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A critical review on reuse potentials of wood waste for innovative products and applications: trends and future challenges

Rosanna Leone [a], Giada La Scalia [a], Manfredi Saeli [b,*]

[a] Department of Engineering, University of Palermo, Viale delle Scienze, Bld. 8, 90128, Italy
[b] Department of Architecture, University of Palermo, Viale delle Scienze Bld. 8-14, 90128, Italy

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ABSTRACT

This study conducts a systematic review of the scientific literature to understand the main trends related to wood waste reuse in the production of innovative and sustainable materials and products, in light of the Circular Economy approach and the Sustainable Development Goals. The main objective is to fill the existing gaps in the literature, outline possible future challenges, and initiate a new phase of experimentation on innovative bio-composite products. Using the Scopus database and applying the software VOSviewer and mySLR, a selected number of papers were analysed to identify trends and areas of interest in the management, valorisation, and reuse of wood waste in various industrial fields. The research mainly considers products that are both tested and in the experimental phase, emphasizing the need for a holistic approach to waste management and proposing the adoption of strategies such as the "6R" principles (reduce, reuse, recycle, recover, redesign, and regenerate). The bibliometric analysis, and a deep analysis of selected studies, revealed a growing interest in the use of wood waste in long-term applications, such as construction, bio-fuels, energy, and biocomposite materials, offering novel opportunities to promote sustainability, waste management, and reduce the environmental impact associated with this waste.

1. Introduction

The pursuit of sustainable development has increased attention on the conservation of non-renewable natural resources, the minimization of waste production, and the reduction of Greenhouse Gas emission [1]. In this context, the innovative use of waste-based materials, particularly those derived from wood streams, presents a promising solution [2,3]. Industrial activities, including the wood industry, generate enormous quantities of waste annually, posing challenges in waste management, treatment, and disposal, leading to financial losses and deep environmental impact [3]. Generally, the usual waste final destination is landfilling with massive environmental footprint, often associated to deep land and water contamination, and health concerns for humans and living beings in general. Therefore, to address these issues, the European Union (EU) has set ambitious green targets for waste reduction and recycling as valid alternative to landfill use, hence reducing such practice and promoting a real Circular Economy focused on resource efficiency, pollution reduction, and climate change mitigation [4]. EU key regulations include the Waste Framework Directive [5] and the Waste Catalogue [6], along with the Circular Economy Action Plan [7]. These initiatives emphasize the principles of "reduce, reuse, recycle", encouraging the reuse, recycling, and extension of product lifecycles to minimize waste and maximize resource efficiency [8]. This shift from viewing waste as a treatment and disposal issue to management and valorisationas a proper resource promotes innovation, new economic opportunities, and job creation [9]. Increasing the use of wood, for example, in long-term applications – that also means considering collateral end-of-life applications - would help achieving the Sustainable Development Goals and promoting the Circular Economy approach [10]. Wood-based products have consistently demonstrated a lower carbon footprint compared to other building materials such as steel, aluminium, cement, and bricks [11–13]. To date, wood waste is generated by various industries, particularly the furniture manufacturing and design sectors, as well as construction in general, presenting both challenges and opportunities. A holistic approach to solid waste management, including the adoption of a "Zero Waste" philosophy [14,15], is extremely urgent to improve the quality of the environment, still compromised by humans' indiscriminate actions. Therefore, the implementation of lean production strategies and the "6R" principles (reduce, reuse, recycle, recover, redesign, and regenerate) has

* Corresponding author.
E-mail address: manfredi.saeli@unipa.it (M. Saeli).

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been proposed to reduce wood waste in the furniture industry and move towards a more sustainable model [16,17]. These strategies not only minimize waste, but also promote resource efficiency and the extension of product lifecycles, in line with circular economy principles [18]. Furthermore, there are already studies in the scientific literature addressing strategies for reusing these wastes, such as the use of agricultural residues as a base material for biofuel production [19] or novel functional building materials [20,21], the transformation of food waste into high-quality compost for organic farming or the use of industrial waste for the generation of novel eco-friendly building materials [22, 23]. These approaches not only help to reduce the environmental impact caused by waste but also offer innovative economic opportunities through the valorization and reuse of waste materials. Among the produced organic wastes, wood residues occupy a primary position being still enormous amounts of wood waste that are not reused and usually landfilled or incinerated, causing further significant environmental impact [24,25]. The combustion of wood waste generates massive quantities of ashes and residual substances that cause environmental damage, ecological challenges, and health problems, especially if not managed properly [26]. Additionally, a significant percentage of wood waste currently used as fertilizer can cause soil pollution due to the presence of heavy metals [27].

Therefore, the main objective of this paper is to provide a comprehensive overview of current strategies for wood waste reuse, focusing on the most tested and experimental application areas, the products already realized, and the literature gaps that require further study. To this end, the analysis aims to answer the following research questions (RQ):

RQ1: What types of wood waste are generated and from which industrial processes or activities do they originate?
RQ2: What are the current practices, challenges, and future directions in the management and utilization of wood waste across different industries?
RQ3: What thematic areas could be further explored?

Unlike prior reviews that addressed generic themes on bio-waste valorisation or narrowly focus on selected technologies or applications only, the novelty of the present study stands on the proposal of a targeted and replicable review framework that, in this case, is exclusively focused on wood waste and their reuse intended for material and product development, basing on the scientific literature indexed in the databases. Moreover, a further point of novelty of this work lies in the combined use of hybrid methodologies that associate bibliometric mapping (i.e., VOSviewer, MySLR), with full-text qualitative analysis, and AI driven clustering.

The analysis begins with a comprehensive bibliometric survey aimed at identifying studied themes and application areas related to wood waste. Subsequently, a literature review is conducted on a selected number of papers to examine in detail the strategies that have been employed to address this issue, focusing on the reuse of waste as a resource and the progress made in this field.

The document is structured as follows: Section 2 describes the wood production process and the types of waste that are generated from the various processing phases; Section 3 describes the methodological approach for the bibliometric analysis and the subsequent literature review; section 4 presents the results of the bibliometric analysis and of the literature review of the articles selected for their relevance on the topic, while conclusions are presented in Section 5.

2. Wood waste: processes and types

To answer to the first question ***RQ1*** it is crucial to distinguish between the two terms, "wood waste" and "waste wood". The former typically refers to wooden materials that are unsuitable for construction due to various factors, such as structural limitations, their origin from residual construction elements, or their use in temporary structures (e.g., formwork). This term also encompasses lumber from pallets used in the transportation industry, as well as other by-products of the woodworking process. In contrast, the term "waste wood" is employed to describe wood of low quality, contaminated wood, or wood derived from low-grade species [28]. Wood is characterized by primary and secondary growth of the trunk, evidenced by the formation of concentric annual rings (American Institute of Timber [29]). This material is extremely versatile, easily workable, and biodegradable, showing significant advantages in a variety of applications as construction, furniture making, and the production of everyday objects. However, wood processing generates significant amounts of waste at the various stages of the manufacture process for wood-based construction elements, furniture, and architectural products [25]. The production chain, from forest to sawmill/carpentry, includes operational phases that produce various types of waste (American Institute of Timber [29]: Lykidis et al. [30]; Leone et al. [20]), as here briefly discussed and further summarized in Table 1.

1. **Felling**: The transition from tree to log requires advanced technical skills to ensure a clean cut and controlled fall. In this phase, delimbing and debarking, either manual or mechanical, produce the first waste types: branches and bark. These wastes can be reused as natural fertilizer or fresh wood chips (Bois Raméal Fragmenté - BRF), used in agriculture for mulching and soil enrichment.
2. **Chipping and Steaming**: Consists of cutting logs into smaller pieces to facilitate handling and steaming to remove impurities. Here, wastes such as chips and sawdust are also generated.
3. **Stacking and Seasoning**: Wood log pieces are sent to the sawmill where every piece is carefully examined to find out flaws and selected for type of end-use, then dried and seasoned to balance internal moisture and avoid possible slotting and/or deformations. This phase also generates waste, especially during cutting into selected sizes for beams, slats, and boards.
4. **Final Cutting**: This phase causes the largest quantity of waste, including sawdust, chips, and offcuts. Sawdust is particularly abundant and shows a lower utilization rate compared to other waste's types such as bark, branches, or chips [31].

Wood products are then treated with antiseptic agents and fire

Table 1
Main wood wastes deriving from the various manufacturing processes.

Waste and By-product	Generative Process	Description
Sawdust	Sawing	Fine wood particles produced during cutting
Bark	Peeling	Outer layer of the trunk removed during peeling
Dried nut shells	Nut processing	Woody shells of dried fruits
Beams, strips, boards	Structural cutting and processing	Larger wood pieces used in construction
Planing residues	Planing	Small fragments produced during planing
Shavings	Sawing or cutting	Small wood fragments generated during processing
Wooden dust	Sanding	Fine particles created during sanding
Packaging materials	Packaging production	Wood materials utilized for packaging purposes
Rejected trunk segments	Selection and cutting	Trunk parts deemed unsuitable and removed
Offcuts	Various manufacturing phases	Leftover small pieces from manufacturing processes
Straw fibers	Vegetable fiber processing	Vegetable fibers derived from straw processing
Wood ash	Various processing methods	Ash produced from various wood processing
Branches	Sawing or pruning	Tree branches cut during various processing stages

retardant, generating additional waste. About 20% of the construction and demolition (C&D) waste is wood [32]. Sectors such as agriculture, forestry, the pulp and paper industry, the food sector, and other commercial activities also contribute to wood waste production [33].

3. Materials and methods

To address the key contributions and answer the research questions outlined above, a structured methodological approach, consisting of several consecutive steps, was implemented. The Scopus database, chosen for its relevance, was initially used to conduct the study, focusing on the period from 2000 to 2024 to analyze the temporal trends of the documents. Based on pre-established “inclusion” and “exclusion” criteria, non-relevant documents were discarded. The remaining documents were then listed and subjected to a comprehensive text analysis; thus, obtaining the final list of documents for the literature review.

The primary objective of this methodology was to address ***RQ2***, aimed to identify the most explored topics and application areas of wood waste by professionals and academics to date. To achieve this goal, the Scopus database was used, and keywords were linked using the logical operator "AND". The search was restricted to articles and reviews published exclusively in English. By using the string "wood AND waste" in the "Article Title", "Abstract", and "Keywords" fields of the Scopus database, a total of 17,349 documents were obtained.

Figs. 1-3 provide an overview of the research on wood waste indexed in the Scopus database. Fig. 1 shows the number of documents that were published on the topic from 2000 to 2024. It is observed that the resulting trend is extremely positive meaning that the topic is gaining increasing scientific interest. This is driven by the rising number of studies focused on waste reuse in general, as well as the growing demand from industries to find practical solutions to increase sustainability in manufacturing processes.

The interest in wood waste began at the beginning of the 1970s when “Zero Waste” concept started to arise as an ambitious goal to tackle the growing waste problem and promote sustainability among industries. Such interest has increased significantly since 2000 when the concept of Circular Economy spread globally as a viable approach to transform the producer countries into a resource-efficient society able to reduce waste generation, while increasing reuse and recycling practices, ensuring a safe disposal of non-recyclable waste, and promoting more sustainable consumption processes [1]. This trend also reflects a growing scientific-academic interest and heightened environmental awareness regarding the sustainable management of wood waste, mainly following the worldwide regulations on wastes treatment and reuse. Finally, the number of studies has recently increased indicating a strong commitment for innovation and the adoption of circular economy policies. For this specific reason, the analysis conducted in this review study focused on the years 2000-2024.

Fig. 2 illustrates the number of publications on wood waste, listed by country or territory. By analysing the scientific output of various geographical regions, it is possible to identify the leading nations conducting research in the field and evaluate the research distribution, and interest, globally. More particularly, United States, China, and India, are leading the research activities for both the number of the present Institutes and fundings dedicated to waste recovery. That is probably due for the enormous quantity of wood waste produced in those territories that arises serious problems to the economic compartment. Brazil and Canada also show significant interest in the topic, though to a less extent. Russia, Spain, Japan, the United Kingdom, Germany, and Italy, exhibit a moderate level of research activity in this field. Finally, Fig. 3 includes a pie chart that visualizes the distribution of these documents by subject area of interest.

It is observed that direct applications in Environmental (20.8%) and Engineering (13.5%) studies arise the major interest in wood waste research among researchers worldwide. That is easily explainable by the latest global research directions towards sustainability, the easier drawbacks on society, and the potential of technological transfer to market. Also, Energy (10.9%) plays a key role for the immediate potentials on the environment beyond the various possibilities of using wood waste as a renewable energy source. Material science and Chemical engineering account for 9.3% each, with studies generally dedicated to novel materials development and/or characterization. Agriculture and biological sciences cover 8.9%, while Chemistry represents 7.0% with specific studies on materials’ chemistry. Other disciplines, including biochemistry, genetics, physics, astronomy, and earth sciences, collectively account for approximately 15.6%. Finally, 11.7% of the documents fall into unspecified categories, underscoring the extreme multidisciplinary nature of wood waste research. Subsequently, the search was refined by building upon an initial query using the keywords "wood AND waste", which returned 17,349 documents. The addition of the condition "circular AND economy" reduced the number of results to 453. Further refinement was made by adding the new condition

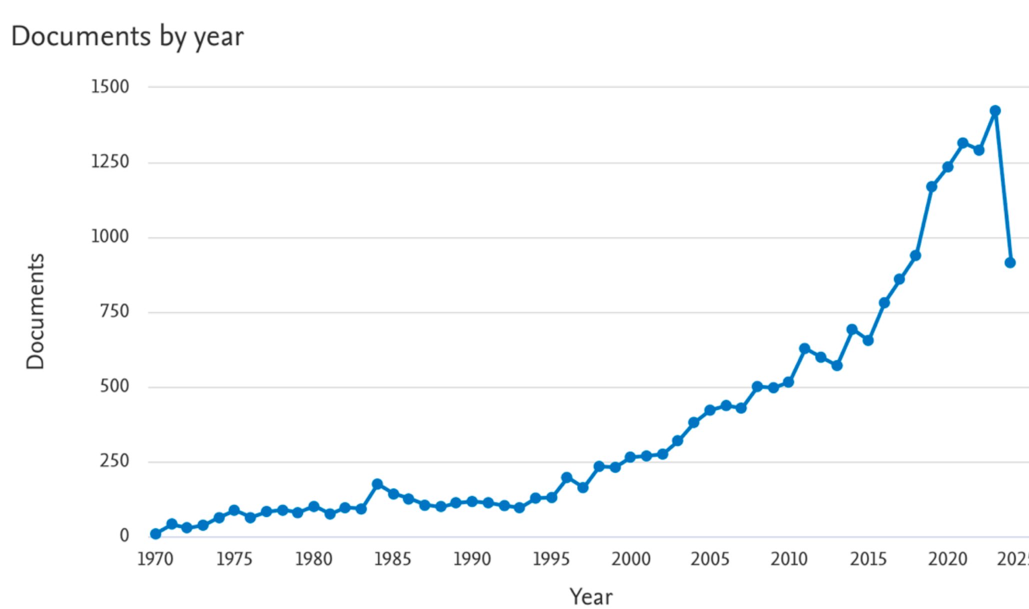

Fig. 1. Number of documents published by year.

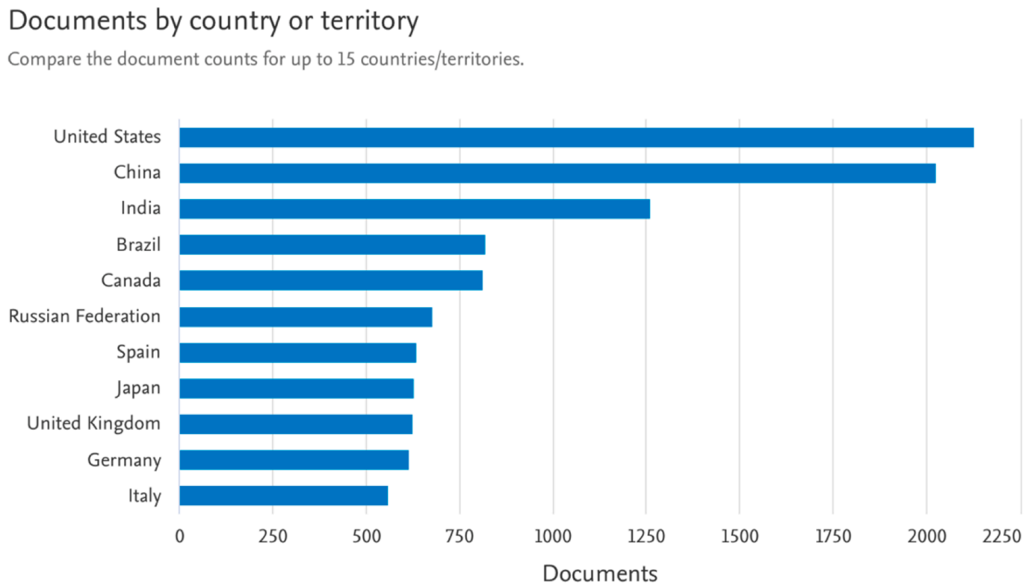

Fig. 2. Number of documents published by country/territory.

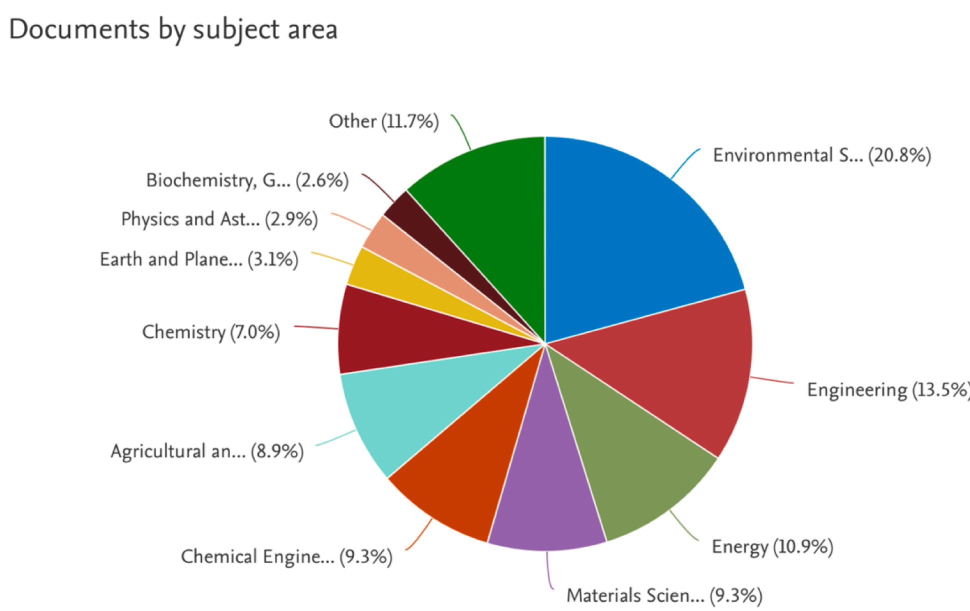

Fig. 3. Documents by Thematic Area.

"products", narrowing the results to a final set of 167 documents.

To refine the dataset and ensure consistency in the level of peer-reviewed visibility, a journal quartile filter was applied in order to select papers published in first-quartile (Q1) journals only, according to the Scimago Journal Rank for the year of publication. That filtering step, carried out using the Scimago database in combination with an Excel spreadsheet, resulted in a novel final set of 96 documents. The dataset was exported in CSV format on March 15, 2024, and used for further bibliometric and topic modeling analysis.

Subsequently, the research was refined by combining bibliometric and topic modeling analyses to explore the structure and focus of the selected literature. Two complementary software tools were employed to analyse the selected documents: VOSviewer and My Systematic Literature Review (MySLR). VOSviewer was used to generate three types of bibliometric maps:

1. Co-occurrence Map – to identify key terms and themes based on keyword frequency;
2. Co-citation by Source Map – to reveal interlinked citation patterns among journals and publications;
3. Co-authorship by Country Map – to explore international collaborations and geographic distribution of research.

These visualisations supported a preliminary understanding of research trends, thematic clusters, and knowledge networks within the corpus [34–36].

To refine the analysis, the dataset was processed using MySLR, which supports the management and evaluation of systematic literature reviews. In particular, it enabled the import and organisation of bibliometric data, including titles, authors, journals, publication years, methodologies, and key findings [37,38].

A Latent Dirichlet Allocation (LDA) model was then applied using the same MySLR to uncover hidden thematic structures within the corpus.

The model parameters were as follows:

- Number of topics: 4 (selected based on interpretability and internal validation);
- UMass coherence score: –3.67;
- Perplexity (log scale): –7.33.

Although these scores were negative, this is ordinary for log-scaled validation metrics and did not imply poor model performances. Moreover, the obtained values were consistent with accepted thresholds in topic modeling literature and further validated through manual inspection of the topics generated.

Among the identified four topics, the one titled "Sustainable production and materials" emerged as the most relevant to the selected research objectives, encompassing 61 out of the 96 papers. Therefore, this topic was selected for in-depth qualitative analysis. A full-text screening of the 61 papers was then conducted to assess their alignment with the specific aim of exploring wood waste reuse for material and product development. While all documents contained the search keywords, 28 were excluded after careful reading, as they did not explicitly focus on reuse pathways or provided limited detail on valorisation strategies of wood waste in the context of product or material innovation. The final dataset comprised 33 papers that directly contributed to the construction of thematic clusters based on specific reuse approaches and technological directions. To classify the 33 selected papers thematically, a hybrid clustering process was conducted. We employed the tool ChatGPT-4 to assist with initial categorisation, using prompts such as “Based on this abstract, which theme best represents the article’s main focus among the following categories?” and “Summarise the main topic of this article in one sentence using keywords”.

Although generative AI supported the clustering, all outputs were independently reviewed by the authors through iterative full-text readings to validate accuracy and alignment with the review objectives. The papers were then grouped into summarising five thematic clusters (see Section 4).

Evidently the use of AI may present potential limitations such as misinterpretation of domain-specific language or subtle conceptual differences. For this reason, to avoid any bias, the final classification reflects the authors’ critical judgement and responsibility.

The overall methodological workflow is summarised in the flow diagram (Fig. 4), which outlines the main steps of the review process.

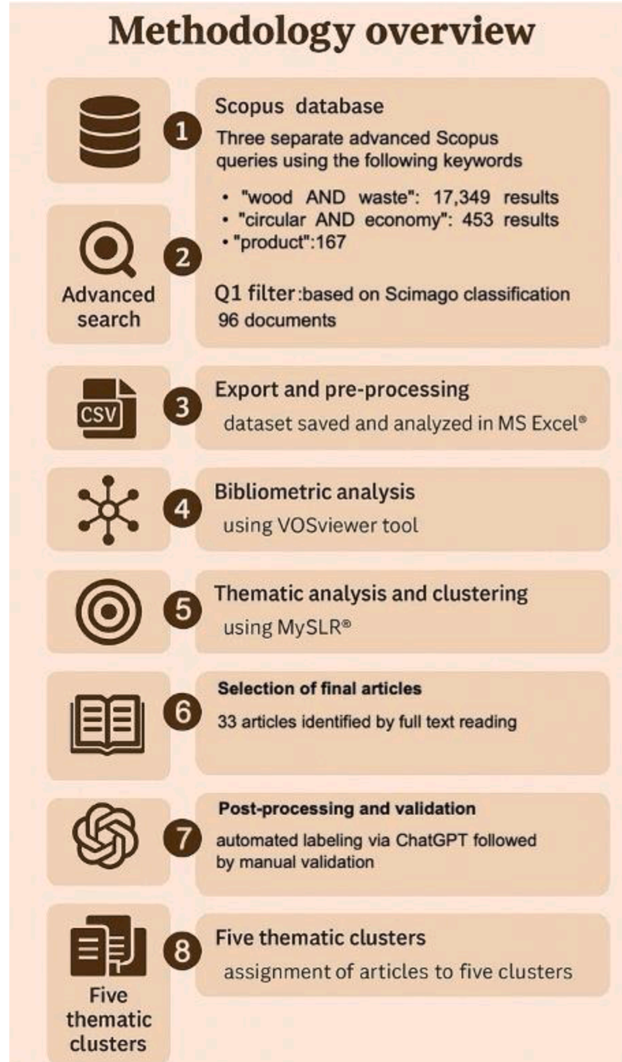

Fig. 4. Overview of the methodological workflow used for the systematic review on wood waste reuse.

4. Results and discussion

4.1. Bibliometric analysis

The co-occurrence map, shown in Fig. 5, was designed with VOSviewer. Here, a minimum threshold of 5 co-occurrences per keyword was set, with a manual reduction to 40 keywords after removing some detected 15 duplicates.

Although the complete analysis covers a period of over 20 years (2000-2024), the co-occurrence map shows that most of the studies, basing on the selected keywords, are concentrated between 2019 and 2022, as indicated by the colour scale representing the average year of publication. Between 2019 and 2020 (blue mark), concepts such as “waste treatment”, “wood plastic composite”, and “mechanical properties” emerge, suggesting a shift in the scientific focus towards the feasibility of manufacturing novel products starting from wood waste, including applications in the construction sector. The growing interest in reusing wood waste in construction is notable, with particular attention to mechanical properties, and materials such as concrete and biocomposites. In 2021 (green mark), concepts such as “circular economy”, “environmental impact”, and “LCA” (Life Cycle Assessment) emerge, indicating increased attention to waste circularity and environmental impact analysis. Finally, in 2022 (yellow mark), an interest in techniques such as reuse and pyrolysis arises, suggesting further developments in material science and material sustainable management.

Fig. 6 shows the co-citation map by Q1-ranked journals. Here, the criterion of at least 15 citations per source was applied, resulting in 57 relevant sources and a total of 957 links. The “Journal of Cleaner Production” emerges as the journal with the highest number of citations (183) among the 96 analysed documents and the most links (44) between journals. It is followed by “Bioresource Technology” with 118 citations and 43 links, and “Resources, Conservation and Recycling” with 69 citations and 36 links. This map represents a valuable tool for researchers seeking to identify the leading journals in the field of wood waste. For the co-authorship map by country, a minimum of 3 documents per country was set, resulting in 17 entities and a total of 52 connections.

It is interesting to note that the analysis of the 96 selected documents reveals a discrepancy with the data shown in Fig. 3, which listed the United States as the leading country in general wood research. From VOSviewer analysis (Fig. 7), it further resulted that Spain produced the highest number of publications (15 documents), followed by the United Kingdom (14 documents), China (12 documents), and Italy (10 documents).

As already stated, the original pool of publications displayed a wider geographical distribution (cf. Fig. 3); however, that became more

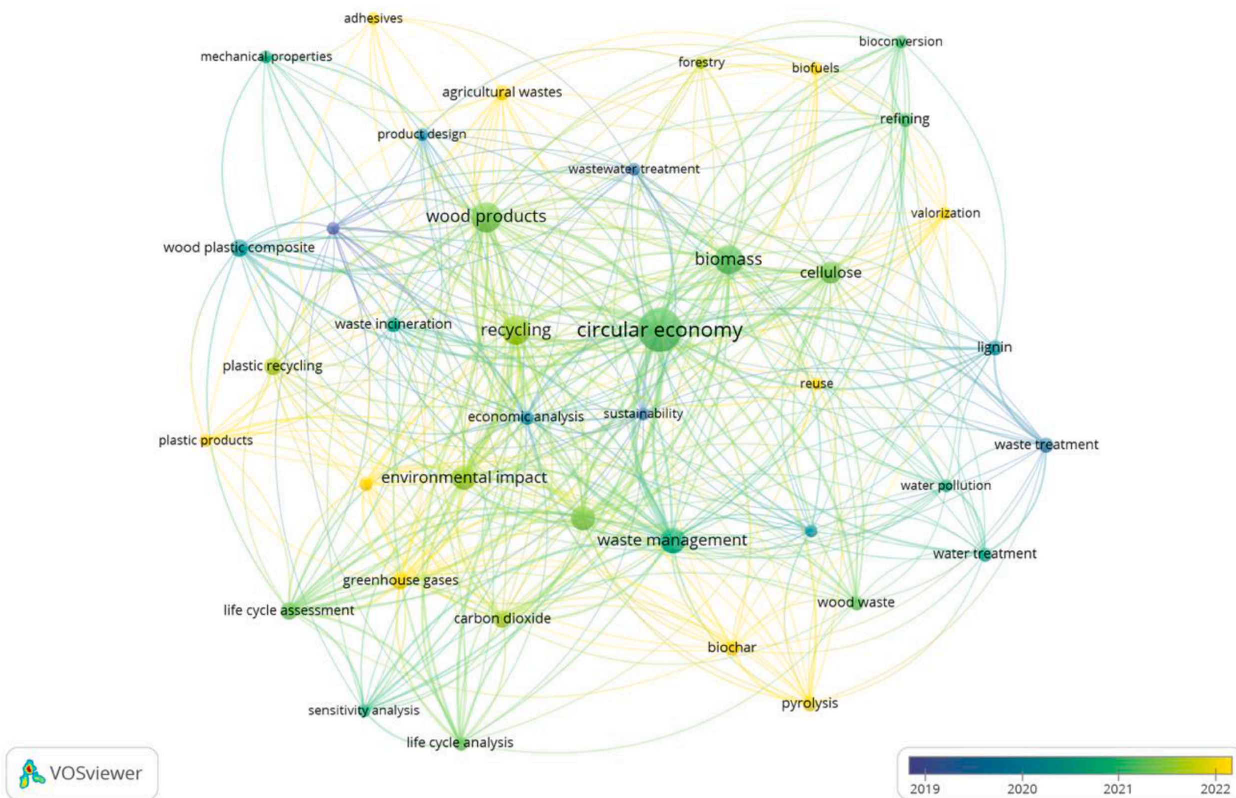

Fig. 5. Co-occurrance map designed on the selected 96 documents (coloured bar indicates the average year of publication).

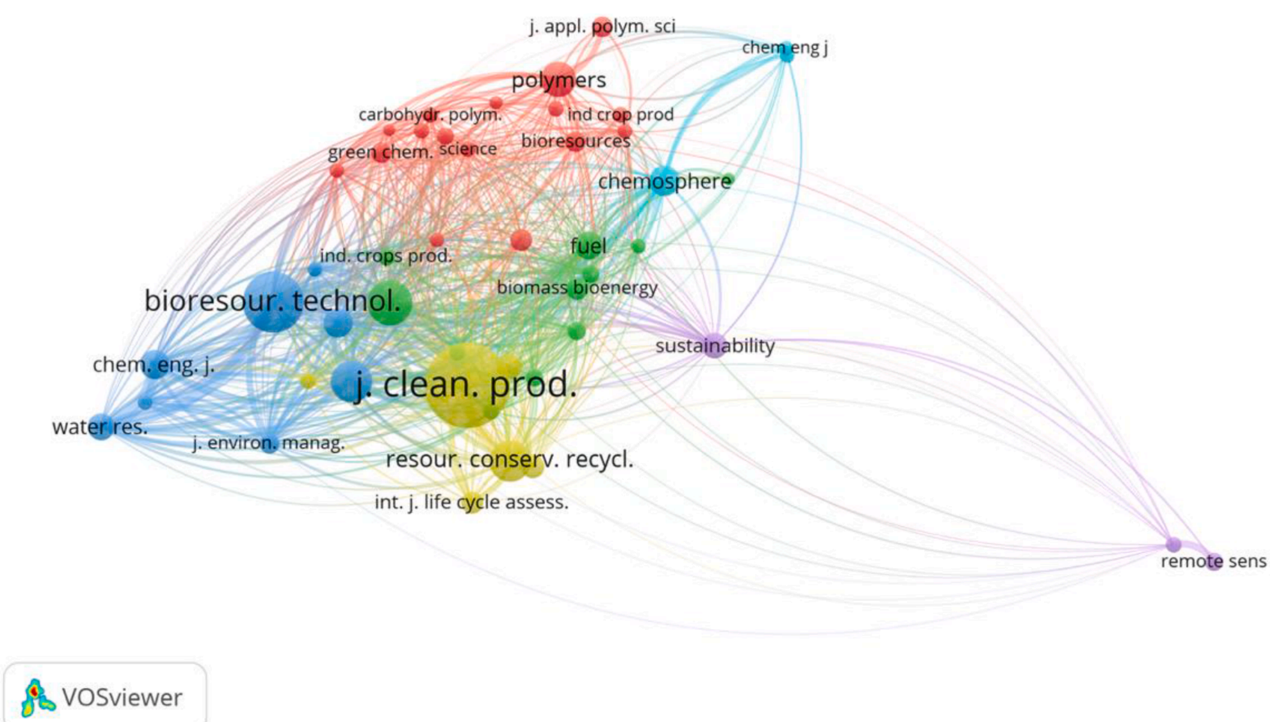

Fig. 6. Co-citation network of documents published in Q1 Journals by source.

limited after applying quality-based filters (Q1 journal filter), applied during the selection process. Consequently, the final dataset resulted deriving from high-income countries (e.g., Spain, UK, China, and Italy). While that criterion ensured the inclusion of peer-reviewed and high-impact studies, it also led to a restriction in geographic diversity compared to the broader initial dataset. This narrowing effect may introduce geographic bias, underrepresenting innovative practices and reuse strategies emerging in low- and middle-income countries. Further

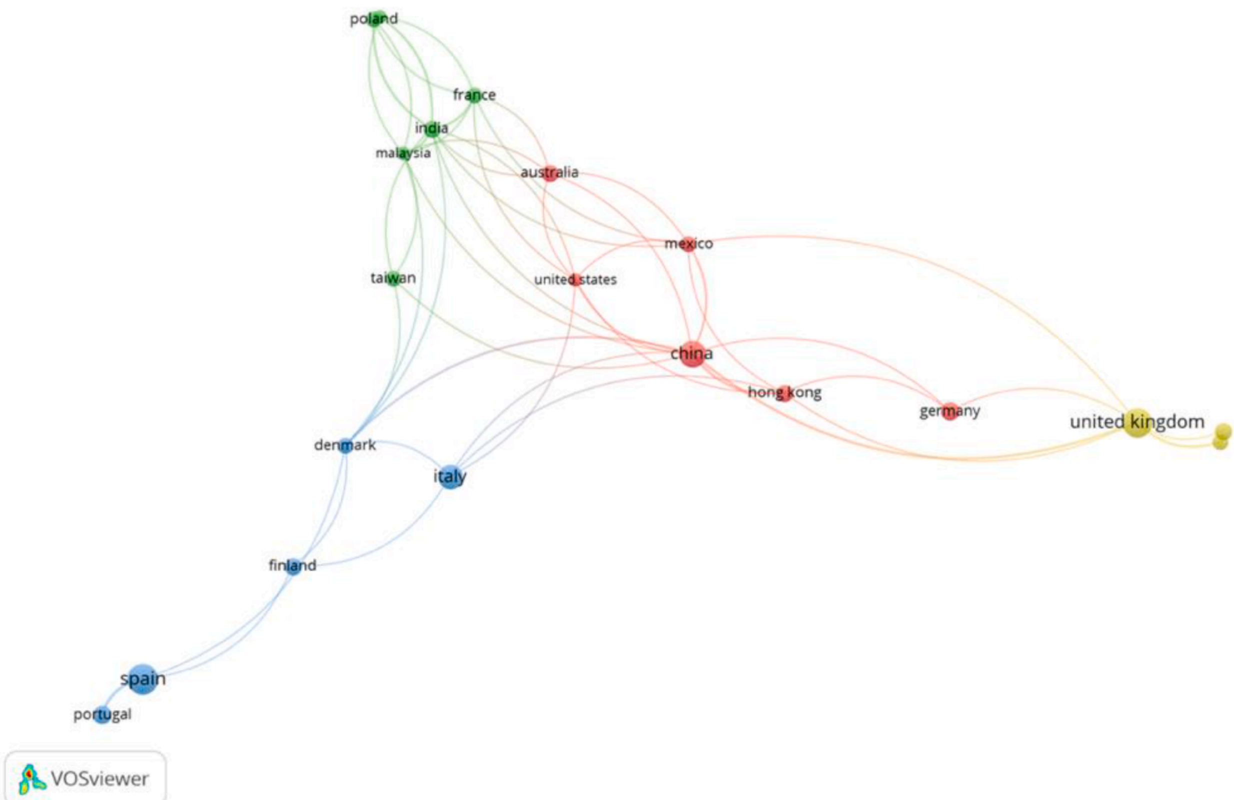

Fig. 7. Network of documents published in Q1 Journals by country, with co-authorship links.

studies will address more impacting geographic distributions.

Fig. 8 presents the occurrence of the mostly used words, individuated for research area, and presented as word clouds, as generated by MySRL. It is observed that clouds mainly identify four key topics of investigation. Each topic was here named based on the predominant words extrapolated from texts and titles of the considered articles. This analysis revealed the specific areas of interest explored by each topic, highlighting the variety of the involved fields and the increasing importance of themes related to reuse and sustainability in materials research. The results clearly show the relevance and multidisciplinary of these topics, reflecting the growing interest in sustainable practices.

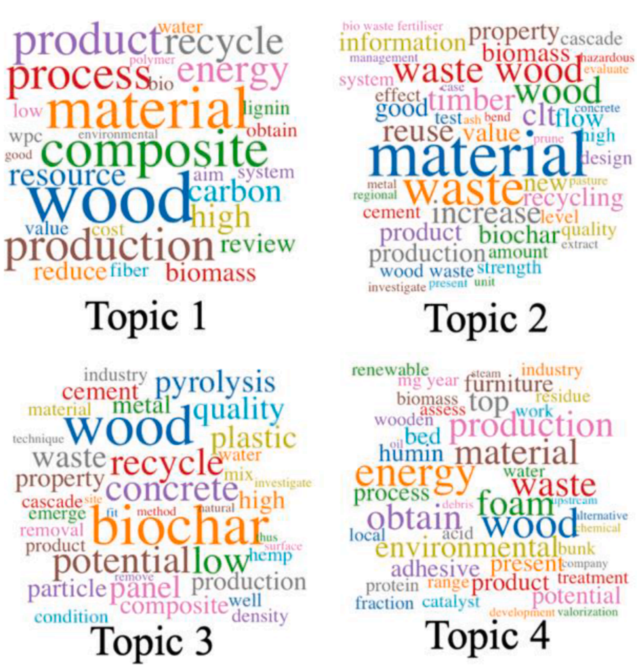

Fig. 8. Clouds of words identifying the main research topics.

Following, a synthesis of the four topics used to classify the selected 96 papers is provided.

Topic 1. **Sustainable Production and Materials.** Highlights a predominant focus on production and materials, with particular emphasis on composite materials and wood. What emerges is a strong interest in recycling processes, resource management, and energy, with significant concern for environmental aspects and economic sustainability. Technical terms like “lignin” and “polymer” suggest a scientific or industrial context. This topic includes 61 articles, making it the most represented among the four.

Topic 2. **Sustainable Waste Management.** Shows a marked interest in waste management and material sustainability, with an emphasis on wood and biomass-derived materials. Terms like “recycling”, “reuse”, and “biochar” indicate a clear trend towards ecological and innovative practices, while the presence of terms such as “system” and “design” highlight the methodological aspects of material management and application. This topic comprises 14 articles.

Topic 3. **Composite Material Recycling.** Reflects a broad range of research topics, highlighting recycling, use in composite materials, pyrolysis, and applications in the cement and plastic industries. The variety of terms indicates a multidisciplinary approach to the management and reuse of wood waste. This topic is represented by 11 articles.

Topic 4. **Renewable Wood Energy.** Shows strong interest in using wood waste as a renewable energy source, in the manufacture of novel materials, in the furniture industry, and in chemical applications. The variety of terms indicates a multidisciplinary approach, with particular attention to environmental sustainability and innovation in the reuse and valorisation of wood waste. This topic includes 9 articles.

Finally, Fig. 9 illustrates the distribution of the four analysed topics resulting from 2016 to 2024, with the number of occurrences reported on the y-axis, as managed by MySLR.

Topic 1, identified by the light blue colour, stands for the highest number of occurrences yearly. This consistent predominance is due to its relevance and the growing interest in the subject it represents, which is particularly crucial for current trends in the field. In 2022, Topic 1 reached its peak with 14 occurrences, the highest value recorded during the considered period, indicating a clear dominance over other topics. This observed high peaks reflect the increasing importance and centrality of Topic 1 in research. **Topic 2**, marked in green, emerges for the very first time in 2017, and shows a steady presence in the following years, with significant peaks in 2019 and 2020. Although less predominant, Topic 2 demonstrates stability and considerable importance over time. The peaks observed in 2019 and 2020 are linked to legislative initiatives and research programs focused on waste management, circular economy, and improved sustainability, likely due to rising environmental awareness.

In contrast, **Topics 3** and **Topic 4**, represented by yellow and red columns respectively, show a more irregular presence, both gaining relevance from 2019 onwards. This clearly indicates the very recent interest of the scientific community on these topics.

Overall, from 2020 there is a significant increase in occurrences for all the analysed topics, even though a consequential trend/sequence cannot be clearly detected. Year 2022 emerges as particularly significant for research activities, primarily due to the peak in Topic 1. Such increase can be attributed to greater global awareness and worldwide policies promoting research in sustainability and resource management. Moreover, the massive resumption of research activities immediately after the covid pandemic, has rapidly increased the number of investigations and publications. In the subsequent years, 2023 and 2024, the distribution among topics becomes more balanced, suggesting a growing diversification of areas of interest and discussion. However, Topic 1 continues to be the most frequent, highlighting its persistence as a central theme in the field.

In summary, the evolution of topic occurrences reflects a combination of changes in research priorities, responses to global needs, technological advancements, and regulatory influences.

4.2. Literature review

In light of the findings from the bibliometric analysis outlined in Section 4.1, and to address the RQ2, the 61 papers associated with Topic 1 - previously identified as the most prominent research stream from 2016 to the present (cf. Fig. 9) - were analyzed. The aim of this examination is to determine the factors that contributed to the prominence of this research stream, assess the main outcomes achieved so far, and explore future expectations in this field. From the word cloud of Topic 1 (cf. Fig. 8), it emerged that the predominant research keywords are – apart from wood – “materials” and “composites”, primarily used in the construction sector. To explore greatly this topic, a further analysis was conducted by dividing it into up to five subcategories with the assistance of ChatGPT. This innovative approach allowed for a better understanding of the specific areas of interest and their implications. The need to develop more sustainable materials and processes has driven research towards these subcategories. ChatGPT, using information from titles and abstracts of each paper contained in the uploaded repository Excel file, enabled the development of five distinct clusters within which relevant articles were identified. To identify the articles relevant to each cluster, a thorough analysis of all 61 selected articles was conducted. From that analysis, 28 articles were excluded, as they, despite containing the selected keywords, addressed topics that were not specifically focused on wood waste. The presented table categorizes the 33 reviewed articles

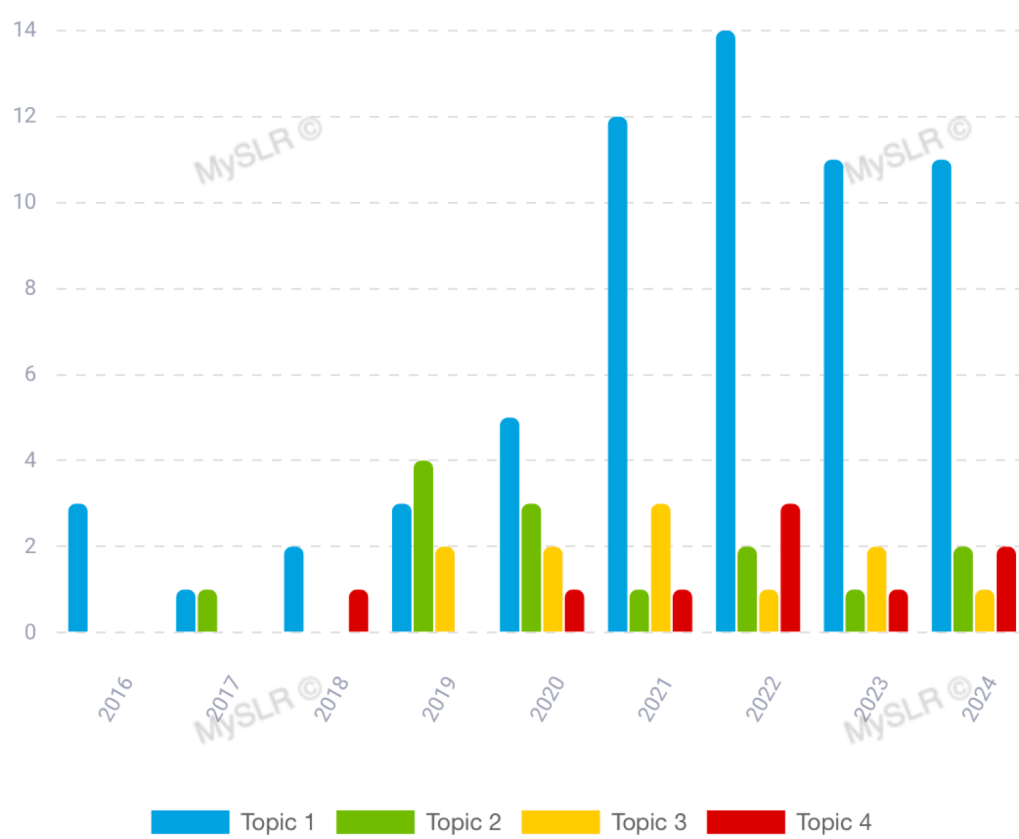

Fig. 9. Trend chart of the 4 identified topics managed with MySLR from 2016 to 2024.

into five clusters based on common themes. The second column contains a brief description of the main topics covered in each cluster, while the third column indicates the number of articles associated with each cluster. The fourth column lists the reference of each publication. Table 2 categorizes the 33 reviewed articles into the five clusters, each grouped based on common research themes (column 1); column 2 provides a brief description of the main topics addressed by each cluster; column 3 specifies the number of papers associated with each cluster; finally, column 4 lists the references for each publication within its respective cluster.

To complement the frequency-based analysis, an additional evaluation was performed to explore the scientific visibility of each thematic cluster. For this purpose, the total number of citations for each of the 33 reviewed articles (from Scopus) was collected, and retrieved the journals' impact factor where every paper was published (based on the most recent Scimago Journal Rank). These values were then aggregated by cluster, allowing the computation of two indicators for each group: a) the average number of citations per article and b) the average journal impact factor.

Fig. 10 presents these two metrics side by side for each cluster, with values independently normalized on a 0–1 scale to ensure comparability despite their different ranges and units. While some clusters showed strong performance in both dimensions, others stand out in only one dimension, highlighting the variability in scientific attention and journal prestige among the various research streams. To support interpretation, absolute values were also reported in parentheses above each bar.

A comparative analysis of the five identified clusters follows.

Table 2
Clustering of the 33 reviewed papers into the five main research streams, by ChatGPT implementation, as emerged from wood waste literature review.

Cluster	Cluster description	n° documents	Reference
Cluster 1	Valorisation of wood waste in light of the circular bioeconomy approach, with a focus on improving soil fertility and implementing sustainable agricultural practices.	8	[39–46]
Cluster 2	Innovation in composite materials, with a particular focus on the valorisation of wood waste through bio-composites and the production of innovative materials.	10	[47–56]] [
Cluster 3	Energy recovery and sustainability, with a focus on pyrolysis processes for the energetic valorisation of wood waste and the management of renewable energy and biomass.	7	[57–63]
Cluster 4	Sustainability in construction and building materials, with a focus on sustainable building systems and the use of innovative construction materials.	6	[64–69]
Cluster 5	Challenges and solutions in sustainable waste management, with a focus on innovative strategies to improve efficiency and reduce environmental impact.	2	[70,71]

4.2.1. *Cluster 1: Valorisation of wood waste in light of the circular bioeconomy approach, with a focus on improving soil fertility and implementing sustainable agricultural practices.*

The studies collected in the cluster on wood waste valorization and the circular bioeconomy explore advanced strategies to optimize the reuse of lignocellulosic waste, highlighting the crucial role of the bioeconomy, in alignment with recent international directives (e.g., European regulations). Romaní et al. [43] initiated research on valorizing by-products from the pulp and paper industry. In particular, wood chips and mixed sludge were reused to implement an innovative method for bioethanol production that integrates autohydrolysis and organosolv processes. Saccharification and simultaneous fermentation tests (SSF) were conducted to measure the biomass-to-ethanol conversion efficiency, revealing a yield increase of 60% with the addition of sludge as carbon and nitrogen source. This approach not only valorizes lignocellulosic waste but also addresses sludge treatment, highlighting synergies between different waste streams. Similarly, Tibor et al. [44] investigated the production of biochar and activated carbon from forest and agricultural residues using an innovative industrial pyrolysis process to convert 20% of the waste into high-quality biochar and other 60% into recoverable condensates, such as wood vinegar, tar, and alcohol. Furthermore, the study emphasized the importance of using syngas derived from pyrolysis to activate part of the biochar into carbon, suitable for applications in water treatment, metallurgy, and cosmetics, thus contributing in reducing dependence on fossil fuels. Liguori et al. [42] provided an overview of biological processes for lignocellulosic waste biorefineries, demonstrating how fermentation and enzymatic technologies can improve the efficiency and sustainability of biorefineries. These processes allow the production of biofuels and high-value chemicals, promoting a reduction in fossil resource use and contributing to a circular economy implementation. Arias et al. [40] proposed a biorefinery model for the extraction of resveratrol from agro-industrial waste, such as peanut shells and wood bark, using eco-friendly extraction methods. This approach improved production efficiency and reduced environmental impact compared to traditional methodologies, showing the feasibility of obtaining high-quality resveratrol from waste materials and opening new perspectives for valorizing such resources. Zuševica et al. [46] studied sustainable soil management using a mixture of wood ash and digestate to enhance soil fertility demonstrating that a 2:1 ash-to-digestate ratio could push plant growth and photosynthesis without causing eutrophication. This work underscores the importance of waste reuse for more sustainable agricultural practices. Grimm et al. [41] investigated the cultivation of mushrooms on lignocellulosic waste substrates, such as straw and sawdust promoting a closed-loop approach to agricultural waste, reducing environmental impact. Wu et al. [45] and Almeida et al. [39] focused on material innovation. The former study developed carbon anodes derived from lignin for potassium-ion batteries, offering a more sustainable alternative to lithium batteries; the latter explored the use of invasive species for producing lignocellulose-based polyelectrolytes, proposing renewable solutions in the energy and environmental sectors. In summary, these studies demonstrate how the circular bioeconomy can offer innovative solutions for sustainable energy, materials, and chemical production by optimizing the reuse of lignocellulosic waste. Each study contributes significantly to sustainable wood waste management, reducing environmental impact and generating new economic opportunities in an increasingly sustainability-oriented economy.

4.2.2. *Cluster 2: Innovation in composite materials, with a focus on the valorisation of wood waste through bio-composites and the production of innovative materials.*

This cluster of studies explores innovation in composite materials, with a focus on the valorization of wood waste through bio-composites and advanced sustainable materials manufacture. The studies analyze the production of wood-plastic composites (WPCs) and bio-composites derived from industrial and agricultural waste, aiming to develop eco-

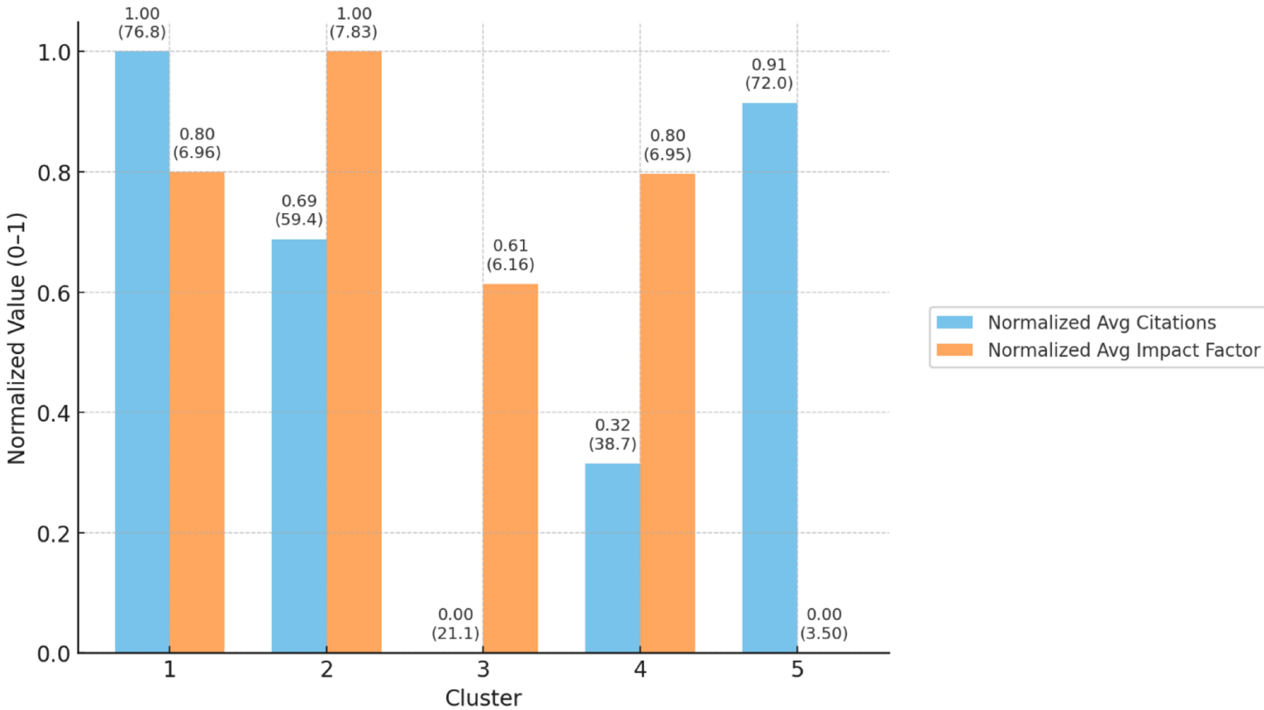

Fig. 10. Normalized average citations and impact factors per cluster.

friendly and high-performance materials that could contribute to an improved circular economy. Specifically, the studies in this cluster demonstrate how wood waste can be transformed into high-value materials, offering functional advantages in terms of performance and versatility, as well as significant environmental benefits. For instance, Petchwattana et al. [52] investigated the use of sawdust waste in WPC production, focusing on the effects of a bio-plasticizer (tributyrin) on material strength. The methodology involved the plasticization of composites made of polylactic acid and wood waste (PLA/WS) using various concentrations of tributyrin (from 2.5 to 15% by weight). Samples underwent tensile, impact, and thermal tests, including differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), to assess mechanical and thermal properties. The addition of the plasticizer enhanced elongation at break and impact resistance, improving composite ductility, though it reduced tensile strength due to a decrease in storage modulus. Additionally, DSC analysis revealed that the plasticized composite crystallized at a lower temperature than pure PLA, with a higher degree of crystallinity. Similarly, Jorda-Reolid et al. [49] mixed WPCs with micronized argan shells (MAS), as filler, and bio-based polyethylene from sugarcane (Bio-HDPE), as matrix, by extrusion and injection molding, with compatibilizers such as halloysite nanotubes and bio-based additives incorporated to enhance adhesion and mechanical properties. This resulted in a composite with increased rigidity and thermal stability, suitable for sustainable industrial applications. Khan et al. [50] applied LCA to compare the environmental impact of wood, plastic, and WPC pallets, incorporating wood and plastic waste from construction and demolition sectors in Finland. Results indicated that WPC pallets can offer significant environmental advantages over traditional alternatives due to the use of recycled materials and enhanced durability. Jier et al. [48] and Leng et al. [51] focused on the production of fire-retardant WPCs. The former developed composites with recycled plastic and agricultural waste, achieving excellent mechanical and fire resistance properties through uniform dispersion of a flame retardant. The treated WPCs showed a 24.2% increase in tensile strength, a 73.6% increase in elastic modulus, and an 8.3% improvement in impact resistance. Leng et al. created a bio-based flame retardant using phytic acid-tyramine salt (referred to as PATA) and ammonium, which significantly reduced heat release and smoke emissions, enhancing material safety. Sommerhuber et al. [55,56], in an initial phase, developed WPCs using recycled acrylonitrile-butadiene-styrene (ABS) and polystyrene (PS) from electronic waste. They integrated wood particles (both virgin spruce and recycled particleboard) in different proportions (30% and 60%) and applied a coupling agent to improve wood-plastic adhesion, aiming to assess the effectiveness of recycled materials in producing WPCs with competitive physical and mechanical properties. To further evaluate the environmental impact LCA was implemented on virgin and recycled materials, considering end-of-life options such as recycling and energy recovery, to identify an environmentally sustainable pathway for WPCs. The WPC production process included wood drying, extrusion of recycled plastic granules, and material blending in an injection molding machine. Samples were tested for mechanical and physical properties (density, water absorption, flexural and tensile strength), microstructure analysis using electron microscopy, and elemental analysis to detect heavy metals in recycled materials. Results from LCA studies indicated that increasing virgin wood improved density, water absorption, and mechanical performance, thanks to the effectiveness of the coupling agent. Moreover, composites made from secondary materials have lower environmental impacts than those made from virgin materials, particularly considering the global warming and acidification potential. The studies concluded that recycling is generally a preferred end-of-life option for WPCs, although its effectiveness is influenced by the amount of virgin material in the recycled composite. Energy recovery remains advantageous in the absence of efficient recycling systems for these composites. Ge et al. [47] and Ramesh et al. [54] examined pyrolysis as a method for valorizing agricultural waste and developing robust, durable WPCs. In the former study, the authors conducted an in-depth analysis of pyrolysis as a promising technology for agricultural waste valorization, highlighting waste can be transformed into various products, including solids (biochar), liquids (bio-oil and pyroligneous acid), and gases. The results demonstrated practical applications for the pyrolysis products: biochar as a soil amendment and carbon sequestration tool, gases for energy generation, and oils for biofuel production. In the latter study, the authors systematically reviewed existing studies on various WPC processing techniques, such as injection molding and extrusion. They evaluated the impact of rheological properties on final products, with particular attention to material formulations, including wood flour and polymeric additives. They also discussed the use of wooden bio-based adhesives, like lignin and tannin, as alternatives to synthetic adhesives. The review showed the versatility of WPCs and their potential in various industrial sectors. Finally, Platnieks et al. [53] explored the use of recycled cellulose to enhance the hardness and thermal stability of bio-composites, generating biodegradable and high-performance materials for multiple applications. The primary objective was to evaluate the effectiveness of recycled cellulose reuse derived from Tetra Pak to improve the properties of polybutylene succinate (PBS)-based bio-composites. Results showed that waste-based cellulose addition significantly improved composite hardness and Young's modulus compared to pure PBS. The bio-composites also exhibited superior thermal stability and biodegradability in soil, confirming their suitability as sustainable materials. Collectively, these studies underscore the potential of wood and agricultural waste to manufacture innovative, safe, and sustainable materials for industrial and construction sectors, aligning with the principles of sustainability and the circular bioeconomy.

4.2.3. Cluster 3: Energy Recovery and Sustainability, with a Focus on Pyrolysis Processes for Energy Valorisation of Wood Waste and the Management of Renewable Energy and Biomass.

The grouped studies explore sustainable energy recovery methodologies for treating and valorizing wood waste, particularly through physical and chemical processes like pyrolysis. These approaches aim to convert waste into valuable energy resources, supporting the circular economy. Paredes-Sanchez et al. [62] investigated the use of wood biomass in urban areas by developing a hybrid thermal system model for district heating. The main objective was to develop a methodology for assessing the energy potential of wood processing industry residues for thermal energy production and promote sustainable and resilient energy communities, reduce fossil fuel dependency, and support the green energy transition. Wood waste biomass from primary and secondary processing industries, such as wood chips, sawdust, and scraps were analyzed to assess energy output and cost, considering technical, economic, and environmental constraints. Results showed that hybrid thermal systems using local wood biomass provided economic and environmental benefits, potentially meeting part of the heating demand in urban areas and demonstrating wood waste's value in sustainable resource management. Poskart et al. [63] explored pyrolysis of lignocellulosic waste, particularly alder and pine chips, to generate green energy. Using analytical methods, carbon, hydrogen, nitrogen, and sulfur content was measured in the resulting materials. Moreover, the calorific value was measured to model pyrolysis behavior and assess gas quality resulting in a natural gas dependency reduction with economic benefits. Their study underscored pyrolysis's role in energy recovery within a circular economy, maximizing resource efficiency and minimizing waste generation. Similarly, Ferrari et al. [58] applied pyrolysis to agricultural waste to produce biochar, bio-oil, and gas for industrial use, promoting circular bioeconomy principles and mitigating pollution. Here, the thermochemical conversion process was detailed whilst producing solids (biochar), liquids (pyrolysis oil and pyroligneous acid), and gaseous products emphasizing potential in carbon sequestration, water purification, and soil fertilization. Pyrolytic extracts, such as wood vinegar and bio-oil, also have various industrial uses, though bio-oil quality needs improvement to compete with fossil fuels. Moreover, the generated non-condensable gases can be reused for heat or electricity production, hence enhancing the overall energy efficiency in the process. In line with these studies, Farjana et al. [57] implemented LCA approach to evaluate the environmental impact of engineered wood panels, comparing end-of-life options such as recycling and energy recovery. Their main finding supported pyrolysis as a sustainable energy recovery method for wood biomass management. By modeling three end-of-life scenarios (landfill, recycling, and energy recovery), indicators such as climate change, land use, and resource consumption were assessed. Recycling proved to be the most sustainable option, reducing primary resource use and environmental impact more effectively than landfilling or energy recovery, although the latter still showed a lower impact than landfill disposal. Harindintwali et al. [60] took a biological approach, using nitrogen-fixing bacteria to degrade lignocellulosic biomass and produce biofuels via bacterial digestion. This study links waste valorization with sustainable natural resource management. The authors aimed to use nitrogen-fixing and cellulolytic bacteria to convert lignocellulosic biomass (LCB) into biofuels and soil amendments. Such bacterial-based method significantly improved LCB conversion, reducing the need for nitrogen additives and advancing sustainable biomass management with potential implications for circular biorefineries. Morales-Máximo et al. [61] focused on producing briquettes from pine residues for rural communities, aligning with the EU 2030 target (reduce greenhouse gas emissions by 40%, achieve a 32% share of renewable energy, and decrease overall energy consumption by 32.5%). The study involved the indigenous community to address local energy needs through alternative fuels derived from wood residues. The energy consumption patterns, and available wood residues were evaluated through interviews; biomass availability was estimated monthly and annually for briquette production, by laboratory and field tests in order to assess briquette performance for energy savings and greenhouse gas mitigation. Moreover, production costs were compared to firewood prices, demonstrating that pine residue briquettes could offer energy savings and greenhouse gas reduction, diversifying energy sources and promoting a sustainable energy transition. Gil [59] examined the potential of waste-to-energy technology in valorizing industrial waste, focusing on the mechanical properties and performance of the resulting energy materials. The study identified technical and regulatory barriers to improve efficiency of the analysis of low-energy materials densification, an engineering process that enhances biofuel management and transport in comparison to fossil fuels. Results indicated that densified biofuels have a higher energy density, enabling to compete with traditional fuels. However, technological challenges remain, including regulatory requirements and optimization of densification to reduce production and transport costs. Collectively, all these studies highlight the transformative potential of energy recovery methodologies, such as pyrolysis, in providing green solutions for managing industrial wood-based waste, while focusing on optimizing the life cycle of materials and processes.

4.2.4. Cluster 4: sustainability in construction and building materials, with a focus on sustainable construction systems and the use of innovative building materials.

The studies on sustainability in construction materials demonstrate how the valorization and reuse of wood-based waste from industrial and agricultural processes can offer innovative solutions for outdated construction systems. Pedreño-Rojas et al. [69] examined the integration of wood biomass ash from a thermoelectric plant as a supplementary cementitious material, presenting it as a viable alternative to landfilling. The composites were tested for compressive strength and hardness to assess their suitability for non-structural applications, and morphological analysis tools were employed to observe the microstructure and ash distribution within the material. The hydraulic properties of this ash enhance the mechanical performance and energy efficiency of gypsum-based panels, meeting performance needs and contributing to efficient energy management in buildings, with positive impacts on climate change mitigation—a sector where construction plays a significant role. Caldas et al. [65] addressed the use of recycled wood chips from wood panel factories in new bio-concrete for structural applications. Through an LCA, the authors evaluate various scenarios for greenhouse gas emissions mitigation and climate change. Their study focuses on optimizing the wood supply chain and demonstrates that reusing wood waste provides advantages over virgin wood, helping reduce logging activities and promoting CO_2 sequestration. Labianca et al. [67] explored the incorporation of biochar and recycled materials into high-performance cement products and 3D-printable concrete pastes. Using SimaPro software to model various production alternatives, they demonstrate that biochar enhances concrete's mechanical properties while reducing the need for Portland cement (OPC), known for its high environmental impact. The study provides a comprehensive framework toward carbon neutrality, highlighting how these materials reduce greenhouse gas emissions and offer economic potential. Balti S [64] evaluated the use of wood waste and paper pulp in gypsum composites to enhance both the energy and mechanical performance of the material. Statistical analysis validated the results, and water absorption tests were conducted on samples to assess their moisture resistance. The results indicated structural stability of the materials despite water absorption. This holistic approach enables an increase in the amount of waste reused and a reduction in environmental impacts, demonstrating the structural stability of these materials. The authors emphasize the importance of adopting concrete practices to standardize these materials and facilitate their adoption in the market. Lee et al. [68] analyzed the use of agricultural biomass and recycled wood particles and chips, which represent the main component in the production of industrial particleboards, to improve raw material supply chains challenged by recent legislative changes. The review proposed various waste mixes to evaluate the advantages and disadvantages of reusing agricultural wastes in particleboards as a substitute for primary wood raw materials. However, the authors concluded that each type of agricultural biomass presents issues that could hinder profitable industrial use, such as high moisture content that increases weight and transportation and storage costs, low density translating to reduced mechanical strength, and other challenges at the industrial level. Consequently, the use of wood remains nearly unavoidable, though the study highlighted promising applications of wood waste in developing industrial recycled wood products. Thus, this study showed that integrating recycled wood materials into building products can provide sustainable solutions without compromising technical performance. Finally, Grohmann et al. [66] proposed the reuse of pruning waste from Tilia species as insulating materials. Their circular approach suggested that these wastes can effectively improve energy efficiency in buildings and reduce the costs associated with urban green space management. The paper analyzes the ecosystem benefits of managing urban green spaces, such as heat mitigation and improved air quality, while also discussing the economic and logistical challenges that public administrations face in caring for urban trees. The results indicated that finding suitable uses for pruning waste could unlock financial resources necessary for effective urban tree management. The authors further emphasized the need for additional research to valorize urban waste and promote policies supporting sustainability. In summary, these studies demonstrate that integrating wood waste into construction materials can enhance the environmental impact of production chains and offer high-performance solutions, promoting sustainable building practices and helping reduce CO_2 emissions in the construction sector.

However, it is important to note that while many wood waste-based construction materials offer clear environmental benefits, the reuse of chemically treated wood, such as MDF panels or CCA-treated timber, may raise toxicological concerns for humans' health and the environment. These include potential risks related to formaldehyde emissions, heavy-metal leaching, and dust inhalation during processing [72,73]. Such aspects will be carefully assessed in future studies to ensure both environmental and human health safety.

4.2.5. Cluster 5: challenges and solutions in sustainable waste management, with a focus on innovative strategies to improve efficiency and reduce environmental impact

Studies on the challenges and solutions in sustainable waste management focus on the technical and policy issues that hinder the adoption of circular practices, especially within the wood resource sector. Jarrea et al. [71] conducted an in-depth literature review on the concept of "wood cascading" aimed at identifying factors influencing the implementation of this practice in transitioning biodiversity-based industries toward a circular economy. Wood cascading, intended as the effective wood supply chain, was also analyzed evaluating both barriers and enablers. Main findings suggested that a successful and profitable wood cascading requires overcoming various political and technical obstacles, categorized into five main areas: policy, market, technical implementation, environmental impacts, and stakeholder engagement. They also explored the significance of each factor in the existing literature, analyzing interrelations to provide a clearer understanding of the dynamics influencing wood cascading. Their results clearly indicate that, while the concept of a circular economy has gained priority within global policies, the practical realization of wood cascading faces challenges similar to those in broader circular economy initiatives. While the majority of the policy references in the reviewed literature was linked to European frameworks only, it is important to acknowledge that other regions have also issued robust initiatives and directives in the field of wood waste and circular economy. For example, the U.S. Environmental Protection Agency developed the Waste Reduction Model (WARM) to provide life cycle-based emission factors for a wide range of waste management strategies, helping quantify environmental trade-offs in material reuse and disposal [74]. In China, the national government launched the Zero-Waste City program to integrate circular principles at the urban scale, aimed to reduce waste generation and improve resource recovery systems [75]. Similarly, the ASEAN Standard for Legality of Timber (SLT) provides a common regional framework to ensure the legal sourcing and sustainable use of timber in Southeast Asia [76]. Although these international frameworks were not prominent in the reviewed *corpus* of this study, they represent in any case a valuable reference for further comparative analyses on global governance approaches. Their inclusion broadens the policy lens and reinforces the importance of context-specific strategies in supporting wood waste reuse across different regulatory, socio-economic, and technological systems.

This research highlights the need to address these challenges to improve biomass efficiency through reuse and recycling within forestry and bio-based sectors. Similarly, Gagnon et al. [70] examined circular strategies for the forestry sector, emphasizing the importance of promoting policies to encourage wood products recycling/reuse and greater synergy among industries and governments. Their study, mainly conducted on Canadian forest products, enabled to gather diverse perspectives on current waste practices and identify obstacles and opportunities, focusing on the construction and packaging sectors. Findings, extendable to other contexts than Canada, revealed that the forestry sector is making progress in reducing resource consumption during production. However, the implementation of reuse, recycling, and energy recovery strategies is inconsistent, varying significantly by product and region. Reusing reclaimed wood represents a substantial opportunity, though technical and regulatory barriers remain, particularly in the construction sector. Moreover, while cardboard enjoys a high recycling rate, there are notable opportunities for improvement in reuse and fiber loss reduction. Overall, these studies illustrate the complexities of sustainable wood management and underscore the critical need for coordinated strategies and targeted policies to facilitate the integration of wood waste reuse within bio-based manufacturing sectors.

5. Conclusion

This review analysed 33 peer-reviewed studies, selected through a structured bibliometric and qualitative approach, to explore how wood waste is being reused for the development of innovative and sustainable materials and products. Starting from a literature pool of over 17,000 documents retrieved via Scopus, a stepwise filtering and clustering process led to the identification of five main thematic areas: bio-economy valorisation, bio-composites, pyrolysis and energy recovery, construction materials, and policy and governance.

The findings demonstrated that wood waste is progressively being reframed from an environmental burden to a high valuable secondary resource, with increasing integration into circular economy strategies globally. Among the most promising pathways, main findings resulted that bio-composites stand out for their potential to replace virgin materials while offering high mechanical performance and CO_2 immobilisation capacity (e.g., [65,67]). Moreover, pyrolysis technologies are also gaining relevance as renewable solutions for energy recovery and carbon valorisation. In the construction sector, wood waste is being reused more consistently in mortars, gypsum-based composites, and insulation products, contributing to the decarbonisation of the built environment.

That transformation, already documented in several studies grouped in Clusters 2 and 4 (e.g., [65,69]), aligns with the objectives of the 2030 Agenda for Sustainable Development, promoting more efficient resource management, and reduced environmental impacts. Moreover, the integration of wood waste into industrial symbiosis frameworks offers systemic opportunities to convert waste into value within and across production chains (e.g., [70,69]).

However, several critical gaps remain. The reviewed literature reveals a notable geographical skew, with a dominance of European case studies and limited representation from low- and middle-income countries. Additionally, the absence of harmonised testing protocols and regulatory frameworks continues to hinder the industrial scalability of waste-derived products [70,71]. Another relevant concern is the reuse of chemically treated wood (such as MDF panels or CCA-treated timber), which may involve significant health and environmental risks. Issues like formaldehyde emissions, heavy metal residues, and fine particulate exposure should be thoroughly assessed in future interdisciplinary studies, especially when evaluating large-scale applications.

Based on these insights, a set of concrete research priorities emerge. Future work should:

- assess toxicological and environmental risks associated with treated wood reuse, particularly in relation to chemical additives and occupational safety;
- develop harmonised standards and certification protocols for secondary wood-based materials, supporting their safe market integration;
- investigate the design and testing of fire-retardant additives and coatings in a full life-cycle perspective;
- explore design-for-disassembly and modularity principles to enable circularity in construction components;
- and expand cross-regional comparisons to include policy and regulatory frameworks beyond the European context, such as those introduced by the US EPA WARM model, China's Zero-Waste City initiative, and ASEAN's timber legality standards.

Finally, the hybrid methodology adopted in this review, combining bibliometric mapping (VOSviewer, MySLR) with qualitative synthesis, can be replicated to analyse other industrial or agro-waste streams, thus contributing to broader circular economy research.

Fully unlocking the potential of wood waste valorisation will require coordinated efforts across scientific, industrial, and policy levels, addressing not only technological innovation but also safety, standardisation, and equity. This review provides a comprehensive foundation upon which more inclusive, replicable, and sustainable waste-to-resource strategies can be built, reaffirming the role of wood waste as a key enabler of circularity, innovation, and environmental transition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to identify research clusters and assign each relevant paper to an exact category based on information taken from titles and abstracts. After using this tool/service, the authors verified, reviewed, and edited the content as needed and take full responsibility for the content of the publication.

Data availability statement

The data that support the findings of this study are available from the corresponding author, [MS], upon reasonable request.

CRediT authorship contribution statement

Rosanna Leone: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Giada La Scalia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Manfredi Saeli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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