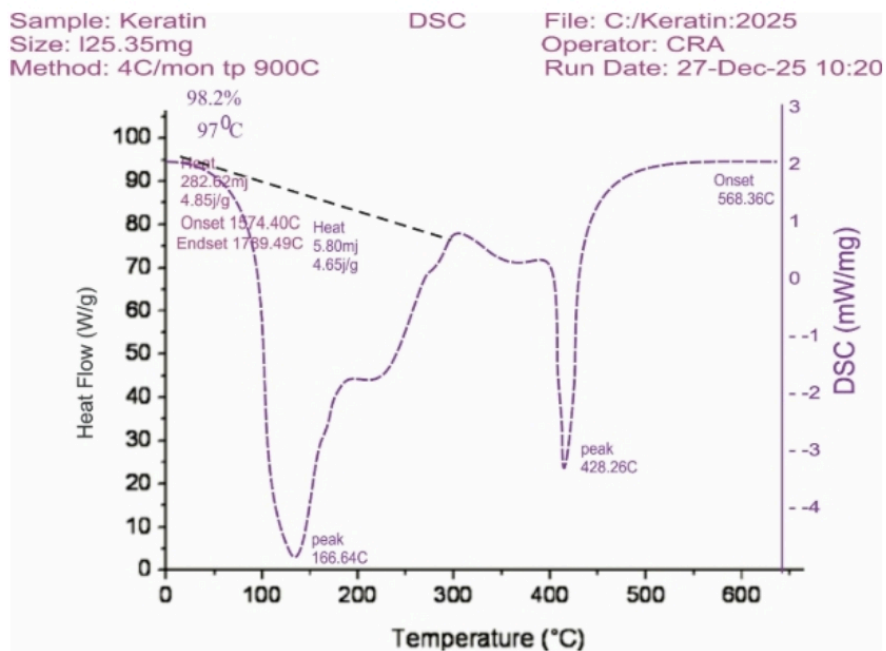


Figure 3

DSC characterization of (a) extracted keratin and (b) keratin-based bioplastic film.

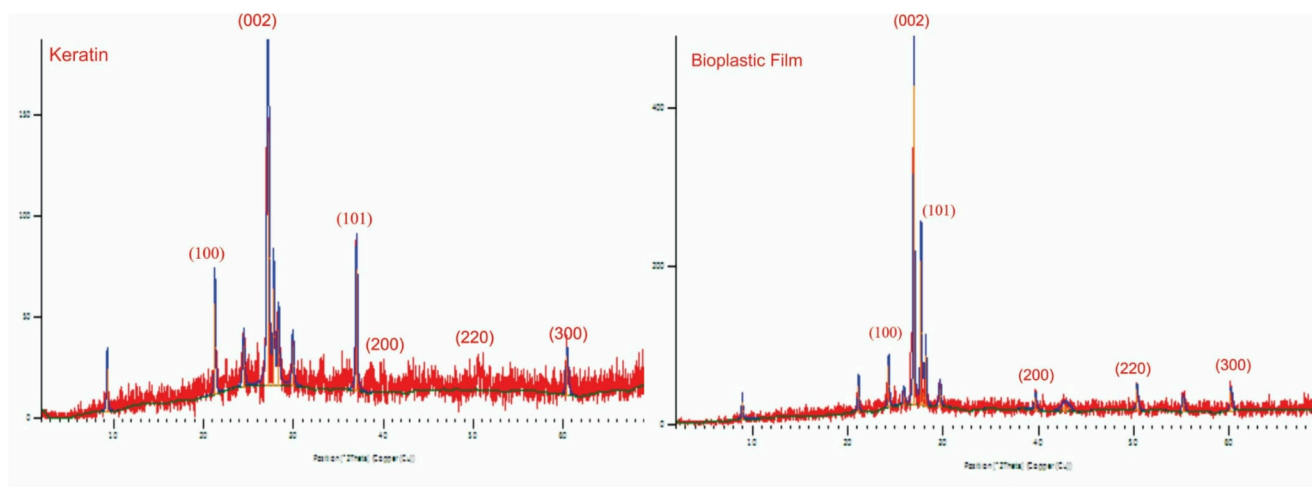


Figure 4

XRD characterization of keratin extracted from chicken feather and (b) keratin-based bioplastic film.

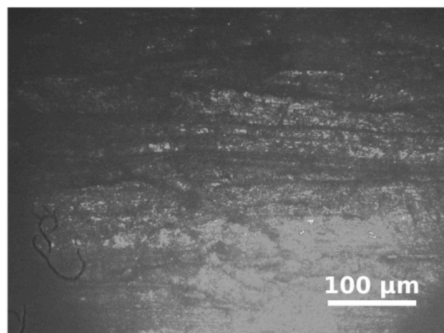
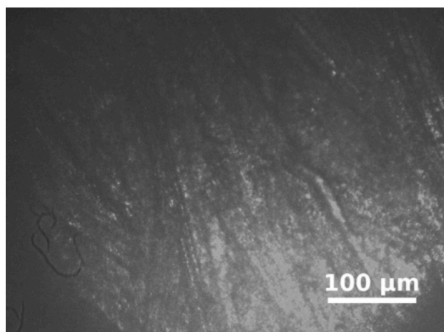
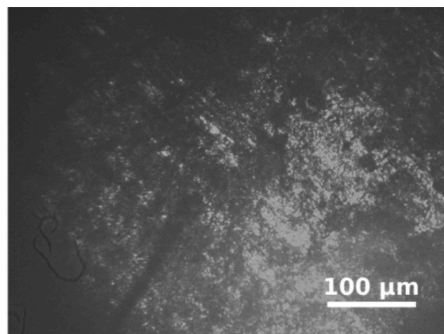
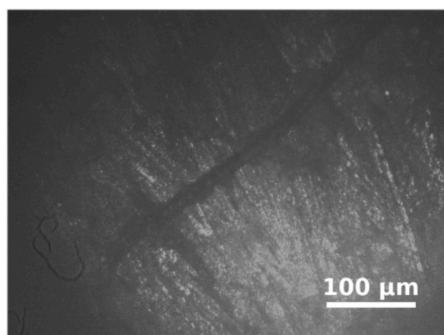


Figure 5

Optical micrographs of mild steel exposed to 0.8 g/L KBP at 303, 313, 323 and 333 K, respectively, from the present study.

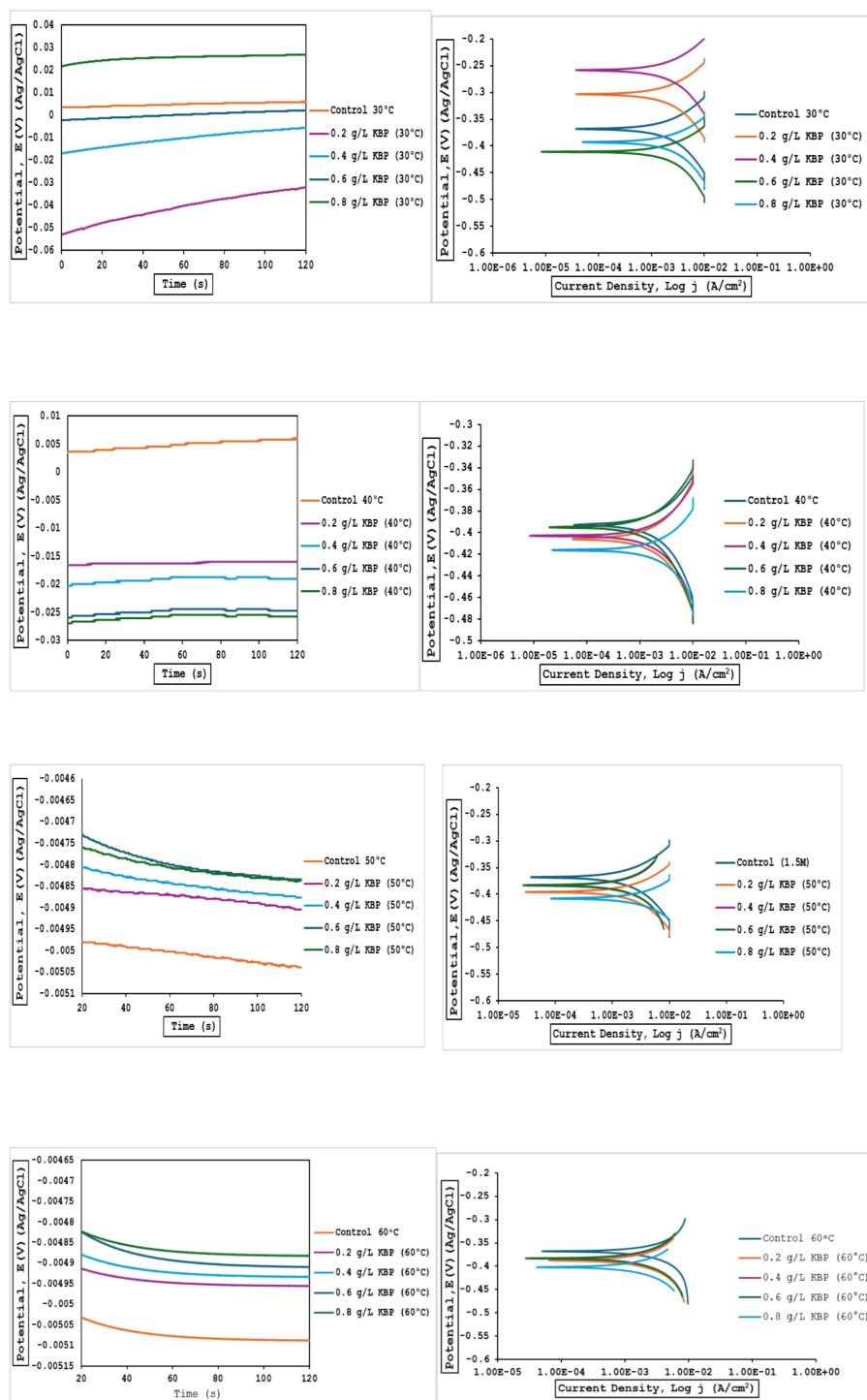


Figure 6

Potentiodynamic polarization curves for OCP @ 30, 40, 50 and 60°C/303, 313, 323, 333K and varied time for LSV @ 30, 40, 50 and 60°C/323K respectively. The curves show concentration-dependent suppression of corrosion current.