Study on agricultural waste utilization in sustainable particleboard production

Francis O. Okeke[1*], *Abdullahi* Ahmed[1], *Adil* Imam[1], *Hany* Hassanin[1]

[1]School of Engineering, Technology and Design, Canterbury Christ Church University, Kent, UK

Abstract. The construction industry plays a crucial role in the global economy, but its heavy reliance on forest resources has led to significant environmental concerns, such as deforestation and climate change. The growing demand for sustainable and affordable building materials has driven researchers to explore the potential of agro-industrial wastes as alternative raw materials for particleboard (PB) production. This study aims to contribute to the growing body of knowledge on sustainability in the built environment by examining the trends, key factors, and environmental implications of utilizing agro waste in particleboard manufacturing through a comprehensive review of recent research. Utilizing the PRISMA approach, this study selects and systematically reviews 50 journal articles and conference papers from Scopus database, published between 2000 and 2024. Research findings reveals a diverse range of agro waste such as sugarcane bagasse, rice husks, corn stover, peanut shells, wheat straws and coconut fibers etc, been successfully used as raw materials for particleboards manufacturing. The bibliometric analysis highlights present focus on production processes, adhesive systems, particle properties, and material optimization. Also, the performance of agro based particleboards is influenced by the type and proportion of agro waste, particle size and geometry, adhesive type and content, and processing conditions. While the use of synthetic resins currently dominates the research landscape as binders, there is growing appetite for bio-based and natural adhesives. However, challenges such as seasonal availability and the need for additional processing must be addressed for large-scale adoption. The study concludes with recommendations for collaborative research, eco-friendly adhesive development, and supportive policies to promote the use of agro waste particleboards in sustainable construction.

1. Introduction

The global population is increasingly concentrated in urban areas, with the United Nations projecting that the world's urbanization rate will rise from 56.2% to 60.4% by 2030 [1]. This trend is particularly pronounced in less developed regions, which are expected to account for 96% of urban growth over the next decade [2]. The rapid expansion of cities in these areas poses significant challenges for achieving sustainable patterns of consumption and production, as outlined in The Sustainable Development Goals Report [3]. As the world continues to urbanize, the construction industry plays a crucial role in shaping the built environment and its impact on sustainability. The development of environmentally healthy buildings and the identification of new, adaptable, and productive materials that minimize environmental impacts have become increasingly important research areas [4,5]. Sustainable construction practices not only reduce the ecological footprint of buildings but also contribute to the well-being of occupants and the resilience of communities [6]. To address the challenges associated with rapid urbanization and the need for sustainable development, researchers have been exploring various strategies and innovations in the built environment. These include the use of recycled and renewable materials, energy-efficient technologies, green building design principles, and circular economy approaches [7,8]. By investigating and implementing these solutions, the construction industry can play a vital role in mitigating the environmental impacts of urbanization while promoting social and economic sustainability.

[*]Corresponding author: f.okeke142@canterbury.ac.uk

Consequently, as the Earth's climate is undergoing rapid changes, primarily driven by human activities, and the ramifications of this global crisis are becoming increasingly apparent, affecting both developing and developed nations alike. Recognizing the urgency of the situation, the European Commission set an ambitious target of achieving a climate-neutral Europe by 2050 [9]. Though to realize such related goals, the construction sector must play a pivotal role, given its significant environmental footprint [10]. The building and construction industry's contribution to climate change is multifaceted, encompassing energy consumption, generation of solid waste and greenhouse gases, and the widespread lack of proper insulation in existing structures, which results in substantial energy losses [11,12]. The urgent need for more sustainable building practices has spurred researchers to explore innovative solutions and working towards a more sustainable future. For instance, Moreno et al. [13] demonstrated the feasibility of producing fire-resistant, low-density cellulose boards using the sustainable raw materials of waste newspaper, evidencing good mechanical and fire resistance properties of the boards. Subsequently, another promising area of research focuses on the development and application of eco-friendly materials and building panels from agro waste. According to Aisien et al. [14] Agricultural residues such as the stalks of most cereal crops, rice husks, coconut coir, bagasse, corn cobs, peanut shells etc are cheap and abundantly available in many developing countries such as China, Nigeria, India, Philippines, Malaysia, Indonesia, and Sri Lanka.
Particleboard, a versatile engineered wood product introduced in the 1930s [15], is manufactured by bonding wood chips or other lignocellulosic materials with an adhesive or suitable binder under specific conditions of heat and pressure. Particleboard has become a significant commodity in the global wood products trade, owing to its consistent properties, dimensional stability, and adaptability to various applications. Previous studies have provided valuable insights into the use of non-wood biomass in particleboard manufacturing. Lee et al. [16] offered a comprehensive classification of these alternative raw materials, while Mohsen et al. [17] reviewed the production of particleboards from various agricultural wastes using different adhesive systems. Furthermore, Baharuddin et al. [18] critically appraised the physical and mechanical properties of particleboards produced from diverse raw materials and binders, demonstrating the potential of certain organic wastes to serve as substitutes for wood fibers in particleboard production. These studies collectively highlight the growing interest in exploring sustainable alternatives to traditional wood-based materials in the particleboard industry.
This paper aims to contribute to the growing body of knowledge on sustainability in the built environment by examining the potential of agro-industrial wastes as alternative raw materials for the production of particleboards and composite panels and their contribution to sustainable construction practices. The utilization of these abundant and renewable resources not only reduces the reliance on virgin wood but also promotes waste valorisation and the development of a circular bioeconomy [20]. Through a comprehensive review of recent research, this study explores the trend in this research domain, key factors influencing the performance of agro based particleboards, and the environmental implications of their production and use. The findings of this review can inform the development of more sustainable and eco-friendly building materials, supporting the transition towards greener construction practices in the face of rapid global urbanization. By highlighting the challenges and opportunities associated with agro waste particleboards, this paper seeks to stimulate further research and innovation in this field, ultimately contributing to the realization of sustainable development goals in the built environment.

2. Literature review

2.1 Global Agro waste production and waste hierarchy

Agro waste is one of the most significant contributors to the generation of waste worldwide. Also known as crop residues or by product, it consists of plant materials that remain after harvesting crops, such as stems, branches, seeds, shells, and leaves [21]. It is estimated that approximately 80% of the total biomass of crops grown for human and animal consumption is considered agro waste [22]. The four most cultivated crops globally according to FAO [22] are sugarcane, corn, cereals, and rice and the combined annual production of these crops exceeds 16,500 billion kilograms. Consequently, the amount of agro waste generated from these crops alone is estimated to be in the range of 13,200 billion kilograms per year. In the European Union alone, approximately 700 million tonnes are generated each year from the fields [23]. These wastes are primarily composed of lignocellulosic materials, including cellulose, hemicellulose, and lignin [24]. These components are tightly bound together, making agricultural waste poorly digestible and generally unsuitable for direct use as animal feed without prior processing. The Lignocellulosic waste is a highly valuable renewable resource material with numerous applications, particularly in the field of material manufacturing. Natural fibers derived from agricultural waste offer eco-friendly advantages, as they are biodegradable, compostable, renewable, and recyclable, thus contributing to the reduction of greenhouse gas emissions [25]. Consequently, lignocellulosic materials serve as an environmentally sound, innovative, cost-effective, abundant, and sustainable source of raw fibers.

Furthermore, biocomposites produced from discarded lignocellulosic fibers align with the principles of biorefinery and the sustainable economy (bioeconomy) [26]. The common practice in managing agricultural waste is through on-field decomposition or burning [27]. The latter, known as stubble burning, is still prevalent in countries like Nigeria, China and India, which together account for one-third of the world's population [28,29]. However, the burning of agricultural waste leads to the release of valuable substances as CO_2, smog, particulate matter, and ash, rather than being utilized for the production of new products [30].

The waste hierarchy is a widely accepted framework that prioritizes waste management strategies based on their environmental impact and resource efficiency [31]. The hierarchy consists of six main levels (Fig. 1), in order of preference: prevention/mitigation, reuse, recycling, recovery, and disposal. When applied to agricultural waste management, the waste hierarchy can guide decision-making and promote more sustainable practices.

- Prevention: The first and most preferred level of the waste hierarchy is prevention, which aims to abate the generation of agricultural waste at the source. This can be achieved through various strategies, such as optimizing crop production practices, improving harvest techniques, and reducing post-harvest losses. Precision agriculture and the use of advanced technologies can also contribute to waste mitigation by optimizing resource use and minimizing crop residues.
- Minimization: this is a crucial level in the waste hierarchy, closely linked to the prevention stage. While prevention focuses on eliminating waste generation altogether, minimization aims to reduce the amount of waste produced when waste generation cannot be entirely avoided. The implementation of minimization strategies extends across various stages of the production continuum, encompassing pre-harvest, post-harvest, and processing phases.
- Reuse: The third level of the waste hierarchy is reuse, which involves using agricultural waste for the same or a similar purpose without significant processing. Examples of reuse in agricultural waste management include using crop residues as mulch or animal bedding. Reusing agricultural waste can help to conserve resources, reduce environmental impacts, and provide economic benefits to farmers.
- Recycling: It is the fourth level of the waste hierarchy, involves processing agricultural waste into new products or materials. Composting is a common recycling method for agricultural waste, which converts organic matter into a nutrient-rich soil amendment. Other recycling options include the production of bio-based materials, such as particleboards, insulation, and packaging materials, using agricultural waste as a raw material.
- Recovery: The fifth level of the waste hierarchy is recovery, which involves extracting energy or other valuable resources from agricultural waste. Anaerobic digestion is a recovery process that converts organic waste into biogas, a renewable energy source, and digestate, a nutrient-rich fertilizer [32]. Pyrolysis and gasification are other thermochemical recovery methods that can convert agricultural waste into bio-oil, syngas, and biochar [33].
- Disposal: The final and least preferred level of the waste hierarchy is disposal, which involves the permanent elimination of agricultural waste without any resource recovery. Landfilling and open burning are common disposal methods for agricultural waste, but they have significant environmental impacts, such as greenhouse gas emissions, air pollution, and soil and water contamination. Disposing of agricultural waste should be considered a last resort, and efforts should be made to minimize the amount of waste that ends up in this stage of the hierarchy.

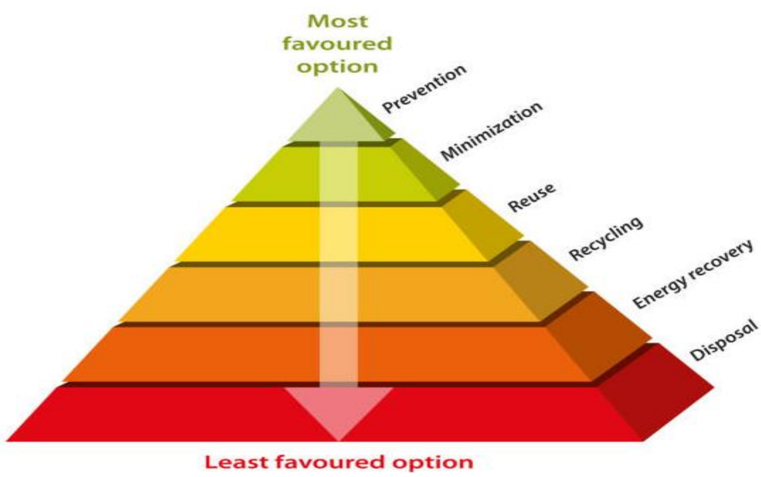

Fig. 1. Waste hierarchy Source: European Commission [34]

2.2 Forest reserve and Particleboard Production

The construction industry plays a vital role in the global economy, contributing significantly to the growth and development of countries worldwide. However, the sector's heavy reliance on forest resources for various applications, such as roofing, ceiling construction, panelling, and furniture manufacturing, has led to significant environmental concerns. The particleboard industry emerged as a solution to two major challenges: the scarcity of timber resources and the necessity to manage substantial amounts of wood waste, such as sawdust, planer shavings, and other relatively uniform residues generated by various wood processing industries [35]. Particleboards have gained widespread popularity due to their ability to convert small, low-grade wood particles, which would otherwise be considered useless, into large, functional wooden panels [36]. Consequently, the demand for wood and wood-derived panels/boards has experienced continuous growth in recent years. In 2020, the production quantity of particleboard reached 96.01 million m^3 worldwide. This, increasing demand has placed a substantial strain on forest resources, leading to deforestation and its associated adverse effects on the environment, as well as a rise in the price of wood [37]. According to the Food and Agriculture Organization of the United Nations, the world's total forest area covers 4.06 billion hectares (ha), which accounts for 31 percent of the global land area. Since 2010, there has been a net loss of 4.7 million ha of forests annually. It is estimated that deforestation occurs at a rate of 10.0 million ha per year, with Africa experiencing the highest net forest loss at 3.9 million ha [38].

Particleboard, a composite panel product typically produced from wood particles such as shavings, flakes, wafers, chips, sawdust, and strands [39], has emerged as a popular material for various applications, including flooring, wall bracing, ceiling boarding, furniture, partitioning, and cladding [40]. The particles in the composite material are bonded together using synthetic resins. However, the growing concern over the environmental impact of using wood-based materials and synthetic resins has prompted researchers to explore alternative sustainable raw materials for particleboard production. These efforts aim to alleviate the pressure on forest resources while providing a viable solution for waste management and creating value-added products from otherwise discarded materials.

2.3 Production process of agro-particle board

Although, the industrial process of particle board production may vary in terms of the use of additional and sophisticated equipment and processes, which is dependent on the scale and required output of performance of the board. The typical production process includes raw material sourcing and preparation, mixing with adhesive and pressing to curing. Consequently, the process of agro waste particleboard production begins with the preparation of raw materials. Natural fibre or residue particles such as chips, straws, peels, husk, shavings, bagasse, strands or dust, are obtained from various sources, including mills, farmhouse, and other agro waste producing facilities. These particles are carefully selected, cleaned, and sorted to ensure consistent size and quality. It may necessitate further processing like drying and grinding the particles to suitable texture. Once the particles are prepared, they are mixed with an adhesive binder, which serves to bond the particles together and provide structural integrity to the finished panel. The most commonly used adhesives in particleboard production are synthetic resins, such as urea-formaldehyde (UF), phenol-formaldehyde (PF), or melamine-formaldehyde (MF). However, the choice of adhesives binder is based on their performance characteristics, cost, durability, intended use, and environmental impact. The mixture of particles and adhesive is then spread evenly to form a mat, which is subjected to high temperature and pressure in a press to cure the adhesive and compress the mat into a solid panel. The resulting particleboard is a flat, dense, and uniform panel product with a smooth surface and consistent thickness. It can be produced in various sizes, thicknesses, and densities to meet the specific requirements of different applications.

3. Research Methods

This study is part of a larger research project investigating the use of agro based building materials as a sustainable solution for the building and construction industry. A systematic review of published literature was conducted, as this method allows for the evaluation, synthesis, and communication of a large volume of research on a specific topic [41]. Previous studies have successfully used this approach, recognizing its advantage of integrating evidence-based knowledge and practical applications [16-18]. The data presented in this study are primarily secondary, derived from an extensive survey of evidence-based literature. The research process follows Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA).

The study involved a comprehensive search of peer-reviewed articles and conference papers published between 2000 and 2024, using the Scopus online database. Scopus was chosen based on its extensive coverage of diverse journals and unique keyword search feature, as highlighted by Falagas et al. [42]. The search terms included "agro particle board" or "agro fibre board" to ensure a comprehensive retrieval of relevant literature. Both journal articles and conference papers were included to capture current international research findings and emerging developments. The searches yielded 113 items, which were further refined based on language (English), subject area (Materials Science, Energy, Engineering, Environmental Science, Agriculture & Biology) and document type (Article, Conference paper, Book chapter). A total of 89 papers emerged from the initial screening. To ensure the inclusion of the most pertinent studies, a two-step selection process was employed. First, the titles of the articles and conference papers were examined to eliminate those not directly related to the subject matter. Second, the abstracts of the remaining articles were reviewed to further refine the selection and include only the most relevant studies discussing the use of agro waste in PB production.

Following this selection process, a total of 50 published works were included in the final review, as evidenced in the references section. The authors thoroughly studied and evaluated the selected papers, focusing on the objectives of highlighting the different agro waste utilized with research trend, key factors influencing the performance of agro waste-based particleboards and the strategies for enhancing their properties in published experimental literature. Both qualitative and quantitative data were extracted from the reviewed articles. Quantitative data were analysed using descriptive statistics in MS excel and visualized using the VOSviewer software, which enables the creation of bibliometric networks and visualizations. Qualitative data were analysed using thematic content analysis, a method that involves identifying, analysing, and reporting themes within the data. The findings from both analyses are presented using charts, and narrative descriptions in the following sections.

4. Results

The Fig. 2 summarizes the number of publications on agro waste particle board research for a period, from 2000 to 2024 as obtains from reviewed papers.

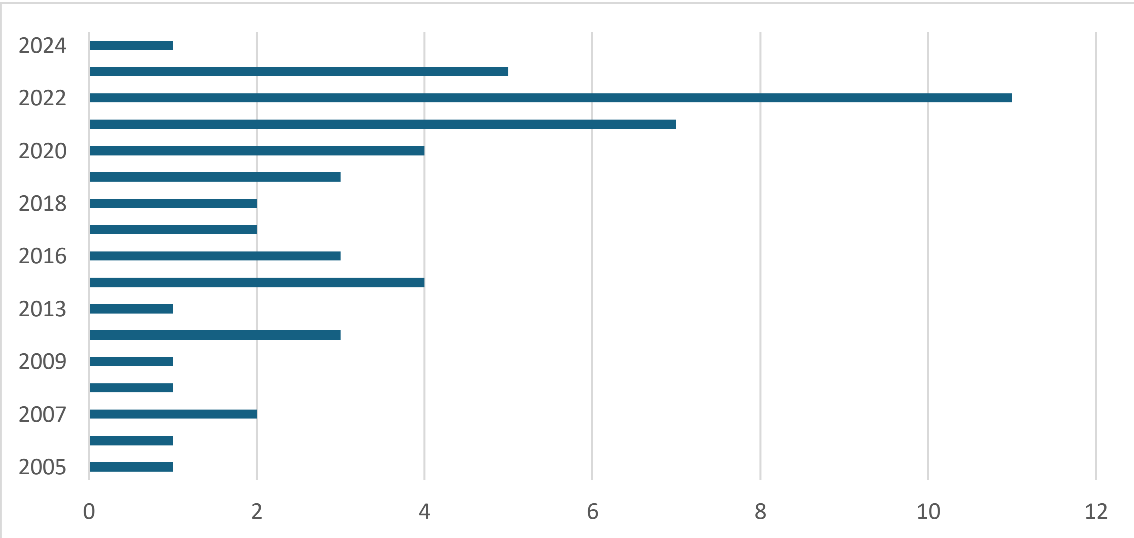

Fig. 2. Annual publication output of review articles from 2000 to 2024

The trend in research output related to agro waste PB production over the specified period shows there is a fluctuation in the number of publications each year, indicating variations in research interest. The number of publications seems to increase gradually over the years, with notable spikes in 2021 and 2022, suggesting growing interest or recognition of the importance of agro waste in research and development. No publication was found from 2000-2004 in the search, though the lower number of publications in earlier years such as 2005-2009 may indicate relatively less attention or research focus on agro waste during that period. The Fig. 3 provides details of the research focus associated with different types of agro waste. The graph provides valuable insights into the research landscape surrounding various types of agro waste employed in PB manufacturing. It highlights the relative attention and interest that different materials have received within the research community. The varying number of publications across agro waste types suggests that some materials have been more extensively studied than others. This disparity in research output could be influenced by factors such as the abundance and availability of specific agro waste materials, their potential applications, and the perceived benefits or challenges associated with their utilization. Sugarcane and rice, with its impressive tally of publications, emerges as a prominent focus of agro waste research. This high number of studies underscores the significant potential and versatility of sugarcane and rice waste as a subject of scientific inquiry. Researchers may be drawn to sugarcane due to its widespread cultivation, the volume of waste generated during its processing, and the diverse range of potential applications for its byproducts. The numerous publications on sugarcane waste could cover various aspects, such as its composition, properties, and potential uses in different industries, including biofuels, biomaterials, and renewable energy. On the other end of the spectrum, some agro waste types have only a single publication associated with them. This lower research output could indicate that these materials have received less attention or have been studied in more niche contexts. The reasons for this disparity could range from limited availability or accessibility of the waste material, challenges in processing or utilizing it, or a lack of perceived value or applicability in research or industrial settings. The bibliometric map in Fig. 4 offers a comprehensive overview of the PB research landscape, identifying the main themes, clusters, and their interrelationships providing valuable insights for researchers and enabling them to identify research gaps, trends, and potential areas for future studies.

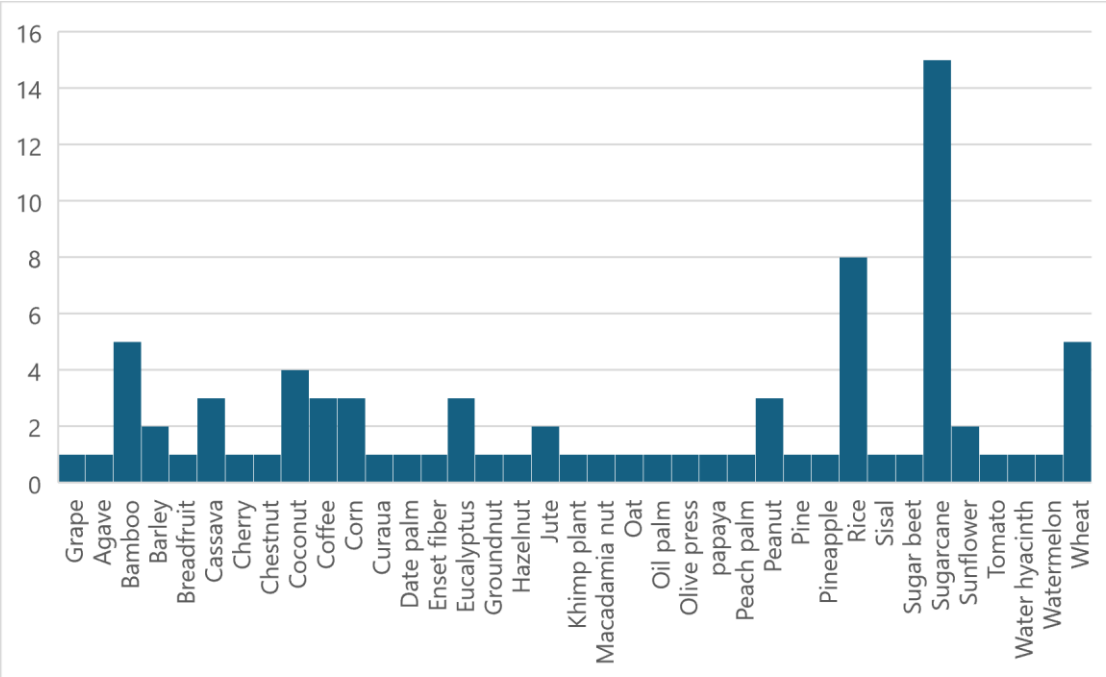

Fig. 3. Agro waste studied in the reviewed articles.

Fig. 4 provides a visual representation of the research landscape related to particle board (PB) based on text data from a bibliographic dataset obtained from Scopus. The map reveals four distinct clusters, each represented by a different colour: red, green, blue, and yellow. These clusters highlight the key themes, topics, and relationships within the agro waste PB research domain. Cluster 1, denoted by red patches and links, consists of 110 items and emphasizes various aspects of PB research. The prominent keywords in this cluster include "study," "production," "board," "fibre," and "value." This suggests that Cluster 1 focuses on the study and production of PB, with a particular emphasis on the use of fibers and the value proposition of PB products. Researchers in this cluster likely investigate the manufacturing processes, raw materials, and economic aspects of PB production. Cluster 2, represented by green patches and links, comprises 57 items and concentrates on the binding components and adhesive systems used in PB. The key terms in this cluster include "adhesive," "adhesive systems," "performance," and "composite." This indicates that Cluster 2 delves into the research and development of adhesives and their performance in PB composites. Studies in this cluster may explore different types of adhesives, their properties, and their impact on the overall performance of PB products. Cluster 3, identified by blue patches and links, also contains 57 items, and focuses on the fundamental elements of PB, namely "particle," "panels," and "particle board." This cluster likely investigates the properties, characteristics, and manufacturing techniques specifically related to particle-based panels. Researchers in this cluster may study particle size, geometry, and distribution, as well as their influence on the mechanical, physical, and thermal properties of PB panels. Lastly, Cluster 4, represented by yellow patches, consists of 55 items and emphasizes the properties of PB, the ratio of mix, and the materials used in production. This cluster appears to focus on the optimization of PB properties through the manipulation of raw material proportions and the selection of appropriate production materials. Studies in this cluster may investigate the impact of different mix ratios and material combinations on the final properties of PB, such as strength, durability, and moisture resistance. the Fig. 5 presents the distribution of based on the nature of adhesives used in the manufacturing of agro waste particle boards derived from the reviewed papers.

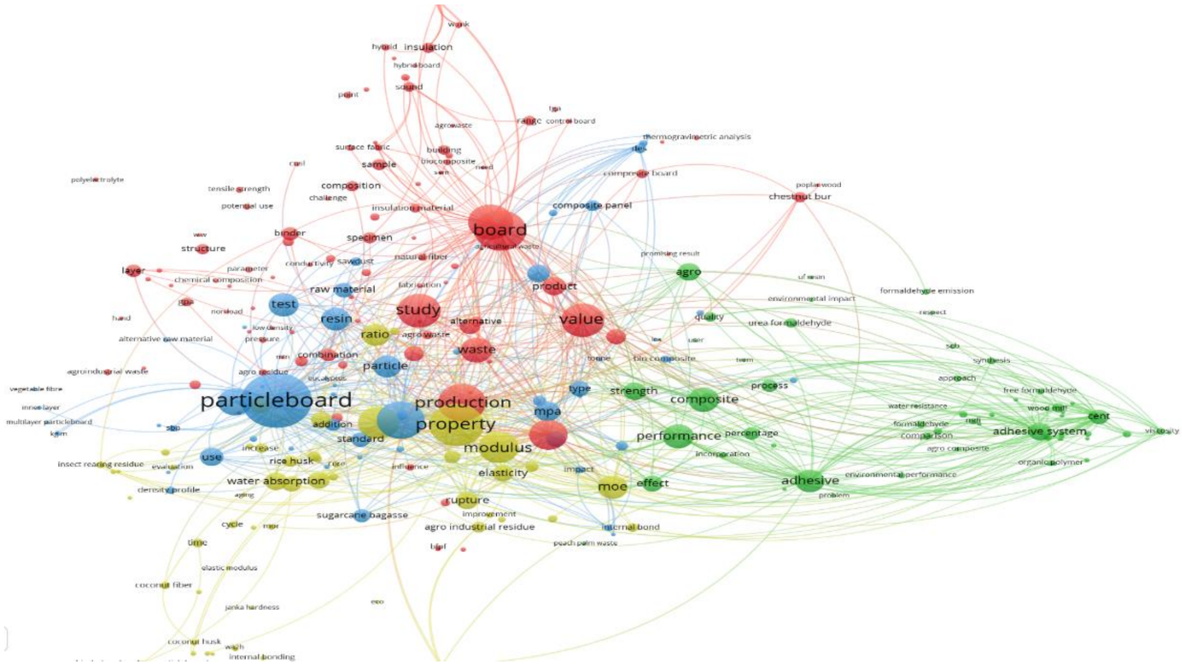

Fig. 4. Bibliometric analysis of dataset

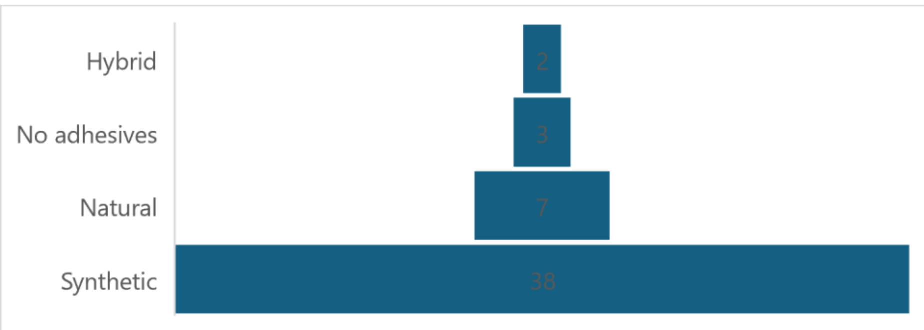

Fig. 5. Adhesive binder employed in particle board production

From Fig. 5, the use of synthetic adhesives still dominates the research landscape with 38 studies employing it use. The use of hybrid adhesives signifies a shift towards innovation and optimization in particle board manufacturing leveraging on the strengths of both types while mitigating their individual limitations. Few studies exploring the use of no adhesives or natural adhesives align closely with sustainable development goals in construction. By eliminating or minimizing the use of synthetic adhesives, these approaches contribute to reducing the environmental footprint of particle board production, offering biodegradable and eco-friendly alternatives while promoting sustainability throughout the product lifecycle.

5. Discussion

The utilization of agricultural residues in particleboard production represents a significant advancement in sustainable materials science, offering a dual benefit of waste valorisation and the development of eco-friendly alternatives to traditional wood-based panels. From the management of waste hierarchy, it is almost impossible to prevent and/or mitigate total waste generation; rather reuse and recycle by incorporating the agro waste in construction can help to prioritize more sustainable and resource-efficient practices, reducing the environmental impact of crop production and promoting a circular economy approach to waste management. The growing global population and increasing demand for sustainable and affordable building materials have driven researchers to explore the potential of agro-industrial wastes as alternative raw materials for PB production as seen in the yearly publication output (Fig. 2). Furthermore, the reviewed literature showcases a wide range of agricultural residues mostly studied, such as sugarcane bagasse [43-46], rice husks [47-49], corn stover [50,51], peanut shells [52,53], coconut fibers [44,54,55], and bamboo [53,56,57], Wheat straw [58,59] among others. Sugarcane bagasse, a fibrous residue obtained after juice extraction, is predominantly available in tropical and subtropical regions. Its high cellulose content, ranging from 32% to 44%, and hemicellulose content of 27% to 32%, make it an excellent raw material for PB production [60]. Sugarcane is the most produced crop resulting in abundance of bagasse which has led to extensive research on its utilization in PB manufacturing. For instance, Fiorelli et al. [44] demonstrated the feasibility of producing high-quality multilayer PB from bagasse and coconut fibers, achieving mechanical properties that met international standards. Similarly, Garzón et al. [45] investigated the durability of bagasse-based particleboards, finding that they exhibited acceptable dimensional stability and mechanical performance after accelerated aging tests. Rice husks, a byproduct of rice milling abundant in major rice-producing third world countries, offer unique properties due to their high silica content of 15% to 20%, contributing to improved fire resistance and dimensional stability in PB [61]. Battegazzore et al. [47] successfully developed rice husk PBs with enhanced flame retardancy using a layer-by-layer functionalization approach. This study highlighted the potential of rice husks not only as a sustainable raw material but also as a means to improve the fire safety of particleboards. Furthermore, Hidayat et al. [49] explored the use of natural rubber latex as a formaldehyde-free binder for rice husk-based panels, addressing concerns about formaldehyde emissions from traditional adhesives. Corn stover, consisting of stalks, leaves, and cobs left after corn harvest, is widely available in many regions as corn is the most produce grain globally. Its cellulose content of 38% to 40% and lignin content of 7% to 21% provide good mechanical properties for PB production [62]. Mayer-Laigle et al. [50] investigated the preservation of corn pith cellular structure for improved insulation properties in agro-materials, demonstrating the potential of corn stover not only as a structural component but also as a thermal insulation material in particleboards. Peanut shells, a byproduct of peanut processing offers a lignocellulosic composition suitable for PB manufacturing. Ercan et al. [52] examined the formaldehyde emission and combustion properties of peanut husk-based composite panels, demonstrating their potential as green building materials with low environmental impact. Coconut fibers, extracted from coconut husks in tropical coastal regions of Asia, Africa, and South America, are rich in lignin (41-45%) and cellulose (36-43%), offering excellent mechanical properties [63]. Fiorelli et al. [44] successfully incorporated coconut fibers into multilayer particleboards, while Narciso et al. [45] explored their potential in medium-density PB production, finding that coconut husks could partially replace wood particles without significantly compromising board properties. Bamboo, rapidly renewable and widely cultivated in Asia, Africa, and South America, offers high strength-to-weight ratios and natural antimicrobial properties. Guan et al. [56] developed binderless bamboo particleboards using biological fermentation, addressing the challenge of synthetic resin usage and demonstrating the potential for fully bio-based PB production. Wheat straw, globally abundant in many regions has been extensively studied for PB production. Khorami and Sobhani [58] investigated the flexural performance of cement-bonded wheat straw boards, while Jové-Sandoval et al. [59] explored its use in earth-straw lightweight panels for thermal improvement of adobe walls, showcasing the versatility of wheat straw in various construction applications. The integration of these diverse agricultural residues into PB production offers several advantages beyond waste valorisation. Many of these materials impart specific characteristics to the resulting particleboards, such as enhanced fire resistance from rice husks or improved acoustic properties from enzyme-treated fibers. Additionally, the regional availability of different agricultural residues allows for PB production tailored to locally available materials, potentially reducing transportation costs and associated emissions. However, the use of agricultural residues in PB production also presents challenges. The seasonal availability of these materials necessitates efficient storage and supply chain management. Furthermore, the variability in chemical composition and physical properties of agricultural residues, unlike the more consistent wood fibers, requires robust quality control measures and adaptive manufacturing processes.

The various clusters in bibliometric map which provides insights into the main research areas within the PB domain and the relationships between them reveals a strong focus on PB production, adhesive systems, particle properties, and material optimization. This information can guide researchers and industry professionals in identifying key areas for further investigation, collaboration, and innovation. Also, the map highlights the interdisciplinary nature of PB research, with links and overlaps between clusters. For example, the study of adhesive systems (Cluster 2) is closely related to the properties and performance of PB (Cluster 4). Similarly, the production aspects (Cluster 1) are connected to the particle characteristics (Cluster 3) and material optimization (Cluster 4).

The performance of these agro based materials is influenced by several key factors, such as the type and proportion of the agro waste, particle size and geometry, adhesive type and content, and processing conditions. Taha et al. [64] found that increasing the pressure and resin content during hot pressing of tomato stalk particleboards led to higher density and improved mechanical properties. Similarly, Amenaghawon et al. [65] optimized the production of particleboards from corn cobs and cassava stalks using response surface methodology, achieving maximum MOR and MOE values at specific combinations of board density, resin loading, and agro waste content. Particle size and geometry also play a crucial role in the properties of agro waste particleboards. Lee et al. [57] reported that boards made from bagasse and bamboo fibers with higher slenderness ratios (length-to-diameter) exhibited better mechanical performance. Borysiuk et al. [66] found that sugar beet pulp particles of different sizes could be strategically incorporated into the face and core layers of PB to maintain acceptable properties while reducing the use of wood particles.

The choice of adhesive is another critical factor influencing the performance and eco-friendliness of agro waste particleboards. While synthetic resins like urea-formaldehyde (UF) and phenol-formaldehyde (PF) are commonly used due to their good binding properties [52,67], there is a growing interest in bio-based and natural adhesives. Fiorelli et al. [44] and de Oliveira Júnior et al. [68] utilized castor oil-based polyurethane resin as a renewable alternative to petrochemical adhesives in the production of sugarcane bagasse and coconut fiber particleboards, achieving excellent mechanical and physical properties. Hidayat et al. [49] explored the use of natural rubber latex as a formaldehyde-free adhesive for particleboards made from cassava stems, rice husks, and wood waste, obtaining promising results. Researchers have also investigated various strategies to enhance the dimensional stability and water resistance of agro waste particleboards, which are often more susceptible to moisture compared to conventional wood-based panels. Basta et al. [43] found that incorporating denatured rice bran into UF resin during the synthesis stage significantly reduced thickness swelling and water absorption of sugarcane bagasse particleboards while maintaining good mechanical strength. Chemical modifications of the agro waste fibers, such as alkali, silane, or acetylation treatments, have also been reported to improve the interfacial adhesion and moisture resistance of the resulting composites [69,70].

The thermal insulation and acoustic properties of agro waste particleboards are other important aspects that have been explored in the literature. Ali et al. [71] reported that loose and bound composites made from agave and wheat straw fibers exhibited low thermal conductivity values (0.043-0.045 W/mK) suitable for building insulation applications. Efe and Alma et al. [72] found that particleboards produced from sunflower stalks had superior heat insulation properties compared to conventional wood-based panels. Taha et al. [64] and Pugazhenthi and Anand [73] also demonstrated the potential of tomato stalks and hybrid coir-sawdust fiberboards as thermal insulation materials. In terms of acoustic performance [74] reported high sound absorption coefficients (up to 0.99) for nanofiber panels made from enzyme-treated enset fibers, especially at higher frequencies. Various Life cycle assessment (LCA) studies have provided valuable insights into the environmental implications of using agro wastes in particleboard production. Silva et al. [75] conducted an LCA comparing sugarcane bagasse particleboards (PSB) with conventional wood-based panels and found that PSB performed better in most environmental impact categories due to reduced wood consumption and lower emissions from raw material acquisition. Pang et al. [76] reported that bio-composites made from rice straw and bamboo using a combination of bio-based and synthetic adhesives had a lower carbon footprint compared to conventional particleboards. The study also estimated that globally utilizing 23.97 million tonnes of rice straw in bio-composite production could save 1.61 million hectares of forest and reduce CO_2 emissions by 63.76 million tonnes annually.

5.1 Potential barrier and future prospect

Despite the promising results, there are still challenges and limitations associated with the large-scale adoption of agro waste particleboards. The seasonal availability and variability of agricultural residues can pose logistical issues for consistent industrial production [77]. The use of synthetic resins, even in reduced quantities, may still impact the biodegradability and recyclability of the composite panels at the end of their life cycle [69]. Some agro wastes may require additional processing or pre-treatments to improve their compatibility with adhesives or to reduce the presence of impurities and inhibitory compounds [78]. Further research is needed to address these challenges and to optimize the performance and sustainability of agro waste particleboards. Guan et al. [56] explored the use of biological fermentation to improve the binderless adhesion of bamboo residues, while Fatima Haq et al. [51] investigated the application of deep eutectic solvents (DES) to enhance the interfacial properties of corn stover, peanut shell, and sugarcane bagasse fibers in bio-composite panels. The development of eco-friendlier and bio-based adhesives, such as lignin, tannin, or protein-based resins, could further reduce the environmental impact of these materials. In addition to technological advancements, policy support and industrial collaboration will be crucial for the successful commercialization of agro waste particleboards. Governments can encourage the use of these sustainable materials through green building certifications, tax incentives, and public procurement policies. Industry partnerships between agricultural producers, panel manufacturers, and construction companies can help establish reliable supply chains and create market demand for these products.

6. Conclusions and Recommendations

The global context of this research highlights the universal need for sustainable construction practices and the importance of finding eco-friendly alternatives to traditional wood-based materials in the panel/board industry. This current study reveals a diverse range of agricultural residues that have been successfully utilized in the manufacture of particleboards and composite panels with sugarcane as most studied. The bibliometric analysis conducted identifies key research clusters and themes, highlighting the focus on production processes, adhesive systems, particle properties, and material optimization. Furthermore, the use of synthetic resins as binder currently dominates the research landscape, though there is a growing interest in bio-based and natural adhesives that align with sustainable development goals. The performance of these materials is influenced by factors such as the type and proportion of agro waste, particle size and geometry, adhesive type and content, and processing conditions. While seasonal availability, variability of agricultural residues, and the need for additional processing or pre-treatments must be addressed to facilitate the large-scale adoption of these sustainable materials. life cycle assessment studies indicate the potential of agro waste particleboards to reduce the carbon footprint and conserve forest resources compared to conventional wood-based panels. Based on these findings, the following recommendations are proposed.

- Encourage collaborative research efforts between academia, industry, and policymakers to further optimize the performance and sustainability of agro waste particleboards, addressing challenges related to raw material availability, processing, and adhesive systems.
- Develop and promote the use of eco-friendly, bio-based adhesives, such as lignin, tannin, or protein-based resins, to minimize the environmental impact of particleboard production and enhance the biodegradability and recyclability of the composite panels.
- Conduct comprehensive life cycle assessments and techno-economic analyses to quantify the environmental and economic benefits of agro waste particleboards, facilitating informed decision-making and policy development.
- Establish industry partnerships between agricultural producers, panel manufacturers, and construction companies to create reliable supply chains, ensure consistent quality, and promote the commercialization of agro waste particleboards.
- Implement supportive government policies, such as green building certifications, tax incentives, and public procurement guidelines, to encourage the adoption of sustainable construction materials and practices, driving the demand for agro waste particleboards.
- Raise awareness among architects, engineers, and construction professionals about the benefits and applications of agro waste particleboards through educational programs, workshops, and case studies, fostering a culture of sustainability in the built environment.

By implementing these recommendations and fostering collaboration among stakeholders, the construction industry can harness the immense potential of agro-industrial wastes, contributing to the development of sustainable and affordable building materials while promoting a circular economy approach to waste management. This paradigm shift towards eco-friendly construction practices will be instrumental in addressing the challenges posed by rapid urbanization and climate change, ensuring a more sustainable future for the built environment. Although some research has focused on addressing in agro waste PB challenges through various strategies like hybrid formulation, surface modifications and eco adhesive systems. Further research on improving the durability, fire resistance, and moisture resistance of these products, along with advancements in bio-based adhesives and processing technologies, will be necessary to overcome the remaining challenges and facilitate their widespread adoption in the building and furniture industries.

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