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Degradation of Chicken Feathers: A Review

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Abstract

The amount of chicken feathers generated as waste from the poultry industry in the last decade has become of technological interest for many researchers regarding both its treatment and application. At a worldwide level, billions of tons of feathers are produced due to the consumption of poultry and, consequently, leading to problems as they are affecting public health and the environment. Biodegradation processes of chicken feathers with the greatest international impact use pure strains, which have been isolated from wastes of poultry farms. Among the strains with the best degradation efficiency (100% in 1 to 7 days) are: *Bacillus* sp., *Kocuria* sp., *Pseudomonas* sp. and *Fervidobacterium* sp. At present, microbial consortia or modified strains are also used to increase the efficiency and profitability of biodegradation. Physicochemical methods include alkaline hydrolysis or alkaline-acid hydrolysis, mixture of oleic substances like soy and glycerol, microwaving, pyrolysis and carbonization. After treatment of poultry waste through different methods, relevant by-products like enzymes, amino acids, anti-oxidant, biofuels, biofertilizers, biopolymers, micro-and macro-particles, flame retardant bases, dielectric materials, super-condensers, among others, are obtained. Hence, the objective of this review is to analyze the different biological and physicochemical methods used for the degradation of chicken feathers emphasizing procurement of byproducts and applications in the biotechnological realm.

Keywords: Biodegradation; Physicochemical degradation; Chicken feathers; Keratinolytic; Byproducts

Introduction

Production of chicken meat brings about the generation of wastes, among them stand out the feathers. According to some authors [1-3] billions of tons of feathers are generated worldwide becoming a problem as they are wastes that affect public health and the environment [4]. These feathers are mainly produced in chicken processing plants and poultry farms and represent a large source of contamination, because between 5% and 10% of the total chicken weight corresponds to feathers [5]. In Mexico, it has been estimated that the total consumption of chicken will be of 3274 million tons for the year 2018 [6], which means that around 163.7 to 327.4 million tons of feathers will be produced.

Some studies on alternatives to diminish or eliminate the contamination problem propose to incorporate the feathers as feed supplement because 95% of its dry weight corresponds to protein (90% keratin) [7]. To increase their solubility, it has been

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suggested to subject the feathers to a process with high pressure and temperature, but this has disadvantages, such as high costs and destruction of some thermolabile amino acids, like histidine, methionine and tryptophan [8].

Kowalska and Bohacz [7] mention that there is a radical change regarding the use of feathers due to the aforementioned problems, hence, new cheaper technologies that generate useful byproducts have been developed in recent years. The use of microorganisms or enzymes produced by them to accomplish fermentation processes is one of the most promising technologies. For these processes, metabolism of microorganisms is necessary, such as of bacteria like *Bacillus* sp., *Chryseobacterium* sp., *Kocuria* sp., *Fervidobacterium* sp., *Brevibacillus* sp., *Xanthomonas* sp., *Pseudomonas* sp., *Leuconostoc* sp., *Scopulariopsis* sp., *Stenotrophomonas* sp. is necessary [1, 9-26] of actinomycetes like *Actinomadura* sp. [27]; of fungi like *Coprinopsis* sp., *Aspergillus niger* [28,29]; of bacterial consortia [30]; and of actinomycetes consortium [31]. In addition, some authors have performed genetic modifications of strains of *Escherichia coli*, *Brevibacillus* sp. and *Bacillus subtilis*, aimed at improving the degradation of chicken feathers in a short time and the bioprocess at different scales (laboratory and industrial level) [3,32,33].

In addition to obtaining by-products of high added value from the biological degradation of chicken feathers, the feathers have been used as adsorbents in the process of removing metals from wastewater [34] and recently its use has been highlighted in the generation of biothermoplastics and nanomaterials [35-37], so that detailed study of its structure results from biotechnological relevance for its application in various industries.

Experimental

Structure of the feather

The process of feather development starts with the formation of a conjunctive papilla (FIG. 1a), as a first placode, with the participation of the dermis and epidermis (FIG. 1b). Later on, it differentiates from the epidermal layer to give rise to the sheath that contains the radii of the down (FIG. 1c). The last stage of the development is characterized by rupture of the sheath that already envelops the incipient down. In the basal strata is the core. The whole placode becomes immersed in the follicle (FIG. 1d) [38].

Once the development is complete, the feather is composed of three different units, the central shaft of the feather called rachis, to which the secondary structure (the barbs) attaches. The tertiary structure of the feathers corresponds to the barbules, which are associated to the barbs (FIG. 1e).

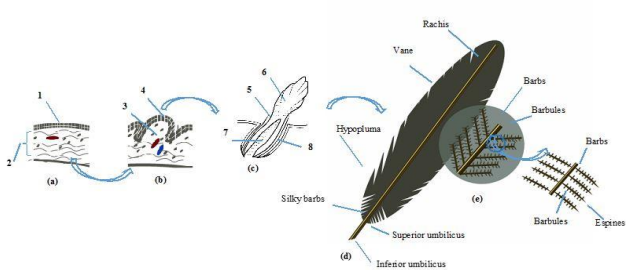

FIG. 1. **Structure of the feather. a) 1-Epidermis, 2-dermis, b) 3-Placode, 4-epidermis. c) 5-Sheath, 6-incipient down, 7-core, 8-follicle, d) Complete feather, e) Barbs and magnification of barbules.**

The axis is formed by a calamus and a rachis, despite being a very light structure; it provides the needed rigidity to keep it firm. The rachis is filled with foam (medulla) and its cross-section has a quasi-rectangular shape that tapers toward the feather's tip. The rachis consists of alternating oppositely oriented fibre layers. The medulla core, made from keratin, shows two levels of porosity, which minimizes feather weight, especially because it occupies a large part of the rachis volume. Besides the rachis is filled with dead substances, pigments and proteins that remained there, resulting from the development of the feather. The lower part of the rachis is wider and hollow, usually nude, it is called the calamus or quill and it is the part by which the feather is inserted into the skin. The calamus has in its lower part an orifice, named *inferior umbilicus,* through which the feather is fed during its growth [39]. On the upper part of calamus, the rachis starts to flatten and there is, just where the calamus ends, another orifice called the *superior umbilicus*, through which the laminar body of the feather emerged as it started to grow. In the lateral margins of the rachis grows the *vane,* a structure like a lamina divided in two opposite parts, it is the visible body and the largest area of the feather, formed by a complicated network of interwoven hooks that are the barbicels that connect barbules to each other, interlocking neighboring barbs, providing the texture of a very light tissue able to support a heavy load per area unit, the principle that allows birds to fly.

The rachis runs along the whole feather and could be of 7 inches in length. Barbs have lengths ranging from 1 cm to 4.5 cm depending on their location along the rachis. Barbs in the base of the rachis are longer than those on the tip. The tertiary structures, the barbules, have lengths of approximately 0.3 mm-0.5 mm and have hook structures in their tips [40].

Physicochemical characteristics of the feather

According to Costa et al. [20] the feather has a high percentage of volatile solids of 99 ± 1.4 (TABLE 1), which represents most of the possible degradable matter as it contains 92.0 ± 0.48% of crude protein, of which 82.8 ± 0.51% corresponds to keratin [30] constituted by different amino acids from which nitrogen can be obtained; nitrogen is an essential nutrient for the development of microorganisms capable of degrading chicken feathers. Some other constituents of the feather are fat with 2.79 ± 0.032% [30] and ashes with 0.69 ± 0.08% [1]. Chemical demand of oxygen ranges from 1200 to 1408 g/kg [20,30].

Feathers are composed of keratin. It is a semi-crystalline protein of small molecular weight (~10 kDa) [41], aside of being rich in amino acids like leucine and serine. Stilborn et al. [42] identified the amino acids present in chicken feathers at 112 days of age, the essential amino acids were arginine, cystine, histidine, isoleucine, lysine, methionine, phenylalanine, threonine, tryptophan, tyrosine and valine; the non-essential amino acids were alanine, aspartic acid, glutamic acid, glycine, proline and serine; the amino acids with the highest concentration were leucine (7.75%), glutamic acid (10.34%) and serine (11.44%).

Due to the aforementioned, the alternative of greatest interest for their degradation is the biological one, from submerged cultures and through fermentation in solid state, as this allows obtaining the enzymes capable of degrading keratin (proteases), as well as byproducts of high added value like the previously mentioned amino acids, proteins, enzymes (keratinases), etc. [21,23,24].

TABLE 1. **Physicochemical characteristics of chicken feathers.**

Variable/Fraction	**Costa et al. [20]**	**Xia et al. [30]**
Total solids (%)	100 ± 0.5	NR*
Volatile solids (%)	99 ± 1.4	NR*
Dry matter (%)	NR*	94.7 ± 0.44
Chemical oxygen demand	1408 ± 59 (g/kg)	1200 ± 0.002 (g/kg)
N-Kjeldahl	137 ± 9 (g N/kg_{waste})	NR*
Crude protein (%)	NR*	92.0 ± 0.48
Organic matter (%)	NR*	99.2 ± 0.69
Fat (%)	NR*	2.79 ± 0.032
Keratine (%)	NR*	82.8 ± 0.51
*NR: Not reported		

Biological Treatment of Chicken Feathers

Microorganisms capable of degrading chicken feathers

The amount of chicken feathers generated as waste in the last decade has become of biotechnological interest for many researchers [26,43,44]. The degradation processes most studied at the international level have used pure strains, most of these strains have been isolated from wastes of the poultry farms [1,13,25,27]. Among the strains that have shown the best efficiency for degradation are *Bacillus pumilis* A1, *Bacillus cereus* Wu2, *Bacillus megaterium* F7-1, *Kocuria rosea*, *Pseudomonas stutzeri*, *Fervidobacterium islandicum* AW-1, *Alcaligenes* sp., *Stenotrophomonas maltophilia and Actinomadura keratinilyca* Cpt29, accomplishing a total chicken feathers degradation in a period of 1.5 to 7 days [1,9,11,13,22,24,26,27]. Considering the difficulty to maintain under sterile conditions the strains with complex substrates, like chicken feathers, studies have been performed for their degradation using microbial consortia or mixed cultures. Xia et al. [30] and Tonkova et al. [31] observed that by the degradation of feathers in a mixed culture, the concentration of soluble protein obtained is two to three times higher than in a culture with pure strains. According to these authors, the use of microbial consortia and mixed cultures leads to lower operational costs and allows escalating the process. An example of this is the one reported by Xia et al. [30], who used reactors at a pilot level (42 L), for the degradation of chicken feathers using an anaerobic consortium isolated from manure and wastes from a slaughterhouse. The concentration of feathers represented 37% of the total solids in the reactor; removal of feathers was accomplished in 146 days. Tonkova et al. [31] who worked with a mixed culture of actinomycetes, observed a degradation of up to 91% at 72 h, however, it must be pointed out that the operational conditions and type of consortium were different (TABLE 2).

For the biological degradation process, feathers must be subjected to a pre-treatment, which consists of washing them with tap water to eliminate wastes from the birds, in some cases they are disinfected with detergents (Tween 80), a buffer solution (100 mM Tris HCl buffer) and sometimes sterilized with a solution of mercury chloride and 1% alcohol. The next step is to

dry the feathers at a temperature of 40°C to 60°C. Finally, they are crushed or cut into small pieces aimed at obtaining a larger area of contact of the carbon source with the microorganisms [9,13,16, 21,23,25,26,28-30,32].

For the growth of the microorganisms in charge of the degradation of the feathers, most authors use mineral media constituted by phosphates, sulfates and chlorides, which are necessary for their metabolism. As nitrogen source, authors use yeast extract, tryptone and nitrates [9,13,14,26]. Glucose, mannitol and wheat bran are used as easy digestible carbon sources. It must be pointed out that the main carbon source used is the chicken feather itself, which contains keratin in the highest proportion (TABLE 2). Many works have mentioned the relevance of the keratinolytic activity of microorganisms during the degradation of feathers, standing out the work by Al-Musallam et al. [28] with a maximal keratinolytic activity of 32, 000 U/mL produced by *Coprinopsis* sp.

Among the microorganisms mostly studied to accomplish degradation of chicken feathers is the genus *Bacillus*, which is able to degrade completely the feathers at different times, depending on the used species [1,13,22]. This genus is capable of using the feather as the sole source of carbon to achieve fermentation, adding to the medium only mineral salts that supply other microelements for the adequate growth of the microorganism Fakhfakh et al. [1] and Lo et al. [22], in some cases, adding an additional nitrogen source like a yeast extract and tryptone [13,23, 26]. As a product of the degradation of feathers, enzymes like keratinase are obtained, whose enzymatic activity is in the range of 3.8 to 1750 U/mL [22,26].

Other microorganisms studied as degraders of chicken feathers are *Leuconostoc* sp. and *Pseudomona microphilus*, however their degrading processes are slower, reaching up to 30 days and they present a low keratinolytic activity of 0.425 and 0.884 U/mL, respectively [21].

TABLE 2. **Biological degradation processes for the treatment of chicken feathers.**

Strain	**Pretreatment**	**Mineral medium**	**Carbon source**	**Reactor type//Operation conditions**	**Fermentation time (d)/Degradation (%)**	**Enzymatic activity**	**Reference**
Bacillus subtilis AMR	-Wash with detergent (linear alkylbenzene sulfonic acid) -Rinse with tap water -Dry overnight at 60°C. -Delipidate by immersion in methanol:chloroform (1:1) solution for 1	-Yeast extract 5 g/L -Peptone 5 g/L -KCl 20 g/L	sucrose 0.5 g/L feathers 10 g/L	-2000 mL Erlenmeyer flask -medium 500 mL -26 ± 2°C -150 rpm -pH 8	12 d/95%	Keratinolytic: 360.6 U/mL	[4]

	hour, -Dry at 60°C -Store at room temperature						
B. methylotrophicus	-Wash under running tap water -Dryat 60°C for48 h -Ground with ultra-fine friction grinder	-Na_2HPO_4 0.376 g/L -NaH_2PO_4 0.46 g/L	feathers 10 g/L	-Bottles 100 mL -medium 70mL -30°C -170 rpm -pH: not reported	2 d/30%	Not reported	[45]
Bacillus subtilis	-Wash with tap water 3 times for 15 min -Wash with distilled water 3 times -Dry at 60°C for 12 h	-Mannitol 10 g/L -Tryptone 10 g/L -$MgCl_2$ 0.1 g/L -KH_2PO_4 0.4 g/L -K_2HPO_4 0.3 g/L -NaCl 0.5 g/L	feathers 2 g/L	-500 mL Erlenmeyer flask -medium 100 mL -inoculum 1 mL (10^6 UFC) -37°C -160 rpm -pH 8.5	1.5 d/100%	Keratinolytic: 3.8 U/mL	[26]
Bacillus pumilis A1	-Wash with tap water 3 times -Wash with distilled water 3 times -Dry at 90°C for 22 h	-KH_2PO_4 0.5 g/L -K_2HPO_4 0.5 g/L -NaCl 2 g/L -KCl 0.1 g/L -$MgSO_4 \cdot 7H_2O$ 0.1 g/L	feathers 50 g/L	-1 L Erlenmeyer flask -medium 100 mL -45°C -250 rpm -pH 10	5 d/100%	Caseinolytic: 560 U mL	[1]
Bacillus altitudinis GVC11	Without pretreatment	Nutrient broth	feathers 10 g/L	-250 mL Erlenmeyer flask -medium 100 mL -inoculum 2%	White feathers: 2d/100% Black feathers: 4d/100%	Keratinolytic: 157 U/mL	[19]

				v/v -200 rpm -Temperature and-pH: not reported			
Bacillus megaterium	-Cut into 5 mm segments -Dry with air	-Phosphate buffer solution 0.5 mMol/L -LB medium	feathers 8 g	-1 L Erlenmeyer flask -37°C -127 rpm -pH: not reported	8 d/ degradation not reported	Not reported	[17]
Bacillus subtilis MTCC 441	-Wash with tap water -Dry at 40°C for 2 d	-K_2HPO_4 0.3 g/L -KH_2PO_4 0.4 g/L -NaCl 0.5 g/L -$MgCl_2$•$6H_2O$ 0.1 g/L	feathers 10 g/L	-250 mL Erlenmeyer flask -inoculum 5% v/v (4×10^7 UFC/mL) -medium 100 mL -pH 7.5 -Temperature and pH: not reported	5 d/97.8%	Keratinolytic: 68 U/mL	[23]
Bacillus cereus Wu2	Without pretreatment	-NH_4Cl 2 g/L -$MgSO_4$•$7H_2O$ 0.2 g/L -K_2HPO_4 1 g/L -$CaCl_2$ 0.1 g/L -KH_2PO_4 0.4 g/L	feathers 10 g/L	Performed on agar plates -40°C -pH 5.3 -rpm: not reported	4 d/100%	Keratinolytic: 1750 U/mL	[22]
Brevibacillus sp. AS-S10-II	-Wash -Dry off -Cut thinly -Suspend in a buffer solution (100 mM Tris-HCl)	Meal broth	feathers 10 g/L	Volume not reported -45°C -200 rpm -pH 8.0	2 d/78 to 82%	Keratinolytic: 1.3 mg/L	[32]

Alcaligenes sp. AQ05-001	Without pretreatment	-NaCl 0.5 g/L -K_2HPO_4 0.7 g/L -KH_2PO_4 1.4 g/L -$MgSO_4 \cdot 6H_2O$ 0.001 g/L	feathers 1 g/L plus a source of carbon (sucrose and whey) and nitrogen (ammonium bicarbonate and urea)	-Agar plates -inoculum 1% v/v-25-30°C -pH 7.5 -rpm: not reported	2 d/100%	Keratinolytic: 8.85 U/mL	[44]
Pseudomonas microphilus	-Cut into small pieces -Wash with tap water -Sterilize with 0.1% mercuric chloride and alcohol -Wash with distilled water -Dry with hot air at 45°C for 24 h	-NaCl 0.5 g/L -NH_4Cl 5.5 g/L -K_2HPO_4 0.3 g/L -$KH_2PO_4$0.4 g/L -$MgCl_2$0.24 g/L -Yeast extract 0.1 g/L	feathers 1 g	-250 mL Erlenmeyer flask -37°C -pH 7.5 -rpm: not reported	30 d/70%	Keratinolytic: 0.884 U/mL	[21]
Pseudomonas mendocina PM2	-Wash with running water -Dry at 60°C for 2 days	-K_2HPO_4 0.3 g/L -KH_2PO_4 0.4 g/L -NaCl 0.5 g/L -$MgCl_2 \cdot 6H_2O$ 0.1 g/L	poultry feathers 10 g/L	-250 mL Erlenmeyer flask -Inoculum 5% v/v (4×10^7 CFU/mL) -medium 100 mL -pH 7.5 -Temperature and-pH: not reported	5 d/91.07%	Keratinolytic: 54.8 U/mL	[23]

Pseudomonas stutzeri	Without pretreatment	-K_2HPO_4 0.3 g/L -KH_2PO_4 0.4 g/L -NaCl 0.5 g/L -$MgCl_2 \cdot 6H_2O$ 0.1 g/L	feathers 10 g/L	-100 mL Erlenmeyer flask -inoculum 5% v/v (1x 10^8 CFU/mL) -medium 100 mL -30°C -125 rpm -pH: not reported	5 d/100%	Keratinolytic: 42 U/mL	[24]
Leuconostoc sp.	-Cut into small pieces -Wash with tap water -Sterilize with 0.1% mercuric chloride and alcohol -Wash with distilled water -Dry with hot air at 45°C for 24 h	-NaCl 0.5 g/L -NH_4Cl 5.5 g/L -K_2HPO_4 0.3 g/L -KH_2PO_4 0.4 g/L -$MgCl_2$ 0.24 g/L -Yeast extract 0.1 g/L	feathers 1 g	-250 mL Erlenmeyer flask -37°C -pH 7 -rpm: not reported	30 d/31%	Keratinolytic: 0.425 U/mL	[21]
Chryseobacterium sp. kr6	-Wash threefold with tap water -Wash with distilled water -Dry at 48°C for 48 h -Stored at room temperature	-KH_2PO_4 0.4 g/L -NaCl 0.5 g/L -$CaCl_2$ 0.015 g/L	feathers 50 g/L	-1 L Erlenmeyer flask -medium 100 mL -30°C -125 rpm -pH: not reported	Not reported	Azocaseinolytic: 160-170 U/mL	[25]
Stenotrophomonas maltophilia R13	-Wash with water -Sterilize	-KH_2PO_4 0.2 g/L	-feathers 1 g/L	-250 mL Erlenmeyer	6 d/100%	Keratinolytic: 82.3 ± 1.0 U/mL	[14]

		-K_2HPO_4 1.4 g/L -NaCl 1.5 g/L -$CaCl_2$•$2H_2O$ 0.05 g/L -$MgSO_4$• $7H_2O$ 0.3 g/L	-Glucose 1 g/L - Polypeptone 1.2 g/L	flasks -30°C -200 rpm -pH: not reported			
Actinomadura keratinilytica Cpt29	Without pretreatment	-NaCl 1.5 g/L -KH_2PO_4 g/L -$K_2HPO_4$1 g/L -KCl 0.5 g/L -$MgSO_4$• $7H_2O$ 1.5 g/L	feathers 40 g/L	-9 Ml Tubes -45°C -pH 9.0 -rpm: not reported	3 d/100%	Keratinolytic: 24, 000 U/mL	[27]
Coprinopsis sp.	-Wash with running tap water -Rinse with water+Tween 80 0.1% (v/v) -Rinsed several times with distilled water -Dry with air -Cut into shorter lengths (1 and 2 cm) -Defatted with Diethyl ether (99.7%) -Powdered and sieved	-K_2HPO_4•$3H_2O$ 100 mg/L -$MgSO_4$•$7H_2O$ 500 mg/L -$ZnSO_4$•$7H_2O$ 5 mg/L -$FeSO_4$•$7H_2O$ 10 mg/L	feather powder 1.5 g	-40°C -pH 7 -pH: not reported	42 d/79%	Keratinolytic: 32, 000 U/mL	[28]
Aspergillus niger	-Wash with water and detergent -Dry at 60°C and milled	30 mL of a solution 0f 0.9% $(NH_4)_2SO_4$ in 0.1 mol/L HCl	0.4 g of whole chicken feather was mixed with 40 g of a wheat bran mixture	-Solid-state fermentation -32°C -pH 5 -rpm: not reported	7 d/ degradation not reported	Keratinolytic: 172.7 U/mL	[29]

Trichosporon loubieri	Chicken feathers and human nails were washed with water and detergent. All keratin substrates were previously delipidated with chloroform /methanol (1:1, v/v). The media were incubated for 7 days at 28°C, centrifuged at 2,000 g for 20 min and concentrated 20 fold by dialysis (cut off 9 kDa) using PEG 4000 overnight at 4°C.	0.01% yeast extract	1% of the different keratin substrates: human hair, animal hair (bovine hide), chicken feather and human nails in 0,1 M acid citric buffer pH 5.5 with 0.01% yeast extract.	-28°C pH: 5.5 -rpm: not reported	7 days/ -Human nail (61.3%) -Animal hair from bovine hide (32.7%). -Human hair (16.4%) -Chicken feathers (8.9%)	Nail keratine: 193.3 U/mL Human hair: 171.8 U/mL Human hair: 145.7 U/mL Chiken feathers: 46.7 U/mL	[46]
Streptomyces sp.	-Wash with warm distilled water -Dried at 45°C in an incubator for 2 days. -Autoclaved at 121°C. for 45 min -Stored at room temperature	-$CaCO_3$ 5 g/L, NaCl 5 g/L, K_2HPO_4 g/L	Feathers 5.0 g/L	-250 ml Erlenmeyer flasks -28°C -pH: 8 -150 rpm	5.5 days/degradation not reported	487 U/mL	[47]
Actinomycetes consortium (3H, 8H y M4)	-Wash with hot water -Sterilize at 134°C for 50 min to 2 atm -Dry at 30°C for 72 h -Cut in pieces	-NaCl 5 g/L -$CaCO_3$5 g/L - K_2HPO_4•$3H_2O$ 3.5 g/L	Feather 5-7 g/L	-100 mL Erlenmeyer flask -55°C -130 rpm -pH 7.5-8.5	3 d/87-91%	Hydrolytic in solid medium, measured in a range of 10 to 28 mm	[31]

Results and Discussion

Byproducts of the biological degradation

The biological degradation process of chicken feathers is environmentally friendly as it does not generate wastes, aside from being economically feasible because it allows obtaining diverse byproducts, from an industrial waste, with a high added value as are soluble proteins and amino acids at diverse proportions (TABLE 3) [21,23], standing out the works of Kani et al. [21] and Chaturvedi et al. [24] who used a *Pseudomonas* strain for the degradation of feathers obtaining a high concentration of amino acids (1.992 mg/mL) and soluble protein (0.546 mg/mL), respectively. These products have applications in the degradation of malachite green absorbed by feathers (about 99.5% degradation after 24 h) and the shaving of goat skins with raw extract of keratinase.

TABLE 3. **Byproducts and applications of biological treatment**

Strain	**Byproduct**	**Application**	**Reference**
Pseudomonas mendocina PM2	Protein: 468.2 mg/L Keratinase	Degradation of malachite green absorbed by feathers (about 99.5% degradation after 24 h)	[21]
Bacillus subtilis MTCC 441	Protein: 546.7 mg/L	Do not metabolize feathers with malachite green	[23]
Pseudomonas stutzeri	Protein: 784.2 µg/mL Keratinase	Shaving of goat skins with raw extract of keratinase	[24]
Scopulariopsis brevicaulis (Sacc.)	Keratinase	The purified enzyme hydrolyzes different materials such as chicken feathers, nails and human hair	[18]
Stenotrophomonas maltophilia R13	Total amino acids: 2298.8 µM Protein: about 43 µg/mL	Obtaining indoleacetic acid (IAA) (327.7 ± 3.9 µg/mL) without l-tryptophan in the medium with antifungal activity	[14]
Bacillus licheniformis ER-15	Keratinase	Hair removal	[16]
Fervidobacterium islandicum AW-1	Amino acids: Histidine, cysteine, lysine, tryptophan and methionine Keratinase	Applications of keratinase enzyme at high temperatures Study of the structural stability of thermostable enzymes at high temperatures	[11]
Chryseobacterium sp. kr6	Feather hydrolyzate	Antioxidant and antihypertensive activity	[25]
Kokuria roseae	Feather meal with lysine, methionine and histidine	Nutritional supplement (Alternative source of protein for bird feed)	[12]
Fervidobacterium pennivorans	Methane gas	Biofuel	[20]

Actinomycetes consortium (3H, 8H y M4)	Biohydrolyzed	Source of soluble protein, amino acids, enzyme and other add products	[31]
consortium of anaerobic bacteria	Methane gas	Biofuel	[30]
Aspergillus niger	Keratinase	Enzymatic enhancement of foods and feed additives made of feathers. Production of amino acids and high molecular weight peptides, which are substrates for cosmetics	[29]
Paenibacillus woosongensis TKB2	Keratinase	Promoter of plant growth. Promotes seed germination (germination rate 87.5%) and seedling growth of *Cicer arietinum*. Nodule formation (3-fold) is induced and soil fertility increase by the alteration of N, P, K and the C/N ratio by 1.2-fold. Improves the amount of fixed nitrogen of free-life (2-fold) and phosphate solubilizers (5.8-fold)	[48]
Bacillus subtilis DB 100	Soluble proteins and NH_2-free amino groups Keratinolytic alkaline protease	Production of enzyme of keratin degradation, it works as a proteaseand as a keratinase	[3]

The produced amino acids and peptides of high molecular weight can be used as substrates for cosmetics [29]. Some other interesting byproducts are used in food supplements for example from a bio-hydrolysate obtained of the degradation of feathers with an actinomycetes consortium, can be used as a source of soluble proteins, amino acids, enzymes and other valuable products [31]. Among the byproducts of greatest interest obtained in this process are the enzyme keratinase, which has been used for the degradation of diverse materials, like nails and human hair [18] and to shave off goat skins [24].

It is important to point out that the degradation process can be coupled to the detoxification of some other contaminant in the environment, such as malachite green, which can be absorbed by chicken feathers and degraded jointly by *Pseudomonas mendocina* PM2 [23]. It is also possible to obtain growth promoters like indole-acetic acid (327.7 ± 3.9 µg/mL) to improve seeds germination and seedlings growth (germination rate 87.5%) and seedling growth of *Cicer arietinum* [14, 48].

Other biotechnological applications relevant nowadays due to the energy problems arising from the depletion of fossil fuels, are the generation of biofuels such as methane a byproduct of the degradation of chicken feathers by *Fervidobacterium pennivorans* and anaerobic bacteria consortia [20,30].

Physicochemical processes in the treatment of chicken feathers

Among the methods of feathers degradation are the physicochemical ones, which include alkaline hydrolysis (with sodium sulfide, sodium or calcium hydroxide) and alkaline-acid hydrolysis (with sodium hydroxide and citric acid), microwaving, polymerization and carbonization; aside from mixture of feathers with oleic substances like soy and glycerol to form polymers (TABLE 4).

Among the alkaline hydrolysis methods is that report by Coward-Kelly et al. [49] in which the authors indicate that, after a digestion with calcium hydroxide at 150°C and 100 rpm, they identified the amino acids that remained after the degradation, these were alanine, arginine, cysteine, leucine, histidine, methionine, among others, some of these were essential amino acids and they were used as supplements for cattle feed. The authors emphasize the importance of degrading the feather to keratin and of this to free amino acids, because keratin is a protein that is not degraded by proteolytic enzymes and is only digested in 18%. They also demonstrate that keratin is deficient in amino acids like arginine, histidine, lysine, methionine and threonine; therefore, it is not recommended for monogastric animals but is adequate for ruminants. On the other side, Chen et al. [50] developed a novel method using microwaves for the degradation of feathers and, like Coward-Kelly et al. [49] identified several amino acids that can be used as nutrient source and to obtain high commercial value products, reporting that from the total content of protein, 71.83% is keratin; in addition, they obtained a high yield in easily separated amino acids and the method is environmentally friendly [50].

From alkaline hydrolysis, some polymers can be obtained and used as basis of a varnish to treat and preserve archaeological wood. Endo et al. [51] obtained a polymer based on duck, chicken and hen feathers hydrolyzed with sodium hydroxide at 70°C for 3 h and found that the best structures of the keratin hydrolysate were those obtained from duck feathers; this because they were characterized by greater crystallinity and anti-alkali structures that contribute to a good dimensional stability. Popular preservation methods include the addition of polyethylene glycols of up to 90% compared to the polymer obtained from duck feathers, of which up to 40% is used for good wood preservation.

Al-Asheh et al. observed the capacity of the feathers treated with alkaline solutions of 0.2 N NaOH as adsorbents of heavy metals of copper and zinc in wastewater [34]. The feathers treated chemically with alkaline solutions have twice the sorption capacity of the untreated feathers. Another hydrolysis used to treat feathers is the alkaline-acid (sodium hydroxide and citric acid) for the production of biothermoplastics, which are poor in water stability and mechanical properties; therefore, authors mixed the keratin extracted from the feathers with acrylate monomers to improve these characteristics. Biothermoplastics are used for the elaboration of biomedical scaffolds; this is one of the most novel applications because they are used for support [35,36].

Another area of opportunity is the development of biomaterials of natural origin, as for example proteins, including collagen, albumin, gelatin, fibroin and keratin. Of these proteins, materials based on keratin are a promise to revolutionize the world of

biomaterials because of their biocompatibility, biodegradability capacity, mechanical durability and natural abundance [52]; however keratin is insoluble in many common solvents like diluted acids, alkalis, water and organic solvents [53]. Some authors consider that the challenge in the production of biopolymers or biothermoplastics is to develop a technique to dissolve keratin to produce solutions capable of re-crosslinking, having a minimal degradation of primary protein chains and being able to be escalated at the industrial level [54]. Currently, a wide array of these techniques is available for the dissolution of hard keratin, often reactions of reduction or oxidation are used and, more recently, ionic liquids are being tested [31].

Some of the most important biomedical applications of natural polymers include drug carriers that are biodegradable and have the quality of controlling the administration of the drug. In these systems, an active therapeutic agent is incorporated into a structure of polymeric network so that the drug is released from the material in a predetermined manner [52].

Another technique for the treatment of chicken feathers is pyrolysis at high temperatures; one of the most recent studies is that reported by Senoz et al. [55] who evaluated the structural changes of the chicken feathers after a pyrolysis process by a constant flow of N_2, posterior to a thermal treatment at 25°C to 600°C. Changes were determined by mass spectrometry, solubility tests and gel chromatography. The thermal treatment below the fusion point provided enough reticulations of the protein matrix to maintain intact the fibrous structure; on the other side, the treatment above the fusion point provided cycling and aromatization reactions to the protein matrix. Release of aromatic carbons and free amines were observed during these transformations, finding that the adjustment of the thermal profile of pyrolysis provides conditions that lead to the fabrication of materials that are useful at high temperatures, like fibers or macromolecules with textile application and in high yield catalyzers.

Some other applications of chicken feathers based on chemical reactions are those mentioned by Zhan and Wool [56] who mixed feathers (30%) with soy oil and glass fibers to produce printed circuit boards used for all types of computational circuits. Mishra and Nayak [57] obtained dielectric materials to be used as isolation, for printed circuit boards, for encapsulators and condensers, by mixing 5% of feathers with epoxy and glass. On the other hand, Zhan et al. [58] carbonized feathers to obtain electrodes for super-condensers. Sun et al. [37] solubilized feathers with 1-butyl-3-methylimidazolium chloride attaining a solubilization of up to 23% to obtain micro and nanoparticles of keratin to eliminate chromium. Among the characteristics of some byproducts obtained by physicochemical methods, stand out the high fusion point and the procurement of high yield condensers and materials with flame retardant properties [55,59].

TABLE 4. **Physicochemical processes: byproducts and applications.**

Process	**Conditions**	**Byproducts**	**Applications**	**Feather Pre-treatment**	**Reference**
Alkaline (sodium hydroxide) and acid (citric acid) hydrolysis	Feathers were treated with various concentrations of NaOH	Bio-thermoplastic	Thermoplastic film for biomedical applications	-Commercial chicken feather fiber (NIXA, MO) -Wash, dry and grind	[35,36]

	For the preparation of the thermoplastic was mixed with glycerol and compressed between aluminum foils.				
Alkaline hydrolysis	Samples of 2 g of chicken feathers were immersed in solutions of NaOH and Na_2S in the range 0.05–0.4 N and 0.05–0.3 N, respectively	Adsorbents	Adsorbents to remove copper and zinc from wastewater	Some of the materials attached to the feathers were first removed, through several washings with tap water and detergent and were then left in the open air for several days to get rid of odors. have been frozen by liquid nitrogen before cutting into small sizes using an electrical cutter	[34]
Mixture of feather keratin With graphite oxide	About 70 g of feather powder, 30 g plasticizer mixture (15 g glycerol and 15 g propylene glycol), 3 g sodium sulfite prepared in 15 mL deionized water and 23 mL graphite oxide dispersión prepared in deionized water	plastics nano-reinforced	Agricultural films, composting bags and biodegradable containers	-washed with hot water -Dry a for three days and then dried at 50°C -Grinding of Feather and size sieve of 0.25 mm perforations.	[41]

Mixture of feathers with glycerol	The deoxidation of the feathers is carried out with 2-mercaptoethanol. Then, the extracted keratin is modified with chloroacetic acid. At the end, glycerol is added as plasticizer	Protein films	For administration and control of drug release Widely used in food, biotechnology, thermoplastics, packaging and other applications	The feathers were washed, dried and ground in small filaments with a length of 1-2 mm. 3 g of feathers were refluxed in hydrated ethanol. They were then pretreated with a solution of HCl Ethanol and HCl were filtered and the cleaned and pretreated feathers	[53]
Mixture of feathers with soybean oil and glass fibers	The plates were formed with modified soybean oil with glass fibers E and 30% feathers. The material was compressed with copper plates and an anti-inflammatory agent	Printed circuit boards (PCBs)	All Computer Circuits	The feather fibers were dried in an oven at 50°C for at least 4 h and then stored in a desiccator prior to use.	[56]
Feathers mixed with epoxy	Feathers were mixed with different percentages of epoxy and glass. The best mixture was with percentages of 5 and 10% epoxy	Dielectric materials	They are used in various applications, including Insulation, encapsulation, printed circuit boards, capacitors and other devices.	The chicken feathers were cleaned with a polar solvent (ethanol) and dried. The quills were removed and short fibers 10-15 mm in length were obtained	[57]
Mixture of chicken feather fibers with LDPE (Low	Feathers=0 to 50% by weight Melting	Polyethylene reinforced with chicken feather	All products made with polyethylene	The feathers are cleaned and separated from	[60]

Density Polyethylene)	temperature=171-168°C Mixing time=15 min The mixture is sandwiched between Teflon coated with aluminum paper and cooled under an aluminum block	fibers		the rachis through a process developed and patented by USDA. They were milled and sieved.	
Mixture of chicken feather protein, melanin, sodium pyrophosphate and glyoxal	Keratin powder was dissolved with melanin and sodium pyrophosphate (1:8:5) in distilled water. Glyoxal was then added at 80°C. The pH was adjusted to 8 at a temperature of 90°C for 2 hours	Flame retardant on flame	For fire prevention of different materials	The feathers were cleaned and dissolved with 10g/L NaOH and 4g/L urea at 90°C for 3 hours. Later keratin solution was neutralized with hydrochloric acid and subsequently filtered. The filtrate was again treated with hydrochloric acid. The protein was obtained by filtration and dried at 50°C.	[59]
Microwave treatment	Hydrolyzed at mild high temperature from 433 to 473 °K. Hydrolisis was carried out with a self-deasing batch-type autoclave reactor power of 1200 W.	Amino acid (arginine, alanine, threonine, glycine, praline, serine, glutamic acid, aspartic acid, cystine y tyrosine). The	By-product with high nutritional value	Duck feather were washed with water, dread and cut into small pieces	[50]

	The reaction about 500 mL Teflon spraying cylinder vessel with a height of about 6 and a diameter of 10 cm	total yield of amino acid at 54.72% with feather containing about 71.83% keratin			
Pyrolysis by thermal	A constant N_2 flow (100 mL/min) was proved for 3 h prior temperature ramps to minimize the oxygen concentration. The temperature was increased to 215°C at a 3°C/min and kept constant for 2, 4, 10, 15 and 24 h	Keratin fibers with aryl carbons and cyclic amines	Keratin fibers for the production of materials with high melting point, catalysts of high performance and for textile use	Chicken feather fiber were provided by Feather fiber Corporation (Nixa, MO)	[55]
Polymerization	Deoxygenating by passing N_2. Polymerization was initiated by adding the oxidant ($K_2S_2O_8$) at pH 5.5 at 60°C for 4 h. The grafting reaction was terminated by adding 1 ml of 2% paradioxybenzene. Afther neutralizing, filtered, washed and dried	Bio-thermoplastic	For biomedical applications	Chicken feather fiber were provided by Feather fiber Corporation (Nixa, MO)	[35]
Carbonization of feathers	The feathers were carbonized by heating to 800°C and activated with potassium	Feather electrode	Electrode for super capacitors	The feather fibers were dried in an oven at 50°C for at least 4 h and then stored in a	[58]

	hydroxide in repeatedly. Subsequently placed in acetylene black and polyvinylidene fluoride (PVDF) which was dissolved in N-methyl pyrolidinone solution and pressed into 1 square centimeter steel mesh and a thickness of 0.2 mm.			desiccator prior to use.	

Future Outlooks

According to what was reviewed in this research on biological and physicochemical treatments of feathers and feather waste, it is observed that studies in the future will be focused on the following points.

- Scaling and optimization of bioprocess, obtaining products with high added value, emphasizing the production of enzymes for use in the medical, food, cosmetic and industrial areas mainly.
- The future research in the physicochemical treatments of feathers is focused in the use of green technology, evolving group of methods and materials environmental friendly for to modify the properties of feathers
- Improvement of nanomaterials for its application in the healthcare sector (For example, as carriers and as excipients to obtain different drug delivery systems and orthopedic devices, etc).

Conclusion

Chicken feathers are potential raw materials to obtain byproducts of high economical and scientific value; this is due to its low cost as waste, large availability and chemical composition, The biotechnological processes for the degradation of feathers pose some advantages over the physicochemical methods like their low energetic costs, being environmentally friendly and the procurement of considerable amounts of enzymes applicable to the chemical, cosmetics and food industries. It is considered necessary to escalate studies because most of the developed physicochemical and biological processes are currently limited to the laboratory scale.

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