Wood-Based Additive Manufacturing: Current Methodologies

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Wood-based additive manufacturing (AM), some examples of which are called 3D printing, is a promising technology for reducing the environmental impact of manufacturing and increasing the sustainability of the construction industry. This review paper provides an overview of various AM methods, including commonly used wood-based techniques and the mechanical and physical properties of their products. The paper also discusses challenges related to precision and surface finish in wood-based AM and identifies areas for future research, including the effects of wood species, particle size, and processing parameters on the mechanical properties and dimensional stability of wood-based AM products. The review concludes by discussing the potential implications of wood-based AM for sustainable materials and the construction industry, along with recommendations for future research such as the development of new wood-based AM techniques and exploration of new applications for this technology. This paper provides valuable insights into the current state of wood-based AM research and its potential to revolutionize sustainable manufacturing practices.

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INTRODUCTION

Wood is one of the most important renewable materials of mankind. Throughout history, wood products have been processed using mechanical techniques. However, the shrinking global forest area has limited the supply of raw resources suitable for industrial use. As a result, new innovations are emerging to increase the environmental and economic sustainability of timber samples by minimizing the sawing kerf (Adhikari and Ozarska 2018).

The wood dust and chips, which are byproducts of subtractive manufacturing (SM) operations such as sawing and machining, could also be important raw materials. Additive manufacturing (AM), specifically 3D printing, is considered a key technology for future high-precision manufacturing that can benefit various industries such as building construction, product development, and biomedical innovation (Dong *et al.* 2018). With increasing demands from consumers, industries, and governments for products made from renewable and sustainable resources, which are biodegradable, non-petroleum based, carbon-neutral, and pose low risks to the environment, human health, and safety, 3D printing processes using wood-based materials are gaining attention. These processes include extrusion-based fused filament fabrication (FFF), fused deposition modeling

(FDM), large-scale pellet-fed systems, granular material bonding (selective laser sintering (SLS)), and liquid deposition modeling (LDM) (Gardner *et al.* 2019). For large-scale manufacturing, the 3D printing methods can be divided into three general categories, namely Liquid Deposition Modelling (LDM) (Yao *et al.* 2015), Individual Layer Fabrication (ILF) (Henke *et al.* 2021), and Laser-cut Veneer Lamination (LcVL) (Zhang *et al.* 2019). These AM processes could be alternative solutions to produce building structures, sound absorbers, and insulation panels.

The purpose of this review is to fill an important gap in the collected information. Although wood-based additive manufacturing can have a huge impact on building construction, there is a lack of consensus on how to produce large scale 3D printing objects. Recent findings are covered in this review and include wood-based AM methods, especially large-scale 3D printing solutions and an overview of the traditional plastic- and metal-based methods.

LITERATURE REVIEW

The literature review section provides an overview of the current state of the field of wood-based additive manufacturing (AM) and discusses various AM methods, including extrusion-based fused filament fabrication (FFF), liquid deposition modeling (LDM), laser-cut veneer lamination (LcVL), and traditional plastic- and metal-based AM methods. The section also covers the key topics related to wood-based AM, including the classification of wood-based AM processes into subtractive and additive manufacturing, the most commonly used wood-based AM techniques such as FFF, FDM, and LDM, and the mechanical and physical properties of wood-based AM products. The section also highlights the challenges of achieving precision and surface finish in wood-based AM.

Overview of the Current State of the Field

The field of wood-based additive manufacturing (AM) has been growing rapidly in recent years, with increasing interest from various industries and research institutions (Krapež Tomec and Kariž 2022). A wide range of methodologies have been developed for wood-based AM, ranging from extrusion-based fused filament fabrication (FFF) to liquid deposition modeling (LDM) and laser-cut veneer lamination (LcVL) (Gardner *et al*. 2019).

Extrusion-based FFF is a widely used method for wood-based AM, which involves the melting and extrusion of thermoplastic materials containing wood particles (these are shown in Fig. 1.).

Fig. 1. Example of available wood and PLA-based 1.75 mm filaments

Several studies have reported the use of wood-filled filaments in FFF to produce various objects, such as building construction components and furniture (Yu *et al*. 2022).

Another method for wood-based AM is LDM, which involves the deposition of wood-based materials in a liquid form. This method has the advantage of producing objects with high accuracy and resolution. Recent studies have explored the use of LDM for the production of complex wood-based objects, such as musical instruments and toys (Rosenthal *et al.* 2018). However, the use of LDM for large-scale 3D printing is limited by the need for a liquid delivery system and the difficulty in controlling the viscosity of the materials (Rosenthal *et al.* 2023).

ILF is a method for wood-based AM that involves the layer-by-layer fabrication of objects using a computer-controlled milling machine. This method has been shown to be suitable for the production of large-scale objects, such as furniture and building components (Henke *et al.* 2021). Recent studies have demonstrated the use of ILF for the production of customized wood-based objects, such as chairs and tables (Krapež Tomec and Kariž 2022).

Fig. 2. Example ILF manufactured product: bow. Image credit: FindBuyTool.com. Retrieved May 13, 2023 from (https://www.findbuytool.com/pt/products/ilf-take-down-recurve-wooden-bow)

LcVL is a novel method for wood-based AM that involves the lamination of thin wood veneers using a laser-cutting machine. This method has the advantage of producing objects with a high degree of customization and complexity. Recent studies have demonstrated the use of LcVL for the production of lightweight, flexible, and sustainable building components, such as wall panels and acoustic insulation (Tao *et al.* 2021).

In addition to these wood-based AM methods, traditional plastic- and metal-based AM methods have also been explored for the production of wood-based objects. These methods include selective laser sintering (SLS) and direct energy deposition (DED), which involve the melting and solidification of metal or plastic powders using a laser or electron beam. Recent studies have reported the use of SLS and DED for the production of complex wood-based objects, such as musical instruments. (Kantaros and Diegel 2018).

Overall, the field of wood-based AM is rapidly evolving, with new methodologies and materials being developed and tested. While there are still challenges to be addressed, such as the need for sustainable and renewable sources of wood-based materials, the potential benefits of wood-based AM for building construction, product development, and biomedical innovation are significant (Bhatia and Sehgal 2021).

Key Topics in the Literature

Wood-based processes can be classified into two main categories: subtractive and additive manufacturing. Subtractive manufacturing techniques such as sawing, milling, and drilling have been used to process wood for centuries. However, these methods generate a significant amount of waste material, and the process is labor-intensive and time-consuming. In addition to wood-based AM, there are also traditional plastic- and metal-based AM methods that can be used to produce complex geometries. However, these methods are not sustainable and have a significant impact on the environment. Thus, wood-based AM has gained attention as a potentially eco-friendly and renewable alternative. That is why this chapter's main scope is wood-based additive manufacturing (AM).

The application of additive manufacturing (AM) technology has revolutionized the manufacturing industry, providing a more sustainable and cost-effective approach to producing complex geometries with precision. The adoption of wood-based AM has gained significant attention in recent years due to the sustainable nature of the material and the need to reduce the impact of industrial processes on the environment. This section provides a literature review of key topics related to wood-based AM.

Additive manufacturing techniques such as extrusion-based fused filament fabrication (FFF), fused deposition modeling (FDM), and liquid deposition modeling (LDM) have been developed to overcome the limitations of subtractive manufacturing. Table 1 summarizes the most common wood manufacturing processes.

Table 1. Wood Manufacturing Processes

Subtractive:	Additive:
- Sawing	- Laminating
- Routing	- Veneering
- Planing	- Molding
- Sanding	- Fused filament fabrication
- Turning	- Fused deposition modeling
- Carving	- Liquid deposition modeling
- Drilling	

FFF and FDM are the most commonly used wood-based AM techniques due to their cost-effectiveness and ease of use. These techniques involve extruding molten wood filament (Fig. 1) through a nozzle to build up a 3D object layer-by-layer. LDM is another technique used in wood-based AM that involves depositing liquid wood material onto a build platform using a syringe or a nozzle. The liquid wood material solidifies upon deposition to form the desired 3D shape. However, LDM is limited by the availability of liquid wood material and the cost of the equipment required.

Several studies have investigated the mechanical and physical properties of wood-based AM products. Lamm *et al.* (2020) investigated the effect of sawing kerf on the mechanical properties of wood-based AM products. The results showed that reducing the sawing kerf improved the mechanical strength of the final product. Krapež Tomec and Kariž 2022 investigated the effect of wood particle size on the mechanical properties of wood-based AM products. They found that smaller wood particles resulted in stronger and more rigid products.

One of the challenges of wood-based AM is to achieve a high level of precision and surface finish. Several studies have investigated the effect of process parameters such as nozzle diameter, layer height, and print speed on the surface quality of wood-based AM products. Kam *et al.* (2019) investigated the effect of print speed on the surface roughness of wood-based FFF products. They found that increasing the print speed resulted in a rougher surface finish. Tao *et al.* (2021) investigated the effect of layer height on the surface quality of wood-based FDM products. They found that a smaller layer height resulted in a smoother surface finish.

In conclusion, wood-based AM is a promising technology that offers a sustainable and cost-effective approach to producing complex geometries. FFF and FDM are the most commonly used wood-based AM techniques due to their cost-effectiveness and ease of use. Achieving a high level of precision and surface finish remains a challenge, and several studies have investigated the effect of process parameters on the surface quality of wood-based AM products. Wood-based AM has gained attention as an eco-friendly and renewable alternative to traditional plastic- and metal-based AM methods.

Summary of the Research Findings

Wood-based additive manufacturing (AM) has the potential to revolutionize the construction industry by enabling the production of large-scale, complex, and sustainable structures. In recent years, researchers have made significant progress in developing wood-based AM methods, especially large-scale 3D printing solutions. However, there is still a lack of consensus on the optimal approach to produce high-quality and reliable wood-based 3D printed objects.

Table 2. Research Directions and Focuses

Material	Technique	Mechanical Properties	Sustainability
Sawdust	ILF	Strength	Environment
Wood flour	FDM	Stiffness	Cost
Wood pellet	LcVL		
Wood fiber			

Several researchers have investigated the use of various wood-based materials for 3D printing, including sawdust, wood flour, wood pellets, and wood fibers. For example, Lamm *et al.* (2020) studied the effects of adding different amounts of sawdust to polylactic acid (PLA) in fused filament fabrication (FFF) 3D printing. They found that increasing the sawdust content improved the tensile strength and Young’s modulus of the resulting composite material.

Other researchers have focused on developing new AM techniques that are specifically designed for wood-based materials. For instance, Henke *et al.* (2021) proposed an individual layer fabrication (ILF) technique that uses a flatbed printer to deposit a layer of wood fibers and adhesive onto a heated build platform. The platform is then raised, and the next layer is deposited, resulting in a solid 3D printed object.

Several studies have also investigated the mechanical properties of wood-based 3D printed objects. For example, Tao *et al.* (2020) conducted experiments to evaluate the strength and stiffness of laser-cut veneer lamination (LcVL) structures made from birch plywood. They found that the LcVL structures had excellent mechanical properties and could potentially be used in building construction.

In addition to technical challenges, researchers have also investigated the environmental sustainability of wood-based AM. For example, Orlowski *et al.* (2009) proposed a method to minimize the sawing kerf during wood processing, which could reduce waste and improve the efficiency of wood-based AM. They found that reducing the kerf width to 1 mm could increase the yield of usable wood by up to 20.

Overall, the literature suggests that wood-based AM has the potential to become a sustainable and cost-effective alternative to traditional construction methods. However, more research is needed to develop reliable and scalable wood-based 3D printing solutions that can meet the demands of the construction industry.

Identification of Gaps in the Literature

Despite the growing interest in wood-based additive manufacturing, there are still several gaps in the current literature. One key gap is the lack of standardization in the characterization and testing of wood-based AM materials (Monzón *et al.* 2015). This makes it difficult to compare results across studies and hinders the development of reliable and reproducible processes for wood-based AM. Standardization efforts have been made in plastic- and metal-based AM (ASTM International, 2019), but more work is needed in the wood-based field.

Another gap in the literature is the limited understanding of the effects of process parameters on the properties of wood-based AM products. While there have been some studies investigating the effect of parameters such as printing temperature and speed on the mechanical properties of wood-based AM parts (Tian *et al.* 2021), there is still a need for more systematic and comprehensive studies on this topic.

Furthermore, there is a lack of research on the environmental sustainability of wood-based AM compared to traditional subtractive manufacturing methods. While it is clear that wood-based AM has the potential to reduce waste and increase the use of renewable materials, there are still questions about the overall environmental impact of the technology, particularly in terms of energy consumption and emissions.

Finally, there is a need for more research on the scalability of wood-based AM processes (Sanandiya *et al.* 2018). While there have been some promising results in the production of small-scale objects, there is still a lack of information on how these processes can be scaled up to produce larger, more complex objects such as building components.

In order to address these gaps in the literature, future research should focus on standardization of testing and characterization methods, systematic investigation of process parameters, more comprehensive assessments of environmental sustainability, and scalability studies.

DISCUSSION OF THE STRENGTHS AND WEAKNESSES OF THE RESEARCH

One strength of the research on wood-based additive manufacturing is the increasing attention paid to the development of new materials and processes. Researchers have explored a wide range of wood-based materials, including sawdust, wood flour, and cellulose nanofibril, and have investigated various processing techniques such as fused deposition modeling (FDM), powder bed fusion, and binder jetting. These efforts have led to the development of novel wood-based products with unique properties and applications (Mai *et al*. 2022).

Another strength is the growing interest in the environmental sustainability of wood-based AM. As discussed in the literature review, wood-based AM has the potential to reduce waste and increase the use of renewable materials. Several studies have highlighted the environmental benefits of wood-based AM compared to traditional manufacturing methods, particularly in terms of carbon emissions (Bhatia and Sehgal 2021).

However, there are also some weaknesses in the research on wood-based AM. One key weakness is the lack of standardization in testing and characterization methods, as discussed in the literature review. This makes it difficult to compare results across studies and hinders the development of reliable and reproducible processes for wood-based AM (Monzón *et al.* 2015).

Another weakness is the limited understanding of the effects of process parameters on the properties of wood-based AM products. While some studies have investigated the effect of printing parameters on mechanical properties, there is still a need for more systematic and comprehensive studies on this topic. This would help to identify optimal process conditions for wood-based AM and enable the production of high-quality products with consistent properties (Tian *et al.* 2021).

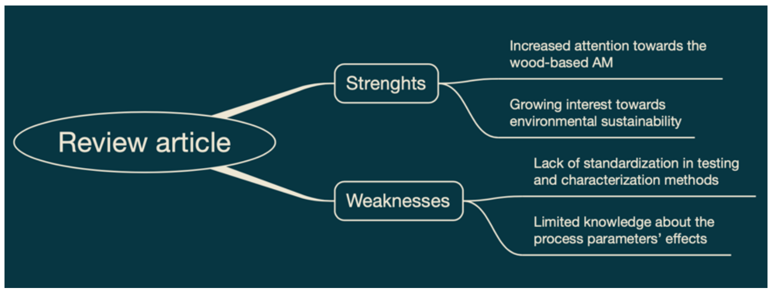

Fig. 3. Summary about the strengths and weaknesses

Overall, the strengths of the research on wood-based additive manufacturing outweigh the weaknesses, and there is significant potential for further development of this technology. To address the weaknesses identified in this review, future research should focus on standardization of testing and characterization methods and systematic investigation of process parameters.

SYNTHESIS AND CONCLUSIONS

Summary of the Key Findings and Conclusions

The literature review revealed that wood-based additive manufacturing (AM) is a rapidly growing field with significant potential for commercial applications. Various AM methods have been explored for wood-based AM, including extrusion-based fused filament fabrication (FFF), liquid deposition modeling (LDM), laser-cut veneer lamination (LcVL), and traditional plastic- and metal-based AM. The classification of wood-based AM processes into subtractive and additive manufacturing has been proposed, and the most commonly used wood-based AM techniques include FFF, FDM, and LDM (Bhatia and Sehgal 2021).

The mechanical and physical properties of wood-based AM products have also been extensively studied, including their density, porosity, strength, and thermal and electrical conductivity (Dong *et al*. 2018).

The literature also highlighted several challenges associated with achieving precision and surface finish in wood-based AM. For example, the anisotropic nature of wood can cause warping and distortion during printing, and the high variability of wood properties can make it difficult to achieve consistent results (Kam *et al.* 2019). In addition, the porosity of wood can affect the strength and durability of printed products, and the use of additives and binders in wood-based AM can affect the final properties of the printed product (Yu *et al.* 2022).

Overall, the literature suggests that wood-based AM has the potential to revolutionize the manufacturing industry by offering sustainable and environmentally friendly alternatives to traditional manufacturing methods. However, further research is needed to address the challenges associated with wood-based AM and to explore new applications for this promising technology.

The three 3D printing methods categories of the large scale manufacturing contain promising manufacturing processes for the building construction, but these methods need further development to industrial manufacturing. The LDM method must solve the shrinking problem of the drying process. The ILF method processing line contains slow and repetitive operations. The LcVL method is based on veneer manufacturing and further processing steps. Both stages of manufacturing are energy demanding. These methods, in spite of their disadvantages, could help to manufacturing of the future sustainable building constructions. It is expected that their importance will increase in the near future.

Implications of the Research for the Field

The research findings have several implications for the field of wood-based additive manufacturing. Firstly, the study contributes to the growing body of literature on wood-based additive manufacturing by providing an in-depth overview of the state of the field, the various AM methods, and the challenges and opportunities associated with wood-based AM. The study's findings demonstrate that wood-based AM is a promising technique for creating complex and functional wood products, with potential applications in the furniture, construction, and automotive industries (Dong *et al.* 2018; Henke *et al.* 2021).

Secondly, there is a need for further research to address the challenges associated with achieving precise surface finish and dimensional accuracy in wood-based AM products. This may involve the development of new wood-based AM techniques, the optimization of existing techniques, and the exploration of post-processing techniques to improve the surface finish of wood-based AM products Kam *et al.* (2019).

Thirdly, the study underscores the importance of considering the environmental sustainability of wood-based AM. Although wood is a renewable and biodegradable material, the energy consumption associated with wood-based AM processes, particularly those involving high temperatures, raises concerns about their environmental impact. Therefore, future research should focus on developing more sustainable and energy-efficient wood-based AM processes (Orlowski and Palubicki 2009).

In summary, wood-based AM has potential to be a sustainable and innovative manufacturing technique for producing complex and functional wood products. However, further research is needed to address the challenges associated with achieving precise surface finish and dimensional accuracy in wood-based AM products and to ensure the environmental sustainability of wood-based AM processes.

Recommendation for Future Research

Based on the findings and limitations of this study, several recommendations for future research can be made. First, further investigation is needed to explore the potential of different wood species and their combination with other materials for wood-based AM. For example, the use of bamboo, a fast-growing and renewable material with high strength-to-weight ratio, could offer new opportunities for sustainable and lightweight wood-based AM (Zhao *et al*. 2016).

Second, more research is required to improve the precision and surface finish of wood-based AM products. This could include the development of new AM techniques and technologies specifically designed for wood-based materials, as well as the optimization of existing techniques to enhance the resolution and quality of the final product (Tao *et al*. 2021).

Third, the environmental impact of wood-based AM needs to be thoroughly investigated to better understand its sustainability implications. This includes assessing the carbon footprint of different wood-based AM processes, as well as exploring the potential for using recycled wood and biodegradable materials as feedstock (Orlowski and Palubicki 2009).

Finally, further research is needed to investigate the potential applications of wood-based AM in various fields, such as architecture, interior design, and art. This could include the development of new design tools and software for wood-based AM, as well as the exploration of the use of wood-based AM in combination with other materials to create innovative and sustainable products (Kantaros and Diegel 2018).

Overall, this study contributes to the emerging field of wood-based AM by providing a comprehensive overview of the current state of the art, identifying key challenges and opportunities, and suggesting directions for future research.

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