A Bibliometric Analysis on Recycling of Wood Waste as Innovative Sustainable Industrial Products

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Abstract: Nowadays, industrial activities continue to generate significant waste volumes, posing new challenges in their management and treatment to avoid economic losses and energy impacts. The growing demand for wood as a crucial raw material across various sectors is resulting in a higher production of waste from end-of-life wood-based products. Thus, recycling the ever-greater volumes of waste wood represents a valuable resource for the production of novel sustainable industrial materials. Accordingly, the interest in exploring the possibilities of reusing wood waste has significantly increased in recent years, driven by the environmental impact of improper wood waste disposal. The aim of the present paper is to examine the evolution of research on wood waste utilization through an analysis of the relevant literature in the field. Specifically, information extracted from bibliometric networks is used to reveal the trends in scientific contributions and identify emerging topics. The relevant literature in the field of wood waste recycling is gathered from the Scopus database, and the VOSviewer tool is used to analyse the international research findings over the last 20 years. The obtained results indicate that the reuse of wood waste may range from their use to generate renewable energy to the development of new sustainable construction materials. In particular, the research on the wood waste reuse in the construction field has attracted significant attention only in recent years, showing that future developments should focus on the economic feasibility of its use on an industrial scale.

Keywords: Wood waste; Sustainability production; Waste utilization; Circular economy; VOSviewer; Industrial symbiosis

1.Introduction

Nowadays, the increasing global energy consumption is causing serious concerns about the depletion of non-renewable resources, which also adversely impacts the environment by e.g. increased CO2 emissions and air pollution, further contributing to global warming and ecosystem deterioration [1]. Population growth has intensified the demand for food and energy resources, thereby enhancing the imperative need of sustainable resources management and waste disposal practices. Simultaneously, industrial activities continue to generate significant waste volumes, posing new challenges in their management and treatment to avoid economic losses and energy impacts. As a result, the European Union (EU) has established ambitious objectives for products recycle and landfill reduction promoting a circular economy transition aimed at savings resources, reducing pollution, and combating climate change [2]. To foster the development of greener practices in waste management, EU has issued a series of regulations and incentives, including the EU Waste Directive (Directive 2008/98/EC), the European Waste Catalogue (EWC) (Directive 2000/532/EC), which comprehensively categorize waste based on the originating industrial sector, and the Circular Economy Action Plan [3]. Therefore, owing to the central role played today by the principles of circular economy in global policies, waste recycling has captured the attention of numerous researchers in the fields of production management and industrial engineering [4,5,6,7]. In particular, the use of low-carbon materials such as wood is recognized to be crucial, and recycling its waste offers numerous benefits in terms of e.g. deforestation and CO2 emissions reduction [8]. With this recognition, the present paper proposes a bibliometric analysis, to highlight the evolution of research contributions on wood waste and identify emerging topics. To this purpose, the software VOSviewer is employed to analyze scientific contributions on wood waste derived products over the past 20 years, revealing a growing interest in wood reuse practices, especially in the construction sector, and highlighting the current need to address economic and environmental sustainability concerns on an industrial scale to cover the gap in literature. The paper is organized as follows. Section 2 discusses the wood production process, exploring the origin and types of wood waste generated during the wood processing stages. The difference between "wood waste" and "scrap wood" is also highlighted. Section 3 describes the research method, focusing on the use of VOSviewer for bibliometric

analyses. Finally, Section 4 analyzes the results obtained before concluding the document in Section 5.

2.Wood Production Process

Wood continues to play a predominant role in finishes, decorations, and furnishings, demonstrating a sort of resurgence of craftsmanship excellence in the wood sector [9]. However, since the early 21st century, there has been a significant increase in the utilization of wood, not only for traditional usage but also in innovative sectors such as energy, advanced construction materials, and wood-derived chemicals. The latter has unavoidably led to a higher generation of waste from wood processing and disposal [10]. Therefore, valorizing and recycling this resource could represent not only a financially advantageous opportunity but also a significant step towards the promotion of circular economy and environmental sustainability. Indeed, recycling wood waste could serve as an abundant and ecologically sustainable source of raw materials for producing new artefacts, meeting the growing demand for construction materials and wood-derived products [11]. Furthermore, the diversification of wood waste sources, including residues from sectors such as agriculture, forestry, food industry and paper production, underscores the importance of adopting sustainable management practices to foster responsible materials use and promote circular economy and environmental sustainability [12].

The production process of wood-based products (e.g. construction elements and furniture) involves a series of operational phases that generate a wide variety of waste. In Table 1, the main by-products generated at different stages of the production process are listed, starting from wood collection in forests to processing activities at sawmills and carpentry workshops. Waste produced include sawdust, wood chips and trimmings. In particular, sawdust accumulates in large quantities, while its utilization rate is significantly lower compared to other by-products such as bark, branches, wood chips, and pruning [13]. In addition, wood products often undergo specific treatments depending on their intended use (e.g. application of antiseptics and fire protection), which can result in additional by-products or waste [14]. Therefore, it is crucial to clarify the conceptual distinction between two key terms in the wood industry, namely "wood waste" and "scrap wood". The first one refers to wooden materials that are not suitable for reuse due to reasons such as structural limitations or temporary elements such as formwork. This category also includes by-products from wood processing. On the other hand, the term "scrap wood" refers to low-quality or contaminated wood species of poor quality [8].

Table 1: By-products generated by different processing processes

Waste and by-product	*Generative process*	*Description*
Bark	Peeler	Trunk outer layer removed during peeling
Branch	Cutting with saws or pruning	Trees' branched parts, often cut during various processing
Shavings	Processing with saws or cutters	Small fragments of wood resulting from various processing
Cuttings	Various phases	Small pieces left over from manufacturing processes
Sawdust	Cutting with saws	Thin slices of wood cut during processing
Packaging	Packaging manufacture	Wooden materials used as packaging
Dried fruit shells	Nut processing	Woody fruit shells
Straw	Vegetable fibres processing	Vegetable fibres manufactured from straw processing
Beam, strips and boards	Cutting and processing of structural elements	Larger pieces of wood used in construction
Residues from planing	Planer	Small fragments generated during planing
Unused trunk	Selecting and cutting	Unsuitable parts of the trunk removed during selection
Wooden dust	Processing with sanders	Small fine particles produced during sanding
Wooden ash	Various processing	Volatile particles produced during various processing

3. Research Method

VOSviewer is a valuable tool, particularly for conducting the bibliometric analysis of scientific documents. It develops detailed citation networks, enabling the exploration of connections between scientific articles, keywords, and authors within specific research fields. This feature facilitates the identification of the most prolific authors and collaborations, while also reveling

thematic clusters and tracking the evolution of research areas of interest over time. Additionally, VOSviewer offers the possibility to generate publication, country, and journal maps, based on co-citation networks. Users have also the possibility to adjust the number and relevance of keywords, allowing for complete customization of analyses. Moreover, the software supports data mining, mapping, and clustering of articles retrieved from different database [15]. VOSviewer is hence a versatile and comprehensive tool for exploring and understanding the landscape of contemporary research, providing a solid foundation for decision-making and guiding future development in the scientific domain [16,17,18,19]. In the present paper, documents to be analyzed by VOSviewer were searched on the Scopus database, owing to its extensive collection of academic contributions. The keywords "wood waste" and "waste utilization" were entered into the field "article title, abstract, keywords", limiting the search period from 2000 to 2024. As a result, a dataset of 2,176 documents was obtained and exported to VOSviewer to perform the bibliometric analysis. Afterwards, three bibliometric maps were developed:

- The co-occurrence map, aimed at identifying those terms frequently associated with the keywords of interest.
- The citation map by country.
- The citation map by source.

Regarding the co-occurrence map, a minimum number of 20 co-occurrences was set for every keyword, generating a list of 326 keywords. However, VOSviewer does not distinguish between singular and plural. Therefore, 56 duplicate keywords were manually removed, so reducing the number of keywords to 270.

For the citation map by country, a minimum number of 5 documents per country was imposed, and only 63 out of 122 countries met this criterion. Finally, for the citation map by source, the same criterion of at least 5 documents per source was forced, thus limiting the analysis to 85 relevant sources.

4. Results and discussion

Although the analysis spans more than a 20-year period, the co-occurrence map in Figure 1 highlights that the majority of studies on the selected keywords are concentrated from 2012 to 2018 (as indicated by the color scale representing the average year of publication). Specifically, in 2012 and 2013 (marked by the purple color), concepts such as "combustion" and "renewable energy resources" emerge. This is in line with the initial phase of the scientific research on the recovery and reuse of wood waste, primarily focused on the incineration of non-recyclable residues to generate heat. This approach resulted in the loss of recoverable materials and involved the presence of contaminants (e.g. glues, paints, and non-wood materials), whose treatment was specifically regulated based on the degree of contamination, consequently complicated the recycling process [20]. From 2014 to 2017 (represented in green), terms like "wood products", "fly ash", or "fertilizers" emerge. The latter highlights the interest to develop wood waste derived products also as fertilizers, although this may lead to soil contamination with heavy metals [21]. From 2018 onwards (represented in yellow), concepts such as "construction industry", "tensile strength", or "compressive strength" emerge, indicating a shift in the scientific landscape. It is noteworthy the increasing interest in reusing wood waste in the construction sector, with a focus on mechanical properties, concretes, and bio-composite materials. However, a more in-depth analysis reveals that many waste materials remain unused, resulting in serious environmental impacts [22]. Consequently, numerous scholars propose alternative use of wood waste, such as the employment of wood ash to enhance the sustainability of cementitious materials [23]. A highly researched area concerns the transformation of wood into a transparent material through physicochemical processes involving lignin degradation. As a result, innovative solutions as substitutes for glass are obtained, offering significant potential for use in architecture and engineering [24]. Additionally, composite materials based on wood waste and recycled plastic have been developed for construction and furniture [25]. Moreover, wood wastes are becoming increasingly important in sectors such as biomedicine and aviation, contributing to the development of lightweight and durable materials [26]. Finally, studies are also emerging on the so called "smart wood", which can respond to environmental stimuli, opening up new prospects in the field of advanced materials [27]. The main results of VOS clustering technique to indexed keywords reveal that there has been an extensive exploration of new materials at the laboratory scale in recent years. However, the papers review indicates a lack from the perspective of the industrial scale up as well as no one seems to have investigated on the economic feasibility of the development of these new materials.

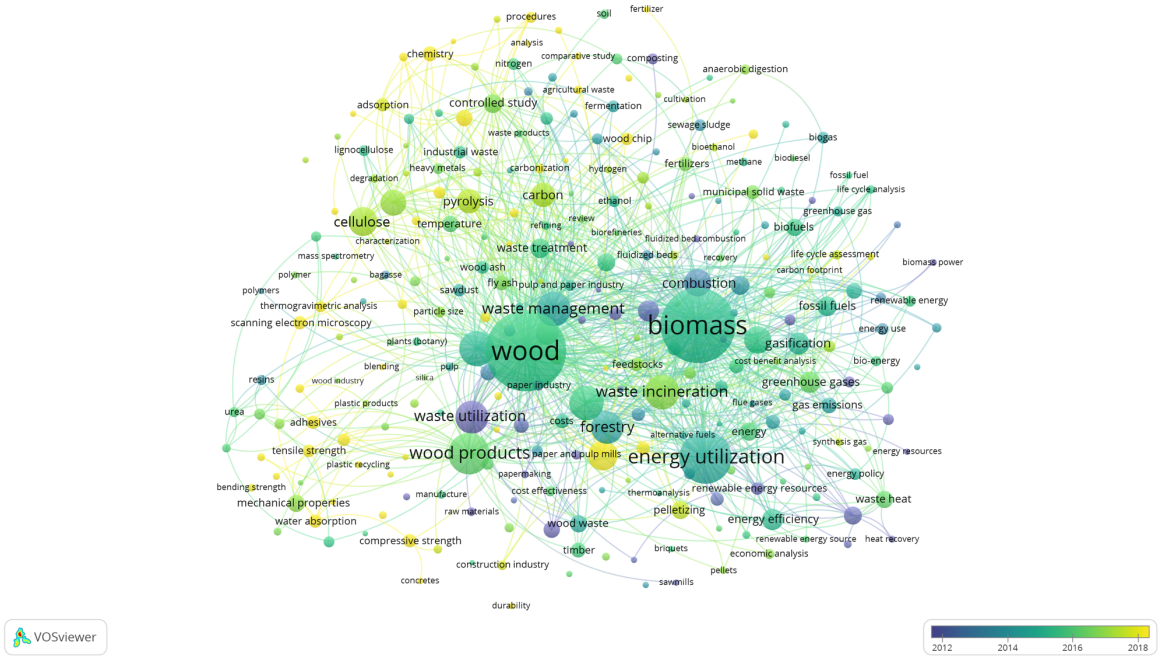

Figure 1: Co-occurrence map

In Figure 2, the map of citations by country is given. Through the color scale, it clearly highlights those publications related to the keywords "wood waste" and "waste utilization" are predominantly concentrated from 2014 to 2020. In 2014 and 2015, the purple-colored bubbles emphasize that the United States, Canada, Japan, and some European countries were the main contributors in the field. Over the years, the topic has gained interest from other countries. A notable example is China, distinguished on the map of Figure 2 by the largest green bubble. In 2019, China alone produces 354 publications and has 28 connections with other countries.

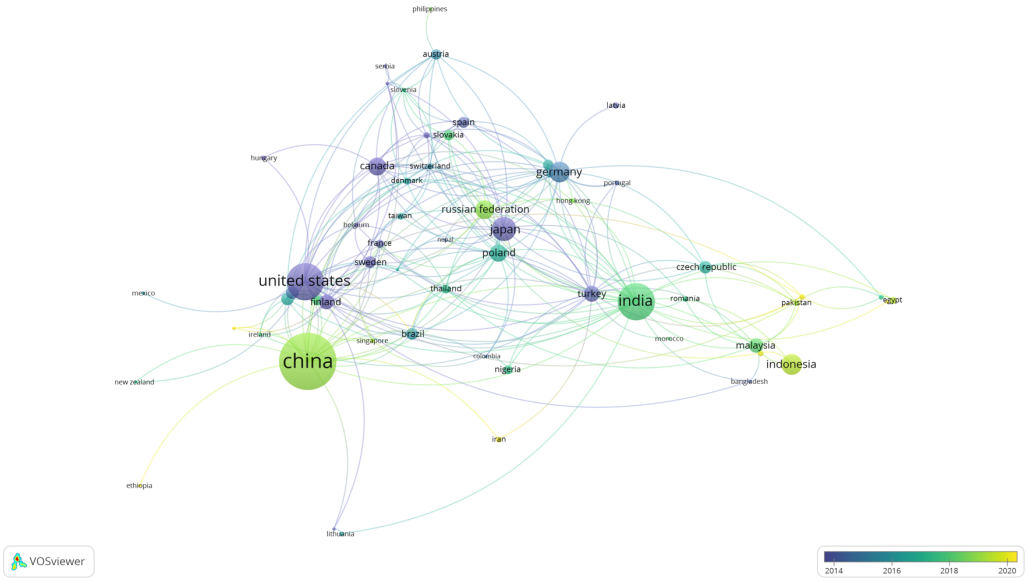

Figure 2: Map of citations by country

Finally, the map of citations by journal is presented in Figure 3. "Journal of Cleaner Production" has published the highest number of documents, with a notable peak in 2018 and 2019 when the Journal published 51 articles, cited in turn by other 20 journals. From the color scale, "Biomass and Bioenergy" and "Waste Management" journals also addressed the topic of interest from 2013 to 2015, with 40 and 41 published documents respectively. This map can help researchers to identify the main journals addressing the problem of wood waste.

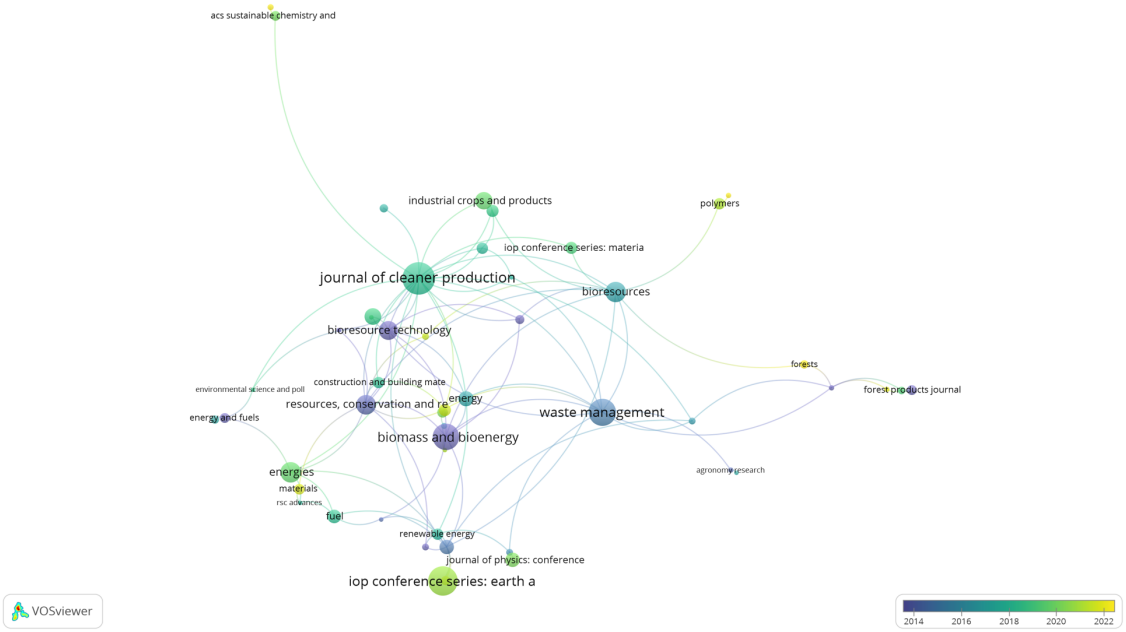

Figure 3: Map of citations by journal

5. Conclusions

The goal of this paper was to explore the research directions on wood wastes reuse by means of a bibliometric analysis. The wood production process generates numerous waste materials, highlighting the urgent need for effective and innovative management to maximize economic, environmental, and energy benefits. As a result, wood recycling emerges as a key element for the sustainable development of the sector, offering a range of opportunities to reduce environmental impact, create new markets, and contribute to climate change mitigation. The importance of careful and sustainable management of wood waste has been also emphasized at the European level, by issuing numerous *ad-hoc* regulations.

The bibliometric analysis conducted highlights a significant rise in interest regarding the recycling of wood waste from 2014 to 2020. While wood waste reusing was initially focused on the incineration of non-recyclable residues to generate energy, recent efforts have moved on understanding and testing their properties within bio composite materials. This transition suggests a potential for multiple environmental benefits, underscoring the importance of further studies and researches to overcome current limitations. Actually, challenges to be faced are still numerous, including the management of the huge amounts of unused waste, which could cause environmental damage and threaten biodiversity.

The main findings highlight that there has been an extensive exploration of new materials development at the laboratory scale in recent years. On the other hand, the papers review reveals that only few studies have focused on the industrial scale up, and no one seems to investigate on the economic feasibility of these new materials development.

Future research developments might extend the analysis considering not only keywords but even the citations between papers to extract a series of works representing the backbone of the new development of the wood waste management.

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References

[1] Aridi, R., Yehya, A. (2022). *Review on the sustainability of phase-change materials used in buildings.* Energy Conversion and Management: X, Volume 15.

[2] European Commission. (2020). *A new Circular Economy Action Plan.* Retrieved from https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[3] Burns, K., Bonaceto, C. (2020). *An empirically benchmarked human reliability analysis of general aviation.* Reliability Engineering & System Safety, 194.

[4] Saeli, M., Micale, R., Saebra, M.P., Labrincha, J.A., La Scalia, G. (2020). *Selection of novel geopolymeric mortars for sustainable construction applications using fuzzy topsis approach.* Sustainability, Volume 12, Issue 15.

[5] La Scalia, G., Saeli, M., Adelfio, L., Micale, R. (2021). *From Lab to Industry: scaling up green geopolymeric mortars manufacturing towards Circular Economy*. Journal of Cleaner Production, 316, 128164.

[6] Saeli, M., Senff, L., Tobaldi, D.M., La Scalia G., Seabra, M.P. Labrincha, JA. (2019). *Innovative Recycling of Lime Slaker Grits from Paper-Pulp Industry Reused as Aggregate in Ambient Cured Biomass Fly Ash-Based Geopolymers for Sustainable Construction Material*. Sustainability 11, 3481.

[7] Adelfio, L., Giallanza, A., La Scalia, G., La Fata, C.M., Micale, R. (2023), *Life cycle assessment of a new industrial process for sustainable construction materials*. Ecological Indicators, 148, 110042.

[8] Embrey, D.E., Humphreys, P., Rosa, E.A., Kirwan, B., Rea, K. (1984). *SLIM-MADUD: an approach to assessing human error probabilities using structured expert judgment*. NUREG/CR- 3518. US Nuclear Regulatory Publication.

[9] Churkina, G., Hassegawa, M., Herrmann, T., König, L., Nepal, P., Prestemon, J., & Verkerk, P. J. (2021). *Forest Sector Outlook Study 2020-2040*. United Nations Economic Commission for Europe, 1020-2269.

[10] Bernstein, A., Sargent, E.H., Aspuru-Guzik, A., Cogdell, R., Fleming, G.R., Van Grondelle, R., Molina, M. (2016). *Renewables Need a Grand-Challenge Strategy*. Nature, 538, 30.

[11] Azambuja, R., de Castro, V.G., Trianoski, R., Iwakiri, S. (2018). *Riciclaggio dei rifiuti di legno provenienti da costruzioni e demolizioni per produrre pannelli truciolari*. Boschi. Cienc. Tecnologia.

[12] Besserer, A., Troilo, S., Girods, P., Rogaume, Y., Brosse, N. (2021). *Cascading Recycling of WoodWaste: A Review*. Polymers,13, 1752.

[13] Lykidis, C., Grigoriou, A. (2008). *Hydrothermal Recycling of Waste and Performance of the Recycled Wooden Particleboards*. Waste Manag. 28, 57–63.

[14] G. d. l. APAT-ARPA. (2005). «Documento di studio del comparto - Falegnamerie e Segherie Artigianali». https://www.arpa.vda.it.pdf

[15] Jan, N., Ludo, V.E. (2009). *Software survey: VOSviewer, a computer program for bibliometric mapping*. Conf. Scientometric. Informetrics 84 523–538.

[16] Effendi, D.N., et al. (2021). *Bibliometric analysis of scientific literacy using VOS viewer: Analysis of science education*. J. Phys.: Conf. Ser. 1796 012096.

[17] La Scalia, G., Micale, R., Enea, M. (2019). *Facility layout problem: Bibliometric and benchmarking analysis*. International, Journal of Industrial Engineering Computations 10.

[18] Giallanza, A., La Scalia, G., Micale, R., La Fata, C.M., (2024). *Occupational health and safety issues in human-robot collaboration: State of the art and open challenges*. Safety Science, 169, 106313.

[19] Van Eck, N.J., & Waltman, L. (2010). *Software survey: VOSviewer, a computer program for bibliometric mapping*. Scientometrics, 84(2), 523–538.

[20] Lykidis, C., Grigoriou, A. (2008). *Hydrothermal Recycling of Waste and Performance of the Recycled Wooden Particleboards*. Waste Manag. 28, 57–63.

[21] Rey-Salgueiro, L., Omil, B., Merino, A., Martı´nez-Carballo, E., Simal-G, A.J. (2016). *Organic pollutants profiling of wood ashes from biomass power plants linked to the ash characteristics*. Sci Total Environ 544:535e43.

[22] Hossain, M.U., Wang, L., Iris, K.M., Tsang, D.C., Poon, C.S. (2018). *Environmental and technical feasibility study of upcycling wood waste into cement-bonded particleboard*. Constr. Build. Mater. 173 474–480.

[23] Ates, F., Kyu, T.P., Kyeong, W.K., Byeong-Hun, W., Hong, G.K. (2023). *Effects of treated biomass wood fly ash as a partial substitute for fly ash in a geopolymer mortar system*. Construction and Building Materials, Volume 376, 2, 131063.

[24] Chutturi, M., Gillela, S., Yadav, S.M., Wibowo, E.S., Sihag, K., Rangppa, S.M., Bhuyar, P., Siengchin, S., Petar, A., Kristak, L., Sinha, A. (2022). *A comprehensive review of the synthesis strategies, properties, and applications of transparent wood as a renewable and sustainable resource*. Science of the Total Environment, 0048-9697.

[25] Xia, Q., Chen, C., Yao, Y. (2021). *A strong, biodegradable and recyclable lignocellulosic bioplastic*. Nat Sustain 4, 627–635.

[26] Linkun, X., Zhenguan, T., Lu, J., Breedveld, V., Hess, D.W. (2015). *Creation of superhydrophobic wood surfaces by plasma etching and thinfilm deposition*. Surface & Coatings Technology, 0257-8972.

[27] Zhai, K.Z., Cao, Z., Wang, W.Y., Li, L., Li, J., Liu, J., Xie, Y., Gan, W. (2023). *A sustainable pore wall strengthening for strong and fire-retardant nanopolymerised wood*. Chemical Engineering Journal, 1385-8947.