IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Green Approaches And Applications In The Extraction Of Keratin From Chicken Feathers: A Sustainable Waste-To-Resource Strategy

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Abstract: Chicken feathers, a significant waste product of the poultry industry, are increasingly recognized as a sustainable source of keratin, a protein with high tensile strength and biodegradability. Traditional keratin extraction methods, relying on harsh chemicals, pose environmental concerns. This abstract explores recent advancements in green extraction technologies, including enzymatic treatments and deep eutectic solvents, which offer reduced environmental impact while preserving keratin's functional properties. Extracted keratin exhibits versatility across biomedicine, cosmetics, agriculture, and materials science. In biomedicine, its biocompatibility makes it suitable for tissue engineering and drug delivery. Cosmetics utilize keratin's conditioning abilities, while agriculture benefits from its use in slow-release fertilizers. Material science explores its potential in bioplastics and environmental remediation. This review examines the efficiency, scalability, and environmental costs of green extraction technologies compared to traditional methods. It also explores innovative applications of feather-based keratin and identifies commercialization successes and ongoing challenges. By promoting sustainable waste-to-resource strategies, this study aims to contribute to circular bioeconomy models, minimizing environmental contamination and generating value-added products from poultry waste.

Keywords: Chicken feather, keratin, green extraction technologies, circular bioeconomy

I. INTRODUCTION

Chicken feathers are among the most plentiful but under-exploited poultry industry waste products, with over 40 million tons being produced worldwide each year (Ezejiofor et al., 2014). With about 90% keratin, a fibrous structural protein containing high cysteine content, these feathers exhibit excellent properties such as high tensile strength, thermal stability, and biodegradability (Mi et al., 2020). Historically considered problematic waste in need of disposal by landfilling or burning, chicken feathers are being increasingly seen as a sustainable renewable material that can be converted into high-value products using the proper extraction and processing technologies (Tesfaye et al., 2017; Mozhiarasi & Natarajan, 2022).

The traditional processes of keratin extraction have been based mostly on severe chemical treatments comprising strong acids, alkalis, or reducing agents that not only require high amounts of energy but also produce toxic by-products (Shavandi et al., 2017; Chilakamarry et al., 2021). Such methods go against the ideas of green chemistry and sustainable development and demonstrate the imperative need for environmentally friendly options. Recent developments in green extraction technologies—such as enzymatic treatments, deep eutectic solvents, ionic liquids, and microwave processes—have shown great promise for the recovery of keratin from feather waste with reduced environmental impact and maintenance of the protein's functional characteristics.

Chicken feather-extracted keratin presents outstanding flexibility in a variety of applications that cut across biomedicine, cosmetics, agriculture, and materials science (del Valle Raydan, 2024; Sharma & Gupta, 2016). Biomedically, keratin-containing materials present exceptional biocompatibility and can be developed into scaffolds for tissue engineering, drug delivery systems, and wound care products (Sarma, 2022; Diwan & Sah, 2023). Cosmetics have now started using keratin extracted from feathers in hair care products due to its hardening and conditioning abilities (Fernandes et al., 2023; Tinoco et al., 2022). Also, applications in agriculture are slow-release fertilizers and biodegradable mulch films, and material science applications reach into bioplastics, composites, and environmental remediation adsorbents, proving the protein's significant functional diversity (Liyakat, 2024; Machado et al., 2022).

The goal of the current review is to thoroughly explore novel developments in green extraction technology for chicken feather keratin in terms of efficiency, scalability, and environmental cost, as well as compared with traditional methods. Additionally, we aim to explore potential and innovative uses of feather-based keratin across various sectors and identify successful cases of commercialization and continuing challenges. By promoting the innovation of sustainable waste-to-resource policies for chicken feather valorization, this study aims to help augment circular bioeconomy models that minimize environmental contamination while generating value-added output from what was previously thought to be nothing but garbage.

II. KERATIN: STRUCTURE, PROPERTIES AND POTENTIAL

Keratin, the most abundant protein of chicken feathers, has a complex hierarchical composition with a high level of cysteine residues (7-13%) that give rise to disulfide bridges, establishing strong cross-linked networks (Maurya & Singh, 2024; Pourjavaheri, 2017). The structural proteins are divided into two broad categories: α-keratins (major in mammals) and β-keratins (major in avian feathers). Chicken feather keratin takes a specific β-sheet conformation with a distinctive amino acid profile characterized by high contents of serine, proline, and glycine in addition to cysteine, all of which synergistically confer its unique properties (Nuutinen, 2017; Donato & Mija, 2019). Such molecular organization leads to fibrous microstructures with a central medulla encircled by crystalline zones, providing exceptional mechanical strength and resistance to degradation.

The exceptional properties of feather keratin are due to its special structural features and chemical makeup (Gregg & Rogers, 1986; Zhang & Fan, 2021). Having a density less than cellulose (0.89 g/cm^3) but significant mechanical strength (tensile strength of 180-200 MPa), feather keratin has a very high strength-to-weight ratio. Its high surface area (2.5 m^2/g) and hollow interior structure make it an excellent thermal insulator and sound absorber. In addition, keratin in feathers exhibits excellent heat stability (tolerating up to 220°C), resistance to organic solvents, and selective biodegradability—stable under common conditions but biodegradable under certain enzymatic or microbial pressure (Athwal et al., 2023; Spyka et al., 2021). The prevalent availability of functional groups such as carboxyl, amino, and thiol groups allows various chemical modifications and supports binding to a wide variety of materials.

The applications of chicken feather keratin are numerous across industries due to its diverse characteristics and sustainability (Sharma & Gupta, 2016; Gupta et al., 2023; de Q Souza et al., 2023). Biomedically, materials derived from keratin have been effective in serving as scaffolds for tissue engineering, drug delivery systems, and wound dressings for stimulation of cellular proliferation and tissue regeneration. Keratin's water-holding capacity, film-forming characteristic, and hair-strengthening property find use in the cosmetic and personal care industries in producing shampoos, conditioners, and skin care products (Infante, 2001). Agricultural uses involve slow-release fertilizers and biodegradable mulch films that conserve nutrients while mitigating environmental losses (Sarkar et al., 2018; Priya et al., 2024). Material science applications also cover bioplastics with enhanced mechanics, heavy metal and oil-adsorbed remediation compounds, and bio composite reinforcement agents that offer alternatives to man-made polymers in different functions.

The conversion of chicken feather waste to high-value keratin products is a paradigm change in sustainable resource management that satisfies both waste disposal issues and raw material shortage problems (Ossai et al., 2022; Jana et al., 2023; Choudhury, 2023). Realization of the potential of feather keratin, though, needs the overcoming of many challenges such as the creation of genuinely green extraction processes that will maintain the functional properties of keratin and keep environmental damage low (Wang et al., 2024; Athwal et al., 2023). Processing challenges like feather cleaning, decontamination, and quality control on a regular basis need to be overcome in parallel with scale-up issues (Islam et al., 2023). Also, economic feasibility is contingent upon setting up effective supply chains, minimizing processing expenses, and developing markets that appreciate the value of bio-based commodities. As research pushes forward green extraction technologies and new applications, chicken feather keratin is ready to become a key player in circular bioeconomy models, transforming a problematic waste stream into a valuable one.

III. CHICKEN FEATHER AS A SOURCE OF KERATIN

Chicken feathers are a renewable and plentiful source of keratin, with the global poultry industry producing around 8-10 billion tons of feather waste each year (Tesfaye et al., 2017; Maurya & Singh, 2024; de Q Souza et al., 2023). Weighing 90-95% keratin by weight, the feathers form a largely underexploited resource which is commonly sent to waste by environmentally unsuitable means such as landfill, incineration, or rendering to low-grade animal feed. The hierarchical structure of chicken feathers, which comprises a central rachis, barbs, and barbules, results in a hierarchical architecture that is responsible for their superior mechanical properties and large surface area (Lingham-Soliar, 2014; Reddy & Yang, 2007; Xu et al., 2024). This structural arrangement, combined with the inherent properties of keratin, renders chicken feathers highly desirable as a source of keratin compared to other keratinous wastes. Moreover, the regular supply of feathers from processing plants provides a stable supply chain for possible industrial uses, offering a chance to convert a waste management issue into a valuable resource stream.

The keratin obtained from chicken feathers has unique characteristics that distinguish it from mammalian keratins and other protein sources. Chicken feather keratin is mainly β-keratin, which has a higher ratio of hydrophobic amino acids and cysteine residues that form extensive disulphide bridges (Maurya & Singh, 2024; Nuutinen, 2017; Banasaz & Ferraro, 2024). Such a unique amino acid composition gives rise to feather keratin's high resilience, water resistance, and thermal stability. The molecular weight of keratin in feathers usually falls in the 10-30 kDa range, which is ideal for different processing technologies (Vineis et al., 2019; Shavandi et al., 2017). A greater surface area is also found in chicken feather keratin when compared with wool keratin and shows excellent biocompatibility, biodegradability under certain conditions, and very good adsorption characteristics. These attributes, coupled with its lightness (0.89 g/cm^3 density) and natural availability, make chicken feather keratin a prime candidate for material development in a sustainable context in numerous industries.

The sustainable use of chicken feather keratin represents a major breakthrough in circular economy principles, especially as industries try to find bio-based substitutes for synthetic materials (Ossai et al., 2022; Salazar Sandoval et al., 2024; Donato & Mija, 2019). Transforming this waste stream into value-added keratin products has great environmental advantages, such as relief from landfill pressure, alleviation of greenhouse gas emissions linked to feather degradation, and saving petroleum-based resources through replacement with renewable feedstocks. Despite these advantages, challenges remain in developing commercially viable extraction methods that maintain keratin's functional properties while adhering to green chemistry principles. Traditional extraction approaches often employ harsh chemicals that compromise both the protein's integrity and environmental sustainability (Jain et al., 2024; Ahmed et al., 2024). This fact points to the acute need to promote green extraction processes that can isolate feather keratin effectively with less resource usage and environmental footprint, enabling the progression from theoretical waste-to-resource measures to real-world industrial application.

IV. CONVENTIONAL KERATIN EXTRACTION METHOD

Traditional methods for keratin removal from chicken feathers have been mainly based on hydrolysis involving the use of aggressive chemical reagents to degrade the strong disulphide cross-links responsible for stabilizing the protein structure (Wang et al., 2024; del Valle Raydan, 2024). Alkaline hydrolysis using sodium hydroxide or potassium hydroxide in the concentration range 0.1-1.0 M and temperature between 80-100°C has been extensively used owing to its efficacy in solubilizing keratin. In a similar way, acid hydrolysis procedures utilize strong acids like sulfuric acid, hydrochloric acid, or phosphoric acid at high temperatures (80-120°C) to break the keratin framework (Shavandi et al., 2017; Athwal et al., 2023; Rashwan et al., 2025). Reduction-oxidation (redox) methods are another traditional approach, where the disulphide bonds are cleaved by reducing agents such as sodium sulphide, 2-mercaptoethanol, or dithiothreitol and then by oxidizing agents that inhibit reformation of the disulphide bonds. These traditional techniques usually yield 50-85% extraction, but frequently involve considerable protein degradation, loss of functionality, and production of environmentally harmful by products (Ganjeh et al., 2023; Rashwan et al., 2025).

The environmental and operational disadvantages of traditional extraction processes are enormous and of many-fold nature (Sharma et al., 2018). These processes use copious amounts of water (20-100 L per kg of feathers) and energy (high-temperature upkeep over long periods of time), and produce copious amounts of acidic or basic wastewater that must be neutralized and treated prior to release. The severe chemical conditions not only undermine the structural integrity and viability of the recovered keratin by means of undue hydrolysis but also create occupational risks to the employees in the form of corrosive reagents and possibility of hydrogen sulphide gas generation during sulphide-based reductions. Moreover, scalability issues come in the form of high costs of chemicals, corrosion of equipment, and complicated downstream processing needs to remove impurities (Cruz et al., 2018). The aggressive nature of these conventional approaches fundamentally contradicts green chemistry principles, particularly regarding atom economy, reduction of hazardous substances, and energy efficiency.

The drawbacks of traditional extraction methods have spurred the quest for alternative, environmentally friendly methods that retain keratin's useful properties while reducing resource usage and waste production (Ossai et al., 2022; Giteru et al., 2023). Traditional methods often produce keratin hydrolysates with greatly diminished molecular weight and impaired functional properties, restricting their use in high-value applications that demand intact protein structures. In addition, the elaborate purification steps required to eliminate chemical residues add further process complexity and expense (Nfor et al., 2008). Chemical agent recycling and recovery continue to pose challenges, presenting issues of closed-loop processing (Liu et al., 2022; Sherwood, 2020). As regulatory structures continue to prioritize environmental sustainability and chemical safety, traditional extraction methods come under heightened scrutiny and possible limitation. These combined constraints highlight the imperative need for green extraction alternatives that are as efficient in extraction as conventional methods while meeting the environmental, economic, and safety issues inherent in traditional methodologies, necessitating the paradigm shift towards genuinely sustainable valorisation of chicken feather waste (Cannavacciuolo et al., 2024).

V. GREEN AND SUSTAINABLE EXTRACTION APPROACHES

Enzymatic extraction has proven to be a viable green method for keratin recovery from chicken feathers using proteolytic enzymes that specifically break peptide bonds without compromising the structural integrity of the protein (Spyka et al., 2021). Microbial keratinases from Bacillus licheniformis, Streptomyces pactum, and Chryseobacterium sp. have shown high efficiency in feather keratin solubilization under mild conditions (pH 7-9, 30-50°C) (Purchase, 2016; Qaphela, 2021). These biological catalysts function with high specificity, reducing unwanted degradation and with extraction yields of 60-75% with much lower energy requirements than conventional processes. Fungi-based extraction using Aspergillus niger or Trichoderma species also offers benefits through concurrent enzyme production and keratin extraction in solid-state fermentation systems (Ahmed et al., 2024; Corbu et al., 2023). The combination of enzymatic processes with ultrasonic or microwave aid has also increased extraction kinetics and recovery by facilitating enzyme penetration and substrate accessibility. These bio-catalytic methods are ideally in line with the principles of green chemistry by avoiding harmful reagents, decreasing energy demands, and producing biodegradable by-products while preserving keratin's functional characteristics (Lozano, 2022).

Deep eutectic solvents (DESs) and ionic liquids (ILs) are yet another area of innovation in green extraction technologies for feather keratin (Polesca et al., 2023; Athwal et al., 2023). DESs resulting from the combination of quaternary ammonium salts such as choline chloride with hydrogen bond donors like urea, glycerol, or organic acids yield low-toxicity, biodegradable solvents with the ability to break the intricate structure of keratin (Hayyan et al., 2024). These eutectic mixtures function well at mild temperatures (60-90°C) with extraction recoveries similar to traditional procedures (70-85%) with little protein degradation (Katrak & Ijardar, 2024). Likewise, biocompatible ionic liquids, especially those containing cholinium cations or amino acid-derived anions, have proven very effective in dissolving feather keratin via hydrogen bond disruption and electrostatic interactions. The greatest strengths of these designer solvents are that their physicochemical properties are tunable, have low vapor pressure, outstanding thermal stability, and are recyclable through anti-solvent precipitation methods, overcoming most critical sustainability issues in industrial processing without compromising the molecular weight and secondary structure of keratin.

New physical and hybrid technologies have further enriched the green extraction toolkit for valorisation of feather keratin. Steam explosion methods utilize high-pressure saturated steam (10-40 bar) with quick decompression to induce structural disruptions that make keratin more accessible without chemical additives (Zhao et al., 2012; Rigueto et al., 2024). Subcritical water extraction employs water at high temperature (150-250°C) and pressure (5-10 MPa) ranges where its dielectric behaviour is completely transformed, allowing effective keratin solubilization by hydrolytic reactions controlled by careful temperature regulation (Shavandi et al., 2017). Pulsed electric field technology uses brief, high-voltage pulses (15-40 kV/cm) to form temporary pores in cell matrices, allowing extraction while reducing energy usage. Furthermore, hybrid methods involving the integration of several green technologies—e.g., enzymatic-ultrasonic systems or mechanochemical-assisted extractions—have exhibited synergistic effects that maximize extraction efficiency while ensuring environmental sustainability. These new paradigms of extraction all collectively overcome the drawbacks of traditional methods by significantly lowering chemical usage, improving energy efficiency, and reducing waste generation while yielding keratin with retained functionality for high-value applications.

VI. APPLICATIONS OF EXTRACTED KERATIN

In the biomedical field, keratin from chicken feathers has proven to be an excellent biomaterial with immense potential due to its intrinsic biocompatibility, biodegradability, and cell-binding sites that facilitate cellular adhesion and proliferation (Diwan & Sah, 2023; Feroz et al., 2020). Keratin scaffolds prepared using electrospinning, freeze-drying, or 3D printing technologies have been found to be highly effective in tissue engineering, facilitating the regeneration of skin, bone, and nerve tissues (Soleymani Eil Bakhtiari & Karbasi, 2024). The incorporation of leucine-aspartic acid-valine (LDV) and arginine-glycine-aspartic acid (RGD)-motif sequences in feather keratin supports efficient cell adhesion, whereas its biodegradation under controlled conditions offers an extracellular matrix for a short period to reconstruct the tissue (Esparza, 2017; Vasconcelos, 2011; Xu, 2014). Feather keratin has also been developed as drug carriers with controlled release kinetics for different drugs, such as antibiotics, anti-inflammatory drugs, and growth factors. Further, keratin-based wound dressings exhibit outstanding moisture management, antimicrobial activity, and the capability to promote re-epithelialization, speeding up the wound healing process while reducing scarring (Ye et al., 2022; Kumaran, 2014). Biomedical applications specifically take advantage of green extraction approaches that maintain the higher-order structure and biological functionality of keratin without causing the protein degradation characteristic of harsh chemical processes.

The materials science uses of keratin from feathers are an important area of sustainable material innovation, with bioplastics and composites being of major interest (de Oliveira et al., 2025). Keratin bioplastics made via thermoplastic processing or solution casting have remarkable mechanical performance, with 5-20 MPa tensile strengths and elongation at break values of 10-150% based on plasticizer level and processing conditions (Dou et al., 2016; Ying, 2019). These biodegradable products of petroleum alternative plastics have gained usage in packaging materials, crop films, and consumer products. When blended in polymer blends containing polylactic acid (PLA), polyvinyl alcohol (PVA), or thermoplastic starch, feather keratin acts as a bio-filler that gives mechanical strength enhancement along with an improvement in biodegradability (Latos-Brozio et al., n.d.; De et al., 2023). Keratin-based materials have exhibited highly efficient adsorption capacities toward heavy metals (lead and chromium, 80-150 mg/g), dyes, and oil pollutants because of their rich functional groups and novel hierarchical structure. In addition, functional materials like flame-retardant coatings, thermal insulation materials, and electromagnetic shielding materials have been effectively engineered by exploiting keratin's intrinsic nature and chemical modification ability, broadening the actual application scope of this ubiquitous biopolymer (Mishra et al., 2018).

The cosmetic, agriculture, and energy industries are other areas where keratin obtained from feathers is creating major changes with new applications (Sharma & Gupta, 2016; de Q Souza et al., 2023). Keratin hydrolysates are used as active ingredients in hair care products in cosmetics and personal care, offering strengthening and conditioning properties through repair of the cuticle and retention of moisture. Feather keratin peptides with molecular weights of less than 1000 Da have exhibited skin anti-aging activities through stimulating collagen production and protection against oxidative stress (Li et al., 2023). In agriculture, slow-release fertilizers coated with feather keratin matrices enhance nutrient efficiency and decrease environmental leaching, and keratin-containing biodegradable mulch films increase soil health and eradicate plastic waste (Gupta et al., 2023; Vadillo et al., 2025). The energy industry has used feather keratin as precursor material for carbon fibers and as elements in biofuel cells, where its high nitrogen content helps improve electrochemical performance. These varied uses not only present sustainable substitutes to synthetic products but also generate value-added products out of a waste stream, representing circular economy values (Arvelo-Gallegos et al., 2017; Scheel, 2016). With advances in extraction technology moving toward increasingly green methods, the quality and usability of extracted keratin will continue to advance, increasing its application potential and market acceptance within these different industries (Giteru et al., 2023; Wang et al., 2024).

VII. CHALLENGES AND FUTURE DIRECTIONS

In spite of tremendous advances in green extraction methods for chicken feather keratin, there are still some challenges that make large-scale industrial application difficult. Scalability is a major issue, as most of the promising green technologies work very well at the laboratory level but encounter serious challenges during scale-up, such as decreased efficiency, longer processing time, and equipment constraints. Enzyme-based extraction technologies, though green in nature, have a problem with high costs of enzymes, low enzyme stability, and inconsistent extraction yield based on feather pretreatment conditions. Ionic liquids and deep eutectic solvents have a problem with their recovery and recyclability, viscosity during processing temperatures, and toxicity of some of the formulations. Moreover, the economic viability of green extraction processes is hindered by increased initial investment requirements compared to traditional processes, generating adoption barriers in spite of long-term sustainability advantages. Quality standardization is another barrier since the molecular weight distribution, purity, and functional properties of the extracted keratin tend to vary based on extraction parameters, feather origin, and processing history. This mismatch makes product development and regulatory approval more difficult, especially for biomedical and cosmetic products where safety and performance requirements are high.

Future directions for research should be the development of integrated biorefinery strategies that integrate several green technologies to achieve highest extraction efficiency with least environmental footprint. Hybrid methods involving enzymatic treatment with physical support (ultrasound, microwave, or pulsed electric fields) appear to hold special promise for increasing processing kinetics without sacrificing keratin functionality. Design of more specific and thermostable keratinases using protein engineering will help overcome cost and stability issues of enzymes, while continuous-flow systems can potentially enhance process economics by increasing yield and minimizing labor. New generation separation and purification technologies, such as membrane-based processes and keratin-optimized chromatographic procedures, will play a critical role in maintaining reproducible product quality. Further, computational simulation and artificial intelligence can expedite parameter optimization and formulation development while diminishing the requirement for empirical tests. As demand for sustainable materials expands, cooperation between industry, academia, and regulators will be important in developing consistent quality measures, providing long-term performance, and fostering supportive policy frameworks that appreciate the environmental advantages of feather keratin use, eventually turning this voluminous waste stream into a worthwhile contribution to the circular bioeconomy.

VIII. CONCLUSION

The sustainable harvesting and exploitation of keratin from chicken feathers is an appealing waste-to-resource approach to tackle several environmental issues and create economic value in various industries. Through the transition from traditional, chemistry-based extraction processes towards more sustainable means—such as enzymatic process, deep eutectic solvents, ionic liquids, and newly developing physical methods—considerable achievements have been achieved in maintaining keratin's desirable functional properties and minimizing environmental footprint. The incredible diversity of feather keratin has opened the door for its use in biomedical materials, bioplastics, environmental cleanup, cosmetics, agriculture, and more, illustrating the prospect for converting an industrious waste stream into value-added products. Despite scalability, economic viability, and quality standardization challenges that remain, continuing efforts to explore hybrid technologies, biorefinery strategies, improved keratinases, and better separation methods present promising avenues. With intensifying global sustainability needs and circular economy values increasingly on the forefront, valorizing chicken feathers via environmentally friendly extraction methods represents a best practice example of transforming farm waste into renewable resources toward an ultimately more sustainable and resource-saving future that benefits both environmental protection and economic growth.

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