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Valorizing Poultry And Agro-Waste Through Keratin And Lignin Extraction And Its Possible Utilization

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ABSTRACT

Growing concerns about environmental sustainability and waste management highlight the critical need to value agro-waste and poultry waste. Chicken feathers, an underutilized waste from the poultry industry, and rice husk, a lignocellulosic residue produced in substantial way, offer prospects as renewable materials for biopolymer manufacture. This study describes a straightforward, scalable, and environmentally friendly approach for extracting keratin and lignin from various biomass sources that uses fewer harsh chemicals and requires less energy than previous methods. Keratin was extracted using reduction techniques, while lignin was separated from rice husk using alkaline extraction. The extraction procedure produced 7.0% (w/w) keratin and 30.0% (w/w) lignin, above reported yields in the literature while maintaining structural integrity. Fourier Transform Infrared spectroscopy (FTIR) confirmed characteristic functional groups, while X-ray Diffraction (XRD) analysis revealed partially crystalline keratin and amorphous lignin, suitable for diverse applications. Keratin and lignin are potential options for advanced biomaterials such as biodegradable films, coatings, adhesives, composites, packaging, and biomedical scaffolds because of their rich reactive capabilities, biodegradability, and renewable availability. This work reveals a low cost and practical way of converting agricultural and poultry waste into value added bio-based polymers, in line with circular economic principles and contributing to a lower environmental load. The technique and characterization results provide a realistic foundation for researchers looking into sustainable biopolymer production, with the potential to promote material science, packaging innovation, and biomedical engineering.

KEYWORDS- Biopolymer, agro-waste, sustainability, alkaline, renewable, biomedical, packaging.

1. INTRODUCTION: -

The world's population expansion and human activity have resulted in a massive accumulation of industrial, agricultural, and poultry waste, causing major environmental challenges. Expanding industrialization, population increase and rising consumer demand are putting pressure on existing waste management strategies (De Silva et al., 2023). Poultry is a vital source of food, income, and cultural identity for rural communities in developing countries. It also provides economic services, meat, eggs, raw materials for industries, waste byproducts, and employment opportunities (Attia et al., 2024). As a result, there is an urgent need to investigate sustainable and novel techniques to convert these abundant biomass resources into high-value functional materials. This is consistent with the concepts of the circular economy, which advocates for repurposing trash into valuable products while limiting environmental damage (Ikponmwosa Aiguobarueghian et al., 2024; Mandpe et al., 2023).

One protein source that is greatly underutilized is keratin (Nuutinen et al., 2022a). It is a fibrous structural protein that is a common biopolymer found in animal waste, particularly chicken feather w (Perez-Puyana et al., 2023). Every year, millions of tons of chicken feather waste which contains more than 90% of keratinous proteins accumulate worldwide. These feathers, a major waste product of the poultry industry, are largely unused (Mrajji et al., 2020). Although conventional techniques frequently use chemicals, which may degrade protein structure and impede performance, this plentiful resource provides a viable path to keratin extraction (Chinomso Iroegbu & Ray, 2022). Keratin-based polymers are in high demand worldwide, mostly because to their extensive application in the personal care, cosmetics, and developing biomedical industries. The global keratin market was estimated to be worth USD 1.66 billion in 2024 and is expected to increase at a compound annual growth rate (CAGR) of roughly 6.4% to reach USD 2.40 billion by 2030. Keratin, which is an extracted waste, is produced by the protein manufacturing industries. The worldwide waste-biomass ratio is increasing by extracted trash (Waqas Ali Shah et al., 2023). A

complex biopolymer, keratin is made up of 19 amino acids joined by peptide bonds to form ladder like polypeptide chains. The molecular chain may be tightly packed with alpha (α) helices or beta (β) sheets, which gives the keratin its stable structure.(Alberto & Chua, 2024). It has unique features, including biodegradability, biocompatibility, and significant mechanical strength, making it a suitable choice for the development of sustainable biomaterials(Feroz et al., 2020a). Its hierarchical structure and ability for self-assembly add to its utility in advanced material design (Pakkaner et al., 2019). Keratin, a natural, cystine-rich fibrous protein, has intriguing potential as a biopolymer for advanced biomaterials because of its inherent biocompatibility, self-assembly capabilities, and renewable nature. Furthermore, the extraction of keratin frequently requires severe chemical treatments such as reduction, oxidation, or ionic solutions, which can disrupt its original protein structure and result in heterogeneous mixtures, complicating reproducibility and property control (Feroz et al., 2020b).

Lignin, a highly fragrant and hydroxylated polymer obtained from plant biomass, can work in tandem with keratin(Grigsby et al., 2020). The market for lignin-based polymers is expanding globally because of its appeal for sustainability and industry wide adaptability. The global lignin market was estimated to be worth USD 995 million in 2023 and is projected to grow at a compound annual growth rate (CAGR) of approximately 5.0% to reach USD 1.33 billion by 2029. It is an amorphous aromatic biopolymer, is one of the most prevalent renewable organic compounds on Earth, purely second to cellulose(Karunarathna & Smith, 2020). Rice husk, a lignocellulosic agricultural byproduct produced frequently during rice milling, is a conveniently available and affordable supply of lignin (Bisht et al., 2020).With an average weight of 20% of the grain, rice husks (Oryza sativa) contain the primary constituents of cellulose (38.3%), hemicellulose (31.6%), lignin (11.8%), and silica (18.3%) (Amirullah et al., 2025). Despite being a basic material for many different uses, lignin's complicated and irregular structure limits its large-scale utilization (Huo et al., 2025). Syringyl (S), guaiacyl (G), and p-hydroxyphenyl (H) are the three primary units that make up the mostly anamorphous, three-dimensional polymer known as lignin (Rashid et al., 2021). It is a substantial component of plant biomass and an important byproduct of the pulp and paper industries. Its complex chemical composition, rich in phenolic hydroxyl groups, offers enormous promise for numerous applications, such as bioplastics, adhesives, and composites (Yu & Kim, 2020). As a sustainable substance, lignin provides an eco-friendly alternative to petroleum-based polymers, helping to build bio-based technologies with lower environmental footprints (Chelliah et al., 2023). Despite their numerous uses such as biofertilizer, livestock feed, absorbents, and construction materials, rice husks are still frequently seen as a waste product of milled rice and are therefore frequently burned outdoors or disposed (Amirullah et al., 2025). Rice husk has high lignin concentration makes it a desirable raw resource for sustainable material development. The extraction of lignin from such agro-waste streams not only addresses waste management challenges but also provides a cost-effective supply of this valuable biopolymer for diverse industrial uses (Mateo et al., 2025). Traditional industrial techniques frequently produce lignin with low molar mass and high dispersity, which results in blends with poor mechanical properties and restricted compatibility with standard polymer matrices (Wang et al., 2020; Yan et al., 2025).

The complimentary chemical functions found in both macromolecules control the conjugation of lignin and keratin into a biopolymer network. The peptide backbones of keratin, a structural protein, are rich in functional groups, including amide carbonyls, amino (–NH_2–NH_3^+), carboxyl (–COOH–COO^-), hydroxyl (–OH), and cysteine thiols (–SH), which can form disulfide bonds (Breakspear et al., 2024). In contrast, lignin is a polyaromatic biopolymer that is rich in carboxylic acid groups, phenolic hydroxyls, and aliphatic hydroxyls. Its reported pKa ranges for carboxyls and phenolics are approximately 3–5 and 6–11, respectively, allowing for ionization and reactivity at different pH levels (Zheng et al., 2024). Hydrogen bonds between the amide groups of keratins and the hydroxyl moieties of lignin, as well as electrostatic interactions between the protonated amino groups of keratins and the deprotonated carboxyl or phenolic groups of lignin, are the main modes of interaction when blended. Experimental research demonstrates a notable affinity of keratin peptides for lignin surfaces and nanoparticles in comparison to cellulose supports these non-covalent interactions (Nuutinen et al., 2022b). In general, these covalent coupling, ionic pairing, and complementary hydrogen bonding processes allow for the creation of cohesive

keratin–lignin mixes with adjustable characteristics, which makes them feasible options for applications involving sustainable biomaterials(Chinomso Iroegbu & Ray, 2022; Grigsby et al., 2020).

The current study focuses on establishing a simple, cost-effective, and environmentally sustainable method for extracting keratin from chicken feather poultry waste and lignin from rice husk agro-residues, two abundant but underutilized biomass resources as shown in (figure 1). Unlike many previously described approaches that use harsh chemical treatments, high energy consumption, or multi-step fractionation procedures, the suggested methodology employs a simplified extraction process that is geared for scalability and environmental friendliness. This work is intended to create useful, renewable polymeric materials for sustainable packaging, coatings, and advanced composites by combining these two biopolymers. This method not only values low-cost agricultural and poultry byproducts, but it also demonstrates a more feasible and environmentally friendly pathway for producing bio-based polymers, bridging a critical gap between laboratory scale lignin and keratin utilization and translation into industrially viable biomaterials. Authors support that the present work will be helpful for many researchers in the field of keratin and lignin for making biopolymers and biocomposites.

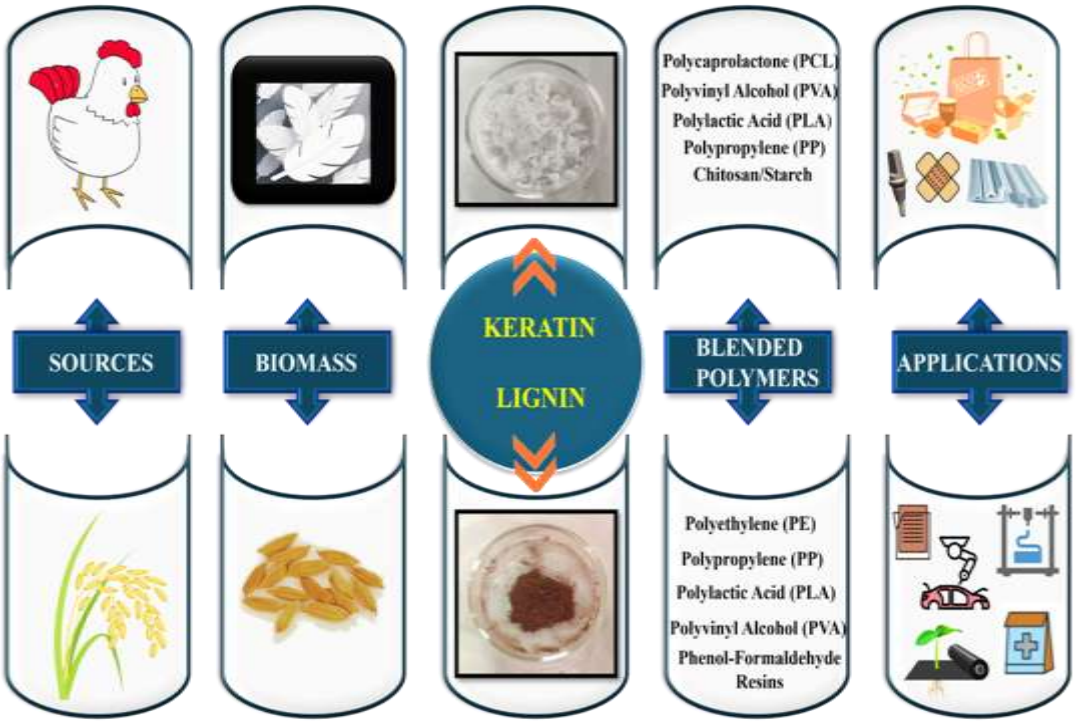


Figure 1: Overview of keratin and lignin source obtained, collected biomass, extracted images, blending with different polymers and applications in varied fields respectively.

2. MATERIALS AND METHODS

2.1 Materials

Chicken Feathers procured from the local butcher shop of Raipur, Rice Husk from rice mill Balaji Rice Industries Private Limited, Kharora, Raipur (C.G.), Sodium Dodecyl Sulfate (SDS), β-mercaptanol, Urea, NaOH (Sodium hydroxide), H_2SO_4 (sulfuric acid), Hydrogen Chloride (HCL), Dioxane, Ethanol, purchased from Sigma-Aldrich.

2.2 Biomass Cleaning and pre-treatment

2.2.1 Keratin biomass source

Chicken feathers were obtained from a nearby butcher store and cleaned before using. The feathers were dipped in a detergent solution and soaked overnight to remove surface impurities, then thoroughly rinsed with deionized water to remove any remaining detergent or particle matter. The cleaned feathers were air-dried at room temperature, cut into small pieces to and weight about 7grams for 7%(w/v), and then kept

in sterile, airtight zip-lock bags for future experimental use. Following an overnight immersion in an ethanol solution of 2% for additional purification.

2.2.2 Lignin biomass source

Rice husks have been collected from a nearby rice mill and thoroughly cleaned to remove any pollutants and plant material. The husks were manually separated, sliced into small pieces, then processed with a motorized grinder. The powder was sieved using a 300 µm screen to ensure homogeneous particle size distribution. The processed rice husk powder was packaged in sterile, airtight zip-lock pouches and kept dry until further use.

2.3 Extraction of Keratin

To extract keratin, chicken feathers were first processed using a 7% (w/v) keratin solution as given in (figure 2). Before being extensively cleaned to get rid of contaminants, the feathers were carefully cut into tiny pieces and weight about 7g followed by ethanol purification, these pre-treated feather pieces were rinsed with distilled water. After cleaning, hot air oven was used to dry the feathers. To solubilize the keratin, the dried feather material was mixed with a solution that contained stock solution of (500 ml), to which addition of prepared cleaned and chopped feathers with 2.4% (w/v) urea, 0.6% (v/v) β-mercaptoethanol, and 0.7% (w/v) sodium dodecyl sulfate (SDS).After that, this mixture was constantly agitated using a magnetic stirrer and left to break down for four days. A semi-solid keratin solution was produced after degradation process, using a technique primarily outlined by (Mattiello et al., 2023)(Nayak & Gupta, 2017)

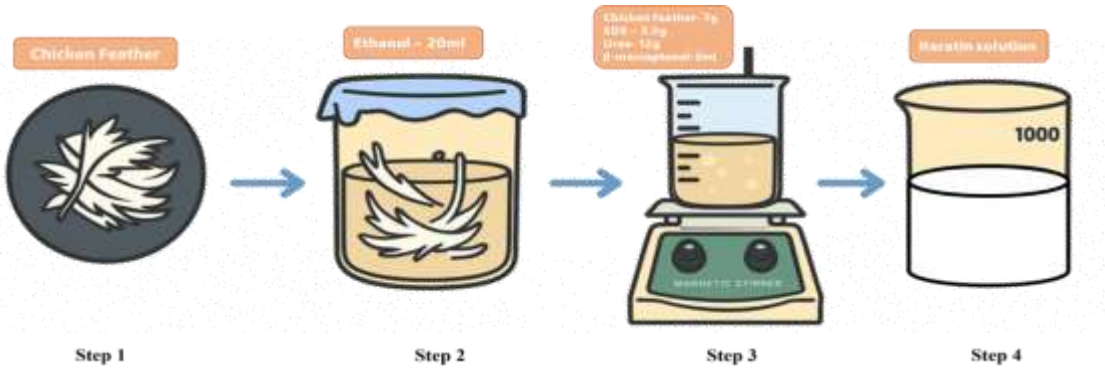
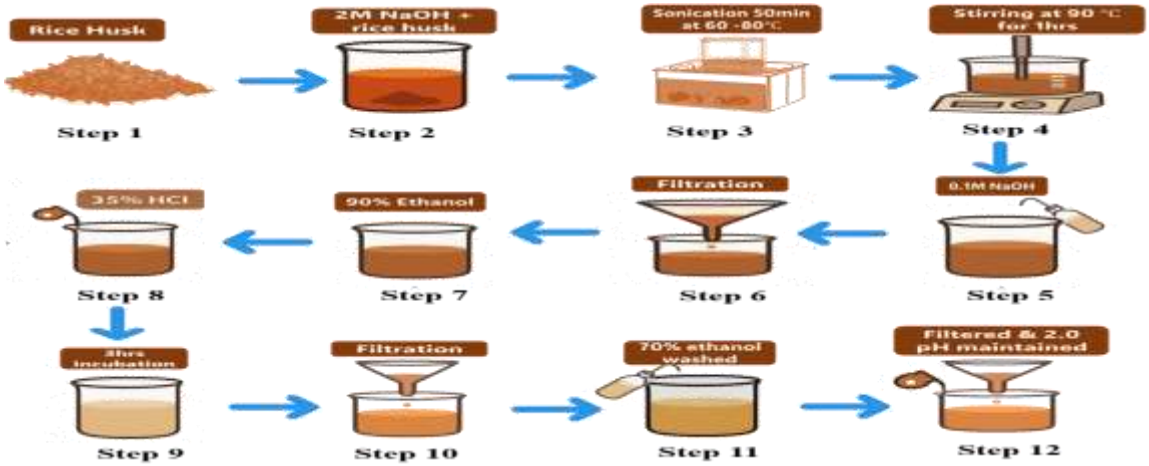


Figure 2: Schematic representation of extraction of keratin methodology presented diagrammatically. step 1- chicken feathers were cleaned and cut, step 2- ethanol treatment for purification, step 3- the dried solution treated with chemicals, stirred continuously for 4 days and step 4- semi solid keratin extract obtained.

2.4 Extraction of Lignin

Fractionization of rice husk powder was conducted were it was taken about 5g, underwent processing as described in (Dinh Vu et al., 2017). The sample was moved to a different beaker with 50 milliliters of a



2M NaOH solution. After that, these combinations were sonicated for 50 minutes to keep the temperature between 60 and 80 °C. The solutions were constantly agitated in a magnetic stirrer at 90 °C after sonication. After filtering the resultant mixtures, 20 milliliters of 0.1 M NaOH solution were used to completely wash the solid residues. Two liters of 90% ethanol were then added to the recovered filtration. After carefully adjusting and maintaining the pH of this solution at 5.5 using 35% hydrochloric acid, the combination was let stand for three hours before going through a second filtration. Ten milliliters of 70% ethanol were used to wash the resulting precipitate. The resultant filtration was subsequently dried by evaporation. Following extraction, the recovered residue was cleaned with a HCl of pH 2.0 solution and refrigerated to dry as described in (figure 3) below.

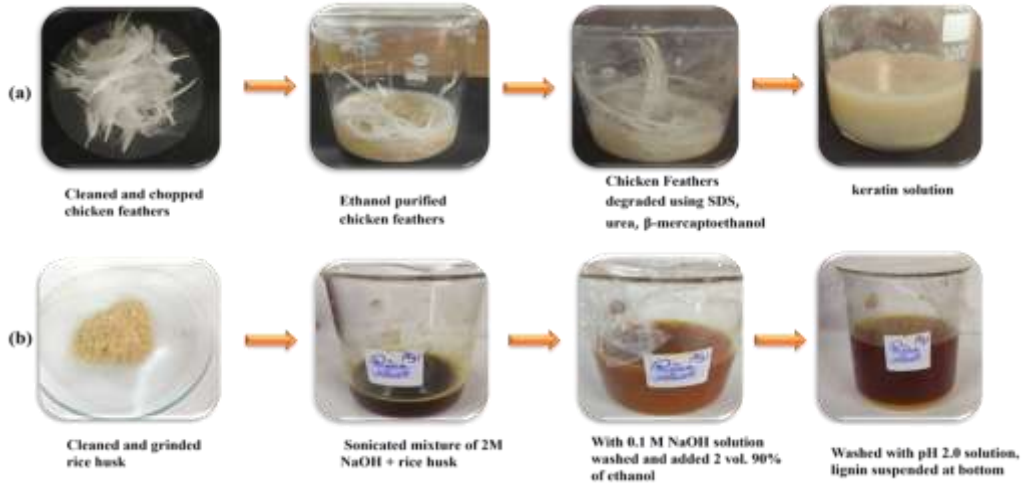
Figure 3: A schematic illustration of lignin extraction, step 1- rice hush was cleaned and grinded, Step 2- rice husk was treated with 2 M NaOH, step 3- sonicated (60-80 °c for 50 minutes), step 4- stirred at 90°C, step 5- filtering the solution, step 6- residues were washed with 0.1 M NaOH, step 7- followed by 90% ethanol precipitation, step 8- pH adjustment (5.5) with 35% HCl, step 9- then the mixture was incubated for 3hrs, step 10- filtered, step 11- washed with 70% ethanol, evaporated, step 12- then washed with a pH 2.0 HCl solution, yielding brown solution.

3. RESULTS AND DISCUSSION

3.1 Extraction of keratin and lignin using chicken feathers and rice husk

Stepwise keratin extraction process as shown in (figure 4 (a)) Keratin extraction involves the following steps: (1) cleaning and chopping chicken feathers into small pieces; (2) purifying with ethanol to eliminate any remaining contaminants; (3) undergoing chemical treatment to solubilize the proteins; and (4) obtaining semi-solid keratin concentrate. (b) Lignin extraction: (1) rice husk was cleaned and sieved to achieve uniform particle size, (2) lignin was solubilized with a NaOH solution, (3) lignin was precipitated using 2 volumes of 90% ethanol, and (4) lignin was isolated by adjusting the pH to 5.5 with HCl.

Figure 4: The extraction process of (a) keratin from chicken feathers (b) Lignin from rice husk



3.2 Extracted keratin and lignin

After the extraction process, the initial weight of the corresponding raw materials was initial dry weight reduced by 7.0% (w/w) keratin and 30.0% (w/w) lignin. (Figure 5) displays the physical characteristics of the two extracted biomaterials. The lignin appears as a tiny, dark-brown particle mass, whereas the keratin sample has a light white fibrous base.

Figure 5: The extracted image of (a) Keratin(b) Lignin

3.3 Functionals analysis

3.3.1 FTIR analysis of keratin

The chemical analysis was done by Fourier transform infrared spectroscopy (FTIR) to examine the chemical functional compound analysis of keratin has absorption bands 3351.2 cm^{-1} attributed to N-H stretching's vibrations of peptide linkages associated with hydrogen bonding's in proteins. 2942 cm^{-1} is C-H stretching indicates aliphatic CH_2 & CH_3 chains of amino acids side groups(Nayak & Gupta, 2015). Amide Ⅰ indicates by 1624.97 cm^{-1} strong and sharp peak of C=O stretching in peptide bonds, the region (1700-1600 cm^{-1}) is highly sensitive to protein secondary structure i.e. α helix and the β sheet. 1463.21 cm^{-1}(Posati et al., 2019). Amide Ⅱ bonds associated with CH_2 bending and C-N ≈stretching vibrations confirms peptide bonds and side chains methylene groups. 1233 cm^{-1} Amide Ⅲ bonds falls in ray of (1220-1330 cm^{-1}) C-N stretching and N-H bending supports the presences of polypeptide backbone(Mattiello et al., 2023) as shown in (figure 6a).

3.3.2 FTIR analysis of lignin

The Fourier transform infrared spectroscopy (FTIR) evaluation of the lignin sample as shown in (figure 6b) (4000-500 cm^{-1}) revealed absorption bands that aligned with known structural patterns. The extensive O-H stretching at around 3345 cm^{-1} suggests phenolic and aliphatic hydroxyl groups. Peaks at 2910 and 2800 cm^{-1} indicate C-H stretching from methyl/methylene and aromatic methoxyl side chains (Mateo et al., 2025). Aromatic skeletal vibrations of guaiacyl and syringyl units are identified by sharp absorptions at 1592cm^{-1} and 1507cm^{-1}. The band at 1453 cm^{-1} is due to methyl/methylene C-H deformation. The 1320-1240 cm^{-1} area corresponds to C-O and C-O-C stretching in aromatic and ether compounds. The alcohols and ethers exhibit sharp C-O stretching between 1200-1000 cm^{-1}, while aromatic C-H deformations in the fingerprint region about 995 cm^{-1} and 830 cm^{-1} prove the presence of aromatic rings (Abdelaziz & Hulteberg, 2017; Bryant et al., 2023; Md Salim et al., 2021).

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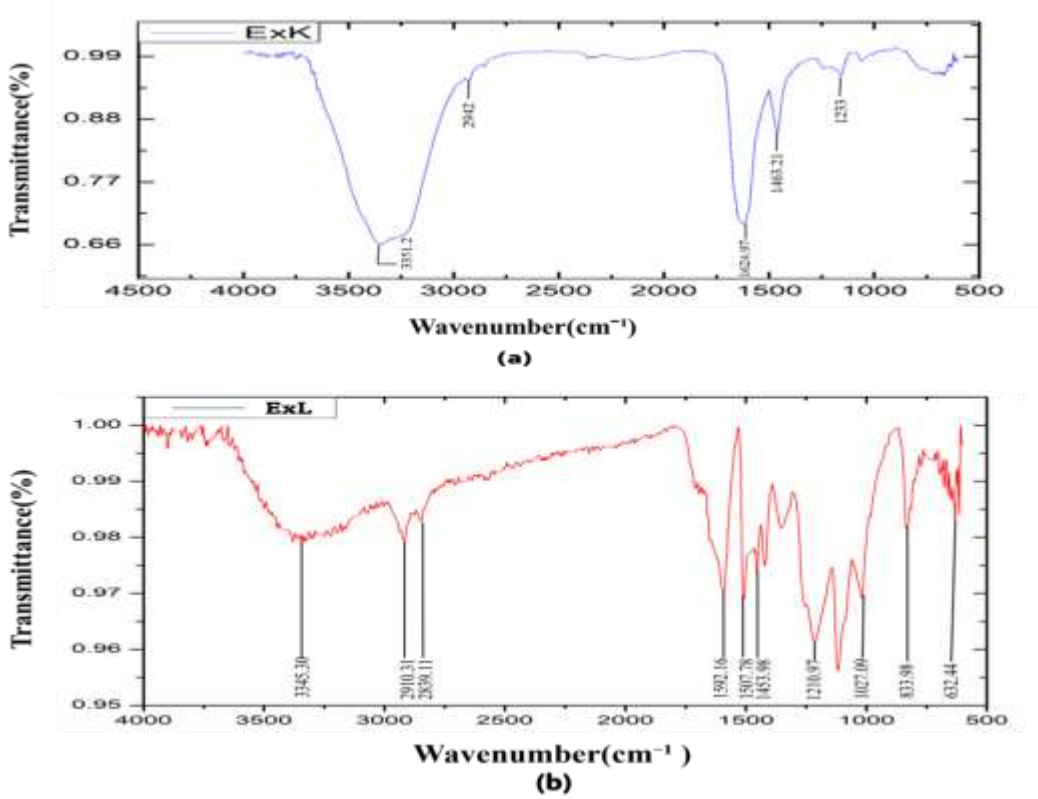


Figure 6: FTIR (Fourier transform infrared spectroscopy) graph report of extracted (a) Keratin observed to be 5 transmitted peaks of functional compounds (b) Lignin has 10 peaks showing the functional groups respectively.

3.4 The crystallinity analysis

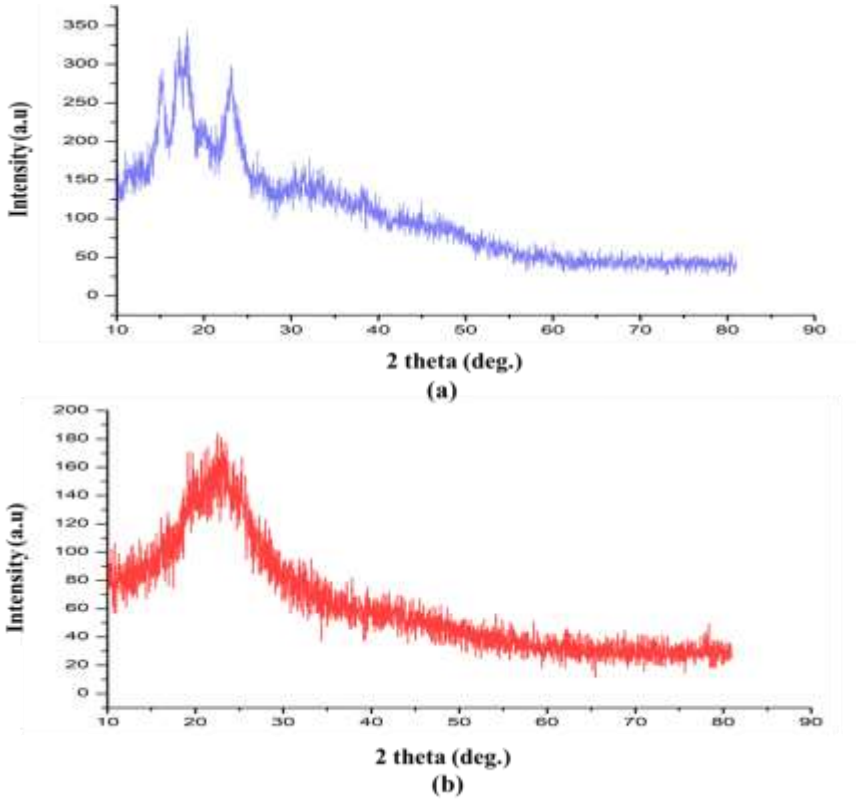
3.4.1 XRD analysis of keratin

The X-ray diffraction (XRD) results in extracted keratin as shown in (figure 7a), the diffraction peaks depict the presence of crystalline regions is indicated by sharp peaks between approximately 10° and 25° (2θ), 9-10°a less intense broad peak with the core of these peaks around 19° and 22.5° represents the crystalline phase of α-keratin, which is frequently linked to the interchain hydrogen bonding in the backbone of polypeptides. The second peak, close to 22–23°: represents densely packed crystalline domains or an organized β-sheet structure. Amorphous areas in the keratin matrix are represented by the broad halo that stretches between 25° and 50°it indicates a moderate to high crystalline content, which ensure mechanical strength with flexibility for biomaterials.

3.4.2 The XRD analysis of lignin

The amorphous structure of lignin in (Figure 7b) demonstrates the broad diffraction maximum at 22.2°(2θ). with an approximate peak intensity of ~17 in the X-ray diffraction (XRD) pattern of the extracted lignin. The remaining crystalline, which shows powder lines in this area, is compatible with the weak shoulder that is seen at around 18° to 19°(Gupta et al., 2015; Rajamma et al., 2010). In contrast, sodium lignosulfonate is primarily amorphous and is therefore not anticipated to produce crisp reflections. There are no more crystalline peaks that may be attributed to lignin, indicating that the polymeric fraction is primarily amorphous (Gea et al., 2020) (Syahidah et al., 2023)

Figure 7: The X-ray diffraction (XRD) analysis of extracted (a) Keratin observed high peak range between 10° and 25° (2θ) (b) Lignin showed peak intensity at 22.2°(2θ).



4. CONCLUSION

This study demonstrates a practical and eco-friendly method for optimizing the extraction of lignin and keratin from two significant agro and poultry wastes: rice husk and chicken feather. Higher yields than conventional methods were obtained by the repeatable extraction process, which recovered 30.0% lignin and 7.0% keratin. The isolated keratin had a light white fibrous structure, whereas lignin was a fine dark-brown powder, indicating effective isolation and minimum thermal or chemical degradation.

while maintaining crucial structural and functional properties validated by investigations FTIR spectroscopy which confirmed the presence of amide I, II, and III bonds in keratin, reflecting the retention of its polypeptide backbone and α-helix/β-sheet secondary structure, while lignin spectra revealed characteristic phenolic and aliphatic hydroxyl groups, methoxyl side chains, and aromatic skeletal vibrations of syringyl and guaiacyl units, confirming its chemical integrity. X-ray Diffraction (XRD) analysis revealed a semi-crystalline structure in keratin (peaks at ~19° and 22.5° 2θ), consistent with its hydrogen-bonded polypeptide arrangement, and a predominantly amorphous nature in lignin (broad halo at ~22.2° (2θ), which is favorable for chemical modification and polymer blending.

The results highlight these biopolymers great potential as building blocks for eco-friendly polymers, films, coatings, and bio composites, providing a substitute for materials generated from petroleum. This

approach overcomes the problems of waste accumulation and promotes the industrial use of sustainable materials by lowering chemical consumption, streamlining purification, and increasing efficiency. The techniques described here offer a reproducible framework for further research aiming to create biopolymers with adjustable characteristics by blending, crosslinking, and sophisticated processing. In addition to showing a scalable method for recovering keratin and lignin, this work establishes the foundation for future advancements in material science and green chemistry, offering researchers a useful point of reference for creating high-performance, reasonably priced biopolymers from a variety of waste streams.

Data Availability

The research data used to support the findings of the study are included in the article.

Author contributions

Olibha Xalxo: conceptualization (lead), performed the methodology (lead), and writing of the original draft (equal). Kush Kumar Nayak: data curation (lead), investigation (equal), and writing and editing (equal). Varaprasad Kolla: investigation (equal) and supervised (lead).

Conflicts of Interest

The author declares that there are no conflicts of interest.

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REFERENCES

1. Abdelaziz, O. Y., & Hulteberg, C. P. (2017). Physicochemical Characterisation of Technical Lignins for Their Potential Valorisation. *Waste and Biomass Valorization*, *8*(3), 859–869. https://doi.org/10.1007/s12649-016-9643-9
2. Alberto, V., & Chua, G. K. (2024). Effects of spray drying chicken feather keratin with Arabic gum encapsulation for nutrient supplementation. *Engineering and Applied Science Research*, *51*(6), 680–693. https://doi.org/10.14456/easr.2024.64
3. Amirullah, R., Kusuma, P. M., & Sari, N. K. (2025). The Effect of Particle Size and Time in the Ashing Process on the Yield of Rice Husk Silica Extraction. *G-Tech: Jurnal Teknologi Terapan*, *9*(1), 60–67. https://doi.org/10.70609/gtech.v9i1.5733
4. Attia, Y. A., Aldhalmi, A. K., Youssef, I. M., Bovera, F., Tufarelli, V., El-Hack, M. E. A., El-Kholy, K. H., & Shukry, M. (2024). Climate change and its effects on poultry industry and sustainability. In *Discover Sustainability* (Vol. 5, Issue 1). Springer Nature. https://doi.org/10.1007/s43621-024-00627-2
5. Bisht, N., Gope, P. C., & Rani, N. (2020). Rice husk as a fibre in composites: A review. In *Journal of the Mechanical Behavior of Materials* (Vol. 29, Issue 1, pp. 147–162). De Gruyter Open Ltd. https://doi.org/10.1515/jmbm-2020-0015
6. Breakspear, S., Nöcker, B., & Popescu, C. (2024). Chemical bonds and hair behaviour—A review. In *International Journal of Cosmetic Science* (Vol. 46, Issue 5, pp. 806–814). John Wiley and Sons Inc. https://doi.org/10.1111/ics.12967
7. Bryant, N., Engle, N., Tschaplinski, T., Pu, Y., & Ragauskas, A. J. (2023). Variable lignin structure revealed in Populus leaves. *RSC Advances*, *13*(29), 20187–20197. https://doi.org/10.1039/d3ra03142j
8. Chelliah, R., Wei, S., Vijayalakshmi, S., Barathikannan, K., Sultan, G., Liu, S., & Oh, D. H. (2023). A Comprehensive Mini-Review on Lignin-Based Nanomaterials for Food Applications: Systemic Advancement and Future Trends. In *Molecules* (Vol. 28, Issue 18). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/molecules28186470
9. Chinomso Iroegbu, A. O., & Ray, S. S. (2022). Lignin and Keratin-Based Materials in Transient Devices and Disposables: Recent Advances Toward Materials and Environmental Sustainability. *ACS Omega*, *7*(13), 10854–10863. https://doi.org/10.1021/ACSOMEGA.1C07372
10. De Silva, S., Carson, P., Indrapala, D. V., Warwick, B., & Reichman, S. M. (2023). Land application of industrial wastes: impacts on soil quality, biota, and human health. In *Environmental Science and Pollution Research* (Vol. 30, Issue 26, pp. 67974–67996). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s11356-023-26893-7
11. Dinh Vu, N., Thi Tran, H., Bui, N. D., Duc Vu, C., & Viet Nguyen, H. (2017). Lignin and Cellulose Extraction from Vietnam's Rice Straw Using Ultrasound-Assisted Alkaline Treatment Method. *International Journal of Polymer Science*, *2017*. https://doi.org/10.1155/2017/1063695
12. Feroz, S., Muhammad, N., Ranayake, J., & Dias, G. (2020a). Keratin - Based materials for biomedical applications. In *Bioactive Materials* (Vol. 5, Issue 3, pp. 496–509). KeAi Communications Co. https://doi.org/10.1016/j.bioactmat.2020.04.007
13. Feroz, S., Muhammad, N., Ranayake, J., & Dias, G. (2020b). Keratin - Based materials for biomedical applications. In *Bioactive Materials* (Vol. 5, Issue 3, pp. 496–509). KeAi Communications Co. https://doi.org/10.1016/j.bioactmat.2020.04.007

14. Gea, S., Siregar, A. H., Zaidar, E., Harahap, M., Indrawan, D. P., & Perangin-Angin, Y. A. (2020). Isolation and characterisation of cellulose nanofibre and lignin from oil palm empty fruit bunches. *Materials*, *13*(10). https://doi.org/10.3390/ma13102290

15. Grigsby, W. J., Scott, S. M., Plowman-Holmes, M. I., Middlewood, P. G., & Recabar, K. (2020). Combination and processing keratin with lignin as biocomposite materials for additive manufacturing technology. *Acta Biomaterialia*, *104*, 95–103. https://doi.org/10.1016/j.actbio.2019.12.026

16. Gupta, A. K., Kumar Gupta, A., Mohanty, S., & Nayak, S. K. (2015). Preparation and Characterization of Lignin Nanofibre by Electrospinnig Technique. *International Journal of Scientific Engineering and Applied Science (IJSEAS)*, *1*. www.ijseas.com

17. Huo, P., Mo, X., Zhang, L., & Sun, S. (2025). Uncovering banana growth and soil biochemical properties transformation after lignin-based liquid compound fertilizer. *Industrial Crops and Products*, *225*. https://doi.org/10.1016/j.indcrop.2025.120456

18. Ikponmwosa Aiguobarueghian, Uwaga Monica Adanma, Emmanuel Olurotimi Ogunbiyi, & Nko Okina Solomon. (2024). Waste management and circular economy: A review of sustainable practices and economic benefits. *World Journal of Advanced Research and Reviews*, *22*(2), 1708–1719. https://doi.org/10.30574/wjarr.2024.22.2.1517

19. Karunarathna, M. S., & Smith, R. C. (2020). Valorization of lignin as a sustainable component of structural materials and composites: Advances from 2011 to 2019. In *Sustainability (Switzerland)* (Vol. 12, Issue 2). MDPI. https://doi.org/10.3390/su12020734

20. Mandpe, A., Paliya, S., Gedam, V. V., Patel, S., Tyagi, L., & Kumar, S. (2023). Circular economy approach for sustainable solid waste management: A developing economy perspective. In *Waste Management and Research* (Vol. 41, Issue 3, pp. 499–511). SAGE Publications Ltd. https://doi.org/10.1177/0734242X221126718

21. Mateo, S., Fabbrizi, G., & Moya, A. J. (2025). Lignin from Plant-Based Agro-Industrial Biowastes: From Extraction to Sustainable Applications. In *Polymers* (Vol. 17, Issue 7). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/polym17070952

22. Mattiello, S., Guzzini, A., Del Giudice, A., Santulli, C., Antonini, M., Lupidi, G., & Gunnella, R. (2023). Physico-Chemical Characterization of Keratin from Wool and Chicken Feathers Extracted Using Refined Chemical Methods. *Polymers*, *15*(1). https://doi.org/10.3390/polym15010181

23. Md Salim, R., Asik, J., & Sarjadi, M. S. (2021). Chemical functional groups of extractives, cellulose and lignin extracted from native Leucaena leucocephala bark. *Wood Science and Technology*, *55*(2), 295–313. https://doi.org/10.1007/s00226-020-01258-2

24. Mrajji, O., El Wazna, M., El Bouari, A., & Cherkaoui, O. (2020). Valorisation of waste feathers: Treatments and characterization. *IOP Conference Series: Materials Science and Engineering*, *827*(1). https://doi.org/10.1088/1757-899X/827/1/012020

25. Nayak, K. K., & Gupta, P. (2015). In vitro biocompatibility study of keratin/agar scaffold for tissue engineering. *International Journal of Biological Macromolecules*, *81*, 1–10. https://doi.org/10.1016/j.ijbiomac.2015.07.025

26. Nayak, K. K., & Gupta, P. (2017). Study of the keratin-based therapeutic dermal patches for the delivery of bioactive molecules for wound treatment. *Materials Science and Engineering C*, *77*, 1088–1097. https://doi.org/10.1016/j.msec.2017.04.042

27. Nuutinen, E. M., Valle-Delgado, J. J., Kellock, M., Farooq, M., & Österberg, M. (2022a). Affinity of Keratin Peptides for Cellulose and Lignin: A Fundamental Study toward Advanced Bio-Based Materials. *Langmuir*, *38*(32), 9917–9927. https://doi.org/10.1021/acs.langmuir.2c01140

28. Nuutinen, E. M., Valle-Delgado, J. J., Kellock, M., Farooq, M., & Österberg, M. (2022b). Affinity of Keratin Peptides for Cellulose and Lignin: A Fundamental Study toward Advanced Bio-Based Materials. *Langmuir*, *38*(32), 9917–9927. https://doi.org/10.1021/acs.langmuir.2c01140

29. Pakkaner, E., Yalçın, D., Uysal, B., & Top, A. (2019). Self-assembly behavior of the keratose proteins extracted from oxidized Ovis aries wool fibers. *International Journal of Biological Macromolecules*, *125*, 1008–1015. https://doi.org/10.1016/j.ijbiomac.2018.12.129

30. Perez-Puyana, V. M., Capezza, A. J., Newson, W. R., Bengoechea, C., Johansson, E., Guerrero, A., & Hendeqvist, M. S. (2023). Functionalization Routes for Keratin from Poultry Industry Side-Streams—Towards Bio-Based Absorbent Polymers. *Polymers*, *15*(2). https://doi.org/10.3390/polym15020351

31. Posati, T., Aluigi, A., Donnadio, A., Sotgiu, G., Mosconi, M., Muccini, M., Ruani, G., Zamboni, R., & Seri, M. (2019). Keratin Film as Natural and Eco-Friendly Support for Organic Optoelectronic Devices. *Advanced Sustainable Systems*, *3*(11). https://doi.org/10.1002/adsu.201900080

32. Rajamma, R., Modolo, R. C., Ball, R. J., Labrincha, J. A., Ferreira, V. M., & Allen, G. C. (2010). *Lignin in lime for water repellent mortars. In: APFAC, 3rd Congresso Portugues de Argamassas de Construção Please scroll down to view the document. LIGNIN IN LIME FOR WATER REPELLENT MORTARS.* http://opus.bath.ac.uk/Thisversionismadeavailableinaccordancewithpublisherpolicies.Pleaseciteonlythepublishedversionusingthereferenceabove.Seehttp://opus.bath.ac.uk/forusagepolicies.

33. Rashid, T., Sher, F., Rasheed, T., Zafar, F., Zhang, S., & Murugesan, T. (2021). Evaluation of current and future solvents for selective lignin dissolution–A review. In *Journal of Molecular Liquids* (Vol. 321). Elsevier B.V. https://doi.org/10.1016/j.molliq.2020.114577

34. Syahidah, Pratama, M. R. A., Arif, A., Diza Lestari, A. S. R., Taskirawati, I., Makkarennu, Sulaeha, Triwulandari, E., Restu, W. K., Fatriasari, W., Anita, S. H., & Ghozali, M. (2023). Effect of Lignin Concentration on Crystallinity of TPS/Lignin Biocomposite. *IOP Conference Series: Earth and Environmental Science*, *1277*(1). https://doi.org/10.1088/1755-1315/1277/1/012030

35. Wang, Y. Y., Meng, X., Pu, Y., & Ragauskas, A. J. (2020). Recent advances in the application of functionalized lignin in value-added polymeric materials. In *Polymers* (Vol. 12, Issue 10, pp. 1–24). MDPI AG. https://doi.org/10.3390/polym12102277

36. Waqas Ali Shah, S., Ma, K., Ullah, R., Ali, E. A., Qayum, A., Zahoor, Uddin, N., & Zhu, D. (2023). Laccase and dye-decolorizing peroxidase-modified lignin incorporated with keratin-based biodegradable film: An elucidation of structural characterization, antibacterial and antioxidant properties. *Food Chemistry: X*, *20*. https://doi.org/10.1016/j.fochx.2023.101035

37. Yan, L., Huertas-Alonso, A. J., Liu, H., Dai, L., Si, C., & Sipponen, M. H. (2025). Lignin polymerization: towards high-performance materials. In *Chemical Society Reviews* (Vol. 54, Issue 14, pp. 6634–6651). Royal Society of Chemistry. https://doi.org/10.1039/d4cs01044b

38. Yu, O., & Kim, K. H. (2020). Lignin to materials: A focused review on recent novel lignin applications. In *Applied Sciences (Switzerland)* (Vol. 10, Issue 13). MDPI AG. https://doi.org/10.3390/app10134626

39. Zheng, Y., Moreno, A., Zhang, Y., Sipponen, M. H., & Dai, L. (2024). Harnessing chemical functionality of lignin towards stimuli-responsive materials. In *Trends in Chemistry* (Vol. 6, Issue 2, pp. 62–78). Cell Press. https://doi.org/10.1016/j.trechm.2023.12.001