Advanced Approaches in Rice Straw Valorisation: Efficient Extraction and Purification of Cellulose and Lignin for Sustainable Biomaterials

V. M. Serrano-Martínez*, H. Pérez-Aguilar, M. P. Carbonell-Blasco, F. Arán-Ais and E. Orgilés-Calpena

Footwear Technology Centre (INESCOP), 03600 Elda (Alicante), Spain
*vmserrano@inescop.es

INTRODUCTION

Rice straw is an agricultural waste that is burnt in large quantities in the Albufera of Valencia once the harvest is finished, which generates significant environmental damage. In order to avoid wasting resources and reduce pollution, it is proposed to transform this material, revaluing it to obtain a new value-added product and use it as a source of lignin and cellulose, giving rise to materials for footwear, such as soles, insoles, and adhesives.

In this sense, the revaluation of rice straw produced in the Valencian Community could avoid the emission of 77,850 tons of CO_2 into the atmosphere each year. Our study proposes an innovative solution to this challenge by converting rice straw into valuable biomaterials, primarily focusing on the extraction and purification of cellulose and lignin through advanced biotechnological methods.

EXPERIMENTAL

The extraction of cellulose and lignin from rice straw is a complex process involving several stages and variables that must be carefully controlled to achieve maximum yield and quality of the products obtained. For biorefinery processes there are various treatments such as physical, chemical, and enzymatic. Among the cellulose extraction methods, physical hydrothermal treatment with steam (steam explosion) and alkaline chemical treatment are two of the most widely used due to their efficiency and low cost (Pérez-Limiñana et al., 2022). For lignin extraction, different methods can be used, such as oxidation with peroxides, alkaline treatment, or steam explosion.

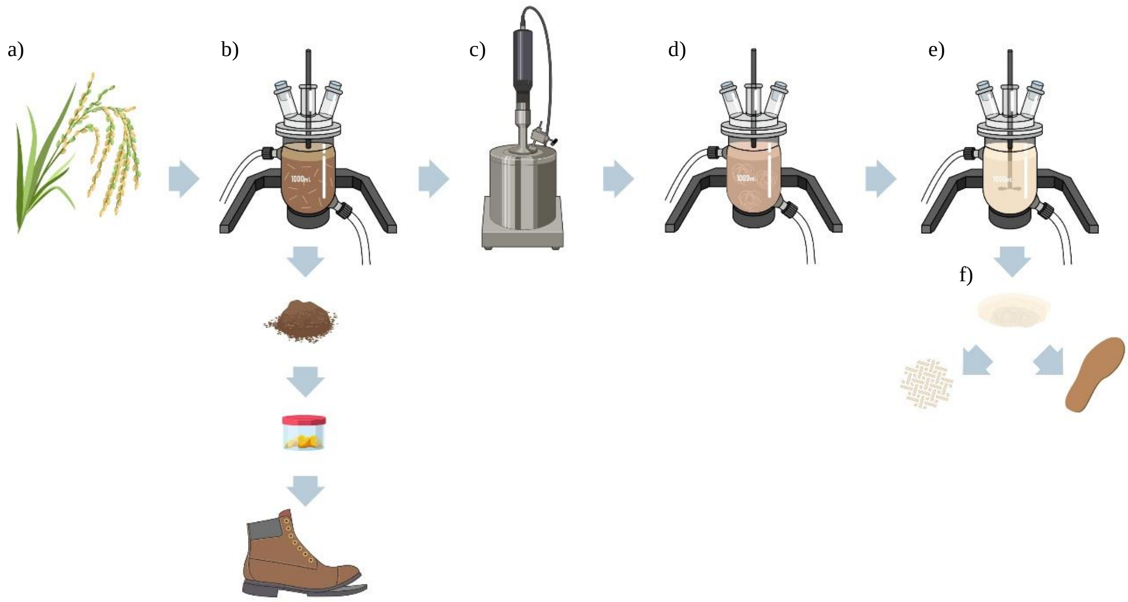

Figure 1. Cellulose and lignin extraction process performed for rice straw revalorization. Being: a) Raw rice straw; b) Pretreatment stage; c) Steam explosion stage; d) Oxidation stage; e) Bleaching stage and f) Obtained cellulose. From step b) lignin is obtained, which can serve as a source for obtaining polyols and then adhesives. Likewise, from step f) cellulose fibres and soles can be obtained.

In this research, steam explosion is used as the main method of lignin extraction, using the reaction supernatant. In this way, the lignin present in rice straw can also be used to produce polyols, one of the main reagents for synthesizing a type of adhesives such as polyurethanes, therefore being rice straw completely revalued (Hernández-Ramos et al., 2021). Simultaneously, our research delves into the purification of lignin. The lignin is subjected to fractionated purification techniques, resulting in various degrees of purity depending on the conditions applied. These purified lignin fractions are characterized thoroughly to assess their suitability for industrial applications, particularly as a source for synthesizing adhesives. The chemical properties and structural characteristics of lignin are meticulously analysed to optimize its use in polyurethane production (Blasco et al., 2022).

Likewise, the aim of this study is to determine how the processing conditions of rice straw affect the cellulose extraction yield, by optimizing the hydrothermal process, pre- and post-processing, as well as the properties of the cellulose fibres (Sarker et al., 2021). Thus, the obtained cellulose undergoes an exhaustive characterization process, encompassing its chemical composition, structural properties, and physical and mechanical characteristics. Figure 1 shows the full process performed in order to extract both cellulose and lignin.

Furthermore, the extracted cellulose is processed to produce nanocellulose, a highly versatile biomaterial with diverse applications in various industries, including textiles and environmental engineering (Sreeraj et al., 2022; Wei et al., 2014). The nanocellulose is characterized comprehensively, focusing on its nanoscale morphology, rheological behaviour, and thermal stability (Shaikh et al., 2021). This detailed characterization ensures that nanocellulose derived from rice straw meets the stringent quality requirements of modern biomaterials.

Analytical techniques like Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetry (TGA), Scanning Electron Microscopy (SEM), Z-Potential analysis, and X-ray Diffraction (XRD) play a crucial role in evaluating the quality and properties of the extracted materials. These methods provide in-depth insights into the chemical composition, structure, and physical and mechanical properties of the cellulose fibres and lignin.

RESULTS AND DISCUSSION

The composition in hemicellulose, cellulose, and lignin of each of the samples obtained for the different processes carried out was studied based on thermogravimetric analysis (Carrier et al., 2011), which has served as a guide for making modifications to the processes and thus being able to evaluate their efficiency.

The results obtained showed an improvement in the quality of the cellulose extracted by reducing the oxidation time and eliminating the pre-treatment stage, thus reducing process times, and obtaining yields over 20%. On the other hand, lignin is extracted from the steam explosion process in the supernatant solution with different degrees of purity depending on the times and conditions of the stage. Likewise, nanocellulose is successfully obtained, with different crystallinities, morphologies and sizes depending on the applied conditions.

Our findings reveal that the optimized extraction, purification, and characterization processes not only yield superior quality cellulose and lignin but also open new horizons in sustainable biomaterial production. By transforming rice straw into valuable resources and thoroughly characterizing the obtained materials, this study contributes to reducing environmental impact, specifically in lowering CO_2 emissions by a significant amount annually. This aligns with the overarching goals of the biorefinery industry and circular economy, presenting a scalable and environmentally friendly approach to managing agricultural waste.

CONCLUSIONS

In conclusion, the research successfully demonstrated the feasibility of extracting high-quality cellulose and lignin from rice straw, coupled with comprehensive characterization efforts. The potential applications of these biomaterials, including nanocellulose and lignin purification, open new avenues for sustainable industrial practices. This study lays the groundwork for further exploration into the efficient utilization of biomass components, highlighting the importance of sustainable waste management and material reclamation in modern industry.

ACKNOWLEDGEMENTS

The authors are grateful to the BIOTECHRICE project through grant TED2021-129932B-C22 funded by MCIN/AEI/ 10.13039/501100011033 and, where applicable, by “European Union NextGenerationEU/PRTR”.

REFERENCES

Blasco, M. P. C., Limiñana, M. Á. P., Silvestre, C. R., Calpena, E. O., & Aís, F. A. (2022). Sustainable Reactive Polyurethane Hot Melt Adhesives Based on Vegetable Polyols for Footwear Industry. *Polymers*, *14*(2), 284. https://doi.org/10.3390/polym14020284

Carrier, M., Loppinet-Serani, A., Denux, D., Lasnier, J.-M., Ham-Pichavant, F., Cansell, F., & Aymonier, C. (2011). Thermogravimetric analysis as a new method to determine the lignocellulosic composition of biomass. *Biomass and Bioenergy*, *35*(1), 298–307. https://doi.org/10.1016/j.biombioe.2010.08.067

Hernández-Ramos, F., Alriols, M. G., Calvo-Correas, T., Labidi, J., & Erdocia, X. (2021). Renewable

Biopolyols from Residual Aqueous Phase Resulting after Lignin Precipitation. *ACS Sustainable Chemistry & Engineering*, *9*(9), 3608–3615. https://doi.org/10.1021/acssuschemeng.0c09357
Pérez-Limiñana, M. A., Pérez-Aguilar, H., Ruzafa-Silvestre, C., Orgilés-Calpena, E., & Arán-Ais, F. (2022). Effect of Processing Time of Steam-Explosion for the Extraction of Cellulose Fibers from Phoenix canariensis Palm Leaves as Potential Renewable Feedstock for Materials. *Polymers*, *14*(23), 5206. https://doi.org/10.3390/polym14235206
Sarker, T. R., Pattnaik, F., Nanda, S., Dalai, A. K., Meda, V., & Naik, S. (2021). Hydrothermal pretreatment technologies for lignocellulosic biomass: A review of steam explosion and subcritical water hydrolysis. *Chemosphere*, *284*, 131372. https://doi.org/10.1016/j.chemosphere.2021.131372
Shaikh, H. M., Anis, A., Poulose, A. M., Al-Zahrani, S. M., Madhar, N. A., Alhamidi, A., & Alam, M. A. (2021). Isolation and Characterization of Alpha and Nanocrystalline Cellulose from Date Palm (Phoenix dactylifera L.) Trunk Mesh. *Polymers*, *13*(11), 1893. https://doi.org/10.3390/polym13111893
Sreeraj, P. R., Mishra, S. Kr., & Singh, P. K. (2022). Characteristic features and functions of nanocellulose for its feasible application in textile industry. In *Nanocellulose Materials* (pp. 105–122). Elsevier. https://doi.org/10.1016/B978-0-12-823963-6.00013-2
Wei, H., Rodriguez, K., Renneckar, S., & Vikesland, P. J. (2014). Environmental science and engineering applications of nanocellulose-based nanocomposites. *Environ. Sci.: Nano*, *1*(4), 302–316. https://doi.org/10.1039/C4EN00059E