IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received March 13, 2021, accepted March 30, 2021, date of publication April 6, 2021, date of current version April 20, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3071459

3D Printing of Plant-Derived Compounds and a Proposed Nozzle Design for the More Effective 3D FDM Printing

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This work was supported by the New Art of Reason (NewArea) - Business Finland.

ABSTRACT Additive manufacturing technology has been developed in the manufacturing industry; however, limited choice of materials and low printing speeds in large-scale production make 3D printing challenging in the industry. Wood and cellulose-based materials have recently drawn a lot of attention for use as 3D printing materials due to their unique properties such as environmental friendliness, cost-effectiveness and abundancy. However, because these compounds are derived from various natural sources, their different particle sizes can result in low 3D printing quality. The objective of this study is to resolve the mentioned deficiencies in the packaging industry by designing a novel 3D printer nozzle based on the material extrusion method (FDM technique), which provides higher printing speed and enhanced quality for wood and cellulose-based materials. The packaging industry can significantly benefit from 3D printing technology for cellulose-based materials by producing high-quality recyclable economical packaging on a large scale according to the clients' demand. The proposed nozzle design enables selecting different geometrical cross-sections of the nozzle dies and any number of extrusion points along the nozzle die simultaneously during the 3D printing process. These capabilities lead to advanced performance and improved speed of 3D printing in large scale manufacturing. The proposed nozzle design provides a novel technique for 3D printing of plant-derived compounds with remarkable advantages such as providing selective variable extrusion and multiple nozzle dies. Compared to other existing 3D printing techniques, the proposed nozzle abilities make it a promising option with higher speed and better functionality for the packaging industry.

INDEX TERMS 3D printing, wood printing, cellulose-based materials, extrusion technique, 3D printer nozzle, packaging industry.

I. INTRODUCTION

3D printing, also called Additive Manufacturing (AM), has the potential to be a technological revolution in the manufacturing industry [1], [2]. It provides an opportunity to produce objects with a high precision rate based on a digital design of the product [3], [4]. Recently, 3D printing has gained immense popularity because of its ability to offer rapid prototypes, make molds and templates to facilitate massive scale production, customer-oriented designs, a high degree of accuracy for complex structures, and efficient and fast customized fabrications for small scale production with economical costs [5]–[8]. 3D printing is making significant changes in various sectors, including packaging, architecture and construction, medical, energy, aviation, food and others [8]–[18]. These industries adopt additive manufacturing to reduce operational costs and enhance operational efficiency [5]. In the packaging industry, which is the focus of this paper, 3D printing makes it possible to offer personalized packaging for clients by making different prototypes at high speed according to their demand. In this way, waste parts can be reduced, protecting the environment, and improving efficient production in manufacturing. It can even go beyond that by making the packaging a part of the products. There are different additive manufacturing technologies, and more importantly, there are various materials for 3D printing, as illustrated in

The associate editor coordinating the review of this manuscript and approving it for publication was Claudio Zunino.

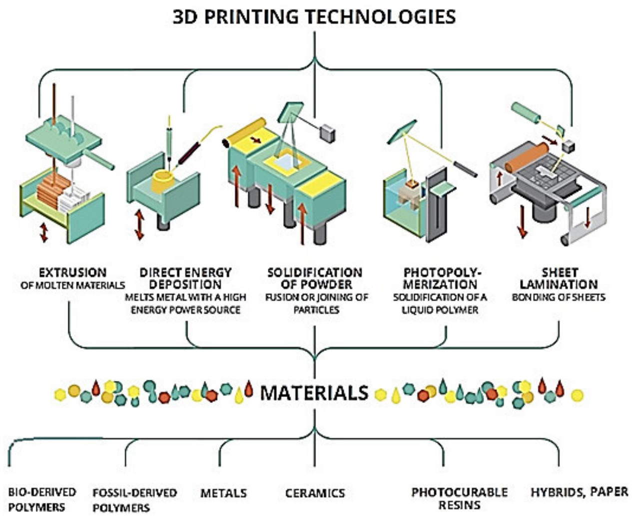

FIGURE 1. **Schematic diagram of additive manufacturing techniques and materials [27].**

Figure 1 [8], [13], [14], [20]–[23]. The prevalent challenge in applying 3D printing in different industries is to apply proper material with essential properties that act as a substrate [20], [24]. 3D printing materials are primarily from polymers such as polylactic acid, nylon, acrylonitrile, and butadiene styrene. Also, ceramics, metals, and thermoplastics are commonly used [10], [25]–[27]. However, these materials are not economical and have hazardous impacts on the environment and humans [28], [29].

Currently, the application of wood and cellulose-based materials in 3D printing has been greatly highlighted [13], [30], [31]. Due to the valuable benefits they provide, various industries tend to use wood and cellulose-based materials for 3D printing [9], [31]–[34]. In the plant cell wall, cellulose is the primary component available readily. They are renewable materials and have an important role in preventing greenhouse emissions and climate change [35]. Renewable products are in continuous demand due to their lower cost and energy efficiency. Moreover, utilizing such materials in 3D printing leads to the effective recycling of 3D printed wastes [35]. Wood and cellulose-based derivatives have interesting, complex structures and properties and are available abundantly. The annual growth of cellulose-based biomass has been estimated to be 1.5 trillion tons [36]. This remarkable growth of bio-based, wood, and cellulose materials provides other opportunities to use these materials in additive manufacturing more. It is not far from expectations that the renewable additive manufacturing sector to be one of the fastest-growing sectors in the developed countries in the near future. With attention to the availability of natural resources in the market, 3D printing is estimated to grow in industrial packaging.

3D printing technologies for wood and cellulose can offer innovative and superior designing and manufacturing methods. Wood and cellulose-based materials are available as bleached pulp as well as lignocellulose. Research on cellulose nanofibrils (CNF), nano-cellulose/micro cellulose (MCC), bacterial cellulose (BC), cellulose nanocrystalline (CNC) have been conducted over the years [28], [37]–[42]. Cellulose, along with its derivatives, offers better design composite constituents. As it is investigated in multiple academic research, wood and cellulose-based products have exhibited efficiency as printing materials in additive manufacturing, improving the outcomes for 3D printing [28], [30], [34], [39]–[46]. Homogeneous printing without nozzle blocking is vital in 3D printing based on biomaterials. A high-quality wood powder can meet this requirement [23]. Nozzle clogging can occur due to improper particle sizes. In most cases, wood particles are segregated to obtain homogenous printed results with better properties. However, this solution alone is not enough to solve these problems. Syntheses of literature also disclose that wood and cellulose materials that have not been subjected to chemical modifications are infeasible to be used as 3D printing material because they are thermally unstable and subject to decomposition before they can be melted [32], [47], [48]. When heat is applied, they become flowable.

The objective of this research work is to propose a novel nozzle design for 3D printing of wood and cellulose-based materials to address deficiencies such as slow printing speed and low printing quality. For this purpose, first, we performed a literature review and investigated the usage of wood and cellulose-based materials applying different 3D printing techniques. Finally, we designed a new nozzle for 3D printing of wood and cellulose derivatives, which provides faster and better performance, with particular attention to the packaging industry. It should be noted that providing detailed chemical properties of cellulose-based materials is out of the scope of this paper.

II. PLANT–DERIVED COMPOUNDS USED IN 3D PRINTING

A. 3D PRINTING OF WOOD

Wood has been used for thousands of years for different purposes like construction, fuel, furniture, packaging, medical supplies, and so-on [49]. Recently, wood is utilized as mixed with different materials to create a composite material or polymer-based material. Wood and wood-based materials can be processed through a wide range of methods and have various applications. The wood tissues contain cell walls, including different layers enclosed by amorphous and intracellular substances responsible for increasing the strength of the trees and enhancing their physical properties [50]. In chemical representation, wood comprises cellulose, hemicelluloses, and lignin at constituent percentages of 45 to 50%, 20 to 25%, and 20 to 30%, respectively [13], [40]. In addition, extractives are also found in the wood cells. They are identified as different substances responsible for maintaining the tree's biological functions, helping them ward off the microorganisms [51]. Structural configuration with the interactional bonding between the cell components at different

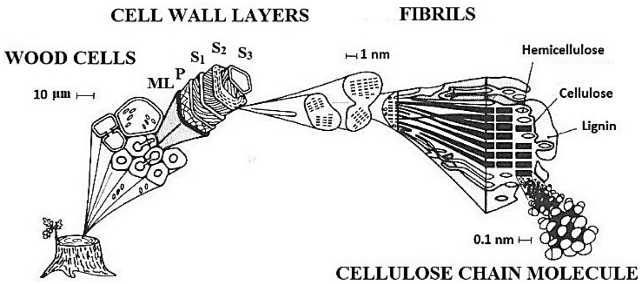

FIGURE 2. Structure of wood tissue cell wall [52].

levels is accountable for influencing the mechanical characteristics of the cell wall. Wood tissue structure is presented in Figure 2 [52].

Without separating into its basic components, wood can be employed in 3D printing by considering the temperature settings and nozzle requirements of the printer. Bringing wood to 3D printing to provide opportunities such as producing wood-like products and printing complex wooden objects in combination with wood was investigated [23]. The effect of wood content in 3D printing materials on the properties of 3D printed parts was investigated. Results showed the tensile strength of the filaments increased with an addition of 10% wood but decreased with higher levels of wood content for filaments with 50% wood content [46]. Using wood chips with binding materials such as cement, gypsum, and sodium silicate with the water-based activator in 3D printing processes was investigated [53]. Large scale building elements were investigated to be shaped by depositing fresh wood chip concrete with the aid of a numerically controlled extrusion system, which showed benefits over mere mineral solutions [54]. 3D printing of wood powder combined with an adhesive has also been studied. The bending strength of 3D printed blocks depended on the amount of wood powder in the mixture and adhesive type [30]. In another study, liquid deposition modeling for 3D printing of wood was studied with almost 90% wood content in the material, which showed promising technology for 3D printing of wood [55].

B. 3D PRINTING OF LIGNOCELLULOSIC MATERIALS

Lignocellulosic materials have been acknowledged as materials that can reduce carbon emissions [56]. Lignin is an amorphous and aromatic polymer and is the most material found in the lignocellulosic biomass. The lignin consists of the unit of a phenylpropane unit with p-coumaryl alcohol, sinapyl alcohol and coniferyl alcohol [57].

3D printing based on fused deposition modeling (FDM) using lignocellulosic materials has been conducted [58]. However, utilization of such material in 3D printing has been identified challenging due to the physical and chemical properties of these materials [59]. For instance, they can decompose thermally before being subjected to extrusion [60]; or insoluble in most solvents [59]. Eventually, the usage of lignocellulose-based materials in 3D printing is still slow in the packaging industry as well. Modifications in lignocellulosic biomass or 3D printing technologies are required to enjoy the benefits of applying lignocellulosic materials in additive manufacturing. For instance, to overcome the thermoplastic nature, they can be incorporated into thermoplastic polymers suitable for FDM printing [13]. Combining plastics with lignocellulose powder is also feasible in 3D printing to improve the quality of printing [27]. The use of the lignocellulosic materials showed printability in additive manufacturing and revealed that these materials did not have strong mechanical properties. In order to improve the quality of printed objects and their mechanical properties, physical and chemical modifications should be performed to improve the interface of lignocellulose material and polymer matrix. In this regard, a study showed that modifications of the FDM technique could improve the mechanical properties [61], [62]. It was also found that if commercially available lignocellulosic- materials include algae polymers, hemp, and bamboo, are applied to nanocomposite, they can improve the mechanical properties of the final product [62]. Reasons for the low quality of lignocellulosic materials in 3D printing can be addressed as the diverse quality of raw materials, polymer matrix consisting of distributed lignocellulose powder in it, and lack of adhesion in the material matrix between the hydrophobic polymer and hydrophilic lignocellulosic, which leads to shape inconsistency of component [63]. Nevertheless, employing lignocellulosic materials as an additive to other materials may improve their printability in the sense of roughness. For instance, it was shown that adding a small amount of pie lignin to PLA filament improved the mechanical properties of PLA [64]. Similarly, in another study, adding lignin to polyhydroxybutyrate (PHB) led to a shear-thinning profile, which enhanced layer adhesion during 3D printing and caused less warpage compared to the 100% PHB printed object [65].

C. 3D PRINTING OF CELLULOSE

The composition of cellulose is linear. It comprises a D-glucopyranose-unit, which is connected to the β -1,4. The connection between the two is because of glycosidic bonds. The sugar unit is with the glucosyl ring in 4C1 chair configuration and one primary and two secondary hydroxyl groups [13]. At the inter and intramolecular level, the bond network of hydrogen is created between cellulose chains of the hydroxyl groups. These bonds are also formed within and, therefore, contribute to the crystalline structure.

Cellulose has infusible property, which makes it impossible to be melt-processed [66]; thus, utilizing a solubilized version of cellulose is a solution for employing it in 3D printing. However, only a limited number of solvents are capable of dissolving cellulose [67], [68]. Water and some organic solvents cannot be utilized for this purpose because the creation of intermolecular and intramolecular hydrogen bonds makes solving of cellulose impossible in these solvents [69]. Ionic liquids (ILs), a group of new organic salts, have been investigated as solvents for cellulose. ILs are liquids which are available in low temperature [70]. Cellulose can be used

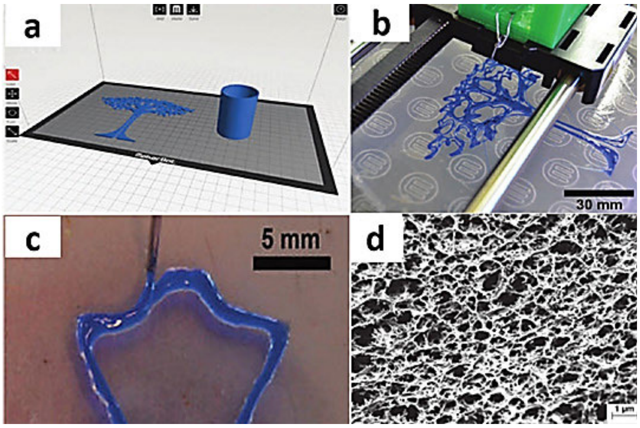

FIGURE 3. Cellulose regeneration through IL with coagulation process in 3D printing [72].

with ionic liquids to dissolute them. When cellulose is dissolved in ILs, it forms a highly viscous solution, [71], [72] which is counted as an impressive property when it is applied as 3D printing material, [33] although it is considered disadvantageous for some other applications. Figure 3 shows this process [72]. Extrusion-based 3D printing of cellulose materials is challenging due to die swell, caused by extruding highly viscous materials through a small diameter nozzle. Problems in cellulose extrudability can deteriorate the quality of 3D-printed parts. Complex objects with high cellulose particles are still challenging to be created using 3D printing technology [31]. These problems have been addressed by researchers, and a variety of techniques have been introduced to overcome them. As a result, considerable improvements in the quality and mechanical properties of 3D-printed cellulose objects have been achieved. Different types of support structures can be provided with easy removal from the fabricated cellulose material, enabling the formation of overhanging features.

1) 3D PRINTING OF CELLULOSE ETHERS/ESTERS

Cellulose esters and ethers are derived from cellulose and are used for a wide range of purposes, including packaging, bio membrane, casings, coating, and binder applications [13], [73]. Water or different types of organic solvents can dissolve cellulose ethers [74], thus support their usage in 3D printing.

Many of the cellulose-based ethers such as carboxymethylcellulose (CMC), hydroxypropyl cellulose (HPC), and ethyl cellulose (EC) have been employed in 3D printing filaments due to their ability to improve and enhance the viscosity of the material. They can also be used as binders in additive manufacturing to provide the desired stability of final products, as binder properties greatly influence additive manufacturing. Rheological properties and shear thinning capabilities of cellulose ether solutions justify their application in 3D printing [13], [32]. They have also been utilized in additive manufacturing for the creation of unsupported spanning structures [75].

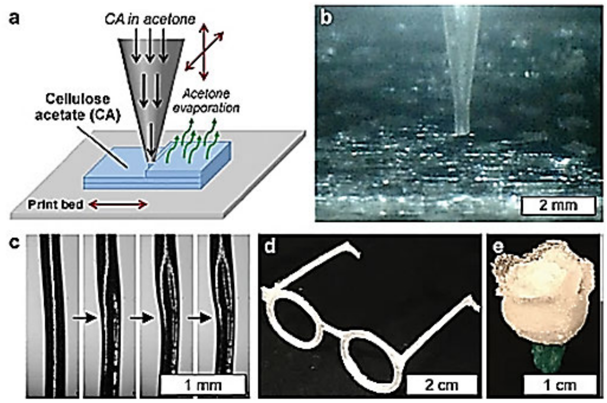

FIGURE 4. 3D printing with cellulose esters [76].

When cellulose is subjected to esterification, it can be converted into various forms. Cellulose acetate (CA), one of the derivates resulting from cellulose esterification, can be utilized in additive manufacturing by applying acetone to dissolve it [30], [76], as presented in Figure 4 [76]. Generally, it can be concluded that the tensile strength and toughness are increased when utilizing ether/esters in 3D printing [77], [78].

2) 3D PRINTING OF MICROCRYSTALLINE CELLULOSE (MCC)

Different processes, like acid hydrolysis, can synthesize microcrystalline cellulose (MCC). MCC has desired features that qualify its suitability for 3D printing utilization in the manufacturing and packaging industry. It has a crystalline structure that is insoluble in water and resistant to reagents. Therefore, for 3D printing purposes, it should be dissolute in a proper solvent like ionic liquids. It can be used as a binder, emulsifier, thickener, stabilizer, rheology modifier, and reinforcing component [13], [32]. Even a small amount of MCC can improve the mechanical properties of printed materials by increasing their strength. Even a small amount of MCC can improve the mechanical properties of printed materials by increasing their strength. Research work showed that when MCC has been added to polycaprolactone (PCL) matrices for obtaining 3D printed scaffolds, better mechanical and biological properties were achieved [79]. Another study was conducted to produce a novel MCC reinforced polylactic acid (PLA), fully degradable bio composites for 3D printing applications [40].

3) 3D PRINTING OF NANOCELLULOSES

Cellulose nanocrystalline, produced from tree cellulose, forms a hierarchical structure combined with disarranged cellulose, comprised of various components including lignin, hemicelluloses, and pectin [80]. Nanocelluloses, which are nano-structured cellulose, are classified into cellulose nanocrystal (CNC) and cellulose nanofibers (CNF). Nanocelluloses are widely used in different applications because of their beneficial properties like their mechanical strength, high

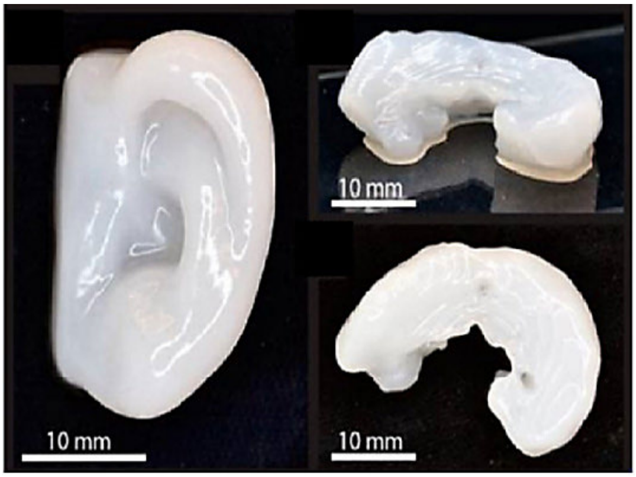

FIGURE 5. 3D printed resembling human ear utilizing CNF/alginate [91].

surface area, the capability to make aerogels, surface modification, and environmental friendliness [81]–[84]. They are made from cellulose sources through a combination of different methods such as physical methods, chemical methods, and enzymatic methods [80], [82], [84].

In packaging applications, nanocelluloses are effective and promising options due to the mentioned properties and their ability to make aerogels/foams; hence they can be utilized instead of polystyrene-based foams [80], [85]. By applying freeze-drying techniques, pure nanocellulose aerogels can be obtained. Aerogels and foams can be used as porous templates [84].

When employing in 3D printing, nanocellulose materials exhibit great results due to their printability, viscous characteristics, shear-thinning behavior, and mechanical properties [13], [34], [86]–[88]. Nanocellulose materials are ideal options to replace current-used 3D printing materials while they can be processed with various 3D printing methods. CNF and CNC can be used as fillers in the polymer matrix in FDM or DIW [32], [84]. Utilizing CNC and CNF with polymers improves the properties of 3D printer filaments and reduces the overall price simultaneously [89].

CNF, a material composed of nanosized cellulose, can be a popular choice for 3D printing [31], [90]. CNF hydrogel has a strong shear-thinning behavior, particularly useful in the 3D printing application [86], [90]. Rheological properties of CNF hydrogels are significantly important in 3D printing due to their impact on final product stability and mechanical features. However, the concentration of material should be adjusted to prevent clogging in the 3D printer. The quality of material can be optimized by adding auxiliary materials, which leads to improved printability [86]. 3D printed resembling human ear utilizing CNF/alginate is illustrated in Figure 5 [91].

CNF hydrogels have great potential to be used in 3D printing in the packaging industry for mass customization and production. Compared to polymer-based hydrogels, CNF hydrogels offer remarkable benefits because they are abundant natural polysaccharides with low cost and better biocompatibility [92]. The most significant advantage of CNF hydrogels is that they are geometrically stable, and the rapid gelation is responsible for ensuring that the object is not deformed during and after printing [84], [87]. From the mentioned points, it can be concluded that usage of CNF can improve the solidity and steadiness of the printed objects by enhancing their properties because of the shearing alignment.

CNC has highly crystalline structures. They are generally produced through the acid hydrolysis of cellulose fibers [93]. CNCs are characterized by their high strength and stiffness, which can be used as a reinforcing agent when included in a polymer matrix [94]. Due to its features, it can improve the mechanical properties of materials. It is beneficial to substitute traditional 3D printing thermoplastics with cellulosic materials such as CNCs. CNC materials may even be a superior option for 3D printing than semi-crystalline CNF because of obtaining higher solid loadings at a specific viscosity and storage modules [32], [87].

The CNC gels were studied to be applied in direct ink writing (DIW) [95]. The porous CNC aerogel can be a great choice for some complex applications [37], [39]. Aerogels with uniform pore structures with minimal structural collapse during drying were fabricated. Moreover, CNC aerogels with minimal structural shrinkage or damage were produced [39], which have the potential to be applied in the packaging industry. However, CNC is not cheap and has weaker shear thinning and gelling properties than CNF, which obscure its utilization in 3D printing. Thus, the application of CNC hydrogels as a single component in 3D printing has not been widely studied [84]. Optimizing the combination of CNC and CNF makes a compromise to meet specific requirements of 3D printing [32], [96].

III. 3D PRINTING TECHNOLOGY USED FOR WOOD/CELLULOSE

There are various techniques for 3D printing, including material extrusion method, direct energy deposition method, powder bed fusion method, binder jetting method, vat photopolymerization method, and sheet lamination method [27]. Each of these technologies has their purposed applications and have been widely studied and explained in other papers [8], [27], [31], [97], [98]. The most proper techniques for 3D printing of wood and cellulose-based materials are briefly discussed in this paper. The focus is on the extrusion method since the suggested nozzle has been designed based on fused deposition modeling (FDM) technology.

A. EXTRUSION TECHNIQUE

Extrusion technique is the most widely used technology in 3D printing due to its simplicity and affordable costs. Different types of materials can be 3D printed using extrusion technology; hence, it has a diverse range of industrial applications. In this technique, the material is excreted from a nozzle to

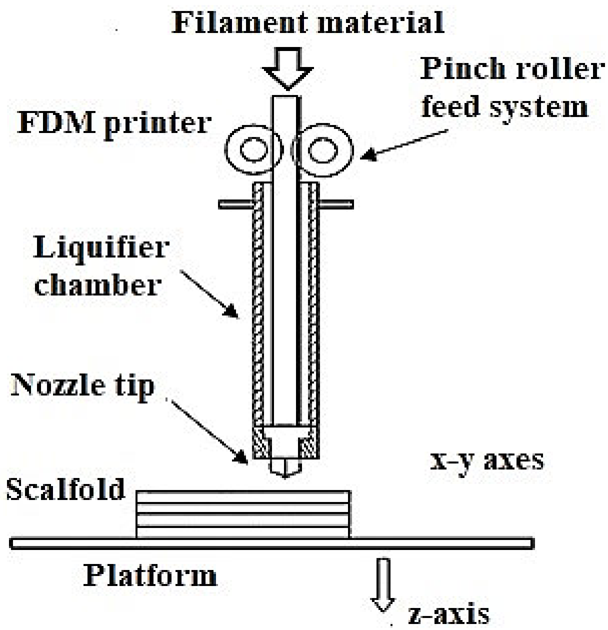

FIGURE 6. 3D printing FDM technique [3].

deposit one layer after the other before the previous one is subjected to cooling in order to achieve structural stability. However, smaller diameter filaments are difficult to be produced when using this technique. This problem occurs due to the die swell process because of viscous liquified material's extrusion through a small nozzle [13], [31]. Direct ink writing (DIW) and fused deposition modeling (FDM) are included in this category.

FDM is the most common 3D printing material extrusion technique, which is proper to be applied in the packaging industry as well. It is easy to use and can fabricate complex geometries. FDM technique is illustrated in Figure 6 [3]. It works based on melting the material, flowing and solidifying. It uses a thermoplastic filament to build the desired object layer by layer [99]. The filament should be made before printing and fed from a large coil to the roller. It then moves through the heater and nozzle to be printed layer by layer on the platform. The material is allowed to be cooled in order to achieve a solid form. An auxiliary cooling device can be used to accelerate the cooling and solidification process. It should be considered that the viscous properties of the melted material determine the force required to extrude the melt [100].

A wide variety of materials, including thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), aliphatic polyamides (nylon), etc. can be used as filament [13], [35]. Despite the valuable benefits of this technology, the quality of the fabricated parts is a considerable problem. Various process parameters influence the micro geometrical property (the surface roughness), geometrical accuracy, and strength of the components manufactured by the FDM technique [101], [102]–[104]. Optimal setting of the process parameters can strongly improve the mechanical properties, surface roughness, and attainable accuracy of the 3D printed parts [101], [104]. The nozzle of the printing machine and filament material can significantly determine the range of process parameters [101]. Factors such as layer thickness, extrusion temperature, build orientation, raster angle, and raster width are determinative in the properties of the parts built using FDM technology [101]. The impact of the FDM process parameters on the different features of fabricated parts has been intensively investigated by many researchers [101]–[104]. FDM technology is mostly used for polymer, ceramics, and composite material 3D printing, but also has been used for 3D printing of cellulose-based materials as well, which leads to reducing carbon dioxide and greenhouse gas emissions and producing 3D printed objects at an economical price [13], [31], [58], [61], [78]. The use of cellulosic materials with polypropylene or PLA in the FDM method was examined [105]. Wood flour-based filaments have been used in FDM printing techniques, which indicated that they are printable. However, such objects have low mechanical properties [106]. It was shown that utilizing wood particles in 3D printing has been problematic because of nozzle blockage in FDM techniques [61]. In this domain, wood floor particle control must enhance its efficiency to be used as filaments in FDM techniques.

In the Direct Ink Writing (DIW) method, slurries or hydrogels are used as 3D printing inks and extruded from a nozzle while a nozzle is moved across a platform. The nozzle is connected to a syringe reservoir. During the syringe displacement, the ink's viscosity is reduced and allows it to flow and build a 3D object. The material that exits the nozzle retains its shape immediately due to the rheological property of shear-thinning [107]. The appropriate chemical and physical properties of inks are vital to meet the printability requirements in this method. For instance, it does not rely on solidification or drying to retain its shape after extrusion, so having enough stiffness to steadily maintain the filament structure after extrusion is critical [13], [108]. As discussed in section II.C.3, hydrogels have exceptional chemical and mechanical properties to be used as 3D printing materials. Supporting rapid prototyping and mass customization make it a great choice for the packaging industry.

B. INKJET PRINTING

Inkjet printing is a fast, flexible, and cost-effective technology that propels droplets of liquid onto plastic substrates [109]. As seen in Figure 7 [3], the thin liquid droplets are ejected from the actuators by thermal or acoustic forces in a user-defined pattern.

Inkjet 3D printing produces high resolution and precise features in a fast process. It provides products with a broad range of materials that can be deposited at low temperatures and pressure. Biomaterials such as hydrogels can also be utilized for inkjet printing. Nowadays, cellulose-derived and nanocellulose inkjet materials have gained popularity as bio- inks, and plenty of studies have been conducted in this field [31], [110], [111]. Hence, with attention

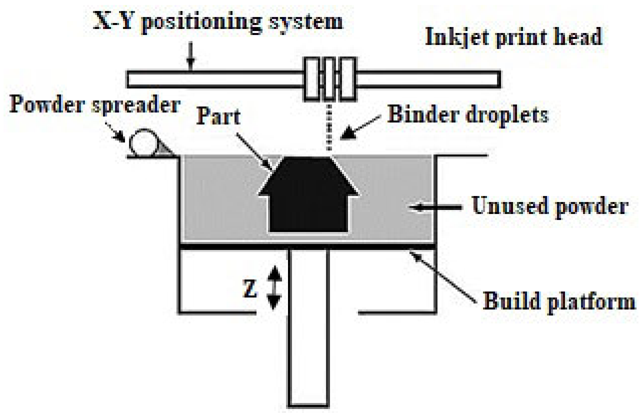

FIGURE 7. 3D printing inkjet method [3].

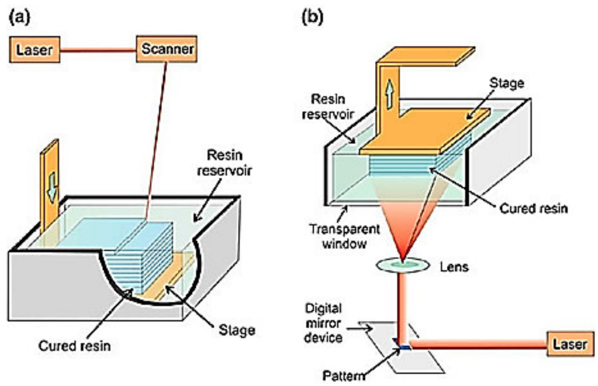

FIGURE 8. 3D printing SLA method [108].

to the above-mentioned advantages and adaptability with cellulose-based materials, 3D inkjet printing has the potential to be effectively used in the manufacturing and packaging industry.

C. STEREOLITHOGRAPHY

Stereolithography or SLA 3D printing is one of the most popular additive manufacturing techniques. As presented in Figure 8 [112], an ultraviolet (UV) laser is aimed at photopolymer resin to draw a pre-programmed design according to a computer design software like CAD. Wherever the laser hits, the resin is photochemically solidified and forms a single layer of the desired 3D object. Afterward, the platform is raised based on the layer thickness, and the new resin is coated below the printed layer. This process is repeated for each layer until the completion of the object. Due to the highly accurate light source in this method, the accuracy pertaining to manufacturing is relatively higher than other 3D printing techniques [113], [114]. It leads to accurate details in the thickness of the layer and enhanced the quality of the surface area. Various photopolymers can be applied in stereolithography for different applications. Cellulose nanocrystals and their derivatives like CNC were also studied to reinforce the mechanical properties of resins [43], [48].

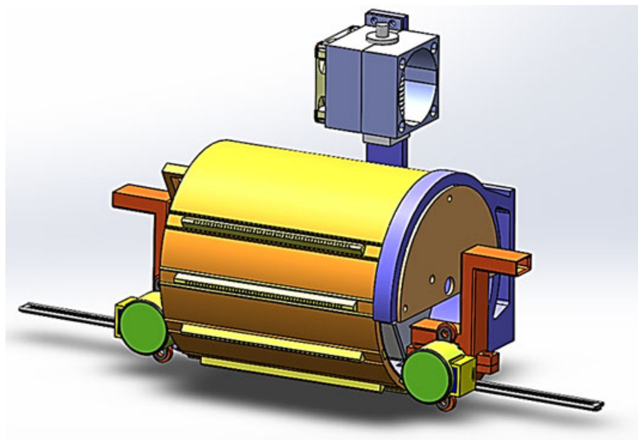

FIGURE 9. Nozzle prototype for paste-based extrusion.

IV. REFINING NOZZLE DESIGN TO FACILITATE PRINTING OF WOOD AND CELLULOSE-BASED COMPOUNDS USING THE FDM TECHNIQUE

The nozzle was designed based on the conducted analysis of bio-based materials and different available techniques for 3D printing with wooden and cellulose based materials which are addressed in previous sections of this paper.

A. MATERIALS AND METHODS

SOLIDWORKS was used to create a 3D CAD model of the nozzle prototype, presented in Figure 9. The new nozzle design is based on FDM technology for the 3D printing of paste-based materials, such as plant-derived compounds. FDM technique can easily be employed in the packaging industry to fabricate simple or complex geometries of paste-based materials. The nozzle cross-sectional view is demonstrated in Figure 10. It consists of a base cylinder that holds a nozzle block with an opening part facing downward for material flow through the nozzle opening. The opening part is blocked by moving flexible selectors that control opening and closing of it through sliding along nozzle opening. Selectors are pushed in and pulled out by two stepper motors located at both sides of the end of the nozzle. By reducing and increasing the length of flexible selectors, the opening space between them can be controlled, which allows them to select various extrusion points for the nozzle die for material extrusion through it [115].

As shown in Figure 10, the base cylinder holds a freely rotating cylinder along its circumference, which contains nozzle dies. Nozzle dies are placed at a 30-degree angle from each other and rotate along with the base cylinder. Different nozzle dies can be selected and used to extrude material when the rotating cylinder faces the nozzle opening. Nozzle dies changing mechanism is presented in Figure 11. By rotating the cylinder that holds the nozzle dies along the base cylinder's circumference, the desired nozzle die can be selected. Both sides of the nozzle are equipped with a drive mechanism that drives flexible selectors, which slide and act

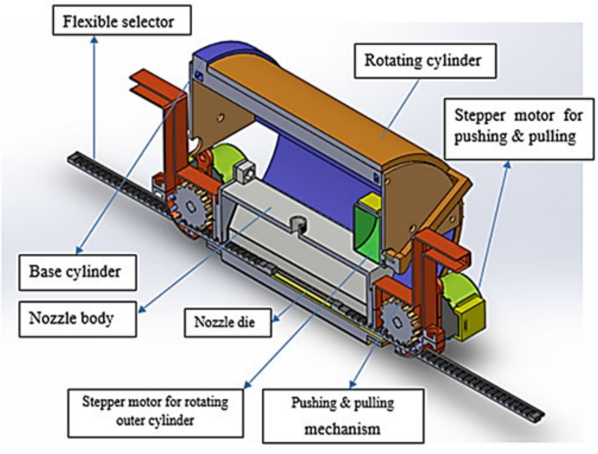

FIGURE 10. Cross sectional view of nozzle assembly and its components.

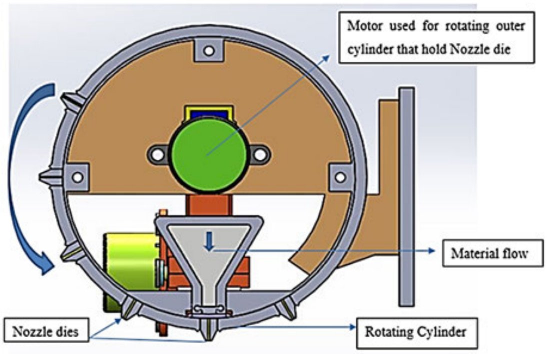

FIGURE 11. Die changing mechanism overview.

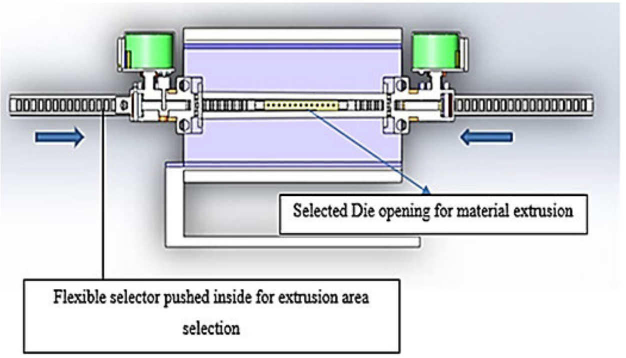

FIGURE 12. Nozzle die changing mechanism overview.

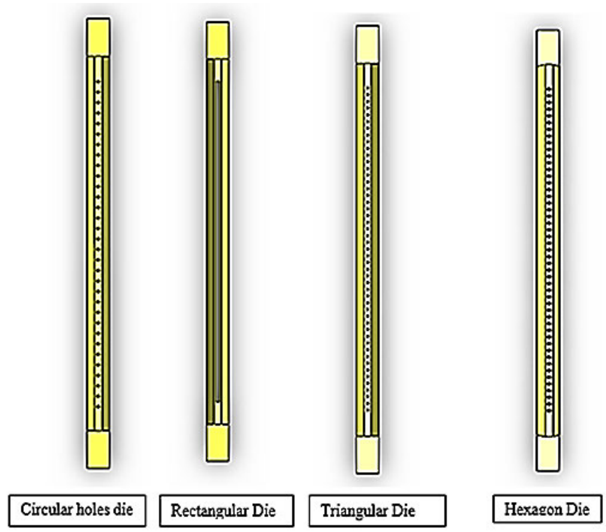

FIGURE 13. Nozzle die changing overview.

as valves for nozzle blocks. Driver mechanism controls the selectors inside the nozzle block, which adjust the open space for material flow through a particular section of the nozzle die. Nozzle block contains the heated fluid paste material, which is pumped by mechanical or controlled air pressure.

B. OPERATION PRINCIPLE

The designed nozzle works based on two concepts, including selective variable extrusion and multiple nozzle die extrusion.

1) SELECTIVE VARIABLE EXTRUSION

Figure 12 proposes the working mechanism of the selective variable extrusion concept. Stepper motor enables the use of variable extrusion through nozzle die via many extrusion points opened and closed by a flexible selector. This mechanism allows the 3D printer to choose any number of extrusion points along the nozzle die to provide the material flow through the nozzle block during the 3D printing extrusion process. Flexible selectors act as valves that slide along nozzle opening by pushing and pulling the mechanism of stepper motors to select the extrusion area for material to flow through the nozzle die.

2) MULTIPLE NOZZLE DIE EXTRUSION

This method implies switching of multiple nozzle dies with varying cross-sections for the material flow of various shapes and sizes during the 3D printing process. Different sections of the object to be printed determine the different shapes and sizes of the extrusion material layer during the extrusion process. This method decreases printing time by switching to different nozzles for various sections according to the requirement of the object to be printed. Figure 13 illustrates nozzle dies with various shapes and sizes.

The suggested nozzle enables to extrude of materials with different shapes according to the geometrical cross-sectional area of the selected nozzle die. The geometrical cross-sectional shapes can be selected for the optimization of the printed product. They provide the possibility to enhance the printing of particular sections during the 3D printing process. One such example can be seen in Figure 14, where a rectangular die was used to extrude the first and upper layer of the triangular extrusion by selecting the nozzle extrusion area with the help of selectors.

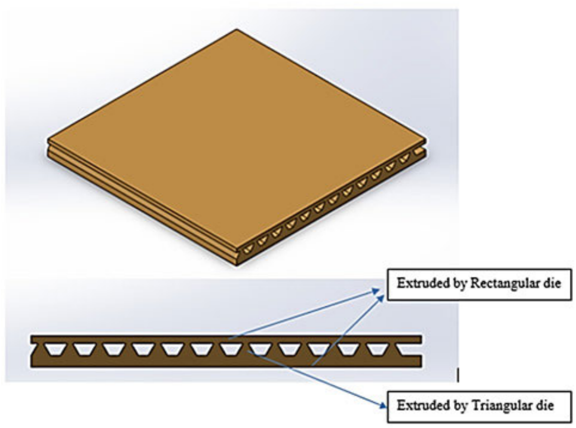

FIGURE 14. Part extrusion visualization by selected nozzle design.

V. RESULTS

Utilizing wood and cellulose-based materials can dispel the cost and environmental concerns of employing additive manufacturing in the packaging industry and offer valuable advantages compared to other materials. Depending on the natural sources that the plant-derived compounds are obtained, fiber size and properties differ. Inappropriate particle sizes can deteriorate the printing quality and cause nozzle clogging, so, in most cases, cellulose-based particles are segregated and homogenized beforehand to achieve resulting products with better features. However, this is not solely sufficient to mitigate these problems. Moreover, 3D printing is inherently a time-consuming process, especially for large-scale production, limiting its application in the packaging industry. The significant advantages of the proposed nozzle design characterized in section 4, such as selective variable extrusion and the possibility to have multiple nozzle dies, distinguish it from other existing 3D printing methods available in the market. These capabilities lead to better functionality and overcome the time-consuming problem in large-scale manufacturing by 3D printing. Thus, offering general or personalized packaging in high-volume and high-speed using 3D printing technology would be possible. The proposed nozzle design is proper to be utilized for 3D printing of all packaging components using plant-derived compounds based on the FDM technique. When prototypes of complex structures or individually customized products are required in high volume, the proposed nozzle design is a promising option. The designed nozzle can drive innovators and researchers to develop new printing strategies for industrial packaging applications.

VI. CONCLUSION

The utilization of wood and cellulose-based materials in 3D printing has gained increasing attention due to their significant advantages such as more environmental sustainability, cost-effectiveness, abundancy, biodegradability, renewability, and energy efficiency. The packaging industry can benefit remarkably from applying cellulose based materials in 3D printing by producing recyclable cost-effective packaging. However, employing cellulose-based materials in 3D printing can cause problems. Fiber sizes and properties of plant derivatives can result in nozzle clogging and low-quality printing products. As nozzle is a vital component of a 3D printer, designing a nozzle, which expedites the 3D printing process and promotes the quality of resulting products, seems inevitable. In this study, the advantages and limitations of using wood, nanocellulose materials, microcrystalline cellulose, ethers/esters, hydrogels, and lignocellulosic materials as single components or combination with other materials in 3D printing have been investigated. More importantly, a novel nozzle has been designed based on FDM technology. The proposed nozzle mechanism has significant prominences over other existing 3D printing methods, including selective variable extrusion and the possibility to have multiple nozzle dies. The suggested nozzle consists of a base cylinder, a rotating cylinder, nozzle dies, moving flexible selectors, and stepper motors. By changing the length of flexible selectors, various extrusion points can be selected, and the opening space for material extrusion can be controlled. Moreover, nozzle dies with various shapes and sizes can be provided. The mechanism allows the 3D printer to choose any number of extrusion points along the nozzle die for material flow. Furthermore, it provides the possibility of switching multiple nozzle dies with different cross-sections to extrude materials with different shapes according to the geometrical cross-sectional area of the selected nozzle die. The new nozzle design can be applied easily for 3D printing of packaging parts using plant derived compounds. All the packing components can benefit from the proposed nozzle design, especially when prototypes of complex structures or individual customized products are on demand. Besides, it can reduce the printing time and improve the printing quality. These potencies make it competent to be utilized for large-scale production where printing speed and quality are determinative factors.

However, the designed nozzle must be fully constructed. Besides, a slicer software interface should be developed, which can use this prototype printing method to slice 3D objects and enable the users to customize slice settings based on the desired nozzle die. The nozzle printing process can be improved by providing more degrees of freedom along the printing axis. All of these would be the future research directions.

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