

Assessing the value of keratin extracted from bovine hair

Project code
2025-1093

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Published by
AMPC

Date submitted
07/05/2026

Date published
11/05/2026

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1.0 Abstract

This project investigated opportunities to add value to cattle hides by using the hair component. Volatile hide prices, increasing disposal and transport costs, and limited domestic value-adding options are creating significant challenges for processors, particularly in regional areas. The aim of the project was to determine whether keratin, the primary protein in hair, could be recovered from bovine hair and used in products such as fertilisers, food and animal feed ingredients, cosmetics, and biodegradable polymers.

The study combined a desk-based literature and patent review with stakeholder engagement, laboratory analysis of bovine hair and tannery hair waste, and market assessment of value propositions. Surveys and interviews with meat processors and tanneries were conducted to understand existing hide processing practices, volumes, and constraints to adoption. Hair samples from untreated hides and tannery hair waste were collected and processed to extract keratin, which was then characterised and assessed for suitability across potential end-use applications.

Results demonstrated that both native cattle hair and Sirolime hair waste are high-protein materials, at $94.1 \pm 1.7\%$ and $79.6 \pm 2.5\%$ protein, respectively, making them suitable materials for keratin extraction. High yields of keratin can be recovered from both hair sources amounting to $86.5 \pm 1.3\%$ for native hair and $92.5 \pm 3.5\%$ for Sirolime hair waste. Characterisation of the recovered keratin extracts indicate that keratin derived from both sources were largely similar in amino acid composition and molecular size distribution. Industry feedback confirmed strong interest in new value-adding pathways that support whole hide utilisation, provided that solutions are low-cost, scalable, and practical.

The project identified aquafeed, fertiliser, and biodegradable absorptive polymers as the most promising valorisation pathways. While keratin shows potential across multiple applications, volume constraints and capital requirements remain key challenges. As a result, recommendations are based on whole hide utilisation with commercial considerations. Overall, the findings indicate clear potential to valorise hides with hair, reduce waste, improve processor returns, and support a more sustainable and resilient red meat supply chain.

2.0 Executive summary

This project investigated whether cattle hair, which is typically removed during hide processing and often treated as waste, could be turned into valuable products. The work was undertaken in response to declining hide returns and rising disposal and transport costs that are creating financial and operational pressure for Australian meat processors, particularly small and regional facilities. The primary audience for the findings is the Australian red meat processing sector, with secondary audiences including tanneries and manufacturers of fertiliser, feed, food, cosmetics and biomaterials. The results provide an evidence base to guide future research investment decisions and to help industry stakeholders understand the practical opportunities and constraints for improving whole-hide utilisation, reducing waste and improving processor returns.

The project aimed to determine whether keratin (the main protein in hair) can be recovered from both untreated bovine hair and tannery hair waste generated during the Sirolime hair-saving de-hairing process, and to identify realistic end uses that could suit Australian operating conditions. The approach combined a literature and patent review with stakeholder engagement (surveys and interviews with processors and tanneries), laboratory extraction and characterisation of keratin from both hair sources, and a market assessment to test feasibility, opportunities and adoption barriers.

Results showed that cattle hair is a high-protein material and that keratin can be recovered at high yields from both sources tested (native hair: $94.1 \pm 1.7\%$ protein and $86.5 \pm 1.3\%$ keratin yield; Sirolime hair waste: $79.6 \pm 12.5\%$ protein and $92.5 \pm 13.5\%$ keratin yield). This indicates that existing hair removal equipment and processes can produce a keratin-rich stream suitable for further upcycling, although industry feedback emphasised that uptake would depend on low-cost, scalable collection and processing and clear commercial returns, with limited and dispersed hair volumes a key constraint. Overall, the work highlights pathways that could reduce disposal costs and waste while creating new value from hides; the most practical near-term opportunities identified were aquafeed ingredients and specialist fertiliser/soil-conditioning products, with biodegradable absorbent polymers and other materials requiring further technical validation and techno-economic assessment. Future work should optimise processing for these products while prioritising regional-scale feasibility and supply-chain models (including aggregating volumes and, where appropriate, blending with other keratin sources or whole hides). Once demonstrated, the innovations should progress to targeted commercialisation pathways and partnerships to support adoption.

3.0 Introduction

The Australian red meat processing industry is experiencing increasing pressure from declining hide prices, rising disposal and transport costs, and limited domestic options for value-adding to hides. While hides have historically represented a significant co-product revenue stream, returns have diminished in recent years, particularly for small and regional processors. In some cases, hides now represent a cost rather than a source of revenue, contributing to reduced whole-of-carcase utilisation and increased waste generation.

Declining demand for bovine hides reflects a combination of structural and market-driven factors, including:

- Changes in global hide supply and competition between major producing regions, including elevated throughput and increased availability of larger hides from the United States.
- Weaker downstream demand for leather and leather goods such as automotive upholstery, footwear, fashion, and furnishings, influenced by a gradual shift toward alternative materials and changing consumer preferences.
- Changes in processing capacity and cost structures in major importing and processing markets, which may reduce effective demand for raw hides, for example, tighter environmental compliance requirements and rising operating and labour costs in China. In addition, increased trading costs between leather manufacturers and target markets.
- Higher costs associated with hide preservation, handling, transport, and compliance, particularly for regional processors.
- Limited domestic processing capacity and exposure to international market volatility, reducing price certainty and confidence in hide markets.

Collectively, these factors have reduced the economic value of hides (Condon, 2025, MLA, 2019) and highlighted the need to explore alternative pathways that support whole hide utilisation and improve processor returns.

One largely under-examined opportunity is the utilisation of bovine hair, which is routinely removed from hides during processing and treated as a waste stream. Cattle hair is composed predominantly of keratin, a sulphur-rich structural protein that is commonly sourced from wool or poultry feathers. Despite the large number of cattle processed annually in Australia, there is limited information on whether keratin can be effectively recovered from bovine hair, particularly hair generated during commercial tanning processes.

A significant proportion of hair waste in Australia arises from the Sirolime process, a hair-saving de-hairing technology developed by CSIRO and widely adopted by tanneries in Australia and globally (Frendrup and Buljan, 2000). In this process, hides are treated through sequential immunisation, hair loosening, and re-liming steps that allow hair fibres to be removed largely intact rather than destroyed. The resulting 'Sirolime hair waste' refers to the solid bovine hair fibres recovered from the de-hairing liquor during filtration and screening steps. While this material is chemically modified through exposure to sulphide under alkaline conditions, limited data exist on the composition, extractability, and functional potential of keratin derived from this tannery waste stream.

The key industry problem addressed by this project is the declining value associated with hides, coupled with a lack of practical, low-cost options to recover value from hair removed during hide processing. The specific knowledge gap is whether bovine hair, both in its native form and post-Sirolime processing, can be converted into a viable keratin co-product suitable for downstream applications.

This research was undertaken to determine technical feasibility of bovine hair processing, while accounting for real-world processing practices, volumes, and constraints faced by processors and tanneries. The primary target audience for this research is the Australian red meat processing sector, particularly processors experiencing declining hide returns and rising disposal costs. Secondary audiences include tanneries, fertiliser manufacturers, feed producers, biomaterials developers, and technology providers with interest in circular economy solutions and animal co-product valorisation. These groups were targeted because successful adoption of any keratin-based pathway requires alignment across processing, regulation, and end-use markets.

The results of this research intended to:

- Provide an evidence base on the technical feasibility of recovering keratin from bovine hair and tannery hair waste.
- Inform processors and tanneries about realistic value-adding opportunities for hair.
- Identify and prioritise keratin applications that align with industry volumes and guide future research investment focused on scalable, low-risk pathways for hide value-addition.

This project is distinct from prior keratin research in that it explicitly focuses on bovine hair under commercial Australian processing conditions, including hair recovered from the Sirolime de-hairing process. While extensive literature exists on keratin from wool and poultry feathers, only a few studies have examined bovine hair, and even fewer have addressed tannery hair waste as a feedstock. By integrating laboratory analysis with stakeholder engagement and market assessment, this project provides a practical, industry-relevant evaluation of whether bovine hair can move from a low-value or waste stream to a valuable co-product within the Australian red meat supply chain.

4.0 Project objectives

The objectives of this project were:

- To conduct a literature and patent search on keratin from bovine hair.
- To engage and interview major stakeholders in beef and leather industries to understand supply chain issues, as well as current process flows, volumes and economics of hair waste and the remaining de-haired hide.
- To conduct a market analysis to fully elucidate the market potential of leather waste-hair and keratin in the following applications: fertiliser, cosmetics, biopolymers for nappies, feed and food.
- To collect samples of bovine hair from untreated hides and treated hair waste from tanneries, and extract, characterise and compare the quality and functionality of the keratin.
- Based on the findings, to propose two value propositions for further research to valorise hair from hides.

5.0 Methodology

5.1 Literature and patent review

A structured literature review was conducted to identify and synthesise published research relevant to bovine hair removal, keratin extraction, and the applications of keratin in food, feed, cosmetics, fertilisers, and bio-based materials. The aim of the literature search was to establish the current state of knowledge, identify most promising applications, and provide context for the subsequent laboratory and market assessments. The literature search was undertaken

using CSIRO library services and major scientific databases, including Scopus, and Google Scholar, to ensure comprehensive coverage of peer-reviewed journal articles, review papers, conference proceedings, and relevant technical reports. These sources were selected to capture both foundational research and recent developments across chemistry, materials science, food and feed science, and industrial processing disciplines.

Search terms were iteratively developed and refined and included combinations of keywords such as bovine hair, hide de-hairing, keratin extraction, hair waste, tannery waste, and keratin applications, along with application-specific terms relating to food, feed, cosmetics, fertilisers, biopolymers, and absorbable polymers. Due to the limited literature on bovine hair waste, searches were broadened to include keratin derived from other sources (e.g., wool and poultry feathers) to provide comparative context.

In addition, a structured patent landscape search was conducted to identify existing and emerging technologies related to bovine hair removal, keratin extraction, and downstream applications of keratin. Patent searches were undertaken using the Derwent Innovations Index (Clarivate Analytics), covering patent literature from 1966 to the present, and were complemented by targeted searches using Google Patents to capture recently published applications and ensure broad global coverage. These databases were selected to provide comprehensive access to patent families, legal status information, and international patent filings across multiple jurisdictions.

Search strategies were developed to capture patent activity across three main areas of interest:

- Animal hair removal from hides and skins, including hair-saving and chemical de-hairing methods relevant to keratin recovery,
- Keratin extraction technologies, with emphasis on methods applicable to bovine hair or tannery-derived hair waste, and
- Applications of recovered keratin, including food, cosmetics, animal feed, and bio-based materials such as biofilms and absorbable polymers, where keratin was explicitly derived from bovine hair.

Identified patents were screened and categorised by feedstock, processing approach, and application area. Artificial intelligence-based tools, with enterprise data protection, were used to support classification and generate summary graphics.

5.2 Stakeholder engagement

Stakeholder engagement was conducted through a questionnaire which aimed to understand hide removal processes and more specifically what happens to hair on the hides. A questionnaire was drafted which was divided into part A (for meat processors) and part B (for tanneries). The questionnaire and data collection process were reviewed by CSIRO's Social and Interdisciplinary Science Human Research Ethics Committee (CSSHREC) and approved under Ethics Clearance 089/25. Through known networks, stakeholders were contacted by phone and email for voluntary participation. The aim was to understand current process flows, challenges and volumes to address value propositions.

5.3 Native hair and Sirolime sample collection and preparation

Samples of native hair and Sirolime hair waste were collected, in triplicate, from a processor and tannery, respectively. Native hair was cut from fresh hides while the Sirolime hair waste was collected from a single batch at 0-, 5- and 10-hour intervals after the hair was separated from the de-hairing liquor. The samples were then shipped to the CSIRO Food Innovation Centre in Werribee, Victoria, for sample preparation and keratin extraction.

Samples went through several preparation steps prior to keratin extraction. Firstly, the samples were disinfected in a solution of 70 % ethanol for 5 minutes before rinsing in deionised water to remove residual ethanol (Figure 1). Secondly, the samples were soaked in a 1 % solution of saponin for 10 – 15 minutes to decontaminate the samples and remove any residual dirt and lipids before a second wash in deionised water to remove residual saponin. Finally,

the initial ethanol/deionised water wash was repeated, and the samples were dried overnight at 50 °C prior to size reduction. The samples underwent an initial size reduction using a rotating blade mill (Pure Juicer, USA) prior to ball milling (Retsch Mill MM 400) and sieving through a kitchen sieve.



Figure 1. Sample preparation steps for native bovine hair and Sirolime hair waste prior to keratin extraction. From left to right: washing and decontamination, cleaned and dried hair fibres, ball milling, and sieving of milled hair powder.

5.4 Keratin extraction and yield

Keratin was extracted from the native hair and Sirolime hair waste, in triplicate, via a modified version of the method used by Sultana et al. (2025). A solution of hair (6 % w/v) in 0.2 M sodium hydroxide was heated at 80 °C for 5 hours before being cooled to room temperature. Sodium sulphite was added (1 % w/v), and the pH was adjusted to 8.5 with 0.1 M hydrochloric acid before the solution was diluted to give a 4 % w/v of hair. Savinase 16L (Novozymes Australia Pty Ltd) was added at 1 % of the starting hair weight and the mixture was heated at 60 °C for 5 hours with stirring whilst maintaining the pH at 8.5 with dilute sodium hydroxide. After this period the mixture was heated to 90 °C for 10 minutes to deactivate the enzyme before being cooled to room temperature. The resulting hydrolysate was centrifuged at 5700 × g for 30 minutes to remove any undissolved hair.

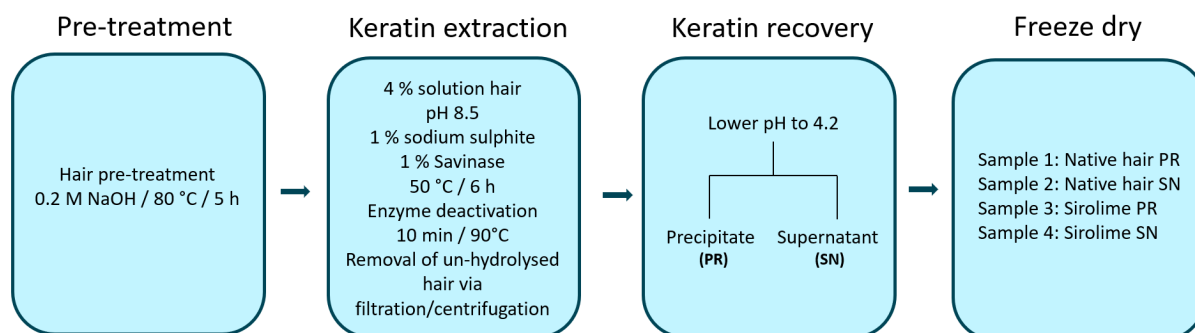


Figure 2. Extraction workflow used to recover keratin from native hair and Sirolime hair waste

The hydrolysed keratin was recovered from this solution in two fractions representing different size ranges of the extracted keratin fragments. Larger keratin peptides were precipitated out by dropping the pH of the hydrolysate to 4.2 using hydrochloric acid. This solution was centrifuged (5700 × g for 30 minutes) and the precipitated keratin was removed and freeze dried to give the precipitate (PR) fraction. Smaller peptides in the remaining supernatant were salted out using small volumes (0.3 – 1.0 mL) of Carrez I (3.7 % potassium hexacyanoferrate) & II (7.3 % zinc acetate) solutions, recovered via centrifugation and freeze dried, as above, to give the supernatant (SN) fraction. The workflow describing the keratin extraction process can be seen in Figure 2. To calculate the yield of keratin in each fraction Equation 1 was used where the protein content of the fractions was compared to the starting protein content of the hair and the yield was expressed as a percentage. Total yield was expressed as the sum of the keratin yield of each fraction.

$$\text{Yield \%} = \frac{\text{Wt extracted keratin fraction (g)} \times \text{protein \%}}{\text{Wt hair (g)} \times \text{protein \%}} \times 100 \quad (1)$$

5.5 Sample analysis and characterisation

5.5.1 Moisture determination

Sub-samples (~400 mg) of native hair and Sirolime hair waste were weighed into metal crucibles and placed in a drying oven at 105 °C for at least 12 hours. The crucibles were removed from the oven and cooled to room temperature in a desiccator and weighed thereafter. Moisture content was calculated according to Equation 2.

$$\text{Moisture \%} = \frac{(\text{Wt of the sample before drying (g)} - \text{Wt of the sample after drying (g)})}{\text{Wt of the sample before drying (g)}} \times 100 \quad (2)$$

5.5.2 Protein analysis

Sub-samples (~100 mg) of native hair and Sirolime hair waste were analysed using the Dumas combustion method on a nitrogen analyser (Vario Max, Elementar, Germany). The protein content was determined by multiplying the nitrogen content by a factor of 6.25.

5.5.3 Differential scanning calorimetry (DSC)

DSC analysis was performed on sub-samples (~20 mg) of native hair and Sirolime hair waste. The instrument was calibrated with Indium as a reference material. Sub-samples were weighed into standard 40 µL aluminium crucibles. A small hole was punctured into the lid of each crucible before the lid and pan were sealed together to avoid rupture during analysis under water vapour pressure which could lead to a loss of sample. An empty crucible was used as a reference. Analysis was performed on a DSC instrument (DSC1, Mettler Toledo, Australia) using the STARe software v.16.1. Each sample was heated from -30 °C to 120 °C, held for 5 minutes, cooled to -30 °C, held for 5 minutes, and reheated to 300 °C. All temperature ramps were conducted at a rate of 10 °C per minute. The peak temperature and the enthalpy of the final transition were calculated from the second heating run of each sample.

5.5.4 SDS-PAGE

0.5g of native hair and Sirolime hair waste were extracted in 10mL of a Tris/HCl buffer (0.05 M, pH 8.5), 8 M urea, 1.5 M 2-mercaptoethanol and 0.25 M sodium dodecyl sulphate at 60 °C for 4 hours. The extracted hair samples were mixed with lithium dodecyl sulphate (LDS) sample buffer (4x) and NuPage sample reducing agent (10x) and then heated for 10 minutes at 70 °C. Either 5 µL or 10 µL of sample was loaded onto an Invitrogen NuPage Bis-Tris mini protein gel, 4-12 % polyacrylamide. An Invitrogen Mark12 unstained protein standard was used as a reference. The gel electrophoresis was run using 2-(N-morpholino) ethanesulfonic acid (MES) sodium dodecyl sulphate (SDS), running buffer (20x) at 200 V for 35 minutes. The gel was then stained with Coomassie stain (SimplyBlue Safe Stain). Stained gels were imaged using a BioRad Gel Doc Go Imaging System with an image size of 12.3 x 8.2 cm.

5.5.5 Amino acids and size exclusion chromatography

Composite samples of the native hair, Sirolime hair waste, precipitate powders, and supernatant powders were prepared by combining equal masses from each of the corresponding triplicate samples to give representative composites for analysis. The resulting composite samples were submitted to an external National Association of Testing Authorities (NATA) accredited commercial laboratory for amino acid analysis and size exclusion chromatography.

5.5.6 Market analysis and value propositions

To understand the relevant industries, market intelligence was gathered from enterprise-approved databases produced by leading global growth consulting companies. Frost & Sullivan and BCC Research databases were used under licence agreements. Using keywords that match the scientific and technical needs of the specific markets, various reports were gathered from the databases to evaluate the following key variables: market size in terms of revenue (in United States Dollar - USD), compound annual growth rates (CAGRs) over defined periods of time, and the drivers and restraints of individual markets.

6.0 Results

6.1 Literature

Extensive research exists on keratin from wool and chicken feathers, but studies on bovine hair, especially hair saved during hide de-hairing, are comparatively scarce.

6.1.1 Bovine hair structure and composition

Bovine hairs and their root sheaths are appendages of the epidermis (Frendrup and Buljan, 2000) that cover almost the entire surface of the animal. The hair primarily consists of ordinary cover hairs along with several specialised variations. These include tactile hairs around the lips, nostrils and eyes, the eyelashes or cilia, and the resistant hairs on the external ear and vibrissae of the nose. Frontal and tail hairs are also specialised variations of hair as they differ in structure and length (Mendiburt et al., 2021). Structurally, each hair fibre is composed of a cuticle (outer layer), cortex (intermediate layer) and medulla (inner hair part) (Figure 3). The hair cortex exhibits a hierarchical arrangement composed of macrofibrils made up of smaller microfibrils. These microfibrils are in turn formed from intermediate filaments (Figure 3). The bovine hair is typically between 82 and 94 μm in diameter (Senthilkumar et al., 2023).

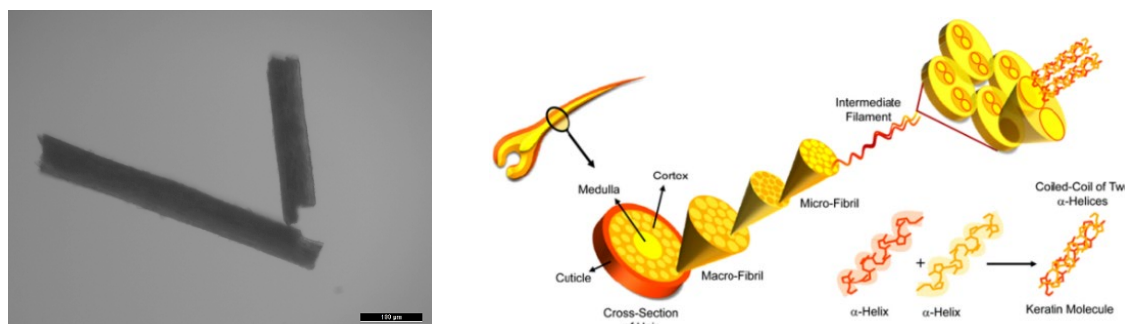


Figure 3. A) Microscopy image of native bovine hair. B) Diagram of structural hierarchy of hair fibre (Lee et al, 2014)

Chemically, on a dry basis, bovine hair is composed of 90-97 % protein, 2 % lipids, and the remainder consisting of nucleic acids, carbohydrates and inorganic substances (de Souza et al., 2022). On a wet basis, protein content has been found to be 83 % for untreated (native) hair and 76 % for treated hair (de Souza et al., 2022). Water, lipids and ash in raw hair have been found to be 13, 1 and 1.5%, respectively (de Souza et al., 2022).

Most of the protein in the hair is represented by keratin molecules. Most of the hair keratin is found in the cortex, a smaller percentage is found in the cortex cells, and a negligible amount is found in the medulla (Anastassakis, 2022) (Figure 1). Hair keratins belong to the “hard” keratin category along with those in nails and feather, whereas the skin contains “soft” keratins (Anastassakis, 2022).

6.1.2 Keratin structure and composition

Keratin (coming from the Greek word meaning horns) is one of the most abundant structural proteins in animals. In a live animal, keratin is an important component of the integumentary system (e.g., nails, hair, feathers, hooves and scales). The integumentary system has waterproofing, waste excretion, temperature regulating, cushioning and pain perception roles in the body. Keratin comprises 65-95% of the hair. Keratin possesses substantial mechanical strength characterised by a Young's modulus higher than collagen. This stiffness establishes it as an important structural biopolymer protein secondary only to collagen (McKittrick et al., 2012, Banasaz and Ferraro, 2024, Sharma et al., 2018a).

Keratins are scleroproteins, with a high content (3-5 %) of sulphur containing amino acid residues (de Souza et al., 2022). They are insoluble filament forming proteins produced by the epithelial cells of vertebrates (Banasaz and Ferraro, 2024). There are 3 keratin configurations (α -, β - and γ -keratins) that differ based on the amino acid composition and arrangement of the polypeptide chains.

α -Keratin is an intermediate filament (7-10 nm) and the largest, structural part of the hair fibre cortex in mammals. They are formed from four right-handed α -helices intertwined to form a left-handed superhelix (protofibril) that is connected to the main axis by hydrogen bonds, and to other adjacent chains by disulphide bonds (via cysteine thiol groups). They have a low sulphur amino acid content and a molecular weight of 40-70 kDa (Ferraro et al., 2016).

β -Keratins are of avian origin, have a β -sheet structure, a molecular weight of 10-22 kDa, and are not present in bovine hair (Banasaz and Ferraro, 2024).

γ -Keratins is the name previously used to describe globular matrix proteins (now known as keratin associated proteins - KAP) (Gong et al., 2010). They contain either a large content of cysteine with a molecular weight of 11-12 kDa, or a large content of cysteine, glycine or tyrosine with a molecular weight of 6-9 kDa (Ferraro et al., 2016).

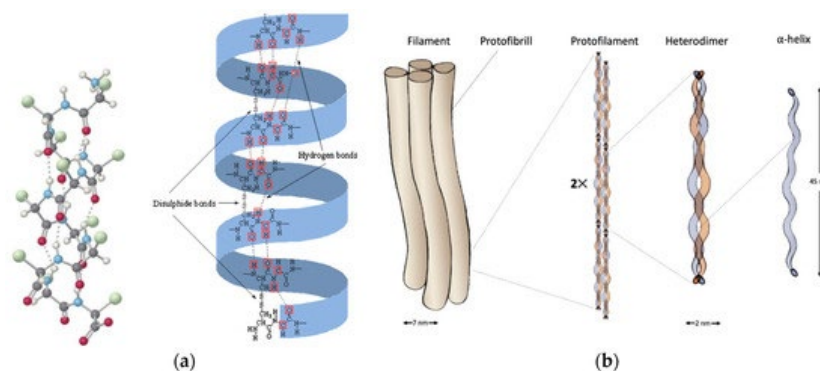


Figure 4. a) Single strand of keratin α -helix. b) molecular formation of keratin filaments (Banasaz and Ferraro, 2024)

Keratin proteins are generally considered a rich source of glycine, alanine, serine and valine, and minor amounts of methionine, lysine and tryptophan (Chilakamarry et al., 2021). Earlier studies found bovine hair to be rich in threonine, arginine and cysteine/cystine (Block, 1939), whereas more recently, Senthilkumar (2023) reported greater cysteine levels along with lower levels of aspartic acid, glycine, leucine, tyrosine and phenylalanine in bovine hair when compared to the horn keratins. The most relevant study on untreated bovine hair and treated hair waste showed that glutamic acid, cysteine and arginine were the most abundant amino acids, and the most notable difference between the untreated and treated hair was the lower amount of cystine and the greater amount of lanthionine due to the chemical transformations during treatment (de Souza et al., 2022). Keratin in general is neutrally charged, and its ionic bonds are weakened under acidic or basic conditions (Chilakamarry et al., 2021).

Table 1. Amino acid composition of untreated hair powder and treated hair waste after hydrolysis (de Souza et al., 2022)

| Amino Acid | Untreated Hair Powder (%) | Treated Hair Powder (%) | Amino Acid | Untreated Hair Powder (%) | Treated Hair Powder (%) |
|---------------|---------------------------|-------------------------|---------------|---------------------------|-------------------------|
| Aspartic acid | 6.5 | 6.4 | Cysteine | 11.7 | 9.5 |
| Threonine | 6.4 | 6.6 | Methionine | 0.4 | 0.5 |
| Serine | 8.6 | 8.4 | Isoleucine | 3.4 | 3.3 |
| Glutamic acid | 14.5 | 15.0 | Leucine | 7.6 | 7.3 |
| Proline | 7.5 | 7.8 | Tyrosine | 2.7 | 2.2 |
| Glycine | 4.7 | 4.4 | Phenylalanine | 2.5 | 2.8 |
| Alanine | 3.5 | 4.0 | Lysine | 3.5 | 3.3 |
| Lanthionine | 0.5 | 2.5 | Histidine | 1.2 | 1.1 |
| Valine | 5.4 | 5.3 | Arginine | 9.5 | 9.6 |

6.1.3 De-hairing methods

De-hairing of bovine hides is usually done in one of the following two ways (de Souza et al., 2022):

- De-hairing methods that destroy the hair such as burning with sodium sulphide or sodium hydrosulphide and lime. These processes have a negative environmental impact, related to the production of hydrogen sulphide which presents a health and safety risk for workers as well as environmental contamination by the formation of solid waste (fleshings) and contaminated wastewater (Morera et al., 2008).
- Hair saving de-hairing methods, which utilise enzymes, enzymes combined with sodium sulphide, and de-hairing with amines, followed by filtration steps for removing the hair from the wastewater. Most hair saving de-hairing processes include immunisation step of applying alkali to increase the resistance of keratin to chemical degradation (avoiding over immunisation), re-liming and sulphide treatment (Frendrup and Buljan, 2000).

Amongst the many de-hairing methods developed to date, the Sirolime process is still one of the most commonly used processes globally. CSIRO developed the Sirolime process in 1981 and it is still used in tanneries in Australia, New Zealand and elsewhere. The method was originally based on impregnating the hair with sodium hydrosulphide without other additives, followed by oxidation with calcium hypochlorite, and the addition of lime to loosen the hair by activating the remaining hydrosulphide in the hair (Frendrup and Buljan, 2000). The process was further modified and simplified, to improve the environmental impact with reusing chemicals and reducing the use of fresh water. A modified version of the Sirolime method is shown in Figure 5. The process is divided in 3 main steps: immunisation, hair loosening and re-liming.

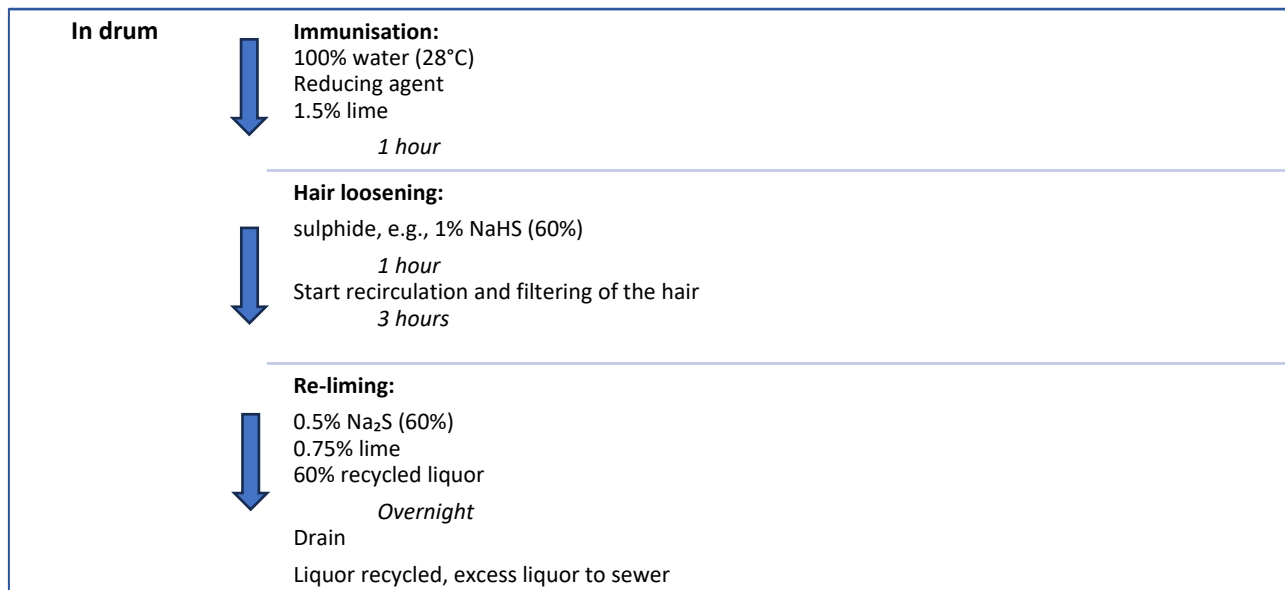


Figure 5. Diagram of the modified Sirolime process developed by CSIRO, adapted from (Frendrup and Buljan, 2000)

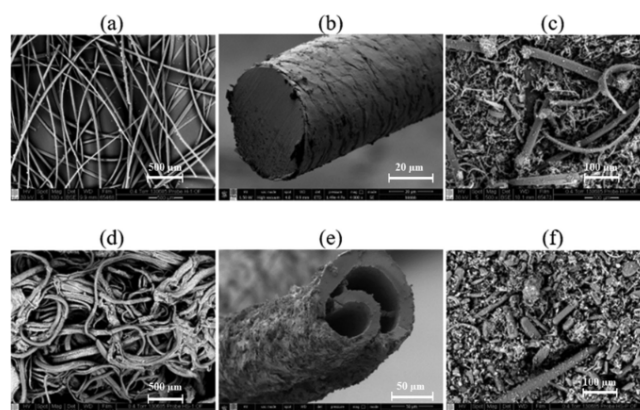


Figure 6. Scanning electron microscopy images of untreated (a-c) and treated (d-f) bovine hair, with before milling (a, d), cross-section (b, e) and after milling condition (c, f) (de Souza et al., 2022)

On a micro scale, bovine hair undergoes physical and chemical changes during the liming steps, which have been characterised through several methods. Scanning electron microscopy shows evident differences between the structure of untreated and treated bovine hair (Figure 6) (de Souza et al., 2022).

On a chemical basis, the immunisation treatment and sulphide treatments make the keratin protein within the treated hair more resistant to chemical degradation and solubilisation, hence disulphide links are replaced by new and more stable cross links (Galarza et al., 2010). The hair treatment also leads to decreased lipid content (with surfactant actions) and increased ash content (from the liming process) (de Souza et al., 2022). Galarza et al. (2010) reported 25-30 % total solids and 11-15 % nitrogen on a moisture free basis from recovered hair from amine treatment, and 80-100 mg H₂S in the recovered wet hair (filtered and drained at 70 % moisture) (Galarza et al., 2010).

6.1.4 Extraction methods

Only one study could be found that had conducted keratin extraction from treated bovine hair (from tannery waste) from hide de-hairing. The study of De Souza (2022) extracted keratin from both treated and untreated bovine hair. Washing with anionic surfactant was followed by milling (knife and centrifugal), and incubated (with shaking) for 3

hours at 55 °C with hydrolysing solutions (2- mercapto-ethanol, sodium sulphide, thioglycolic acid, hydrogen peroxide, sodium hydroxide, and formic acid). This was followed by centrifugation, filtering and freeze drying. The yield varied between 10 and 90 %, with sodium sulphide and hydrogen peroxide being most effective hydrolysis chemicals for untreated and treated hair respectively (de Souza et al., 2022). The order of efficiency of hydrolysing solutions for treated hair was hydrogen peroxide > sodium sulphide > sodium hypochloride > thioglycolic acid > sodium hydroxide > 2-mercaptoethanol, while for untreated hair powder it was sodium sulphide > hydrogen peroxide > thioglycolic acid > sodium hydroxide > 2-mercaptoethanol > sodium hypochlorite > formic acid.

In absence of more bovine keratin extraction studies, the section below summarises some of the learnings of extraction of keratin from other sources, i.e., wool or poultry feathers.

6.1.4.1 Pre- treatment

Extraction of keratin is usually preceded with a milling process to reduce the particle size of the hair into a fine powder, such that the accessibility to enzymes/chemicals is enhanced. Milling can be conducted in multiple ways, with precautions around cysteine oxidation that can occur during grinding (Giteru et al., 2023). Conventional processing relies on ball mill and sieving, however alternative methods include cooling the system, freeze milling, wet and air jet milling (Giteru et al., 2023). Washing, stain removal and fat removal are also used in the pre-treatment for disinfection, uniformity and improved extraction, respectively. Thermal pre-treatment or co-treatment is also often applied to facilitate the action of other extraction chemicals and methods and result in solubilisation.

6.1.4.2 Extraction

There are technical challenges in the dissolution and extraction of keratin in an efficient, eco-friendly, and cost-effective way. Keratin extraction is based on disruption of the disulphide and hydrogen bonds between and within chains. There are several published methods for extraction of keratin from bioresources, including reduction, oxidation, acid or alkali, sulphitolysis, ionic dissolution, enzymatic, microbial, microwave, steam explosion and thermal hydrolysis (Shavandi et al., 2017b).

6.1.4.3 Reduction extraction

Reduction methods cleave the disulphide (–S–S–) bonds of cystine by thiol reagents, producing two thiol (–SH) groups. A number of thiol containing compounds, denaturants, reducing agents and surfactants can be used for achieving this effect including 2-mercaptoethanol, cysteine, dithiothreitol, thioglycolic acid, and thiourea, followed by a surfactant such as SDS (Chilakamarry et al., 2021, Chen et al., 2022). This method maintains the peptide backbone and results in a requirement for further treatment if greater hydrolysis is required. Urea is typically included as a denaturant, swelling fibres, weakening of hydrophobic bonds and allowing reducing agents to access buried disulphide bonds (Shavandi et al., 2017b). Reduction extraction of keratin with 2-mercapthoethanol along with thio-urea application, otherwise known as Shindai method (Nakamura et al., 2002), is generally considered effective, resulting in high extraction yields of more than 75 % in chicken feathers and wool (Shavandi et al., 2017b). Physical methods such as ultrasound have also been combined with the reduction produce and shown to improve dissolution rate (Qin et al., 2023).

6.1.4.4 Oxidation extraction (Peracetic acid, performic acid, hydrogen peroxide)

By reacting with oxidising agents (i.e., 2 % peracetic acid, mild ammonia and HCl and/or sodium) (Chilakamarry et al., 2021, Chen et al., 2022), numerous inter- and intramolecular cystine cross-links in wool are weakened, allowing wool fibres to be broken down into their constituent elements and yielding low-molecular-weight proteins and peptides (Giteru et al., 2023). It has been established that treatment of hair with peracetic acid leads to the transformation of disulphide to sulfonate (Robbins, 1967) and in wool this can provide a disadvantage through partial oxidation of

cysteine to cysteic acid (Giteru et al., 2023). The yield of water-soluble keratin reached up to 57 % when wool was treated with 24 % peracetic acid (Shavandi et al., 2017a).

6.1.4.5 Sulphitolysis extraction (Sodium sulphite, metabisulphite)

Sulphite anions convert cystine bridges to cysteine thiols and sulfonate anion, yielding anionic, water-soluble keratin without overoxidation of the peptide chain (Giteru et al., 2023). Extraction by this method in wool has resulted in yields ranging between 62 and 86 % (Giteru et al., 2023). At the same time, extensive degradation needs to be avoided to prevent loss of amino acids during dialysis (Giteru et al., 2023). A study applying sodium sulphite, urea and SDS to feathers for 6 hours at 100 °C has resulted in 98.3 % dissolution and 64.5 % keratin yield, with the material deemed appropriate for biopolymer applications (Shavandi et al., 2017a, Yousif et al., 2025).

6.1.4.6 Acid or alkali extraction

Acid extraction employs strong acids such as HCl or H₂SO₄ (Chilakamarry et al., 2021, Chen et al., 2022). Hot and strong alkali degrade cysteine, such that the primary chain is damaged by splitting carboxylic and sulphate groups (Giteru et al., 2023). A recent study applied alkaline NaOH for 30 minutes at 80 °C to feathers and resulted in 53.4 % yield and 99.7 % dissolution of keratin and the keratin was deemed suitable for cosmetics applications (Yousif et al., 2025). Another study with 3.5 hours hydrolysis in 0.5N NaOH resulted in a yield of 91.5 % keratin (Mengistu et al., 2023).

6.1.4.7 Ionic dissolution

Ionic liquids are salts composed of organic cation and various organic and inorganic anions melting at <100 °C (Shavandi et al., 2017a). While this is considered a green method, it may require specialised equipment and may result in loss of cysteine (Giteru et al., 2023). To improve the efficacy of extraction, ionic liquids are combined with reducing agents and physical methods such as ultrasound to achieve high extraction yields (Sianita et al., 2025).

6.1.4.8 Enzymatic and microbial extraction

Enzymatic hydrolysis relies on the application of enzymes such as keratinase or Savinase (Chilakamarry et al., 2021, Chen et al., 2022). The enzymatic process can follow alkaline treatment to allow the access of the enzyme to the protein by breaking down of the disulphide bond (Sultana et al., 2025). Protein recovery of alkaline treatment followed by enzymatic treatment has resulted in 94.9 % protein recovery. Some microorganisms have the ability to produce keratinases and these include *Amycolatopsis*, *Bacillus*, *Chryseobacterium*, *Fervidobacterium*, *Kocuria*, *Lysobacter*, *Staphylococcus*, *Stenotrophomonas*, *Streptomyces*, *Thermoactinomyces*, and *Vibrio* (Chen et al., 2022). Strain engineering has been also applied in improving the catalytic ability of microorganisms (Anbesaw, 2022).

6.1.4.9 Microwave

Microwave extraction is considered a green method of extraction; however, it is more capital intensive than other methods. Microwave extraction (180 °C for 60 minutes) resulted in moderately high extraction yields of 60 % in wool (Zoccola et al., 2012). Microwave has also been combined with chemical methods such as the application of L-cysteine, resulting in 56.8 % yield with only 10 minutes of treatment (Wang et al., 2024a).

6.1.4.10 Steam explosion

Steam explosion is a process where the material is exposed to high temperature steam entering its cells resulting in fast decomposition and explosion within milliseconds (Giteru et al., 2023).

6.1.5 Applications of keratin from hair and hair waste

The main valorisation of keratin-based materials is by the utilisation of wool and chicken feathers, and most other keratin composed materials are either wasted or used in small scale as fertiliser and biodegradable surfactants (Shavandi et al., 2017b). Keratin based materials cannot be valorised for fuel due to their sulphur content and subsequent environmental concerns (Shavandi et al., 2017b).

Keratin is explored for a number of properties, including mechanical properties, biocompatibility, biodegradability, oxidation-reduction properties, antibacterial property, hemostasis, multi-responsiveness, chemical modification, and complexation property (Wang et al., 2024b).

Recovered hair can be used without further processing or with minimal processing for applications such as thermal initialisation, plant pots and ocean barriers, or it can be processed and used for applications including feed, cosmetics and biosorbents (Figure 7).

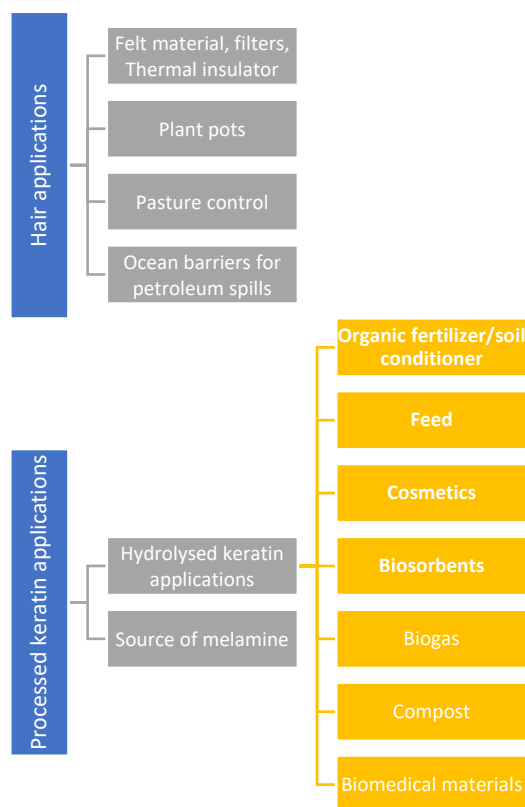


Figure 7. Hair and keratin applications, adapted from Galarza (2010))

6.1.5.1 Food

There is no literature on keratin from bovine hair being explored for food applications. On the contrary, wool derived keratin has been explored for its nutritional, functionality, digestibility and toxicological characteristics. Keratin is indigestible by human enzymes due to the presence of disulphide bonds (Giteru et al., 2023), which mammalian gastrointestinal digestive enzymes cannot break down. For it to be used in the diet it needs to be pre-processed to a form that can be digested by human enzymes, or it needs to be broken down to peptide or amino acid level.

Nutritionally, although keratins from all sources are rich in amino acids, concerns have been raised about the breakdown of some amino acids like cysteine/cystine during the thermal or chemical treatments. Some deficiency has

been reported in arginine, lysine, methionine, threonine, histidine too, but this is extraction technique dependent (Tantamacharik et al., 2022). Enzymatic hydrolysis of feather keratin has resulted in lysates rich in isoleucine, leucine, threonine and valine, which has been stated to resemble soy protein (Tantamacharik et al., 2022).

Taste wise, lower molecular weight hydrolysates rich in hydrophobic amino acids (leucine, isoleucine, proline, phenylalanine, tryptophan and tyrosine) have been associated with a bitter taste profile (Tantamacharik et al., 2022). Plastein reactions have been used to improve nutritional value and functionality, as well as to correct for taste (Tantamacharik et al., 2022).

Keratin products have been associated with positive health effects, specifically antioxidant peptides, antihypertension, and anti-diabetic (Tantamacharik et al., 2022). In addition, keratin derived products have been considered as encapsulation material as well as food packaging. While keratin needs to be pre-processed into monomeric reduced keratin powder and cross-linked before it can be used as packaging material, it is considered a favourable material as it has low allergenicity, is biodegradable, hydrophobic, strong, and biocompatible, and its flexibility can be modified (Tantamacharik et al., 2022).

While there are some mentions in the literature of hydrolysing chicken feathers for keratin-based ingredients in food, mainly for the benefits to the hair (Jana et al., 2021), those claims are not well established. There have been some research efforts on sheep wool in New Zealand to understand best extraction methods, digestibility, and toxicity of keratin as a food ingredient. Safety wise, there are few toxicological studies conducted on animals and one feeding trial in athletes. One toxicological study conducted in New Zealand fed rats with wool derived keratin protein extracted using microwave high pressure technology, and it found that the protein was not cytotoxic at ≤ 2 mg/mL and did not change the weight gain compared to the control (Dias et al., 2022). Another New Zealand study demonstrated not only safe use in rats, but also very high digestibility (94-86 %) achieved using their processing methods (Wolber et al., 2016). The athletes feeding study did not report any negative health effects and noted positive effect on body lean mass (Crum et al., 2018).

Keratin is considered a novel food in Australia and has not been approved to date. There have been two applications to the Advisory Committee on Novel food in Australia (ACNF) in 2009 and 2014 resulting in a novel food determination. In both cases, wool was considered a non-traditional food source where safety has not been established nor the product adequately characterised. This assessment prompts that any future use will require either new data for reassessment by the ACNF or an application to Food Standards Australia New Zealand (FSANZ) for novel food.

Any consideration for food use will require the extraction processes to be performed in a food grade manner, using approved processing aids. Hence, additional issues could arise if keratin is derived from tannery waste where processes are not food-grade (Jana et al., 2021).

Despite no food use, there are a few keratin based dietary supplements available in the global market, with one being sold in New Zealand. Dietary supplements are governed by Therapeutic Goods Administration (TGA) in Australia, but they are subject to separate regulations in New Zealand.

6.1.5.2 Feed

There is no literature on using bovine hair or keratin as feed, however, poultry derived feather and wool derived keratin has been explored across many feed categories and are commercially available. Feed for production animals includes feed for ruminants, swine, poultry and aquaculture. While protein ingredients are valued for all these categories, in Australia, there are restrictions on utilising Restricted Animal Material (RAM) including bovine meals in ruminant feed and often also in poultry and swine. This is to prevent infective diseases such as Bovine Spongiform Encephalopathy in cattle (and human) and Food and Mouth Disease and African Swine fever. There are some exceptions per state that include materials that have been rendered according to the Australian Standard for the hygienic rendering of animal products (in a dedicated facility). While bovine hair meal is not explicitly mentioned in the current regulations,

and there are some mentions in the literature of feather meal derived ingredients for livestock feeding (Huang et al., 2021), the regulatory environment remains complex with state restrictions on bovine meals.

Conversely, aquaculture feed is a suitable application for bovine derived ingredients in general, and bovine hair/keratin in particular. While there is no literature on utilising bovine hair or keratin as ingredients in aquaculture feed, there is some literature in valorising poultry feather and chicken foot keratin for this purpose (Thazeem et al., 2022, Viñas et al., 2025). Feather meal has been evaluated as replacer for fish meal, for example in the diet of catfish (Rashid et al., 2025, Bordignon et al., 2026), while others have explored the opportunity to complement low fishmeal diet (Bordignon et al., 2026). Pre-processing is necessary to convert keratin in a digestible form, and this could include processes including hydrolysis, enzymatic treatment (Pfeuti et al., 2019) and fermentation (Viñas et al., 2026). In some instances, keratin amino acid ingredients have enabled disease alleviation in shrimp (Kersanté et al., 2021).

Petfood is subject to strict hygiene, manufacturing and composition requirements. There is some literature on petfood from chicken feather keratin and there is no literature on bovine keratin. One study by Rahman (2024) has shown that 20 % protein replacement with feather meal was complemented by good palatability properties when fed to Labrador dogs.

6.1.5.3 Cosmetics

Application of keratin ingredients are very common in the cosmetic field, with most applications in hair products where keratin is found to improve hair moisture, shine and softness. Most common sources of cosmetic keratin ingredients are sheep wool, chicken feathers, horn and biotech derived keratin or synthesised keratin (Cruz et al., 2017). To our knowledge, bovine hair has not been used as a keratin source to-date. Keratin peptides are also commonly used in hair product formulation and salon hair treatments. This is mainly to restore the cuticle properties of hair that has been damaged through bleaching, straightening, and permanent waving which makes the hair dry, brittle and lack shine and strength (Barba et al., 2010). It has been found that keratin peptides increased water sorption in human hair and improved mechanical and thermal properties (Fernandes et al., 2012). The efficacy of keratin peptides in improving hair properties after application is measured as a function of hair hydration (Villa et al., 2013). Keratin peptides are a common ingredient in shampoos (Mothé et al., 2018). Hydrolysed keratins are also used in mascaras at 0.2 % and soaps and detergents at 0.028 %. Solubilised keratin proteins can also be used for nail applications (Chilakamarry et al., 2021).

Keratin treatments, often called Brazilian keratin or keratin smoothing treatments, are designed to reduce curl, frizz, and improve hair manageability while enhancing shine and the overall cosmetic appearance of the hair (Weathersby and McMichael, 2013). They are used as substitute and long-term alternative for other straightening methods using chemicals such as reductive agents reducing thio-relaxers and alkaline agents (Cruz et al., 2017). The treatment works by applying hydrolysed keratin proteins that penetrate the hair shaft and become chemically bonded to the hair's natural keratin, typically through heat activation. This process smooths the cuticle, increases resistance to humidity, and allows hair to remain straighter for several weeks to months (Weathersby and McMichael, 2013).

Application of a keratin treatment usually follows a standard multi-step process carried out in a salon setting. The hair is first washed with a clarifying shampoo to remove residue and open the cuticle, allowing better penetration of the keratin solution. The treatment serum, containing hydrolysed keratin and a cross-linking agent, is then applied section by section using a fine-toothed comb to ensure even saturation (Weathersby and McMichael, 2013). The keratin peptides often need to be linked to the hair keratin by cross-linking agents such as formaldehyde, formalin or methylene glycol (Leichner et al., 2019, Weathersby and McMichael, 2013), and the following amino acids are responsible for the binding action: arginine, lysine, tyrosine, histidine, amide derivatives of aspartate and glutamate (Weathersby and McMichael, 2013). Once applied, the hair is blow-dried and then flat-ironed at high heat to activate the chemical bonding and seal the keratin into the hair shaft. Many stylists recommend waiting 48–72 hours before washing the hair again so the treatment can fully set (Weathersby and McMichael, 2013). While these treatments are

popular because they can be used on coloured or chemically processed hair and tend to cause less immediate shaft damage than traditional chemical relaxers, many professional formulations release formaldehyde gas or formaldehyde derivatives when heated. Exposure to these substances has been associated with eye, respiratory, and skin irritation and raises longer-term health concerns for both the client and salon workers, meaning safety and ventilation are critical considerations (Weathersby and McMichael, 2013). A study looking into the health effects did not find negative effects when keratin peptides were used with water but found negative effects in combination with organic solvents (Fernandes et al., 2012).

6.1.6 Mulch and biofertilisers

Biodegradable mulches are applied to soil to regulate temperature, conserve moisture, suppress weed growth and enhance crop yield and quality. Carbohydrate and protein biofilms lack mechanical strength and water resistance. Cross-linking with other materials can improve the stability of the mulch, demonstrated through a lab prepared keratin-CaCO₃ nanoparticle biofilms (Shao et al., 2026).

Fertilisers have a critical role in agricultural production and about 112×10^6 tonnes of nitrogen fertiliser were used in 2023 globally (FAO, 2025) (Chen et al., 2021). Urea is the most commonly used nitrogen fertiliser, but it has challenges such as losses that lead to soil acidification, soil hardening, nutrient imbalance and surface water pollution. Due to the presence of carbon and nitrogen, keratin materials can be used for biofertilisers (Chilakamarry et al., 2021). Composting can be applied to increase the stability of the keratin rich material and degrade the saved hair into a form that improves the soil quality (Galarza et al., 2010).

Keratin applications as fertiliser can include (Chen et al., 2022):

- Fast-release hydrolysate fertiliser
- Slow-release nano-keratin or hydrogel fertiliser
- Amino acid fertiliser
- Biochar fertiliser.

Keratin has also been used as a coating material for urea to allow for slow release, in complexes with acrylic acid and methylenebisacrylamide (Chen et al., 2021). Biofilms currently used in agricultural mulch are of petroleum origin, which are non-degradable and non-renewable, contaminating the environment and accumulating in human tissues (Shao et al., 2026).

6.1.7 Nappies

Nappies are the largest contributor to landfills comprising 30 % of non-biodegradable waste, take more than 500 years to decompose, and serve as a breeding ground for a large range of viruses and bacteria (Khoo et al., 2019). There is no literature specifically on using any form of keratin for nappies. However, it has been shown that keratin is a great candidate for biomaterials overall, as it is biocompatible and biodegradable, and when processed appropriately it exhibits good porosity, pore size, wettability, swelling property and mechanical properties. Keratin can be used in biopolymers in the form of fibrous composites, gels, films, nanoparticles, microparticles, sponges and scaffolds (Chilakamarry et al., 2021), demonstrating applicability to materials in nappies.

There is at least two parts of nappies that can utilise keratin as a raw material, including the surface biofilm and the absorbent material. Keratin based materials have an organic nature and do not have such detrimental effect on the environment as plastic of petroleum origin used in nappies (Płotka-Wasyłka et al., 2022). Keratins have been found to be a great material for protein-based films due to low cost, large availability and high degree of cross-links (cysteine) (Shao et al., 2026). Methods for preparing biofilms from keratin rich materials include solvent casting, freeze drying,

electrospinning, template self-assembly, and soft lithography (Donato and Mija, 2020). Cross-linking with other reinforcement materials increases the strength and water stability of keratin films.

There are many studies that have looked at biofilms that combine keratin with other materials, although not all of them may be suitable for skin contact applications. Co-polymers from the literature include:

- Keratin + SDS + glycerol, SDS alone, Polyacrylic acid (Ranjit et al., 2022)
- Keratin + carboxymethyl cellulose biofilm (Adi et al., 2020)
- Keratin + cellulose + glycerol biofilm (Sharma et al., 2018b)
- Keratin hydrolysate from solid state fermentation + carrageenan (Ekatiwi et al., 2020)
- Keratin from solid state fermentation (*Bacillus* MD24) for a soluble biofilm (Nurkhasanah et al., 2020)
- Keratin powder + chitosan powder + polyvinyl alcohol biofilm (Gül Çelik et al., 2021)
- Keratin + cellulose nanocrystals cross-linked physically with SDS (Zhang et al., 2024)

In relation to absorbent material, a promising study has looked at superabsorbent hydrogels made with keratin hydrolysate (alkaline) with acrylamide, acrylic acid and N, N' methylenebisacrylamide (Arıcan et al., 2021). This study achieved 1791 % absorbance at lab scale (Arıcan et al., 2021).

6.2 Patent search

The patent search revealed 44,706 patent families in total, whereby a patent family is a group of patents that are related, usually by a priority document or documents, relating to one invention. Across the value chain, patent activity reveals distinct technological focus areas as shown in Table 2. In hair removal technologies, which found 1,564 patents, of which 18 related to bovine hair, there is a clear transition toward more sustainable and environmentally responsible processing approaches. Innovations increasingly focus on reducing the use of harsh chemicals through the adoption of enzymatic, microbial, and biotechnological de-hairing methods. These approaches aim to minimise wastewater generation and chemical residues while preserving hair integrity, which is critical for subsequent keratin recovery. Additionally, several patents demonstrate integration between hide processing and protein recovery, indicating a growing trend toward valorisation of multiple components, including both keratin and collagen.

In the area of keratin extraction, which found 1,441 patents of which 84 related to bovine hair, patent activity reflects a shift toward greener and more controlled processing technologies. Innovations include enzyme-assisted hydrolysis, the use of deep eutectic solvents and ionic-liquid-like systems, and improved oxidative and reductive cleavage techniques. These developments aim to enhance solubilisation efficiency, maintain molecular integrity, and improve purification outcomes. The associated patent classifications highlight strong activity in bioprocessing, protein chemistry, and separation technologies, indicating convergence between biotechnology and materials science. Notably, patent filings in this area have increased since 2020, driven by industrial biotech integration and circular design and suggesting renewed interest in keratin as a sustainable and functional biomaterial.

Table 2. Patent landscape summary

| Category | Total Patent Families | Bovine Hair-Specific Patent Families | Specific patent examples (publication number and reference) |
|----------------------------|-----------------------|---|--|
| Hair removal (hides/skins) | 1,564 | 18 (for keratin extraction); 139 (for hair removal) | CN118497430A (Shenzen Chanlong Technology co Ltd, 2024) CN110408728B (Qilu University of Technology, 2021) |
| Keratin extraction | 1,441 | 84 | CN116333085A (Peking University and Beijing Graphene Institute, 2023); IN202231038894A (ICAR National Institute Natural Fibre Engineering & Technology, 2024) |
| Food applications | 4,045 | 26 | CN108727485A (Henan Shuanghui Investment & Development Co., 2018) |
| Cosmetics | 32,435 | 30 | MX384496B (Ciatec A. C., 2021) |
| Feed | 2,254 | 22 | MX2019003594A (Ciatec A.C., 2020) |
| Biofilms/ polymers | 2,618 | 16 | US6270793B1 (Keraplast Technologies Ltd., 2000) CN108404200B (Qilu Univeristy of Technology, 2020); CN102827481B (Tianjin Polytechnic University, 2014) |

Patent activity across application areas is highly uneven and reflects differing levels of technological maturity. Cosmetics dominate the landscape, with over 32,000 patent families identified, although only a small proportion (n= 30) relate specifically to keratin derived from bovine hair. Innovations in this sector focus on keratin-enriched formulations for hair repair, functional peptides, and incorporation into bioactive or antimicrobial systems. In contrast, food and feed applications represent a smaller but emerging area of innovation, with increasing patent activity since 2023. These patents focus on the generation of bioactive peptides, protein enrichment, and improved digestibility through enzymatic and microbial processing.

In parallel, there is growing activity in polymers, biofilms, and advanced materials, particularly over the past five years. Developments in this space include electrospun keratin fibres, biodegradable polymer composites, antimicrobial films, and absorbent materials. These applications highlight the versatility of keratin as a functional biomaterial, particularly in applications requiring biodegradability, porosity, and tuneable mechanical properties.

The patent landscape is also highly concentrated geographically and institutionally. China is the dominant origin of patent filings, accounting for 66 patent family applications, followed by Japan with 6 and India with 4 patent families. Key assignees include Donghua University, Ciatec, and the Institute of Process Engineering of the Chinese Academy of Sciences. In contrast, no patent family filings originating from Australia were identified, and only a very small proportion of global patents are extended to the Australian market (0.97 %). This highlights a clear gap in domestic intellectual property activity despite the availability of significant biomass resources.

Overall, the patent landscape highlights several key trends. These include a strong shift toward sustainable and green processing technologies, increasing convergence across industries such as cosmetics, food, and biomaterials, and

rapid growth in innovation activity since 2020 driven by circular economy and bio-based material demands. Importantly, the analysis reinforces that while keratin technologies are well developed globally, bovine hair remains a relatively underexplored feedstock within this innovation space.

From an industry perspective, this presents clear opportunities as shown in Table 3. Despite the scale of global keratin innovation, the limited patent activity specific to bovine hair highlights a clear opportunity for Australia to establish leadership in this niche through targeted R&D and industry integration.

Table 3. Summary of patent search showing current status and opportunities

| Dimension | Current State | Opportunity |
|-----------------|-------------------------------|-------------------------------------|
| Feedstock focus | Wool & feathers dominate | Bovine hair underutilised |
| Geography | China-led innovation | Limited Australian IP |
| Processing | Chemical-heavy legacy systems | Green extraction opportunity |
| Applications | Cosmetics dominant | Feed, materials & polymers emerging |

6.3 Stakeholder engagement

Responses were received from eleven processors and three tanneries. There was good distribution amongst the processor size, with respondents reporting <100 to >10,000 animals processed per week for respective companies (Figure 8).

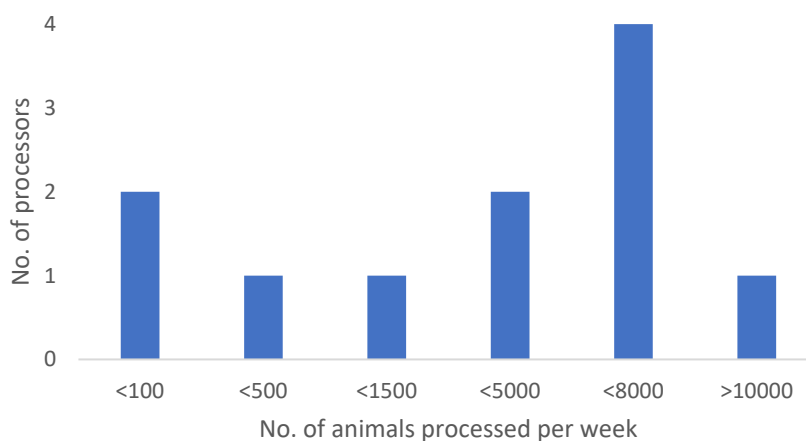


Figure 8. Number of animals processed per week by questionnaire respondents (n = 11)

Processors responded that the biggest challenge regarding hides was declining demand, followed by a lack of opportunities to value-add domestically. There were also equally five responses identifying preservation/transport issues and price volatility. One processor revealed that weekly disposal was costing \$1670 per week plus an additional \$315 per tonne dumped (reflective of January 2026). Along with transport and dumping costs, there were energy costs to ensure hides were stored in cool conditions prior to weekly collection for environmental reasons. With four of the eleven processors reporting hide disposal, it was stated that this is the only option at present due to no other market opportunity. The challenge is reported to extend beyond beef hides, to other species too, whereby small, and especially regional processors, had no market for hides leading to disposal of biomaterial of potential high value.

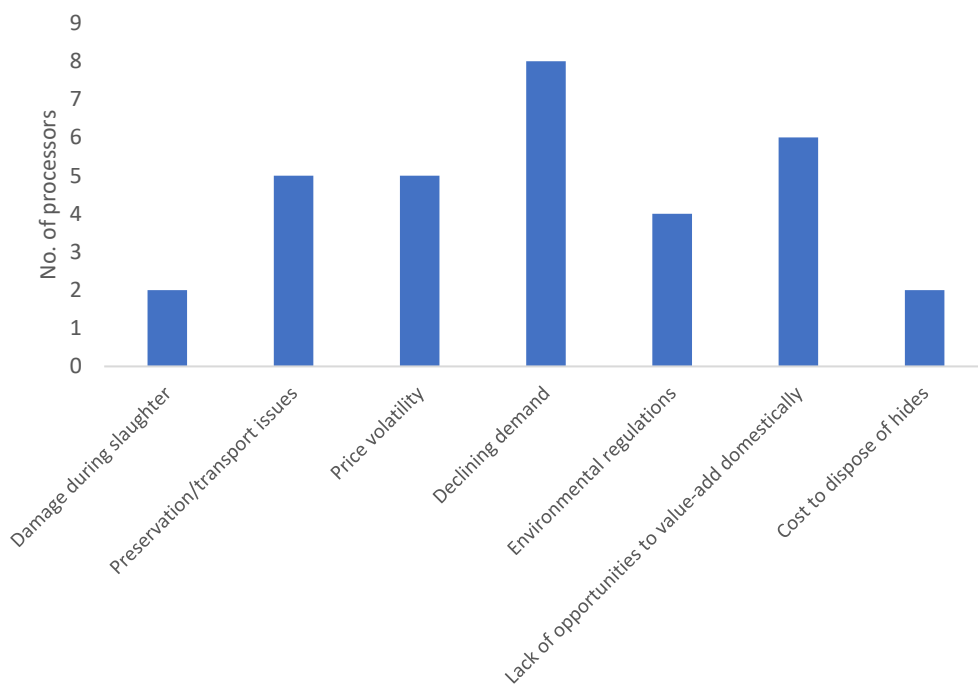


Figure 9. Response to question 'What are the biggest challenges you face with hides? Select all that apply'.

Where hides were sold, further processing always occurred off-site. Five processors reported that further processing occurred domestically and three stated their hides were subject to international processing. One of the eleven processors mentioned that some hides are cut for gelatine processing. In terms of quality concerns, 64 % of respondents said that they do not grade hides, as they either do not have a market, or grading is performed by the tannery. However, flaying quality (n=4) and surface damage, size and shape (n=3) were also reported as important. When asked what percentage of hides are considered low value, five processors said 0-10 %, one processor said 10-25 % and two processors said 75-100 % (with three processors unsure). In all cases, hair remains on the hide until the next point of process/disposal. Six respondents said that they would be willing to trial an innovative hair removal method, however, it would have to have 'substantial gain' due to capex and labour investments, especially where hide volumes are too low to warrant payback. Five processors selected 'I don't know' when asked 'If value could be retrieved from bovine hair, how would you like to obtain it?', with equally three selecting 'by removing after the hide puller' or 'sell the hide with the hair'.

Overall, processors were concerned by the lack of market opportunities and the declining demand for hides as a whole, which should be considered in addition to the hair on the hides. When asked 'how important is value-adding to hides', nearly all answered very important (n=3) or important (n=7), with one processor remaining neutral. While some small processors had turned to disposal, larger processors had still felt the decline in value, and the challenge was beyond beef with similar decline in other red meat species. In terms of opportunities to value-add through applications of hair, processors were open to discussing opportunities, but the value proposition needs to be justified.

Tanneries (n=3) also provided input on the study. Two tanneries follow a standard process i.e., fleshing (cleaning), de-haired, grained, tanned, while one conducts a preservation i.e. brine cured, process for export. All three tanneries reported making past efforts to value add to hides. Survey responses from tanneries provided mixed responses when asked 'Approximately how much hair or hair-waste (by weight or volume) is removed per week?' as follows: Hair waste accounts for 6 - 10 % of the hide weight; fleshing to render ~3 kg/hide, trim waste ~1 - 2 kg/hide; 20-25 m³. Two tanneries reported removing the hair with sulphide and/or enzymes, while the tannery that preserves the hides for export, does not remove the hair. Therefore, the hide is sold to their international customer with hair on. When

removed, the removed hair is either disposed as waste or collected for fertiliser use. The main challenge with hair removal was the cost of equipment (i.e., hair screens, hair press and storage tanks). Hair disposal has associated costs for dumping fees and third-party transport for hair screened out during curing. For a new hair removal process to be successful, priority was given to 1) low cost; 2) less chemicals, environmentally friendly, low labour; 3) fast, no labour, chemical free. The perfect hair removal process was described as one which has automatic chemical addition based on the formulation, environmentally compatible, easily replicable (accommodates seasons, breeds, etc.), less damaging to equipment, class 8 corrosive chemicals dramatically reduced and would include drying capabilities and further enzymatic treatment to convert into pellets. Overall, tanneries, like processors, felt that innovations beyond hair applications for hide applications were needed.

6.4 Sample analysis and characterisation

6.4.1 Characterisation of the native and Sirolime hair

6.4.1.1 Sample preparation

Figure 10, A and B, show images of the milled native hair and Sirolime hair waste. Both hair sources underwent an identical sample preparation and milling process however; there were some differences in the particle size of the resulting hair powders. Upon visual inspection the native hair appeared to largely consist of bigger hair particles, whilst the Sirolime comprised of smaller, more fragmented hair particles. Representative light microscopy imaging of the native hair and Sirolime milled hair can be seen in Figure 10 C and D, respectively, with the scale bar representing 100 microns (μm). The imaging indicates that the particle size of the native hair was generally larger and more uniform than the Sirolime milled hair. These results suggest that the size reduction process may be more efficient for the Sirolime hair waste when compared to native hair, at least for the methods employed in this study. Furthermore, the smaller particle size of the Sirolime hair waste will increase the surface area of the hair for extraction which may improve the keratin extraction efficiency.

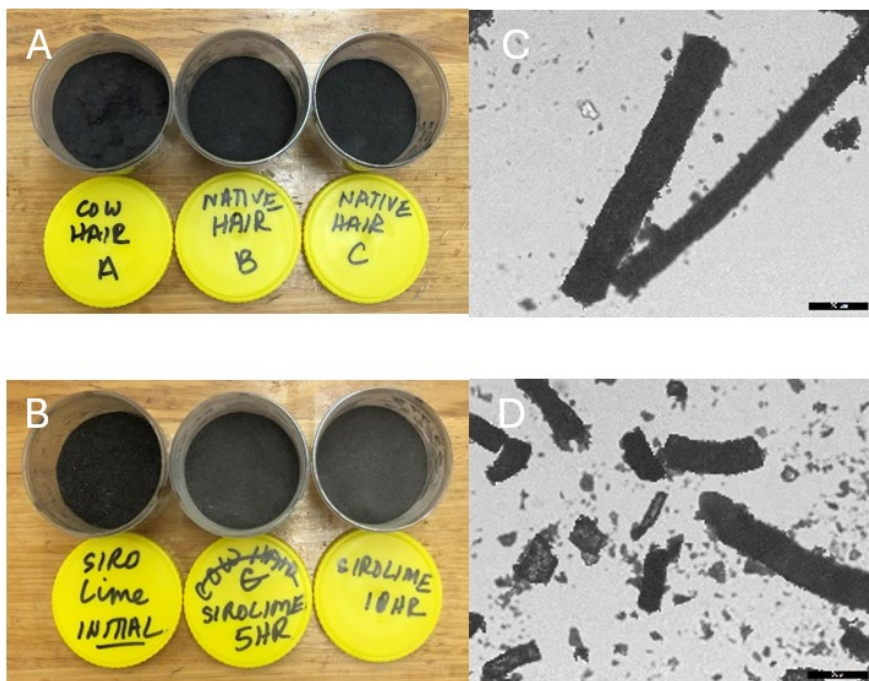


Figure 10. Milled native hair (A) and Sirolime hair waste (B) for keratin extraction and representative light microscopy images of each (C and D respectively). Scale bar 100 μm

6.4.1.2 Protein and moisture

Keratin is the most abundant protein in hair and, as such, the protein content of the native hair and Sirolime hair waste is indicative of their keratin content and therefore suitability as sources for keratin extraction. The protein and moisture content of the native hair and Sirolime waste can be seen in Table 4. Both hair sources were rich in protein, however, there was more protein in the milled native hair at 94.6 %, while the milled Sirolime waste was 79.6 %, representing a reduction of 15 %. This indicates that the Sirolime process does result in a loss of protein, either via protein solubilisation during the process, from a dilution of the available protein via the accumulation of inorganic material used in the Sirolime process, or a mixture of both. de Souza et al. (2022) analysed bovine hair and recovered bovine hair waste from the liquor of a hair-saving process, similar to Sirolime. They found that both the bovine hair and recovered hair were high in protein at 82.9 and 76.2 % and had moisture levels of 12.8 and 12.1 %, respectively. Interestingly, the ash content, which represents the inorganic residue of a sample after combustion, was much higher in the Sirolime hair waste when compared to the untreated hair. The ash content of the recovered hair was 10.05 % while the content in the untreated hair was only 1.46 % which is close to a 70 % increase. The authors attributed this finding to additional inorganic material accumulating in the hair waste from compounds used in the de-hairing process, notably calcium residue from lime. We did not assay the native hair and Sirolime hair waste samples for ash in this study; however, it is possible that a significant amount of inorganic material from the Sirolime process may be present in the Sirolime hair waste, causing a reduction of the protein content compared to the native hair.

Table 4. Protein and moisture content of the cleaned and milled native hair and Sirolime hair waste \pm standard deviation. Results are reported on an 'as is' basis.

| Analysis | Native Hair | Sirolime hair waste |
|--------------------------|----------------|---------------------|
| Protein % w/w (N x 6.25) | 94.6 \pm 2.4 | 79.6 \pm 2.5 |
| Moisture % w/w | 7.5 \pm 0.5 | 8.7 \pm 0.6 |

6.4.1.3 Amino acid analysis

The amino acid profile of the milled native hair and Sirolime hair waste is shown in Table 5. Both hair sources are rich in glutamic acid (102.6 – 97.0 mg/g) and arginine (74.1 – 65.2 mg/g). Total amino acids are reduced in the Sirolime hair waste when compared to native hair (598.1 vs 740.3 mg/g) which is consistent with the lower protein content of Sirolime hair waste. The biggest difference between the profiles is the large decrease in cysteine between the native hair and Sirolime hair waste, from 100 to 22.5 mg/g, respectively, representing a 78 % reduction. This is consistent with disulphide bond cleavage and subsequent cysteine degradation during the Sirolime treatment. de Souza et al. (2022) measured the cysteine content of bovine hair and recovered hair and found a decrease of cysteine in the recovered hair waste of 18.8 % which was coupled with a 5-fold increase of the amino acid lanthionine. The reduction in cysteine was not as sizeable as observed in this study but is consistent with the loss of cysteine during the hair immunisation process whereby cystine residues are converted to lanthionine when the hair is treated under alkaline conditions.

Table 5. Amino acid content of the cleaned and milled native hair and Sirolime hair waste \pm the measurement of uncertainty. Results are reported on an 'as is' basis

| Amino Acid | Native Hair | Sirolime |
|--------------------|------------------|-----------------|
| Histidine mg/g | 8.6 \pm 0.1 | 7.9 \pm 0.1 |
| Serine mg/g | 60.1 \pm 0.7 | 53.4 \pm 0.7 |
| Arginine mg/g | 74.1 \pm 0.9 | 65.2 \pm 0.9 |
| Glycine mg/g | 27.5 \pm 0.3 | 24.7 \pm 0.3 |
| Aspartic acid mg/g | 45.5 \pm 0.6 | 41.5 \pm 0.5 |
| Glutamic acid mg/g | 102.6 \pm 1.3 | 97.0 \pm 1.2 |
| Threonine mg/g | 48.7 \pm 0.6 | 38.2 \pm 0.5 |
| Alanine mg/g | 24.7 \pm 0.3 | 22.7 \pm 0.3 |
| Proline mg/g | 50.5 \pm 0.6 | 45.5 \pm 0.6 |
| Lysine mg/g | 23.8 \pm 0.3 | 16.4 \pm 0.2 |
| Tyrosine mg/g | 29.2 \pm 0.4 | 31.3 \pm 0.4 |
| Methionine mg/g | 3.8 \pm 0.1 | 3.7 \pm 0.1 |
| Valine mg/g | 39.2 \pm 0.5 | 35.7 \pm 0.4 |
| Isoleucine mg/g | 26.1 \pm 0.3 | 23.4 \pm 0.3 |
| Leucine mg/g | 53.1 \pm 0.7 | 48.4 \pm 0.6 |
| Phenylalanine mg/g | 18.7 \pm 0.2 | 17.0 \pm 0.2 |
| Cysteine mg/g | 100.0 \pm 2.6 | 22.5 \pm 0.6 |
| Tryptophan mg/g | 4.1 \pm 0.3 | 3.6 \pm 0.3 |
| Total AA mg/g | 740.3 \pm 10.8 | 598.1 \pm 7.9 |

6.4.1.4 Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) was used to evaluate the thermal behaviour and structural integrity of the native bovine hair and Sirolime hair waste. As keratin is the major structural protein in hair, DSC can provide insight into changes to protein secondary structure, thermal stability and the extent of structural modification caused by processing, in this case, Sirolime treatment. This information will help to inform whether the hair waste keratin is structurally intact and whether the functionality of the keratin has potentially been affected by Sirolime processing.

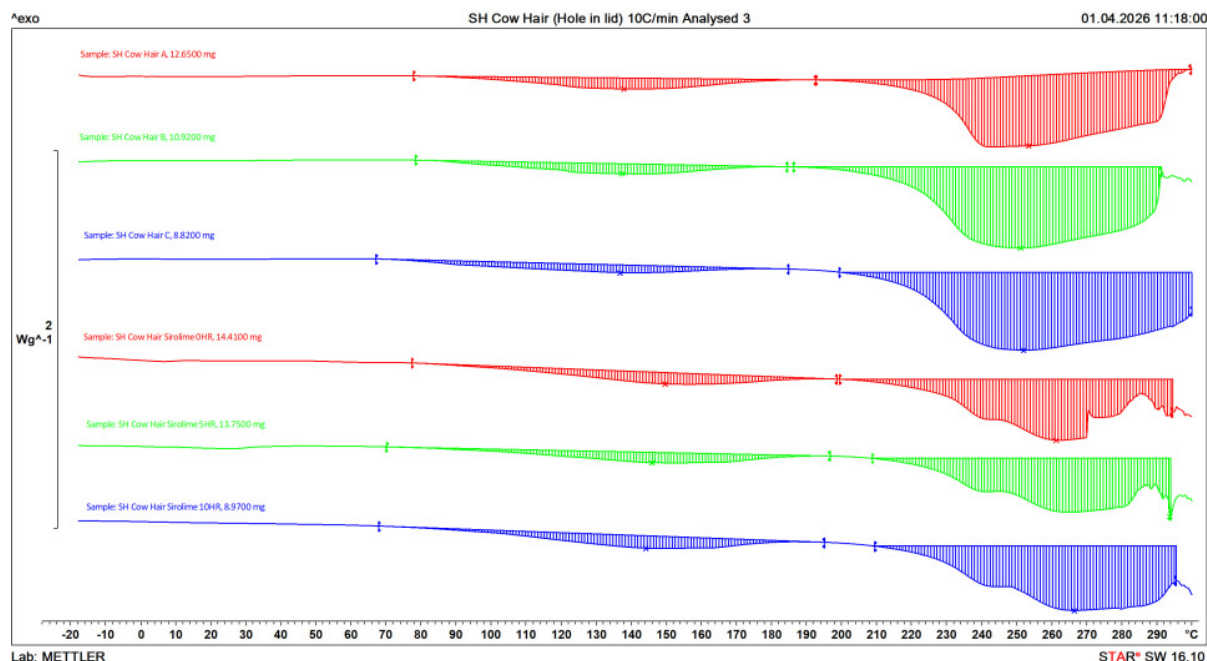


Figure 11. Differential scanning calorimetry (DSC) thermograms for the native hair and Sirolime hair waste samples. The top three curves represent the triplicate native hair samples whilst the bottom three curves represent the triplicate Sirolime hair waste samples

The DSC thermograms (Figure 11) and average peak temperatures and enthalpies (Table 6) showed differences between the two hair samples. Native hair exhibited a lower average peak transition temperature (241.4 °C) but a higher enthalpy (149.6 J/g) than the Sirolime hair waste, which showed a higher peak temperature (273.9 °C) and lower enthalpy (102.6 J/g). These results suggest that the Sirolime de-hairing process has induced minor structural modification to the protein structure, with less energy required to denature the Sirolime keratin. This is likely due to changes to disulphide bonds in the secondary structure of the keratin through the Sirolime process, but the broad endothermic peaks found in both samples suggest the keratin is still mostly intact in the Sirolime hair waste.

Table 6. The mean peak temperature and enthalpy results for the native hair and Sirolime hair waste \pm standard deviation.

| Sample | Peak Temperature °C | Enthalpy J/g |
|-------------|---------------------|------------------|
| Native Hair | 241.4 \pm 19.1 | 149.6 \pm 17.5 |
| Sirolime | 273.9 \pm 17.5 | 102.6 \pm 16.0 |

6.4.2 Keratin extraction and yield

There are several techniques used for extracting keratin from livestock hair. Common methods include using reducing or oxidising reagents, but these can be costly, toxic, and create large volumes of hazardous waste. Enzymatic extraction methods for keratin extraction are a favourable option as the extraction conditions are milder and more environmentally friendly, while maintaining the functionality of the final hydrolysis products (Eslahi et al., 2013). We initially opted to use an enzymatic method with a small amount of reducing agent to extract keratin from the native hair and Sirolime hair waste, but the keratin yields were negligible. To increase the yield, we adopted a hybrid extraction method using a mild chemical pre-treatment prior to the enzymatic hydrolysis with a small amount of reducing agent.

This greatly increased yields and resulted in two freeze-dried keratin fractions from each hair source: a precipitate fraction (PR) and a supernatant fraction (SN).

The final freeze-dried keratin fraction powders are shown in Figure 12. Figure 12 A and B show the freeze-dried keratin precipitate fractions prepared from the native hair and Sirolime hair waste. Both powders were free flowing and very similar in appearance, being black in colour, likely from the co-extraction of the pigment melanin, and both were sparingly soluble in deionised water. There were no obvious visual differences between the precipitate fractions produced from the native hair or Sirolime hair waste. Figure 12 C and D show the freeze-dried keratin supernatant fractions prepared from the native hair and Sirolime hair waste. Again, both the native hair Sirolime hair waste supernatant fractions produced freeze-dried powders that were very similar in appearance, and no obvious visual differences could be observed between them. Both powders were free flowing and beige in appearance, although in contrast to the precipitate fractions the supernatant powders were hygroscopic and highly soluble in deionised water.

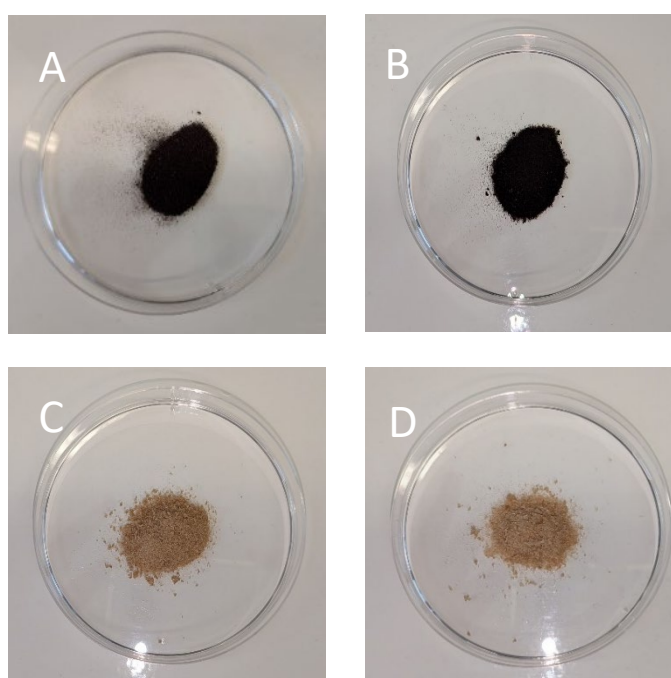


Figure 12. Final freeze dried keratin fractions where A and B is the native hair and Sirolime precipitate, and C and D the native hair and Sirolime supernatant, respectively

The yields of the precipitate and supernatant keratin fractions based on protein content are shown in Table 7. The total keratin yields for both hair sources were very high with a keratin yield of 85.6 % for the native hair and 92.3 % for the Sirolime hair waste. Yields of the precipitate fraction were low for both hair sources, however, more of the precipitate fraction was recovered from the Sirolime hair waste with a 12.4 % yield whilst the native hair yielded 9.0 %. The bulk of the recovered keratin was found in the supernatant fraction for both hair sources and similarly to the precipitate fraction, more keratin was extracted in the supernatant fraction from the Sirolime hair waste with a yield of 79.8 %, while 76.6 % was recovered from the native hair supernatant.

Table 7. Keratin yields from the native hair and Sirolime hair waste precipitate and supernatant fractions \pm standard deviation. The total yield is the sum of the respective fraction yields.

| Sample | Native Hair yield % | Sirolime Yield % |
|-------------|---------------------|------------------|
| Precipitate | 9.0 \pm 0.7 | 12.4 \pm 0.7 |
| Supernatant | 76.6 \pm 0.7 | 79.8 \pm 3.1 |
| Total Yield | 85.6 \pm 0.2 | 92.3 \pm 4.0 |

The results of this study indicate that keratin was extracted more efficiently from Sirolime hair waste than from native hair when using the hybrid chemical/enzymatic extraction method employed. Several factors may explain the improved extraction performance observed for the Sirolime material. Firstly, the milled Sirolime hair consisted of smaller and more fragmented particles than the native hair. Reduced particle size would increase the available surface area of the hair fibres, potentially improving penetration of the chemical pre-treatment solution and increasing substrate access for the enzyme. Secondly, the lower initial protein content of the Sirolime hair waste may have altered the effective enzyme-to-substrate ratio during hydrolysis. Where equal enzyme dosages are applied on a total mass basis, a lower protein substrate concentration would result in a proportionally higher enzyme availability per unit of protein, which may support hydrolysis efficiency and increase solubilisation of keratin-derived peptides. Finally, the Sirolime process itself may induce structural or chemical modifications that favour extraction under hybrid conditions. While it is known that hair-saving treatments such as Sirolime make the hair resistant to reduction methods of keratin extraction (Galarza et al., 2010), it may promote changes to the keratin matrix that improve the efficiency of a mixed chemical/enzymatic extraction process.

6.4.3 Characterisation of the extracted keratin

6.4.3.1 Protein Analysis

The protein contents of the native hair and Sirolime freeze-dried precipitates and supernatant fractions are shown in Table 8. All powdered fractions are rich in protein however, there were differences between both source material and fraction. The precipitated powders had protein contents of 72.9 % for native hair and 84.5 % for Sirolime hair waste, while the supernatant-derived powders contained 72.5 % and 68.7 % protein, respectively. Overall, the Sirolime precipitate fraction exhibited the highest protein concentration of all samples, suggesting effective enrichment of protein during extraction and precipitation. In contrast, the Sirolime supernatant fraction had the lowest protein content, indicating a greater proportion of non-protein components remaining in the soluble fraction. The native hair precipitate and supernatant powders showed similar protein contents, suggesting a more even distribution of recovered solids between fractions.

Table 8. Protein content of the native hair and Sirolime precipitate and supernatant \pm standard deviation

| Sample | Protein % |
|-------------------------|----------------|
| Native Hair precipitate | 72.9 \pm 0.3 |
| Native Hair supernatant | 72.5 \pm 1.3 |
| Sirolime precipitate | 84.5 \pm 2.5 |
| Sirolime supernatant | 68.7 \pm 1.1 |

6.4.3.2 Size exclusion chromatography

Size exclusion chromatography (SEC) provides information on the molecular size distribution and abundance of the keratin derived proteins and peptides extracted from the native hair and Sirolime hair waste and can be used to inform of the potential use cases for each fraction. The SEC of the native hair and Sirolime precipitate is shown in Table 9. Both the precipitate fractions from both native hair and Sirolime hair waste had very similar molecular weight distributions, indicating that the Sirolime process did not substantially alter the overall size profile of the recovered keratin material. For both samples, the dominant fraction was the 10 - 25 kDa range, representing 26.7 % of the native hair precipitate and 27.6 % of the Sirolime precipitate. This was followed by the 5 - 10 kDa fraction (16.0 % and 16.9 %, respectively) and the 25 - 50 kDa fraction (13.1 % for both samples). Collectively, these results indicate that the recovered precipitates primarily comprised of low to mid molecular weight keratin peptides/proteins, with most material falling between 5 and 50 kDa.

Higher molecular weight species were present at lower abundance. Material above 125 kDa accounted for approximately 18.1 % of the native hair precipitate and 16.0 % of the Sirolime precipitate, suggesting a modest reduction in larger protein aggregates in the Sirolime derived sample. Lower molecular weight components below 5 kDa were also present, comprising approximately 17.6 % of the native hair precipitate and 18.6 % of the Sirolime precipitate. This may reflect shorter peptides generated during the extraction process. Overall, the SEC data indicate that both precipitate fractions consisted predominantly of partially hydrolysed keratin proteins and peptides of comparable size distribution.

Table 9. Size exclusion chromatography results for the native hair and Sirolime precipitate fractions.

| Peak | Molecular Weight Range | Native hair PR % Area | Sirolime PR % Area |
|------|-----------------------------|-----------------------|--------------------|
| 1 | > 500 kDa | 11.1 | 10.6 |
| 2 | 250 - 500 kDa | 3.3 | 2.4 |
| 3 | 125 - 250 kDa | 3.7 | 3 |
| 4 | 75 - 125 kDa | 3.9 | 3.4 |
| 5 | 50 - 75 kDa | 4.6 | 4.4 |
| 6 | 25 - 50 kDa | 13.1 | 13.1 |
| 7 | 10 - 25 kDa | 26.7 | 27.6 |
| 8 | 5 - 10 kDa | 16.0 | 16.9 |
| 9 | 2.5 - 5 kDa | 10.3 | 10.8 |
| 10 | 1 - 2.5 kDa | 4.3 | 4.6 |
| 11 | < 1 kDa + retained peptides | 3.0 | 3.2 |

SEC of the supernatant fractions is shown in Table 10. Both native hair and Sirolime hair waste samples were composed predominantly of low molecular weight peptides, with mostly similar profiles between treatments. The major components in both samples were the 2.5 - 5 kDa and 5 - 10 kDa fractions. For native hair supernatant, these

accounted for 33.4 % and 30.8 % of total area, respectively, while the Sirolime supernatant contained 32.7 % and 33.9 %. Combined, peptides between 2.5 and 10 kDa represented approximately 64.2 % of the native hair sample and 66.6 % of the Sirolime sample, indicating that the soluble fractions were comprised mostly of smaller hydrolysed keratin peptides. The 10 - 25 kDa fraction was the next most abundant size range, contributing 20.0 % of the native hair supernatant and 19.9 % of the Sirolime supernatant. Higher molecular weight material above 25 kDa was relatively minor, particularly in the Sirolime sample (3.6 %) compared with the native hair sample (5.2 %), suggesting fewer larger soluble proteins in the Sirolime derived supernatant fraction. Very small components below 2.5 kDa were present at lower levels, with the 1 - 2.5 kDa fraction contributing 7.7 - 7.8 %, and the < 1 kDa + retained peptides fraction contributing 2.8 % in native hair and 2.1 % in Sirolime samples. Overall, the SEC data indicate that the supernatant fractions consisted mainly of small soluble keratin peptides, with the Sirolime sample showing a modest increase in the 5 - 10 kDa range and slightly reduced high molecular weight material compared to the native hair supernatant.

Table 10. Size exclusion chromatography results for the native hair and Sirolime supernatant fractions.

| Peak | Molecular Weight Range | Native hair SN % Area | Sirolime SN % Area |
|------|-----------------------------|-----------------------|--------------------|
| 1 | > 25 kDa | 5.2 | 3.6 |
| 2 | 10 - 25 kDa | 20.0 | 19.9 |
| 3 | 5 - 10 kDa | 30.8 | 33.9 |
| 4 | 2.5 - 5 kDa | 33.4 | 32.7 |
| 5 | 1 - 2.5 kDa | 7.7 | 7.8 |
| 6 | < 1 kDa + retained peptides | 2.8 | 2.1 |

6.4.3.3 SDS-PAGE

SDS-PAGE analysis (Figure 13) revealed clear differences between the starting hair materials and the recovered extraction fractions. The native hair starting material (lane 2) displayed distinct protein bands in the approximate 55–70 kDa region, consistent with intact α -keratin intermediate filament proteins typically found in mammalian hair fibres (Ferraro et al., 2016). In contrast, the Sirolime hair starting material (lane 3) showed little to no visible banding, suggesting that the protein in the Sirolime hair waste was likely poorly solubilised in the extraction buffer. This may be due to the Sirolime process making the hair waste resistant to protein extraction via the method used in this study and will require further investigation to understand this outcome.

The precipitate fractions (lanes 4 and 5) from both native hair and Sirolime hair did not exhibit strong discrete bands, instead showing diffuse staining concentrated toward the lower molecular weight region. This indicates that the precipitated material likely consisted predominantly of lower molecular weight peptides rather than intact high molecular weight keratin proteins. This observation is consistent with the SEC results, which showed the precipitate fractions comprised largely of peptides below 50 kDa, with substantial peptide populations in the 5 -25 kDa range. The supernatant fractions (lanes 8 and 9) showed faint staining starting near the 15 - 20 kDa range indicating the presence of small soluble peptides which is consistent with the SEC results for these samples. Overall, the gel suggests that the extraction process did not recover large intact keratin proteins but instead generated partially hydrolysed keratin peptides distributed between precipitate and supernatant fractions.

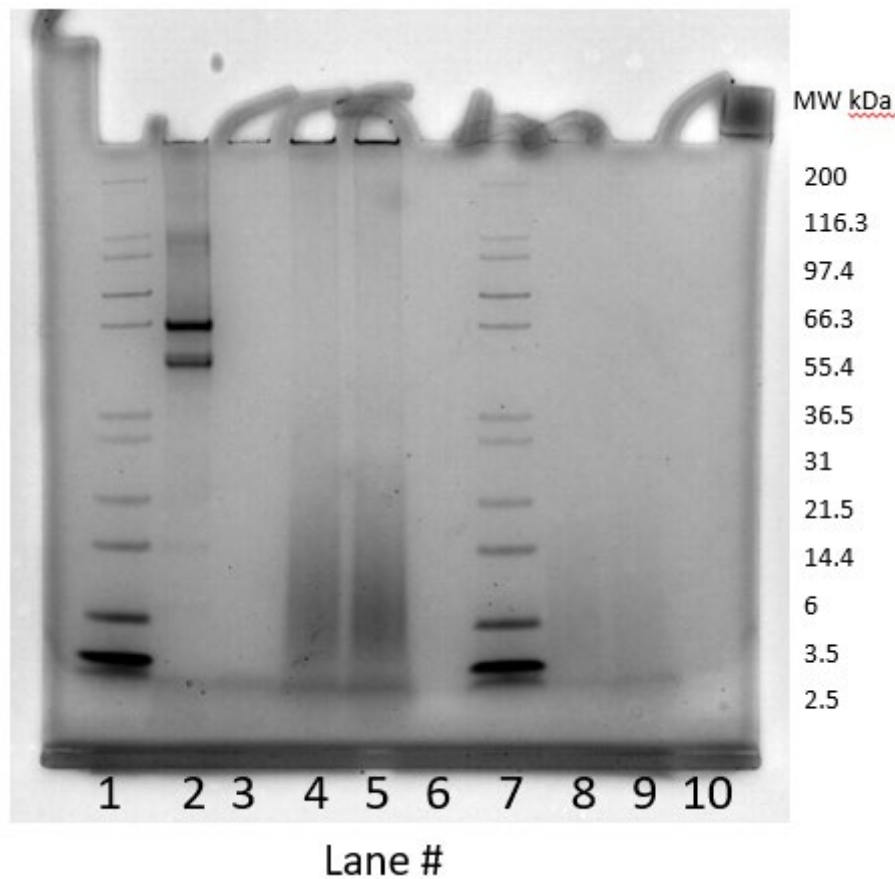


Figure 13. SDS-PAGE of the starting hair sources and the extracted keratin precipitate and supernatant fractions where: Lanes 1 and 7 are the molecular weight (MW) reference, lane 2 is the native hair, lane 3 is the Sirolime hair waste, lanes 4 and 5 are the native hair and Sirolime precipitate fractions, respectively, lane 8 and 9 are the native hair and Sirolime supernatant fractions, respectively, and lanes 6 and 10 are blanks.

6.4.3.4 Amino Acid Analysis

Amino acid analysis of the keratin precipitate and supernatant fractions are shown in Table 11. The precipitate fractions contained higher total amino acid concentrations than the corresponding supernatants, with values of 548.5 mg/g for native hair precipitate and 531.3 mg/g for Sirolime precipitate, compared with 458.8 mg/g and 432.5 mg/g for native hair supernatant and Sirolime supernatant, respectively. Across all samples, glutamic acid was the most abundant amino acid, followed by relatively high levels of leucine, arginine, and aspartic acid. The supernatant fractions generally showed lower concentrations of most amino acids than the precipitates, consistent with the presence of smaller soluble peptides in this fraction. Importantly, all nine essential amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine) were detected in each fraction from both native hair and Sirolime-treated hair, indicating that both recovered products possess nutritionally relevant amino acid profiles.

Table 11. Amino acid content of the native hair and Sirolime precipitate and supernatant freeze-dried powders ± the measurement of uncertainty

| Amino Acid | Native Hair PR | Sirolime PR | Native Hair SN | Sirolime SN |
|--------------------|----------------|-------------|----------------|-------------|
| Histidine mg/g | 9.1 ± 0.1 | 8.9 ± 0.1 | 5.6 ± 0.1 | 5.2 ± 0.1 |
| Serine mg/g | 21.1 ± 0.3 | 19.6 ± 0.2 | 29.2 ± 0.4 | 24.9 ± 0.3 |
| Arginine mg/g | 50.5 ± 0.6 | 46.8 ± 0.6 | 34.8 ± 0.4 | 25.1 ± 0.3 |
| Glycine mg/g | 26.9 ± 0.3 | 26.8 ± 0.3 | 28.4 ± 0.4 | 30.3 ± 0.4 |
| Aspartic acid mg/g | 45.2 ± 0.6 | 44.3 ± 0.5 | 38.0 ± 0.5 | 36.3 ± 0.5 |
| Glutamic acid mg/g | 98.5 ± 1.2 | 96.4 ± 1.2 | 85.0 ± 1.1 | 83.6 ± 1.0 |
| Threonine mg/g | 12.1 ± 0.2 | 10.9 ± 0.1 | 12.7 ± 0.2 | 9.0 ± 0.1 |
| Alanine mg/g | 23.6 ± 0.3 | 23.5 ± 0.3 | 22.3 ± 0.3 | 22.5 ± 0.3 |
| Proline mg/g | 35.6 ± 0.4 | 33.3 ± 0.4 | 39.9 ± 0.5 | 40.1 ± 0.5 |
| Lysine mg/g | 21.0 ± 0.3 | 19.0 ± 0.2 | 13.9 ± 0.2 | 12.2 ± 0.2 |
| Tyrosine mg/g | 39.7 ± 0.5 | 42.0 ± 0.5 | 25.1 ± 0.3 | 24.7 ± 0.3 |
| Methionine mg/g | 5.4 ± 0.1 | 5.5 ± 0.1 | 3.1 ± 0.1 | 3.4 ± 0.1 |
| Valine mg/g | 34.6 ± 0.4 | 33.4 ± 0.4 | 30.7 ± 0.4 | 30.7 ± 0.4 |
| Isoleucine mg/g | 25.9 ± 0.3 | 25.0 ± 0.3 | 19.2 ± 0.2 | 17.8 ± 0.2 |
| Leucine mg/g | 58.9 ± 0.7 | 57.7 ± 0.7 | 42.2 ± 0.5 | 40.1 ± 0.5 |
| Phenylalanine mg/g | 25.3 ± 0.3 | 25.0 ± 0.3 | 13.6 ± 0.2 | 13.1 ± 0.2 |
| Cysteine mg/g | 8.1 ± 0.2 | 6.0 ± 0.2 | 12.3 ± 0.3 | 10.9 ± 0.3 |
| Tryptophan mg/g | 7.2 ± 0.5 | 7.1 ± 0.5 | 2.8 ± 0.2 | 2.6 ± 0.2 |
| Total AA mg/g | 548.5 ± 7.4 | 531.3 ± 7.1 | 458.8 ± 6.0 | 432.5 ± 5.7 |

6.5 Market analysis and value propositions

6.5.1 Keratin in food

Potential positioning of keratin in the food market could involve two primary product categories:

- keratin as a high-protein food ingredient, and
- keratin as a food/dietary supplement.

6.5.1.1 Food supplement

The food supplements sector is being shaped by a shift in consumer expectations, including growing awareness of sustainable practices and environmentally responsible eating habits. Consumers are increasingly seeking products that align with sustainability values while also delivering health benefits. In parallel, the global nutraceuticals market is expanding rapidly. It was valued at approximately USD 399.0 billion in 2023 and is projected to reach USD 571 billion by the end of 2029 (BCC, 2024b). This growth is driven by an expected CAGR of 6.4% between 2024 and 2029, reflecting rising consumer interest in functional foods and supplements (BCC, 2024b). North America constitutes the largest portion of the market (BCC, 2024b).

The market access for keratin food supplements depends on the regulatory framework in the target market. In Australia, food supplements are regulated as complementary medicine by the TGA and need to be listed on the TGA register. Keratin supplement products are currently available through some online channels in Australia, indicating minimal online market presence and no mainstream sales in Australia.

There are few keratin dietary supplements on the global market, with at least one wool derived keratin supplement for hair health being sold in New Zealand retail stores. In New Zealand, food supplements are regulated under Dietary Supplements Regulation 1995, without the need of pre-market approval, therefore the responsibility lies with the company. However, no comparable hair health food supplements products are stocked by major retailers in Australia. Globally, an established example of a keratin ingredient for food supplements is Cynatine NHS®, a proprietary wool-derived keratin hydrolysate (Beer et al., 2014).

Food supplement applications for keratin face several challenges. Keratin is not readily digestible by human or animal enzymes (including pets, livestock, and fish), which necessitates pre-processing and results in additional capital and operational expenditure. In Australia, products positioned as food supplements would also require regulatory listing with the TGA. Further considerations include quality assurance of the raw material, ethical concerns related to the point of keratin sourcing when compared with wool, as well as supply-chain and volume constraints that may limit the ability to ensure a consistent and reliable supply.

Despite these challenges, potential pain relievers exist. Major supplement manufacturers operating in the Australian market, such as Blackmores, Swisse, and Nature's Way, could be approached to understand their interest in addressing an apparent market gap should technical and regulatory hurdles be successfully managed.

6.5.1.2 Protein powders

Market dynamics for protein food ingredients are being driven by a rising global population and sustained growth in consumer demand for protein-rich products, including sports nutrition. These trends are reinforced by the increasing adoption of dietary approaches such as keto and GLP-1-aligned diets, which prioritise high-protein intake. Market signals indicate ongoing innovation in protein products, with observed precedents highlighting continued interest in alternative and functional protein sources. Current innovations within this space reflect efforts to meet evolving consumer preferences while addressing nutritional, performance, and dietary needs. At present, there are no keratin powders available on the market for direct food applications despite some research on wool-derived keratin generating positive indications regarding digestibility, safety, and toxicity.

Food ingredient applications for keratin face a number of significant challenges. Regulatory precedents in Australia demonstrate a complex regulatory pathway. Specifically, the Advisory Committee on Novel Foods (ACNF) has responded to applicants seeking to understand their regulatory pathway with a novel food determination for hydrolysed protein derived from chicken feathers, indicating that the use of keratin as a food ingredient would require regulatory approval through a lengthy and costly application process. In addition, keratin is not readily digestible by human or enzymes necessitating pre-processing steps that add capital and operational expenditure. Further technical requirements include the use of green extraction methods, while keratin-based ingredients must also compete with a

wide range of established conventional protein sources and are not suitable for vegan markets. Ethical considerations regarding the point of keratin sourcing, particularly when compared with wool, as well as supply-chain and volume constraints, may further limit the ability to ensure consistent and reliable supply.

Despite these challenges, several potential pain relievers exist for food ingredient applications. Processing methods for wool are relatively well understood, providing a technical foundation for keratin extraction. The availability of green extraction technologies can help address environmental and safety concerns, while keratin-derived proteins align with keto and GLP-1 dietary requirements due to their high-protein profile. Additional value may be derived through waste-upcycling and “fifth-quarter” utilisation narratives, alongside consideration of regional processing hubs to strengthen supply-chain resilience and reduce logistical constraints.

6.5.2 Keratin in feed

Keratin presents potential opportunities in animal feed markets such as pet food, restricted livestock feed, and aquafeed; however, each segment is characterised by differing processing requirements, evidence thresholds, and regulatory frameworks. Process and regulatory requirements are largest for livestock feed, followed by pet food and finally aquafeed.

6.5.2.1 Pet food

The pet food market is a rapidly growing and highly competitive segment, with a reported CAGR of 5.1%, driven by increasing pet ownership and the ongoing “humanisation” of pets, where pet health and appearance (including fur and coat) are treated similarly to human hair care (BCC, 2023c). North America and Asia Pacific are the key pet food markets (Figure 14). Consumer trends include the rising popularity of raw dog food, demand for convenient formats suited to busy lifestyles, increasing health consciousness, and strong growth in online sales channels (BCC, 2023c). Innovation in this segment is extensive, with products increasingly positioned around plant-based formulations, functional benefits, fresh and refrigerated formats, and sustainability and organic credentials, reflecting evolving consumer expectations and willingness to pay for premium offerings.

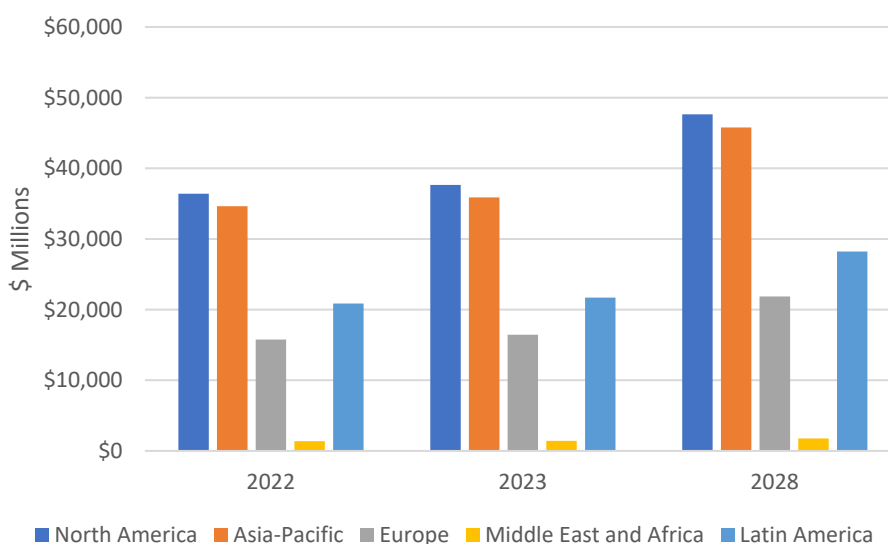


Figure 14. Global market for pet food, by region, 2022-2028 (\$ millions) (BCC, 2023c)

An illustrative example of current innovation in the pet supplements market is the development of skin and coat support products for dogs using wool-derived keratin ingredients, containing the proprietary ingredient keraGEN-IV™

(Keraplast, 2025). These supplements are positioned to support fur and skin health, drawing parallels with human hair-care formulations and responding to the ongoing humanisation of pets. The messaging on the patented ingredient typically highlights the functional role of keratin in supporting collagen structure and anti-inflammatory processes, while also emphasising broader value-based claims, including natural origin, cruelty-free sourcing, regenerative production practices, traceability, and biosecurity. There are also premium, high value, cat food products (i.e. Royal Cannin brand (Royal Cannin, 2026)) that contain a large amount of feather meal keratin, mostly to meet customer demands on ingredients that are anallergenic, and suit cats with irritable bowel disease and sensitive stomachs (McGill University, 2022).

In the pet food segment, key challenges include strict regulatory and industry standards, competition with protein sources perceived as more “ethical,” such as wool, and the need to assure chemical safety following tannery processing. Despite these constraints, potential pain relievers exist, including the application of green extraction methods to address safety and sustainability concerns, as well as opportunities within the fur and coat supplement category, where functional benefits can support premium positioning. While the coat/fur quality supplements for dogs and anallergenic ingredients for dry cat food are emerging innovations that hold promise, the size of the market opportunity is not yet clear and should be reassessed in the future.

6.5.2.2 Poultry, swine, and ruminant feed

The global market on feed for producing animals is dominated by the poultry and swine component, followed by ruminant and aquaculture (Figure 15) (BCC, 2024a). All these market components are on a growth path, with North America and Asia Pacific as the largest markets (Figure 16) (BCC, 2024a). Regulatory and biosecurity constraints, including restrictions on certain animal-derived materials species to species, strongly influence ingredient selection and processing requirements, (for more detail, see the Literature Review – Feed section on restricted use of bovine sources for ruminants). The livestock feed segment is primarily driven by demand for improved poultry and swine nutrition, reflecting the scale and efficiency-focused nature of intensive animal production systems. Market dynamics are shaped by cost sensitivity, feed conversion efficiency, and nutritional performance, with protein quality and amino acid profiles being key considerations. Compared with pet food, innovation is more measured and functionally driven, with adoption dependent on clear economic benefits, safety assurance, and regulatory compliance across different species.

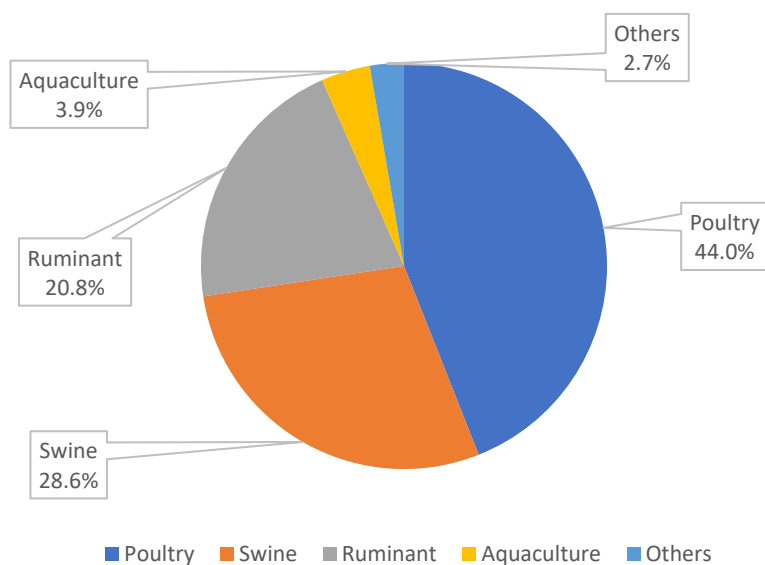


Figure 15. Global compound feed and additive market by feed sector (BCC, 2024a)

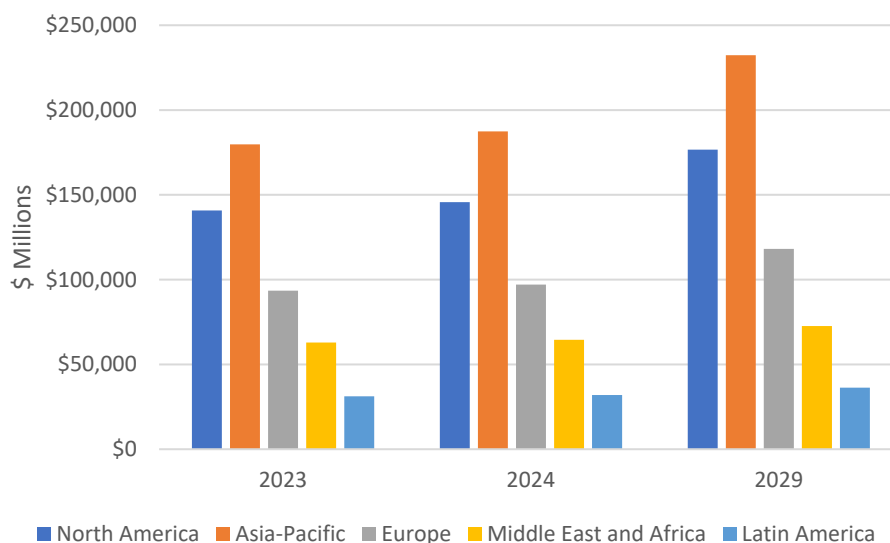


Figure 16. Global compound feed and additive market by region, 2023-2029 (\$ millions) (BCC, 2024a)

Livestock feed applications face significant regulatory barriers, including prohibitions on Restricted Animal Material (RAM) in cattle and restrictions on the use of swill in pig feed, with additional prohibitions applying to poultry and ruminants in Queensland. As with other segments, chemical safety following tannery processing remains an important consideration. Potential pathways to market may exist if bovine hair could be treated as RAM, using feather meal as a regulatory precedent, which could enable exploration of poultry or pig feed applications, where rendering will be required. State to state variation in regulatory requirements also creates inconsistencies that need to be considered.

6.5.2.3 Aquafeed

Aquafeed represents the most promising feed segment, underpinned by the rapid expansion of aquaculture, particularly in the Asia-Pacific region (Figure 17) (BCC, 2024a), which dominates global aquaculture feed consumption. Increasing production of species such as salmon, tilapia, and catfish globally, and barramundi locally is driving rising feed demand, alongside growing regional consumption of fish and seafood. Aquafeed formulation requires large, consistent volumes of ingredients, well-established supply chains, and strong evidence of nutritional performance and safety. Where functional or health claims are made, additional regulatory scrutiny may apply, making the access to market more capital- and evidence-intensive.

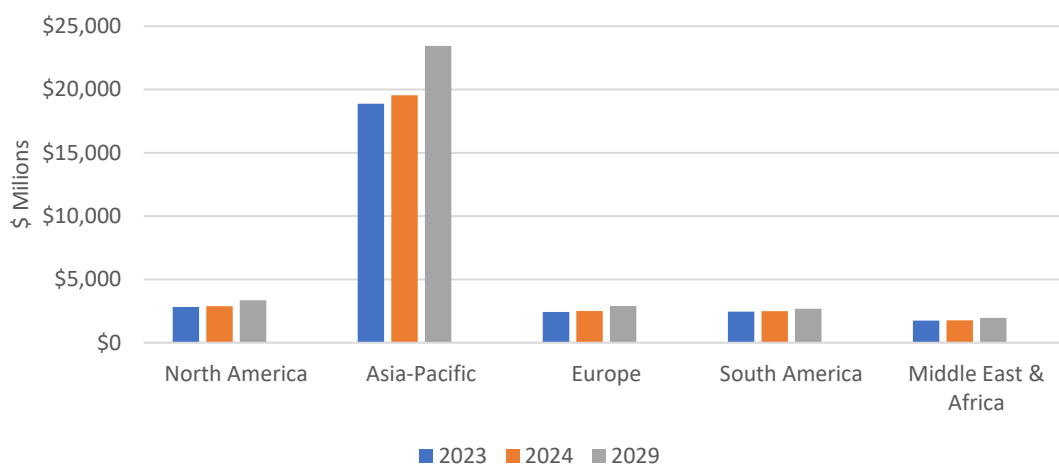


Figure 17. Global compound feed and additive market for aquaculture, by region through 2029 (\$ million) (BCC, 2024a)

Globally, a growing number of aquafeed innovations (KeraAqua (BCF Lifesciences, 2026), PepSol (Empro Europe, 2026)) have been developed using keratin derived primarily from poultry by-products, reflecting interest in alternative, protein-rich feed ingredients. Keratins are one of the richest sources of amino acids, offering a potentially valuable nutritional profile for aquaculture species (Thazeem et al., 2022). Figure 18 presents a comparison of the amino acid composition of the keratin extracted in this project and the KeraAqua and Pepsol aquaculture feed ingredients. The figure clearly shows that the relative abundance of amino acids in extracted bovine keratin both from native and treated Sirolime hair is comparable to keratin ingredients derived from poultry feathers (Figure 18). Some overseas companies have positioned keratin-based ingredients with claims related to fish health and performance. However, in Australia, any claims relating to therapeutic or health benefits in fish would trigger regulatory oversight and require registration with the Australian Pesticides and Veterinary Medicines Authority (APVMA). As a result, while innovation activity is evident internationally, market entry in Australia would be simpler if no health claims are made.

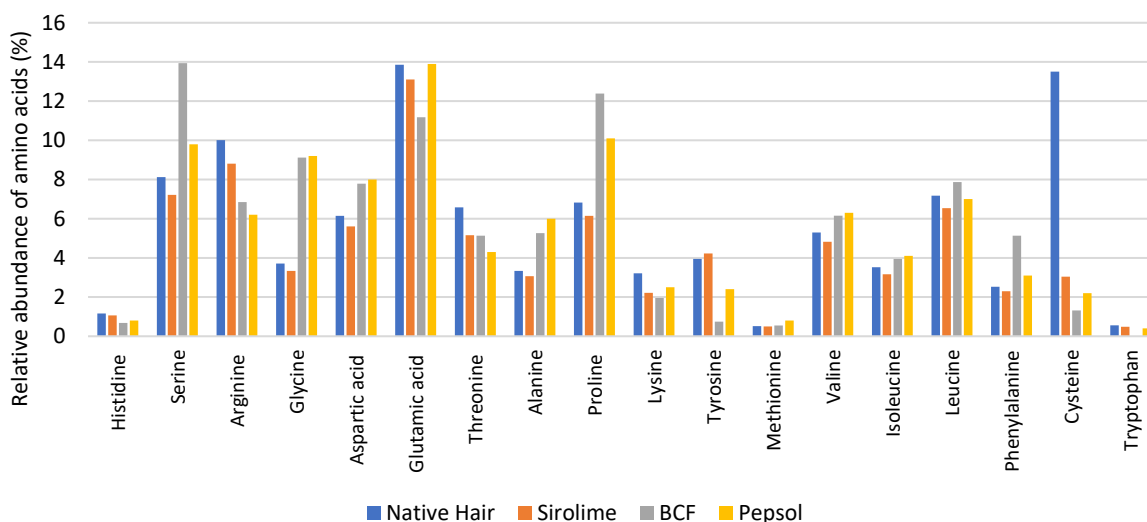


Figure 18. Comparison of the relative abundance of amino acids in native hair and Sirolime hair waste from this study, BCF aquafeed ingredient from (BCF Lifesciences, 2026) and Pepsol aquafeed ingredient from (Empro Europe, 2026)

Aquafeed opportunities present some challenges common with other applications, including the need for large ingredient volumes, the establishment of reliable supply chains, and assurance of chemical safety following tannery processing. In addition, any claims relating to therapeutic or health benefits would require evidence generation and

registration with the APVMA. However, pain relievers include the existence of international precedents for keratin use in aquaculture feed, opportunities to incorporate keratin as part of a broader feed formulation, consideration of blending with hide-derived ingredients, and the ability to avoid APVMA registration if no therapeutic claims are made.

6.5.3 Keratin in cosmetics

Current market signals support positioning a bovine-keratin ingredient within the broader demand for “natural” and “organic” hair-care solutions. Allied Market Research (2025) notes rising consumer uptake of natural and organic products. This aligns this ingredient with organic cattle production, and an ecological processing approach could strengthen its value proposition. In parallel, continued product innovation and diversification are shaping the competitive landscape (Allied Market Research, 2025). For a bovine-keratin cosmetic ingredient to stand out, differentiation in both quality and performance will be important, particularly through clear specification of keratin “peptides”, molecular-weight distribution, and fit-for-purpose delivery systems (e.g., cationic systems designed to deposit more effectively on damaged hair fibres). Market CAGR is estimated at 7.7 % between 2023 – 2028 (Figure 19) (Technavio, 2024b).

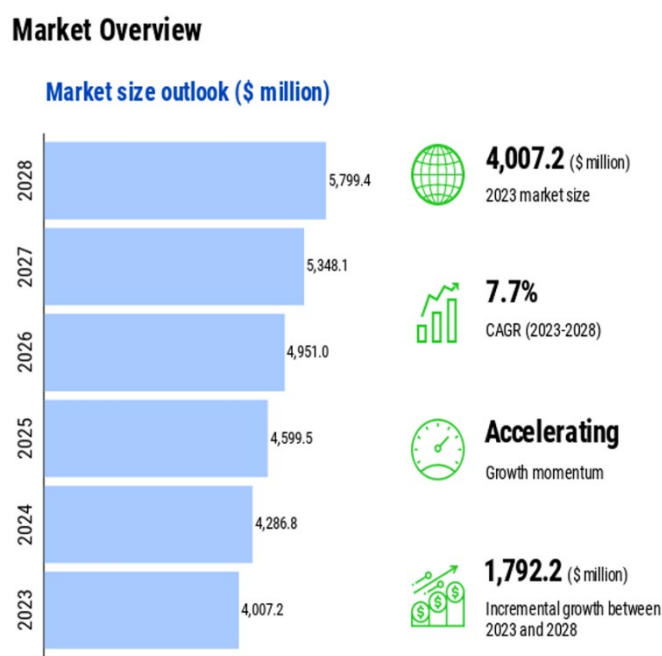


Figure 19. Market overview for keratin-based cosmetics (Technavio, 2024b)

Sustainability and ethical considerations are also becoming more influential in purchasing decisions (Allied Market Research, 2025, Grandview Research, 2026). A credible sustainability narrative, covering animal welfare, traceability, and responsible sourcing, may therefore materially support go-to-market messaging alongside demonstrable product quality. That said, animal-derived inputs can introduce constraints, including lack of vegan/vegetarian positioning and heightened scrutiny of ethical sourcing and traceability. However, the ongoing prevalence of wool- and feather-derived keratin ingredients in the market suggests broad acceptance when functionality is demonstrated.

From a regulatory and reputational perspective, performance claims should be tightly aligned to evidence. While marketing often implies “repair” or “reconstruction,” many benefits are better described as surface deposition/film formation leading to improved feel and appearance rather than true biological change in the hair fibre. Robust substantiation is essential to ensure claims are not misleading or deceptive in line with consumer law requirements.

Finally, adjacent growth categories, particularly hair, eyelash, and eyebrow growth products, represent an emerging area of demand, driven by social media influence and technological advancement, and may offer additional context for innovation-led positioning.

In terms of innovations, formulation innovation in how keratin is delivered and stabilised is also evident. Many at-home and professional serums utilise hydrolysed keratin in combination with a cross-linking chemistry (historically including formaldehyde, formalin, or methylene glycol). However, “formaldehyde-free” systems are increasingly emphasised in response to occupational health and safety (OHS) risks and associated scrutiny (Weathersby and McMichael, 2013, Leichner et al., 2019). Mechanistically, smaller keratin peptides are understood to bind to hair keratin, with amino acids such as aspartic and glutamic acid frequently highlighted as relevant to perceived hair improvement (Weathersby, 2013). Commercially, the category spans mass-market retail products (typically ~\$4 – \$40, companies include Schwarzkopf, Wella, Garnier) through to business-to-business keratin ingredient supply (indicatively ~\$500/2L, companies include Bhave, L’Abrea). Beyond core haircare formats (shampoos, conditioners and masks), keratin and keratin-derived materials are also positioned across nail care (strengthening treatments), decorative cosmetics (e.g., mascaras), and select skincare applications. Current innovation in keratin-based personal care continues to centre on performance-led benefits (moisture retention, shine, softness) and improved manageability, particularly for hair that has been chemically or mechanically stressed. Reported benefits are commonly positioned around restoring or improving cuticle-like properties following bleaching, straightening, and permanent waving, which are associated with dryness, brittleness, reduced shine, and loss of strength (Barba et al., 2010). At the premium end of the market, keratin has also become a signature “salon-grade” ingredient platform, with professional shampoo and treatment formats reaching prices of up to ~\$250 for a 1 kg (i.e. Trulux keratin ingredient). In this segment, keratin services are frequently marketed as a substitute or longer-term alternative to harsher straightening approaches that rely on reductive agents (e.g., thio-relaxers) and alkaline systems (Cruz et al., 2017).

Despite the commercial traction of keratin across both mass and professional channels, several challenges are likely to shape the feasibility and positioning of a bovine-keratin ingredient. In the premium salon segment in particular, products frequently rely on a strong provenance and animal-welfare narrative to justify price points and build consumer reassurance, for example, brands emphasise “100% natural” origin, seasonal harvesting and non-harmful collection practices. A bovine-derived keratin offering may therefore need an equally credible marketing story (origin, traceability, and welfare) while also competing against alternatives able to make simpler positioning claims such as “vegan” and “cruelty free”. At a technical and quality level, animal co-product streams can also raise concerns around odour, colour and purity, and there may be limited baseline awareness among formulators and buyers that bovine keratin can be consistently produced to cosmetic-grade specifications. This creates a further perception risk, where bovine keratin could be viewed as lower value than established wool-based or biotech-derived keratin platforms unless quality attributes and functional performance are clearly differentiated. Supply-side uncertainty (including continuity of sourcing and consistency of input material) may also be a consideration for customers seeking reliable long-term supply.

For more commoditised keratin ingredients, the priority mitigation actions are operational. Establishing a reliable supply chain (including agreed raw-material specifications and contingency suppliers), optimising a low-cost extraction and purification route, and implementing fit-for-purpose quality controls so that odour, colour, impurities, and molecular-weight distribution remain within specification. In parallel, generating application data that demonstrates functionality in relevant end-use formats is essential to support customer adoption and substantiate any performance or marketing claims.

Several practical levers can be used to address these challenges, particularly in the premium salon segment where performance expectations and brand storytelling are highest. First, positioning can remain functionality-led, recognising that demonstrable performance can outweigh consumer hesitation about animal origin when outcomes are clear and repeatable. This should be supported by explicit guidance on claim language (what can be credibly stated, and what should be avoided) and by framing benefits in realistic, evidence-based terms. Premium propositions

can also be strengthened through complementary “free-from” claims where applicable (e.g., formaldehyde-free, ammonia-free) and by developing a circular-provenance narrative that emphasises keratin as an upcycled co-product stream rather than a primary animal input. Differentiation opportunities include breed-derived storytelling (e.g., Angus, Highland) where traceability can be demonstrated, alongside transparent supply-chain documentation covering origin, processing controls, and sustainability credentials. Finally, premium credibility is significantly improved when flagship salon products can demonstrate superior functionality versus benchmarks, underpinned by an optimised, standardised production process designed to reduce batch-to-batch variability and reliably meet customer specifications. In the more commoditised “regular” keratin ingredient market, a different constraint set applies. Pricing pressure can be significant, and extraction and purification costs may be difficult to reconcile with comparatively low ingredient price expectations. As a result, maintaining robust batch-to-batch quality (including control of odour and colour, consistent peptide/molecular-weight distribution, and impurity limits) becomes critical to avoid variability in formulation performance and to meet customer specifications at scale.

6.5.4 Keratin in bioabsorbable polymers e.g., Nappies

The area of disposable hygiene products encompasses several product types including female sanitary pads and tampons, cleaners, hair removal products and adult and baby nappies (BCC, 2023). In the context of the opportunity for keratin, this report section focuses on disposable nappies (babies and adults), given its environmental challenge. In Australia, approximately 2 billion nappies are sent to landfill each year, making up 5 to 15 % of household waste (Sustainability Victoria, 2025). There is also significant use in other markets too. For example, in the EU, 33 billion nappies are used annually (Life Cycle Initiative, 2021). For a child wearing nappies until 2.5 years old, it is estimated that >4,550 disposable nappies are used per child (Life Cycle Initiative, 2021). These products are complex, multi-layer systems (Figure 20) designed for performance, but this complexity makes them difficult to recycle or process at end-of-life. Disposable nappies can persist in landfill for hundreds of years (typically cited as up to ~500 years), due to their high plastic content and the low-oxygen conditions that limit biodegradation (Graham-Nye et al., 2024). While the plastic components remain largely intact, the organic fraction (including human waste and cellulose fibres) decomposes anaerobically, generating greenhouse gases such as methane and carbon dioxide. As a result, nappies contribute both to long-term waste accumulation and ongoing emissions from landfill systems, as well as significant oil use to manufacture the plastic fractions (Graham-Nye et al., 2024).

A typical nappy consists of a polypropylene nonwoven top sheet, an acquisition and distribution layer, an absorbent core containing cellulose fluff pulp and superabsorbent polymers (SAPs), and a polyethylene back sheet (Ichiura et al., 2020). A key issue lies in the absorbent core, which typically contains sodium polyacrylate as the SAP. These materials can absorb several hundred times their own weight in water (typically ~300–500 g water per g polymer under ideal conditions), enabling high liquid retention within absorbent cores (Chang et al., 2021). However, SAPs are mostly synthetic and non-biodegradable, contributing to long-term environmental persistence (Montesano et al., 2015). Nappies account for 69.8 % of the SAP market (Global Market Insights, 2024), and an estimated 5.3 million tons are projected to be sent to landfill by 2030 (Shishkhanova et al., 2025, ChemAnalyst, 2026). Current waste systems, including anaerobic digestion, struggle to process these materials without pre-treatment or separation, meaning most nappies are landfilled.

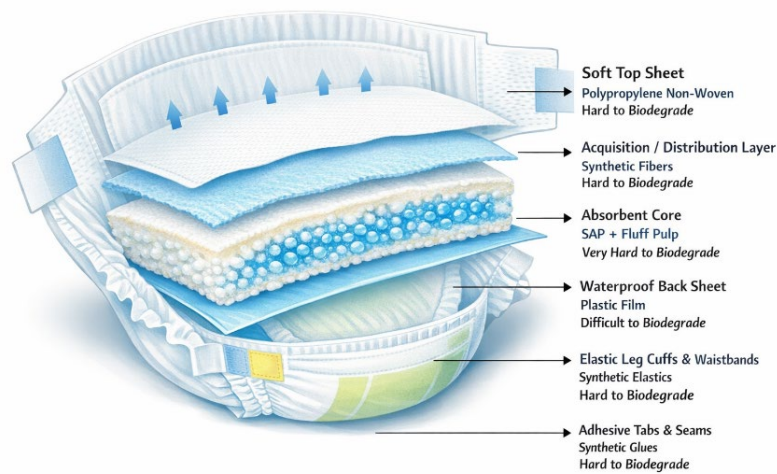


Figure 20. Typical layers in a non-biodegradable disposable nappy – AI generated image

The use of disposable hygiene products such as nappies and feminine hygiene products is set to grow due to population growth, a rising middle class and more women in the workforce with income in developing countries. In addition, an increased ageing population with incontinence and associated challenges is set to contribute to increased use of adult nappies (Thompson Brewster et al., 2022). According to BBC Research (2023a), the total disposable hygiene market was valued at \$78.1 billion in 2021 and will grow at a compound annual gross rate (CAGR) of 7.1 % to reach \$117.3 billion by the end of 2027 (BCC, 2023a). However, growth is projected to be region specific. In regions such as Central and South Asia, there is expected to be over half of projected global population growth to 2037. At the same time, there is increasing consumer and regulatory pressure for more sustainable products. This has created a clear market gap for materials that can deliver both high performance and improved environmental outcomes. However, any new material must meet strict functional requirements, including high absorbency, performance under load, fluid retention, comfort, and compatibility with thin, lightweight product designs, while maintaining price parity and convenience (Graham-Nye et al, 2024).

The increased desire for natural and eco-friendly alternatives has led to the emergence of several reusable nappy companies, however, it remains that disposable products account for 79.5 % of the market share (Figure 21). The major players in the market are Procter & Gamble, Kimberly-Clark and Johnson & Johnson, with a combined global market share of 57.9 % (Figure 22).

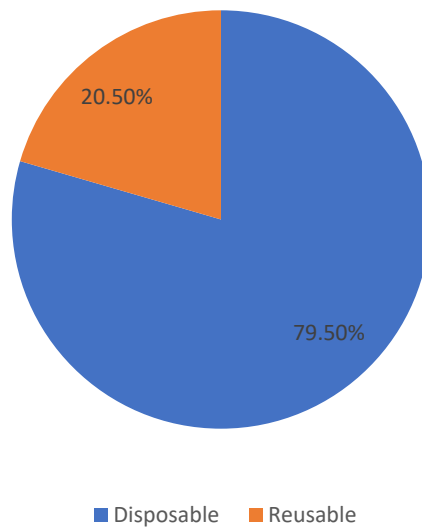


Figure 21. Global Market Share for Baby Care and Feminine Hygiene Products, by Type, 2021 (%) (BCC, 2023a)

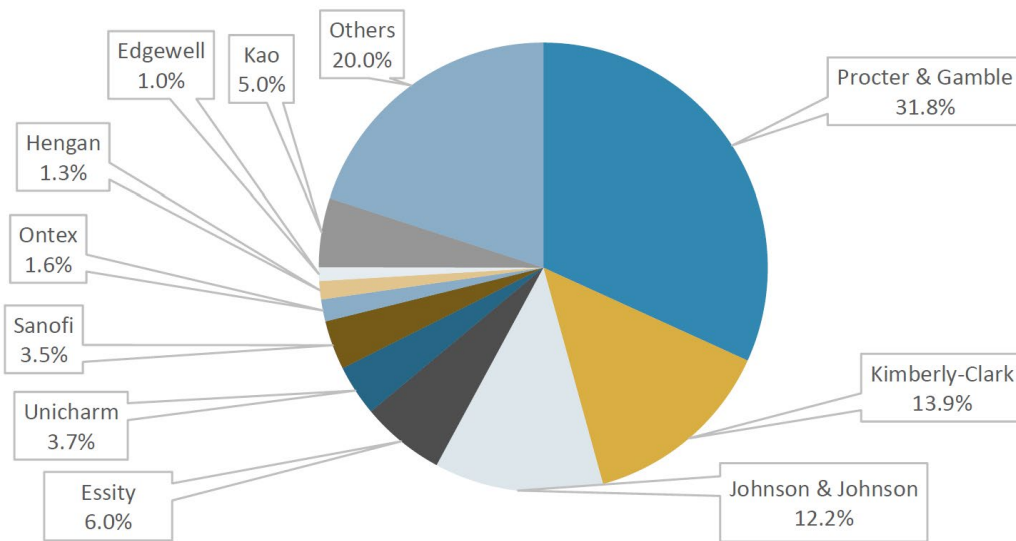


Figure 22. Global market share for baby care and hygiene products, by key manufacturers and suppliers, 2021 (BCC, 2023a)

Consumers are seeking products which are chemical free, eco-friendly, thin and light. While companies are striving to meet these desires, nappies remain majorly non-biodegradable due to performance challenges with natural alternatives. Nonetheless, there is some progress from manufacturers to address environmental concerns as shown in Table 12, with some striving towards hybrid systems and increased biodegradability.

Table 12. Examples of nappy innovation from commercial manufacturers

| Manufacturer | Brand | Innovation |
|-------------------------------|----------------------|---|
| Procter & Gamble ¹ | Pampers Pure Hybrid | Hybrid reusable outer-disposable insert system reducing landfill waste (~25 %); plant-based inputs (e.g. ethanol); ongoing SAP-enabled thin-core optimisation |
| Ontex ² | Moltex Pure & Nature | Incorporates bio-based and partially biodegradable fibres (e.g., pulp, cotton) but remains a hybrid system with non-biodegradable components, |
| Essity ³ | Libero Touch Hybrid | A two-piece nappy with a reusable textile cover and disposable absorbent insert, reducing material use, transport impact, and achieving ~35 % lower climate impact than standard nappies. |
| Kimberly-Clark ⁴ | Huggies | “Nappy Loop” anaerobic digestion system converting used nappies to biogas, compost, and recoverable plastics |
| Dyper ⁵ | Dyper | Bamboo-based fibres with composting service model (bio-based hybrid system) |
| Ecoriginals ⁶ | Ecoriginals | 100 % plant-based materials and reduced-plastic designs (partial biodegradability), up to 91 % biodegrades in 3 months |
| Tooshies ⁷ | Tooshies | 74 % organic bamboo, partial biodegradability |

Websites accessed 23rd of April 2026

¹<https://www.waste360.com/sustainability/pampers-introduces-new-hybrid-diaper-part-reusable-and-part-disposable>

²<https://www.moltexbaby.com/sustainability/>

³<https://www.libero.com/your-stage/artiklar1/baby/how-to-choose-the-right-nappy/>

⁴<https://www.kimberly-clark.com/en-au/sustainability/nappy-recycling>

⁵<https://dyper.com/products/charcoal-enhanced-diaper-pack>

⁶<https://www.ecoriginals.com.au/>

⁷<https://tooshies.com.au/collections/nappies/products/disposable-nappies-with-organic-bamboo>

Current strategies to improve nappy sustainability predominantly focus on incremental material substitution, reduced plastic content, or end-of-life processing solutions such as anaerobic digestion. While these approaches have delivered measurable improvements, they do not fully address the fundamental performance requirements imposed on absorbent hygiene products, particularly absorption under load, fluid retention, rewet resistance, and cost-effective scalability.

This highlights the need to explore alternative biopolymers that offer performance but improved environmental outcomes. As discussed in the literature review and patent sections, keratin’s proteinaceous network structure, has potential to create high absorbency sponge-like polymers with improved biodegradability over conventional SAPs. While keratin has been studied in the context of textiles, biomedical materials, wound dressings, and controlled-release systems, the source has mostly been ovine or feathers, with minimal work on bovine keratin, and where absorption has been demonstrated, it has not been scaled.

This represents a critical knowledge gap, particularly given the pressing need for alternative materials that can complement or partially replace conventional SAPs without compromising performance. However, keratin alone is unlikely to replace SAPs without further processing. Its greatest potential lies in hybrid systems, where it can partially replace or complement synthetic materials. Further work is needed to optimise keratin extraction for this application and combine it with complementary feedstocks to achieve desired performance.

Despite its potential, several challenges must be addressed before keratin can be adopted in this application. Firstly, with the lack of knowledge on bovine keratin, technical advancements are required to develop and demonstrate bovine keratin absorbency performance in a hybrid polymer system. In order for this to be economically viable, extraction and processing need to be developed cost compatibly, using infrastructure that is commercially available. Feedstock volumes, consistency and quality may also present a challenge, where volumes are discussed in the next section. Finally, as SAP is only one part of the multi-layer nappy, technical material advancements and waste management systems may be required to provide optimised environmental outcomes. These challenges highlight that material innovation alone is insufficient; a system-level approach, in combination with technical advancements and commercialisation strategies are required.

The findings indicate that bovine keratin represents a promising but early-stage opportunity within the hygiene sector. Future work should focus on developing hybrid absorbent systems that combine keratin with existing materials to balance performance and sustainability. Priority areas for research include validating absorbency performance under load, optimising material formulations, and assessing compatibility with current manufacturing processes. In parallel, techno-economic analysis is required to determine commercial feasibility, alongside system-level assessment of end-of-life pathways. Given the scale of the market and the limitations of current bio-based alternatives, keratin-based materials may play a valuable role in next-generation absorbent products, particularly where they can reduce reliance on synthetic polymers while maintaining performance.

6.5.5 Keratin in fertiliser and mulch

Nitrogen is an essential macronutrient for plant growth and as such modern crop systems depend heavily on nitrogen fertilisers for sustained productivity and maintaining national food security. Urea, ammonium nitrate and urea ammonium nitrate are all common nitrogenous fertilisers, all of which are produced from ammonia synthesised from atmospheric nitrogen and hydrogen via the Haber-Bosch process. This is an energy-intensive process, highly dependent on fossil fuels, and the production and transportation of nitrogen fertilisers represents a significant source of carbon emissions, estimated to be approximately 2.1% of global emissions (Menegat et al., 2022). Further, dependence on fossil fuels for nitrogen production exposes fertiliser supply chains to price volatility and geopolitical risk to which Australia is particularly vulnerable. Domestic production of nitrogen fertiliser is limited, and the country relies heavily on imports to meet agricultural demand. Urea is the dominant nitrogen fertiliser used in Australia and more than 90 % of supply is imported, exposing Australian agriculture to fluctuations in global fertiliser markets and freight supply chains, and high transportation costs (RaboBank, 2025).

The global nitrogen fertiliser market represents one of the largest commodity chemical markets with a global demand of around 128 Mt of nitrogen (BCC, 2022). As of 2024 the nitrogen market was valued at \$63 billion (Grandview Research, 2025) with an estimated CAGR of 4.7 % from 2022 – 2027 (Technavio, 2020). In Australia, nitrogen fertiliser consumption is approximately 1.5 million tonnes of nitrogen per year, with urea representing the dominant nitrogen fertiliser used, primarily in broadacre agriculture (Norton et al., 2023). While hair waste is a rich source of nitrogen, hair-derived keratin cannot replace the bulk nitrogen fertiliser market used for broadacre cropping due to limitations of feedstock volumes. However, there are smaller segments of the nitrogenous fertiliser market where hair derived keratin could play a role, particularly as a soil improver, bio-stimulant and slow-release fertiliser for horticultural applications.

Amino acid fertilisers are an emerging market, worth \$529.1 million globally in 2024, with a CAGR of 11.7 % from 2024 - 2029 (Technavio, 2024a) (Figure 23). Amino acid fertilisers are an attractive option as they can be prepared as liquid or solid formulations. Moreover, they are positioned as bio-stimulants that can improve plant growth, yields and the nutrition quality of food crops by providing more bioavailable forms of nitrogen (Al-Karaki and Othman, 2023). Keratin-derived hydrolysate products could play a role in this area. The organic fertiliser market is worth \$9.1 billion globally and projected to reach \$13.5 billion by 2028 with a CAGR of 6.8 % (Figure 24). This is due to an increased consumer demand for organic food products. Hair waste from livestock production and processing could play a role in this sector

as animal matter and excreta already make up 33.9 % of all organic fertiliser (BCC, 2023b). As an example, pelletised wool is a small, but growing organic fertiliser market, valued at \$168 million in 2024 with an estimated CAGR of 7.5 % through to 2033 (Growth Market Reports, 2026).

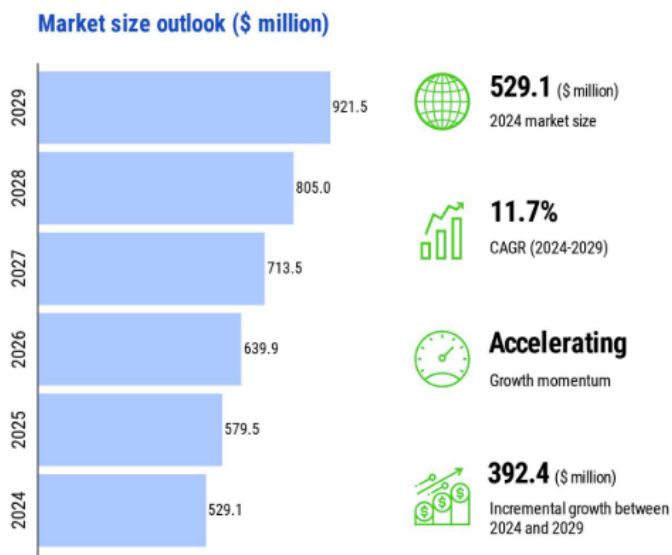


Figure 23. The global market outlook for amino acid fertilisers, 2024 - 2029, (Technavio, 2024a)

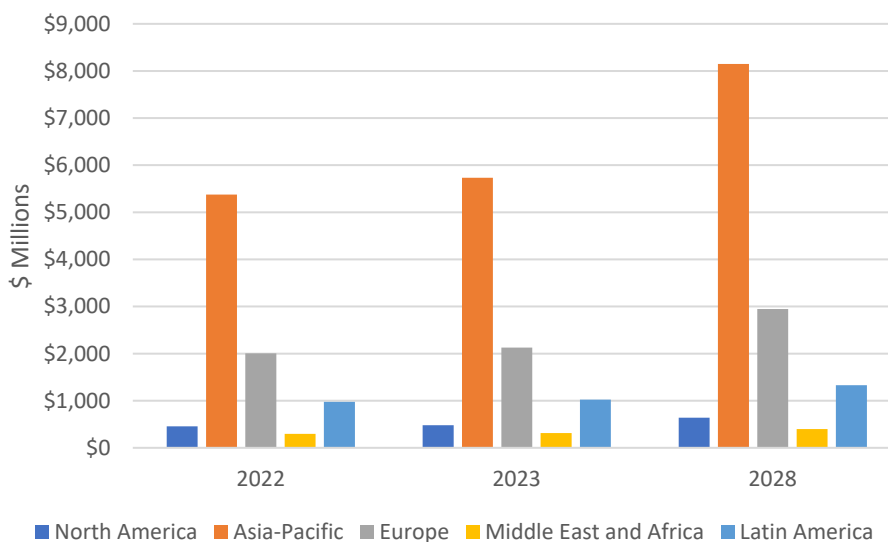


Figure 24. The global market for organic fertiliser, by region, 2022-2018 (\$ millions) (BCC, 2023b)

Commercial fertiliser and mulch applications comprised of keratinous materials from livestock production are currently limited. Despite this, there is interest in developing keratin-derived agricultural inputs as industries seek sustainable fertiliser alternatives, value-addition pathways for waste streams, and circular bioeconomy solutions. Commercial wool-based fertiliser pellets already exist in several markets and demonstrate that keratin fertilisers can be technically feasible and commercially viable (Growth Market Reports, 2026). In Australia, there are several companies that produce wool-based fertilisers and mulch products in various formats. Verigrow is an all-purpose, liquid fertiliser made

from 100 % wool waste. It is marketed as an “All-purpose fertiliser and soil improver,” that is rich in amino acids and total nitrogen, with claims that independent studies have shown that Verigrow can improve several plant health metrics such as biomass, plant height and root mass (Fernland, 2026). Several companies are producing various other products from whole wool. WOOLPEL manufacture raw sheep wool pellets, marketed as a 100 % biodegradable option to increase water retention and aeration in soil, while providing a source of slow-release nitrogen over a 6-month period (Woolpel, 2026). In addition to pelletised wool fertiliser, Woolgrow Australia has several wool-based products, such as the Planket mulch and weed matting, made with 100 % wool waste, with similar claims on benefits to soil health as the pelletised format (Woolgrow Australia, 2026).

Keratinous hair waste from beef processing is a promising source of nitrogen for fertiliser and/or mulch products, but several challenges must be addressed before these products could be made at scale. Limitations of available feedstock volumes restrict the possible applications to smaller scale, more targeted approaches. Supplementation with other sources of keratin, such as waste wool, could help to alleviate this issue but volumes would still be far below the national nitrogen requirement for agriculture. To offset this, keratin-based fertilisers could be developed and marketed as a high-value, premium soil improver for horticultural or home garden markets, leveraging the sustainability and circular economy credentials of the upcycled feedstock. Other challenges include decontamination of recovered hair waste to remove residual processing chemicals, collection of suitable hair waste from geographically dispersed locations, and optimising existing extraction methods for efficiency. While these obstacles are significant, keratin-based materials remain an attractive option for fertiliser production due to relatively low barriers to entry and the opportunity to upcycle a material that is rich in nitrogen but often discarded as waste.

6.5.6 Volumes

Within the Australian red meat industry, bovine hair represents a largely overlooked keratin resource. Australia processed 9.28 million cattle in 2025 (MLA, 2026), at an average hide weight of 20 kg, with some estimates that hair constitutes 2 – 5% of raw hide weight (Bioenergy Consult, 2023). This could correspond to approximately 3,700 - 9,300 tonnes of hair per year. Alternative literature estimates suggest that up to 85 kg of hair may be generated per tonne of salt-wet hide processed, which would equate to approximately 15,800 tonnes annually in the Australian context (Song et al., 2021).

Although many Australian hides undergo processing for leather production, leading to the hair being treated as waste, this project has highlighted that the keratin characteristics in tannery hair waste, subjected to Sirolime processing, remain largely intact, therefore the volume of hair in Australia can be taken as a total without hair lost to tanning. However, it must be noted that some hides are processed for collagen casings and gelatine ingredients and hair waste from those processing streams were not included in this project.

However, in contrast to bovine hair, other keratin-rich biomass streams are either significantly larger in volume or more established within existing value chains. Poultry feathers represent the largest keratin-containing by-product globally, driven by the scale of poultry production. In Australia alone, feather waste is estimated at approximately 86,000 - 111,000 tonnes per year (Poultry Hub, 2026). Feathers contain approximately 90 wt % keratin (β -keratin), making them the most concentrated keratin feedstock (Terefe, 2015). However, unlike bovine hair, feathers are already partially valorised through established pathways including feather meal, fertilisers, hydrolysates, and biomaterials.

Sheep wool represents a fundamentally different category of keratin resource. Australia produces approximately 280,000 tonnes of greasy wool annually (Australian Wool Innovation Limited, 2025). Following scouring, clean wool yields at approximately 60 - 65 % (WoolMark, 2026), composed predominantly of keratin (>90 %) (Cardamone et al., 2009). Shorn wool is a high-value, fully commercialised textile fibre and is not considered a waste stream.

A secondary keratin stream arises from “pulled wool” associated with sheepskins in meat processing. Lamb and sheep slaughter in Australia were 26.1 million and 11.7 million head, respectively in 2025 (MLA, 2025). This results in skins

that retain a portion of wool at the time of processing. The quantity of wool present on sheepskins at slaughter is not explicitly reported in industry literature as a fixed mass or percentage, because it is variable and does not have a primary market. Meat Standards Australia (MSA) sheep-meat guidelines require a minimum wool regrowth of approximately 5 mm (≥ 2 weeks growth) prior to slaughter, confirming that sheep retain a measurable quantity of wool on the skin at processing (MSA, 2014). While this material was once sought for textiles, there is declining demand for wool from certain breeds. As there are no significant fellmongering operations in Australia, skins are often sold with accompanying wool to international buyers (MLA, 2024). Furthermore, there are few market opportunities for wool shorn on farm from crossbreeds for meat production. Therefore, wool from meat sheep represents another underutilised keratin stream that could be combined with bovine hair to address volume constraints.

In summary, bovine hair represents a lower volume source of keratin than poultry feathers (rough estimates indicate approx. 3,700 - 15,800 tonnes of bovine hair vs. 111,000 tonnes of feather waste). However, feather waste already has established uses such as feed and fertiliser. Given the declining demand for hides and skins, which are also a source of protein, they could be combined with bovine hair to increase the economic viability of applications. However, this requires further research such as technical demonstration, collection models and techno-economic assessment.

7.0 Discussion

This project demonstrates that bovine hair, a component of cattle hides that is currently underutilised or treated as waste, represents a technically viable source of keratin with potential value across multiple applications. Through laboratory testing, industry engagement, and market analysis, the work has validated that utilising keratin from bovine hair provides a value adding opportunity. Taken together, the results confirm technical feasibility of extraction, however, commercial feasibility will be determined primarily by low-cost collection, volume aggregation, and fit-for-purpose processing pathways.

Laboratory characterisation confirmed that cattle hair is a high-protein material and that keratin can be recovered at high yields in two fractions (approximately 85 – 90 %) using a hybrid chemical-enzymatic extraction method. Importantly, keratin recovery was successful not only from native hair but also from hair that had undergone the Sirolime de-hairing process. While some modification to protein composition occurred in the Sirolime hair waste during processing, particularly to the sulphur-containing amino acid cysteine, the extracted keratin fractions were otherwise very similar to those obtained from the native hair based on the analytical characterisation performed. Fractions from both hair sources are suitable for a range of downstream applications based on their high protein content, (68.7 – 84.5 %), molecular size distribution, and complete essential amino acid profile. For instance, keratin fragments in the precipitate fractions were primarily composed of larger peptides between 5 - 50 kDa, which may be more suitable for the production of biopolymers or other structural materials, whereas the supernatant fractions were mostly composed of smaller peptides in the 2.5 - 25 kDa range that may be better suited to feed, fertiliser, or other applications where increased solubility is desirable. This finding significantly improves practical feasibility, as it indicates that keratin recovery does not need to be limited to untreated hair streams. From an implementation perspective, the ability to recover keratin from Sirolime hair waste is important because it leverages an existing, collected waste stream using existing infrastructure and processes.

Industry feedback highlighted strong interest in solutions that can value-add to hides. Due to the decline in demand for hides for leather, along with increased hide volumes and other market impacts, alternative value addition pathways for hides are desired. However, support is conditional on solutions being low-cost, low-complexity, and scalable. Volumes of bovine hair alone were identified as a major limitation, particularly for smaller regional processors, meaning bovine hair valorisations is unlikely to be commercially viable in isolation. This reinforces the importance of integrated approaches that combine hair with other co-products or keratin sources to achieve sufficient scale.

The prioritisation of end uses reflects a practical alignment between product requirements and the characteristics of the extracted material, alongside regulatory and scale considerations. The extracted keratin fractions were dominated by low-molecular weight peptides (particularly the supernatant fraction), and all essential amino acids were present, supporting the plausibility of an aquaculture feed protein ingredient pathway where acceptability and performance would need to be demonstrated through feeding trials. In parallel, niche fertiliser applications offer a comparatively direct route to value due to keratin's nitrogen content and lower barriers to market entry. By contrast, higher-value materials pathways (e.g., superabsorbent polymers) require additional performance benchmarking (e.g., absorbency, choice of co-polymer), product development, and scale-up work before commercial viability can be assessed.

Overall, the results suggest that future innovation should focus on whole hide utilisation strategies including but not limited to hair as this could address processors concerns with declining hide prices while also addressing volume constraints of using bovine hair as a feedstock alone. Future research will need to address regional processing constraints and techno-economic assessment to ensure that proposed pathways deliver a clear return on investment to processors and the wider red meat industry.

8.0 Conclusions

This project has demonstrated that bovine hair represents a technically viable and underutilised source of keratin that could be redirected from disposal into value added applications. Keratin can be recovered from both untreated (native) hair and tannery hair waste (from a modified Sirolime process) at high yields, confirming that existing processing practices do not preclude keratin upcycling.

Key conclusions are:

- The literature and patent review confirmed strong global interest in keratin extraction and applications from wool and poultry feathers, but comparatively limited activity focused on bovine hair, indicating an opportunity for targeted Australian research and industry innovation and adoption.
- Stakeholder engagement showed hide value decline and disposal costs are issues for processors. Adoption of any hair/keratin pathway is contingent on low-cost, low-labour, scalable processing with clear returns, particularly for regional sites with smaller volumes.
- Laboratory work demonstrated that bovine hair is a high-protein feedstock and that keratin can be recovered at high yield from both native hair and Sirolime (tannery) hair waste, confirming technical feasibility using industry-relevant waste streams.
- Characterisation results indicate Sirolime processing minimally alters hair composition (e.g., reduced cysteine levels) but does not preclude recovery of keratin peptides, supporting the practicality of recovering value without changing existing de-hairing infrastructure, depending on end-use.
- Market analysis indicates the most credible near-term pathways for bovine-hair-derived keratin are aquafeed ingredients and specialist fertiliser/soil-conditioning products. Biodegradable materials remain a longer-term opportunity that require additional technological development. Keratin use in the cosmetics market is more mature and would warrant performance and consumer marketing challenges, hence it was not selected in the top two value propositions. In addition, food and some feed (e.g. ruminant) applications, are subject to strict regulations.

- Overall, the top two value propositions which emerged are:
 - Develop and validate keratin hydrolysate/peptide ingredients for aquafeed (including feeding trials and commercialisation pathway), and
 - Develop keratin-based fertiliser products.

Aquafeed was identified as the leading priority pathway for upcycling bovine hair-derived keratin, supported by strong demand for alternative protein ingredients and comparatively fewer regulatory constraints than other pathways. Fertiliser and soil-conditioning applications represent a second-priority, near-term pathway that could reduce disposal costs and improve sustainability outcomes. However, higher value materials applications, including super absorbent polymers and other biodegradable products, remain promising but require further validation and coordinated development. While keratin shows theoretical suitability across multiple end-uses, commercial uptake is constrained by relatively low volumes, dispersed supply, and the need for low cost, scalable processing solutions, so recommendations for future work are made with these considerations.

9.0 Recommendations

Based on the findings of this project, the following prioritised recommendations are made:

- Prioritise aquafeed as the first pathway for upcycling bovine hair-derived keratin, given strong market demand for alternative protein ingredients and fewer regulatory constraints.
- Pursue whole hide specialist fertiliser and soil-conditioning applications as a second-priority, near-term pathway, leveraging keratin's nitrogen content and comparatively low barriers to market.
- Treat SAPs and other keratin-based biodegradable materials as a longer-term opportunity, progressing only once performance, cost, and scale requirements can be demonstrated.

Practical applications:

- Progress technical validation for aquafeed ingredients, including optimised hydrolysis for yield, and feed-trial testing with relevant species.
- Conduct chemical residue, quality assurance, preservation and regulatory suitability assessments for targeted end uses (with early focus on aquafeed and fertiliser).
- Support trials that integrate bovine hair-derived keratin into existing organic fertiliser or nutrient recovery systems.
- Undertake techno-economic analysis to assess commercial feasibility at regional and national scales, including supply-chain models and minimum viable volumes.
- Assess strategies to optimise volumes. This could include:
 - Combining bovine hair with other keratin sources (e.g., sheep wool from meat processing)
 - A whole hide utilisation process which hydrolyses the hide and hair for collagen and keratin, respectively, while also considering including skins from other species
- Develop SAP and biodegradable materials concepts through laboratory formulation work and performance benchmarking (e.g., absorption under load).

Adoption and extension:

- Engage with feed companies, fertiliser manufacturers, and biomaterials developers to explore partnerships.
- Develop industry-focused guidance outlining feasible processing models for small and large processors, especially considering collection models to overcome volume constraints.
- Disseminate findings on whole hide-utilisation and value-addition opportunities.

10.0 Project outputs

The following outputs were delivered as part of this project:

- Two milestone workshops held with AMPC
- Stakeholder engagement with meat processors and tanneries to understand current practices, volumes, costs, and adoption constraints.
- This final technical report submitted to AMPC outlining findings, implications, and recommendations for industry.

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