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Keratinaceous Wastes and Their Valorization through Keratinolytic Microorganisms

Debananda Singh Ningthoujam,
Keishing Tamreihao, Saikat Mukherjee,
Rakhi Khunjamayum, Laishram Jaya Devi and
Roshan Singh Asem

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Abstract

Keratin is a fibrous protein mainly found in higher vertebrates such as mammals, birds, and reptiles. It is also a major constituent of human epithelial tissues. Major keratinaceous wastes include skin, hair, wool, feather, horns, hooves, and nails. Large amounts of such wastes are generated from meat industry, poultry houses, and wool industry etc. Though keratinous wastes contain about 90% protein, keratin is usually recalcitrant to normal proteases. Such wastes have been traditionally digested using physico-chemical methods. But such techniques are energy-intensive and technologically demanding. Also, such approaches lead to degradation of certain amino acids such as lysine. In nature, keratinaceous wastes don't accumulate indicating that keratinolytic microorganisms exist in nature. Keratinase producing strains are distributed among bacteria, fungi, and actinobacteria etc. Hence, potent keratinolytic microbes and their enzymes may be used for valorization of keratinous wastes. Efficient degradation of such wastes may generate value-added products such as feed additives, agricultural biofertilizers, and cosmetics. This chapter will give a comprehensive overview of types of keratinaceous wastes, kinds of keratinolytic microbes and keratinases, and valorization of such wastes using keratinase producing strains and/or keratinases.

Keywords: keratinaceous wastes, keratin, keratinolytic, valorization, keratinase, bacteria, actinobacteria

1. Introduction

Keratin, a versatile bioactive polymer is abundantly distributed in nature. Keratin has turned out to be very attractive for many advanced applications, ranging from agriculture to biomedical engineering. It is the major component of epidermis as found in hair, nail, feather, wool, hooves, scales, and horn. An insoluble macromolecule with long polypeptide chains, keratin is recalcitrant to attack by common proteases like pepsin, papain, and trypsin due to its highly supercoiled and tightly packed molecular structure that is stabilized by inter chain cross linking between parallel strands as well as by hydrogen bonding or hydrophobic interaction [1]. Keratins have been subdivided into α and β [2, 3] based on the secondary structure conformations.

In both α and β configurations, keratin fibrils are twisted parallelly forming micro and macro fibrils conferring stability to the keratin fibers [4, 5]. Keratins can also be subdivided into soft and hard keratins based on the sulfur content.

Hard keratins have high disulfide bond content that makes them tough and inextensible as found in feathers, hair, hooves, and nails. On the contrary, soft keratins are more pliable due to low content of disulfide bonds as found in skin [3, 6]. Properties of any keratinous material such as viscoelasticity and stiffness depend on the degree of hydration of the keratin molecule [7].

Among the keratinous materials, feather is the most predominant one. Millions of tons of feathers are liberated annually from poultry processing farms as waste products and approximately 90% is keratin [8]. Presence of keratin makes chicken feather highly stable environmentally [9]. Feather constitutes 95–98% protein, predominantly β -keratin. The major dominating amino acids in the structure comprise glycine, alanine, serine, cysteine, and valine. The structure has less lysine, methionine, and tryptophan [10].

Apart from feather, keratin is also the major constituent of wool, almost 95% of the dry matter of a wool fiber. The wool fiber is actually a collection of elongated cells that consist of multiple types of keratin proteins. The fiber has three main areas classified into cuticle, cortex, and medulla. The major body of the hair fiber, the cortex, is composed of many spindle shaped cells containing keratin filaments [11].

Apart from feather and wool, mammalian hair also contains keratin [12]. Similarly, hoof horn consists of keratin arranged in both tubular and anti-tubular form. However, in ram horns, fibrous proteins which are alpha keratin in nature and rich in cysteine are found [13].

2. Keratinaceous wastes

Each year millions of tons of keratinous wastes get generated globally especially in wool textile industry and in poultry slaughterhouses [14, 15]. Keratinous wastes, generated mainly in the form of feathers, hairs, horns, hooves, and nails are gradually accumulating in the environment. Enormous amount of urban wastes are accumulating in form of sewage under the bottom sediments of rivers and canals making it difficult to solid waste management and is important to recycle it [9].

Feather is the most abundant keratinous waste material liberated in the modern society. Worldwide annual feather amounts to about $8-9 \times 10^5$ tons [12]. Chicken meat processing industry contributes maximum to this amount. This industry is growing rapidly as consumption of chicken meat is common to all sections of society, encompassing all customs and religion [16]. According to the USA Foreign Agricultural Service, the total domestic per capita consumption of chickens is 59 kg in the USA; 48.0 kg in Saudi Arabia, 67.1 kg in Hong Kong, 69.7 kg in Israel, and 35.4 kg in Canada [17, 18]. The large consumption of chicken meat generates huge amounts of chicken feathers worldwide.

As per statistics, around 58×10^9 chickens are slaughtered for meat in the world every year [18, 19]. The United States of Department of Agriculture figured that 46.6×10^9 kg of chicken meat was processed in the USA poultry processing industry in 2014 which generated 40×10^9 kg of feathers per annum worldwide [18, 19].

Besides, during poultry processing, many inedible by-products unfit for human consumption are produced. Locations related with animal husbandry and meat products establishments are major sites of environmental pollution and possible transmission of diseases through improper treatments can be possible [20].

Presence of microbial toxins and high quantities of microorganisms, e.g., microbes, infections, parasites and yeasts are common in poultry products [20]. Thus, slaughterhouse products could also be a potential danger to human and expert efforts are needed for management of the recalcitrant keratinous wastes.

3. Keratin digestion

It is estimated that 58×10^9 chickens are killed each year which generates enormous keratinous wastes that might create environmental pollution. Poultry processing farms throw around 40×10^9 feathers into landfills. Various conventional waste disposal methods such as burial, incineration, and controlled landfilling are practiced. But they have high water and energy demands. Besides, there are also health concerns such as bird flu due to presence of pathogenic microorganisms in dead chicken [21, 22].

The incineration of keratinous wastes release greenhouse gases creating environmental issues. On the other hand, landfilled keratin wastes take a long time to decay and incineration releases greenhouse gases. Also, the costs associated to dispose the feather waste are high as availability of landfill space is reduced. New environmental laws have been developed to enforce generators to deal with environmental wastes in sustainable way. Industries need to recycle, reutilize, minimize, treat, and dispose waste as the last alternative [23]. Therefore, keratin digestion has always been an important issue to maintain a sustained environment.

3.1. Physico-chemical methods

Various physico-chemical methods are being used for decades to digest the keratin thereby mitigating environmental pollution and generating useful resources from keratinous wastes in various aspects.

3.1.1. *Hydrothermal method*

This process usually employs high steam pressure (10–15 psi) and/or high temperature (80–140°C) in presence of acid or alkali. The process yields water soluble polypeptides, oligopeptides, and even free amino acids. The major drawback of this process is that keratin hydrolysis by hydrothermal method may cause partial or complete destruction of certain amino acids. Besides, it also leads to loss of essential amino acids such as lysine, methionine, and tryptophan. Also, the process leads to formation of non-nutritive amino acids such as lysinoalanine and lanthionine from cystine and lysine respectively [24, 25].

Lysinoalanine is never used at all by animals as a source of lysine [26]. Besides, the hydrolysis of other amino acids is also decreased by excessive steam and heat treatments [24]. In addition, lanthionine content was found to be inversely proportional to the digestible amino acids that suggest presence of lanthionine in feather meal represent an excellent index of over-processing. Another phenomenon which also influences protein quality during this process is the racemization of amino acids. This happens readily after alkaline treatments [27, 28], but to a lesser extent during the heating of proteins [29–31]. Feather meal autoclaved with sodium hydroxide reduced amino acid digestibility values when compared with samples without alkali or enzyme treated.

3.1.2. *Acid and alkaline treatment*

The pros and cons of acid and alkaline hydrolysis of keratinous wastes have been described by Asquith [32]. The most satisfactory method to convert keratin quantitatively into their individual amino acids involves acid hydrolysis [33, 34]. Martin and Synge examined partial acid hydrolysis of wool and gelatin at 37°C in an excess of 10 N HCl for several days and were succeeded in release of one third of amino acids [35, 36]. Asquith was able to semi-quantitatively determine some peptide sequences in wool keratin by controlled hydrolysis of keratose fractions [37]. Similarly, partial hydrolysis was used to determine the amino acid sequence of wool proteins [38, 39].

Alkali also hydrolyzes keratin fibers but less selectively than to acids. 0.1 N NaOH rapidly dissolves wool while boiling. However, the process results in destruction of arginine, serine, threonine, cystine, and cysteine. But tryptophan is not destroyed in alkali, and the analysis of alkaline hydrolysates is done by quantitative determination of tryptophan [40]. Wool, if treated with alkali, three new amino acids- lanthionine, lysinoalanine, and 8-aminoalanine could be recovered [40].

3.1.3. *Steam explosion*

Steam explosion is a subtype of hydrothermal method of keratin hydrolysis and have been discussed by various authors [41]. Steam explosion (SE), a hydroelectric pre-treatment of biomass releases the constitutive components. The process involves short exposure and then rapid release of the pressure in an explosive decompression event [42]. Originally developed by Mason, the process has been explored extensively in biomass conversion [43, 44].

Using this methodology, Tonin et al. [45] generated hydrolysate from wool waste. But the yield was 18.66%.

The hydrolysis of wool wastes by steam explosion was also studied by Xu et al., 2006 [46]. A yield of 62.5% hydrolysates was achieved by passing steam at 600°C and 0.8 MPa. Scanning Electron Microscopy results detected that during explosion, some scales on the fiber surface were cleaved and tiny grooves were formed. Differential Scanning Electron Microscopy indicates reduction in thermal decomposition energy of the treated fiber. This reflects destruction of crystals and crosslinks of macromolecular chains in the fiber due to steam explosion. Besides, steam explosion also did some alterations in the fiber properties such as reduction in strength, solubility in caustic solution, and moisture regain.

3.1.4. Ionic liquids

Use of ionic liquids such as 1-butyl-3-methylimidazolium chloride ([BMIM]Cl) or a hydrophobic ionic liquid (IL), 1-hydroxyethyl-3-methylimidazolium bis(trifluoromethanesulfonyl) amide ([HOEMIm][NTf₂]) have been attempted to generate keratin hydrolysates [47–49]. The extracted keratin could also be easily separated from the reaction system. Another ionic liquid, NaHSO₃, was also successfully investigated. The results indicated [BMIM]Cl/[HOEMIm][NTf₂] is an efficient catalyst and solvent for dissolving feathers and could be easily recovered due to its hydrophobicity [47]. The dissolution and regeneration of the waste chicken feathers in an ionic liquid of [BMIM]Cl showed an excellent efficiency (63.5–87.7%).

3.1.5. Reduction and oxidation

Reduction and oxidation have also been used to convert keratinous wastes esp. hair wastes to hydrolysates. Shindai method is a special type of treatment employed for preparing hydrolysates from hair wastes [50, 51]. It is a rapid and convenient procedure to extract human hair proteins for examining the biochemical properties in detail.

The procedure is based on the principle that in the presence of a reductant, a combination of thiourea and urea can effectively remove proteins from the cortex part of human hair. Using this procedure, the extracted fraction from human hair mainly consisted of hard α -keratins with molecular masses of 40–60 kDa, and keratin-associated proteins (KAPs) with a molecular mass of 6–30 kDa. Hair samples when incubated in the Shindai solution containing alcohols such as methanol, ethanol, 1-propanol, 2-propanol, 1-butanol, and 2-methyl-1-propanol, the extraction of KAPs was enhanced, but extraction of keratin was suppressed. Thus by using ethanol, selective purification of KAPs and keratin was achieved.

3.2. Microbial keratin degradation

Microbial degradation of keratin is reported in some bacteria, actinomycetes, keratinophilic fungi, and larvae of the common clothes moth *Tineola bisselliella* [52, 53]. They use keratin as the sole source of C, N, S, and energy. Keratinolytic bacteria were most isolated from bird feathers and the plumage [54–56], composting [57], or feather waste processed by fermentation. The bacteria often belong to the genus *Bacillus* and order actinomycetes. Feather degrading

abilities were mostly found in *Bacillus licheniformis* [54] as well as in *Bacillus pumilis*, *Bacillus subtilis*, and *Bacillus cereus* [57] and in some non-spore forming bacteria *Stenotrophomonas* sp, *Fervidobacterium pannavorans* [58], and *F. islandicum* [59]. Some species of actinomycetes intensively degrade keratins such as *Streptomyces* which includes *S. fradiae* [60], *S. pactum* [61] *S. thermoviolaceus* [62], or other actinomycetes such as *Thermoactinomyces* [63].

Keratin degrading activity is also observed in nutrient-specialized keratinophilic fungi, which uses keratin as nutrient [61]. These types of fungi besides colonizing bird plumage and mammal hair, also colonizes natural habitats where keratin material is available such as places inhabited by birds, humans, and mammals [64, 65].

Fungi exhibiting high keratinolytic activities include the following genera: *Aspergillus*, *Chrysosporium*, *Alternaria*, *Trichuris*, *Monodictys*, *Myrothecium*, *Paecilomyces*, *Stachybotrys*, *Urocladium*, *Scopulariopsis*, *Curvularia*, *Cladosporium*, *Fusarium*, *Geomyces*, *Gleomastis*, *Penicillium* and *Doratomyces* [66–68].

Based on the keratinolytic efficiencies, microbes can be divided in two types: true keratinolytic microbes solubilizing hard keratin structures or potentially keratinolytic microbes which have strong proteolytic effects thereby solubilizing non-keratin proteins which are associated with hard keratins in keratin rich material like feathers, nail etc. They can also degrade soft keratins as found in callus [64].

3.2.1. Microbial keratinase

Keratinolytic microbes possess proteolytic enzymes which are able to degrade the extensive disulfide crosslinking of keratin polypeptides and solubilize the keratin. These keratinolytic proteases are known as keratinases (EC 3.4.21/24/99.11). Keratinases have unique capacity to act on compact substrates such as keratinous wastes compared to traditional proteases [69].

Keratin wastes can be efficiently degraded by bacteria, actinomycetes, and fungi due to presence of the keratinases [70].

The keratinases convert feather keratins into fertilizers and useful feedstuffs [69, 71]. Keratinases are primarily extracellular and they show activity on keratinous substances [72]. However, they are also secreted constitutionally in absence of keratin [73].

Some keratinolytic enzymes are also intracellular [71]. Microbial keratinolytic proteases are mostly serine proteinases and sometimes metalloproteinases, being inhibited by phenyl methane sulfonyl fluoride (PMSF) and other inhibitors of serine proteases [74, 75]. The optimum activity of keratinases range between pH 6.0 and 9.0. The enzymes are either neutral or alkaline proteases requiring Ca^{++} , as the activity is inhibited in presence of Ca^{++} chelating EDTA or EGTA [76]. Keratinases are able to hydrolyze both soluble proteins as well as insoluble, fibrous proteins [77].

Although microorganisms capable of degrading keratinous substrates are generally isolated from soil and poultry wastes, these microorganisms are almost ubiquitous in nature, thriving under diverse ecological and environmental conditions [78].

No keratinases can completely solubilize native keratin. However, keratinase contribute to the valorization of the enormous keratin containing wastes in the form of hair, feathers, dead birds, and animals [70]. These enzymes have gained increasing attention due to their biotechnological applications on valorization of keratinous wastes especially byproducts of agro-industrial processes [79, 80]. These enzymes can also be employed for degradation of prions [81, 82] and β -amyloid fibers [83].

3.3. Alkaline-enzymatic methods

Mokrejs et al., 2010 proposed a two-stage alkaline & enzymatic method to hydrolyse keratinous wastes [84]. It involves initial treatment of wastes with 0.1 or 0.3% KOH at 70°C (1:50 ratio) for 24 h. After adjusting the pH to 9.0, enzymatic hydrolysis is carried out by a keratinase (1–5%), which hydrolyzes the wastes further at 50–70°C for 4–8 h.

This two-stage hydrolysis was applied for processing waste chicken feathers. The amount of hydrolyzed feathers after second stage hydrolysis increased to 90.8% achieving high efficiency under mild reaction conditions leading to the generation of keratin hydrolysate.

4. Valorization of keratinous wastes

Microbial keratinases are gradually getting importance biotechnologically for valorization of keratinous wastes. Microbial keratinases are being used successfully in degrading keratin into economically important keratin protein hydrolysates which can find potential applications as animal feed supplements, bio-fertilizers, biodegradable glues, films, and foils [70, 85]. Also, valorization of keratinous waste by keratinolysis finds useful applications in various industries such as elimination of horny epithelial cells that adheres to textile fibers (Textile Industry), clearing obstructions in sewage systems (Waste Water Management Industry), conversion of poultry or agro-industrial wastes into valuable protein products such as amino acids for livestock feed, pharmaceutical, and cosmetic industries. The details of valorization of keratinous wastes are described below.

4.1. Agricultural products

Organic fertilizers have been prepared from sulfur containing amino acids which are richly present in keratin hydrolysates. Chicken feather composts have been reported to act as bio-fertilizers [55]. Feathers have a high content of nitrogen (13%) and can serve as an excellent compost material or biofertilizers; however, degradation of feather is difficult due to presence of disulfide bonds [86].

Ichida et al., 2001 used compatible strains of *Streptomyces* and *B. licheniformis* as mixed starter culture for inoculating waste feathers in bioreaction vessels. The trials demonstrated bioreactors of compost materials consisting of chicken feathers, straw, and poultry litter while inoculated with feather-degrading bacteria, increased the rate of keratin utilization. Composting is successful if the mixture of organic materials consists of 20 to 40 parts of carbon to 1 part of nitrogen as required by the composting bacteria, actinomycetes and fungi [87].

Besides, feather hydrolysates are promising slow release nitrogen (N) fertilizers [88, 89]. Release of N from feathers has been enhanced by treatment with several keratinolytic bacteria, actinobacteria, and fungi. *Chryseobacterium spp.* is successfully used for preparing slow release N fertilizers from feathers. Such feather-based biofertilizers were found to be effective fertilizers for banana and other crops [63]. Also, feather hydrolysates prepared using thermophilic actinomycetes was successfully applied as fertilizers for ryegrass cultivation. Similarly, Choi & Nelson reported the preparation of slow release nitrogen fertilizer from poultry feather by biodegradation [90].

4.2. Pharmaceutical applications

Chicken feather cholesterol may serve as precursor for bile salt synthesis. Bile salts are used as bio-emulsifiers and biosurfactants in cosmetic industry. Besides, cholesterol is required for synthesis of other pharmaceuticals such as vitamin D3 and steroids [91]. Vitamin D3 is necessary for bone and teeth formation [92].

Keratin has properties suitable for use in biomedical applications like biodegradability, biocompatibility, sterilizability, bioresorbability, functionality, self-assembly, and manufacturability including mechanical and thermal properties [93]. Wool and human hair keratin have been used to prepare protein films, fibers, and scaffolds for tissue engineering. The propensity of extracted keratin to self-aggregate and form 3D structures has enabled it to be used as scaffolds for tissue engineering [94]. Chicken feather keratin can be fabricated into keratin films and the construct can be used in controlled drug delivery [95, 96].

Sun et al., 2009 reported development of keratin microparticles by treating keratin with ionic liquid [48]. Nanoparticles prepared from feather keratin exhibited good biocompatibility and stability thereby opening up the possibility of controlled drug delivery [97]. Such keratin based film generation for controlled drug delivery was also reported [63]. Besides, keratin nanofibers developed by electrospinning is being applied in tissue engineering and regenerative medicine [98, 99].

In addition, keratin biomaterials from chicken feathers are found to be capable of supporting cellular attachment as they possess cell binding motifs, such as glutamic acid-aspartic acid-serine and leucine-aspartic acid-valine binding residues [18].

Recently, human hair keratin has been developed into biomaterials for use in tissue engineering [100, 101].

4.3. Bioactive peptides

Keratinous wastes can also be hydrolyzed to produce bioactive peptides with potential health benefits. Fakhfakh et al., 2012 reported production of keratin hydrolysates containing bioactive peptides with antioxidant activity [102]. Similarly, other authors have studied angiotensin-converting enzyme (ACE)-inhibitory and dipetidyl peptidase-IV (DPP-IV)-inhibitory activities of keratin hydrolysates [103].

These activities find therapeutic applications in medical conditions such as high blood pressure and inflammation.

4.4. Industry

4.4.1. Livestock industry

Chicken feather hydrolysates are rich in amino acids and peptides which are of similar composition with that of soybean and cotton seed extracts. Hence, such feather hydrolysates have found promising applications as animal feed additive [104]. Enrichment with lysine may enhance the nutritive value of such feed additives [105].

Horn meal prepared from raw horns and hooves have also been proposed as animal feed additive. Brandelli et al., 2015 have also proposed keratin hydrolysates as promising animal feed [106].

4.4.2. Cosmetic industry

Keratin hydrolysates may find tremendous applications in the cosmetic industries. Keratin-based cosmetics have been reported as therapeutic agents for skin and human hair. Keratin has been also used as components of blends [107].

Keratin has been reported as components of cosmetic blends along with other natural polymers such as collagen, chitosan, and silk fibroin etc. Keratin or keratin hydrolysates help retaining moisture in the skin by interactions of stratum corneum and hair cuticle with the cosmetics. Also, keratin protects the cortex of the human cell from daily injuries of heat or chemicals. Besides, hydrolyzed keratin is used as a cosmetic ingredient. Topical application of hydrolyzed keratin enhances skin hydration and flexibility [108].

Because of moisture retaining properties, keratin is an important component of shampoos and conditioners, hair loss concealing products, and other hair beautification accessories [109]. The protein hydrolysates provide advantages to the hair by strengthening hair fibers and decreasing fiber breakages. Many plant and animal hydrolysates such as wheat protein, wool, nails, and horns keratin [108, 109] have been used in cosmetic industry as components of hair shading splashes and toners to enhance uniform color retention of hair. Besides, protein hydrolysates act as restorers in hair care processing industry [110].

4.4.3. Automobile industry

Automobile industry is planning to use feathers to produce composite materials that can be used in dashboards, seats, car parts, cushioning, and interior lines [18]. Currently petroleum based raw materials are used in automobile and aeroplane parts. However, material science industries prefer low cost, lightweight, and environmentally sustainable materials. Keratins being low priced and light weight as well as possessing enormous strength due to presence of high cysteine content is a choice by engineers of automobile industry.

4.4.4. Leather and textile industry

Keratinous waste materials have a promising potential in textile industry. Scientists are investigating the potential of chicken feathers for replacing natural fibers and man-made fibers

thereby saving trees in textile processing. Chicken feathers have toughness, flexibility, high surface area, fine diameter, and durability rendering them valuable for replacing natural and synthetic fibers, and wood pulp. However, pre-treatment of feather is important before usage into textile products. The barbs must be stripped off as the barb material of feather shows similar property of a textile fiber [18, 111]. Since feathers contain high nitrogen content, they can be used as flame retardants. Guan and Chen, 2006 reported preparation of hydrolyzed feathers as flame retardant finish [112]. Cotton fibers while treated with this feather-made flame retardant, acquired property of flame retardance.

Chicken feather can also be a good source as textile binding and textile sizing agent in textile printing as keratin has film forming and binding ability. So far, starch and starch derivatives and polyvinyl alcohols were being used as a sizing agent to coat a protective layer on the surface of yarns to improve weaving [113, 114]. Sizing provides tensile strength and abrasion resistance of yarns. But usage of starch is associated with socio-economic problems and polyvinyl alcohol has high cost and poor biodegradability. Therefore, chicken feather could be a promising substitute for starch and polyvinyl alcohol [114].

Similarly, keratin hydrolysates are used in leather industry for usage in filling and retaining. Many processes in leather tanning can cause serious health hazards such as skin and respiratory ailments, including cancer. Recently, Wool has developed biocomposites based on the techniques by aerospace engineers to convert scraped chicken feathers into synthetic leather [18, 115].

4.4.5. Construction industry

Nowadays, composite materials from thermoplastic and natural fibers are being investigated in the construction industry. The natural fibers are mostly cellulosic and provide enormous strength. Usage of natural fibers reduce consumption of synthetic polymers thereby consumption of petroleum products is reduced. However, cellulosic natural fibers are not compatible with the hydrophobic polymer material and chicken feather can be a useful alternative. After separation of feather in various parts such as long fibers, short fibers, and powdered rachis, feathers are easy to melt to be used as reinforced matrix material [18, 114]. Feathers may be valorized to thermoplastic films for use as packaging materials and in other applications. Grafting of feather keratin with acrylic monomers have been shown to improve the thermoplastic properties of feather based materials [116].

Such composites are suggested for usage in thermal and sound insulation as well as ceiling applications. Chicken feather composite boards are being hypothesized to be the substitute for wood and plastic in the construction industry [18].

4.4.6. Environmental remediation

Although being an environmental pollutant, keratinous material, after valorization is commercially used as agents for environmental remediation. Keratinous material has been suggested to be used as environment-friendly electrode materials [117]. Keratin extracted from

feather may be diluted, followed by lyophilization, to generate sponges. Such sponges can be useful agents for clean-up of oil spills. Keratin fibers have promise to be developed into innovative green materials due to their biodegradability, biocompatibility, natural abundance, and mechanical durability [118, 119]. Feather keratins are highly hygroscopic and possess excellent absorption ability. Therefore feathers can be used as efficient purification agents for waste water by removal of heavy metals such as Cu, Se, Zn, and other toxic compounds [120, 121].

4.4.7. Energy sector

Keratinous wastes have been used to generate bio-hydrogen [122]. Initially keratinous wastes are converted into a fermentation product rich in amino acids and peptides. Next, minerals are added to the product to serve as substitute for bacto-peptone. The enriched fermentation product is then subjected to further anaerobic fermentation by a thermophilic archaea *Thermococcus sp.* to generate bio-hydrogen.

Also, chicken feathers contain good amount of fat. The fats after extracting from feather meal by solvent extraction can subsequently be transesterified to biodiesel using catalysts. It is estimated that hundreds of millions of liters of biodiesel can be generated from chicken feather waste globally. This would reduce the petroleum dependency as well as cut the carbon emissions [18].

5. Conclusions and future prospects

Published literature shows keratin is a raw material for production of a diversity of value added products. Huge amounts of waste keratinous biomass generated by food, wool, and livestock industries may be utilized gainfully as feedstocks/raw materials for production of keratin and keratin hydrolysates at industrial scales. Valorization of keratinous wastes will not only generate many commercial products but will also ameliorate the environmental pollution from such wastes, and also help boost pharmaceutical, food, and cosmetic industries.

Keratinolytic enzymes will be better alternatives for digestion of keratinous wastes as compared to physico-chemical methods. This dictates search for more efficient keratinolytic bacteria and their enzymes.

Use of keratinous wastes for production of biofertilizers is one of the most recent applications of such waste biomass. Such biofertilizers will be better alternatives to fossil fuel based synthetic fertilizers and will help mitigate climate change.

There is urgent need for developing better keratinolytic strains, characterizing better keratinases, improve methods for generating keratin hydrolysates, and finding other novel applications of keratinaceous wastes.

Research in this area has a promising future.

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Conflicts of interests

The authors declare no competing interests.

Author details

Debananda Singh Ningthoujam*, Keishing Tamreihao, Saikat Mukherjee, Rakhi Khunjamayum, Laishram Jaya Devi and Roshan Singh Asem

*Address all correspondence to: debananda.ningthoujam@gmail.com

Advanced State Level Biotech Hub (AdL SBTHub), Department of Biochemistry, Manipur University, Canchipur, Manipur, India

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