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Review article

The potential of adopting natural fibers reinforcements for fused deposition modeling: Characterization and implications

Muhammad Hamza Nazir [a], Ali H. Al-Marzouqi [a], Waleed Ahmed [b,*], Essam Zaneldin [c]

[a] *Department of Chemical Engineering, United Arab Emirates University, 15551, Al Ain, Abu Dhabi, United Arab Emirates*
[b] *Engineering Requirements Unit, United Arab Emirates University, Al Ain, 15551, United Arab Emirates*
[c] *Civil & Environmental Engineering Department, United Arab Emirates University, Al Ain, 15551, United Arab Emirates*

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ABSTRACT

Natural fibers or their derivatives have gained significant attention as green fillers or reinforcement materials due to their abundant availability, environment-friendly nature and biodegradability for sustainable development. Despite the availability of modern alternatives such as concrete, glass-fiber/resin composites, steel, and plastics, there is still considerable demand for naturally occurring based materials for different applications due to their low cost, durability, strength, heat, sound, and fire-resistance characteristics. 3D printing has provided a novel approach to the development and advancement of natural fiber-based composite materials, as well as an important platform for the advancement of biomass materials toward intelligentization and industrialization. The features of 3D printing, particularly fast prototyping and small start-up, allow the easy fabrication of materials for a wide range of applications. This review highlights the current progress and potential commercial applications of 3D printed composites reinforced with natural fibers or biomass. This study discussed that 3D printing technology can be effectively utilized for different applications, including producing electroactive papers, fuel cell membranes, adhesives, wastewater treatment, biosensors, and its potential applications in the automobile, building, and construction industries. The research in the literature showed that even if the field of 3D printing has advanced significantly, problems still need to be solved, such as material incompatibility and material cost. Further studies could be conducted to improve and adapt the methods to work with various materials. More effort should be put into developing affordable printer technologies and materials that work with these printers to broaden the applications for 3D printed objects.

1. Introduction

Bio-composite materials have evolved as alternatives to conventional materials, mainly in response to the worldwide demand for renewable resources [1]. Polymer composites based on natural fibers are commonly employed in technical applications e.g., automotive, aerospace, construction materials, electronic gadgets, and sporting goods [2,3]. The mixing of natural fibers, nanofillers, and polymers is the most recent strategy for developing new materials with superior thermal and mechanical characteristics, broadening

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* Corresponding author.
E-mail address: w.ahmed@uaeu.ac.ae (W. Ahmed).

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their range of applications [4]. Using clay or nano-clay materials in organic–inorganic hybrid nanocomposites has recently received considerable interest from the scientific community. Because clay may increase the flexibility and stiffness of natural fibers, the development oforganic–inorganic hybrid nanocomposites with natural fibers and nano-clay is a fascinating topic. Food packaging, therapeutic devices, and the automotive industry are potential applications fororganic–inorganic hybrid nanocomposites [5,6]. Earth's use for construction has occurred throughout human civilization's history. Earth has remained a popular choice for building construction applications owing to the ease of construction offered by the material properties, availability, thermal comfort, local employment criteria, and minor negative environmental consequences [7].

Even in rural regions, the earth remains the most common building material. The use of earth varies depending on climate and geographic location [8]. In contrast to cold temperatures and subtropical or temperate climates, the earth is used in diverse ways in hot, humid climates. Rammed earth, adobe bricks, cob, or earth in conjunction with wood and stone are all commonly used in construction [9]. However, such construction is a large-scale consumer of natural resources and a significant polluter of the environment. According to the Global Alliance for Buildings and Construction, construction contributes to 40% of CO2 emissions, with construction materials accounting for 11%. As a result, architects, designers, and engineers are increasingly attempting to improve their environmental performance. Thus, there is a new approach toward energy-efficient design based on creating and using natural and local construction materials with as little environmental impact as possible [10]. Montmorillonite, kaolinite, smectite, chlorite, kenyaite, ilerite, zeolite, and other clays can be utilized to make polymer composites. Montmorillonite, derived from bentonite, is the most basic nano-clay and is widely used due to its accessibility, environmental friendliness, and well-studied chemistry [7,11]. Modified montmorillonite is commonly found in commercially available nano-clays, e.g., Cloisite and Garamite. Because of its abundant availability and high form factor, nano-clays are frequently used as a reinforcing agent for polymeric composites. Adding nano-clay to a nanocomposite increases the overall physical performance. In polyester resins, the addition of nano-clays improves the mechanical characteristics while reducing shrinkage [12].

The inclusion of the nano-clay Anomer I30 E increases the tensile stiffness of an epoxy matrix while lowering the strain at failure. Including graded nano-clay increases polyester resins' tensile strength, modulus, and flexural strength. The inclusion of Garamite nano-clay improves mechanical characteristics by causing more significant stress transfer at contact. The properties of nanocomposites can be improved without changing the processing conditions [13]. Despite the availability of modern alternative materials such as concrete, glass-fiber/resin composites, steel, and plastics, there is still considerable demand for clay-based goods due to their durability, strength, heat and sound insulation, and fire-resistance. Hence, clay is widely used as an essential construction material [14,15].

New techniques have been developed to produce alternative clay-based construction materials with enhanced performance and properties compared with those produced by the conventional firing process [16]. Blending is one of the oldest techniques for stabilizing clay, whereby the clay is mixed with various cementing materials e.g., cement, lime, and other waste. Sand is a porous media with weak tension behavior and geotechnical qualities that change depending on environmental variables. Population growth and urbanization have led to a significant demand for construction in unstable and erosive areas with poor geotechnical features. As a result, these sand and environmentally sensitive regions need appropriate stabilizing solutions [17,18]. Various soil management procedures have been developed for stabilizing unstable soils before development. The recommended techniques can be divided into two categories: (i) mechanical stabilization methods and (ii) chemical stabilization methods. Representative mechanical approaches include displacement and replacement, stage structures, preloading, stone columns, soil nailing, and synthetic reinforcing applications.

Chemical stabilization procedures involve deep in-situ mixing or surface stabilization employing cement, fly ash, bottom ash, bentonite, gypsum, silica fume, and blast furnace slag [19,20]. Ashes of various organic components obtained from burning processes have also been used for chemical stabilization [21]. However, the abovementioned traditional stabilization methods may create severe environmental problems, i.e., global warming due to significant CO_2 emissions, high energy costs, non-renewable resource depletion, and the release of heavy and toxic compounds into the atmosphere [22]. As a result of the global focus on a healthy future, ecofriendly solutions are highly favored in geotechnical and geo-environmental engineering [23].

Blending and stabilizing clays with other waste or byproduct materials produce various benefits, e.g., reducing landfill, solving waste management problems, protecting the environment, saving energy, and reducing the final product cost [24]. To ensure that clay-based construction products have suitable strength for civil engineering applications, heat is required for curing, sintering, and drying. Due to the low thermal conductivity of clay-based construction materials and the sluggish heat transmission rate from the surface to core, using standard heating methods is a slow process. Furthermore, traditional heating techniques have several drawbacks, e.g., higher energy consumption, long processing times, high processing temperatures, and adverse environmental implications [25,26]. Several types of natural materials, such as wood chips, natural fibers, biochar, and carbon materials, have been utilized to enhance clay's adhesive, mechanical, thermal, physical, and chemical properties before construction. Using nano-clay materials in organic–inorganic hybrid nanocomposites improves flame retardancy and thermo-oxidative stability [27].

Natural fibers such as pineapple leaf fiber, date palm fiber, bagasse, jute, bamboo, kenaf, and abaca have been used to reinforce polymer composites. These fibers are biodegradable, readily available, sustainable, and have a wide range of mechanical, thermal, and physical properties. Natural fiber-reinforced composites require additional processing during assembly to achieve specific design criteria. There have been few studies on processing natural fiber-reinforced composites using 3D printing technology. Several methods have been adopted to develop composite materials; however, 3D printing technology using natural materials and clays has recently gained widespread interest as a simple, efficient, and economical technique for developing different materials of various shapes, sizes, and dimensions.

Different polymeric composites, e.g., MOFs, filters, and membranes, have been developed using 3D printing technology, resulting in improved quality and efficiency of these materials. The filters created using 3D printing exhibit excellent wastewater treatment performance, resulting in improved water quality [28]. Furthermore, other silica, clay, sand, polymer-based composites, and fibers developed through 3D printing offer enhanced CO_2 adsorption from flue gas compared with conventionally produced materials. However, minimal information is available regarding the reinforcement of clay using these natural fibers and their applications using 3D printing technology. Although the different outcomes of various materials using natural resources have been reported, there is an urgent need to study new pathways for developing novel materials using 3D printing technology, as the limited data currently available offer little information regarding cost-effective, efficient, and environmentally friendly synthesis.

To comprehend the most cutting-edge trends in research in the area, it is crucial to evaluate the current research trends in 3D printing of biomass polymer composites. This paper first provides an overview of the fundamental characteristics of natural fibers and their derivatives before discussing the key issues of their application with biodegradable polymer composites using 3D printing technology. Furthermore, a comprehensive overview of fiber reinforcement techniques and applications based on the fiber reinforcing mechanism is presented. With the help of past research, this paper also discusses the evolution and current state of 3D printing technology using natural fibers, as well as strategies to improve fibers' lifetime and reinforcement capabilities. With the following contributions, this study may help the researchers to explore the recent development in this field through the following aspects:

- Overview of the requisite characteristics of natural fibers or biomass for 3D printing.
- Analysis of 3D printed materials reinforced using natural fibers discussed in the literature regarding physical and mechanical characteristics.
- Highlighting various reinforcement and printing parameters to obtain superior and desired properties, and Critical analysis of productivity of 3D printed objects discussed in the previous studies.

2. Classification and applications of natural fibers in polymeric composites

Several researchers have attempted to use the strengthening properties of natural plant fibers. Differences in local production, usage, and inclusion of fiber materials mean there is no consensus on geotechnical techniques. This review aims to improve our understanding of each plant fiber's clay-reinforcing potential by linking fiber application strategies to clay properties and interactions. Applications of natural fibers in various industries are listed in Table 1.

The classification of natural fibers derived from different parts of plants is illustrated in Fig. 1.

2.1. Palm fibers

The date palm is widely cultivated for its fruit. Around 19 types of date palms, with more than 5000 cultivators worldwide, make up this plant's global biodiversity. The date palm tree, the tallest Phoenix species, can reach up to 23 m [43]. After harvesting date farm fruits, the date palm rachis and leaves are amassed in great quantities. These fibers are possible sources of cellulosic fiber. Fibers from these leaves and rachis can be used to reinforce thermoplastic and thermosetting polymers. Researchers have also utilized the fibers from date palms in automotive applications [44]. The fibers from palm tree leaves have been combined with other waste products to produce materials with high ultimate compressive strength, making them appropriate for use as construction materials. Studies have examined the use of spent coffee beans, fly ash, bagasse ash, recycled glass, and rice husk ash to improve the characteristics of parent materials. The results suggest enhanced compressive strength compared to parent materials [45–48]. However, few studies have discussed the usage of palm fibers for soil reinforcement. Different types of fibers can be used to enhance concrete's mechanical and physical properties to overcome the limitations associated to concrete i.e., low tensile strength, strain, bending resistance and high brittle nature [49,50]. However, these fibers cannot use alone as they increase the porosity of cementitious composites. Therefore, they are used along with some other materials to reduce their negative impact. Date palm fibers are commonly used for the reinforcement of cementitious materials because of their abundant availability, easy processing, and sustainable nature. Adamu et al. [51] evaluated the

Table 1
Different industrial applications of natural fibers.

Industry	Type of fiber	Applications	Refs.
Aerospace	carbon, glass, and aramid fibers	Tails, Wings, Propellers, aircraft interiors, lavatories, cabin dividers, wall ceiling, and helicopter fan blades	[29,30]
Automotive	Jute, cotton, flax, wool & sisal fibers	Door and window frames, Door shutters, Mirror casings, Dashboard, floor protection & panel, dashboards, railway parts, seat coverings	[31,32]
Marine	Carbon & glass fibers, honeycomb, thermoplastic resins	Boat hulls, ships, submarines, racing & superyachts, canoes, surfboards, and fishing rods	[28,33]
Building and construction	Jute, coir, bamboo & hemp fibers, HDPE	Roofing sheets, Bricks, Furniture panels, Storage tanks, pipelines, cellular beams & plates, ceiling, floor & wall partition, insulation, sunscreens	[34,35]
Sports and leisure products	Flax/carbon fibers, oil palm empty fruit bunch	Ice skating boards, Bicycle frames, Baseball bats, Tennis rackets, helmets, fishing nets, hockey sticks, archery, ski poles and postboxes	[36,37]
Electronic equipment	Cotton, nylon, and carbon fibers, carbon nano tubes	Mobile and laptop casings, transistors, sensors, batteries, supercapacitors, Projector & stabilizer covers,	[38,39]
Others	Pineapple leaf, sugar palm, jute & kenaf fibers	Textiles, Weapons, paper weight, body armor, medical implants, wound dressing, drug delivery, antibacterial applications, Paper, and food packaging	[40,41]

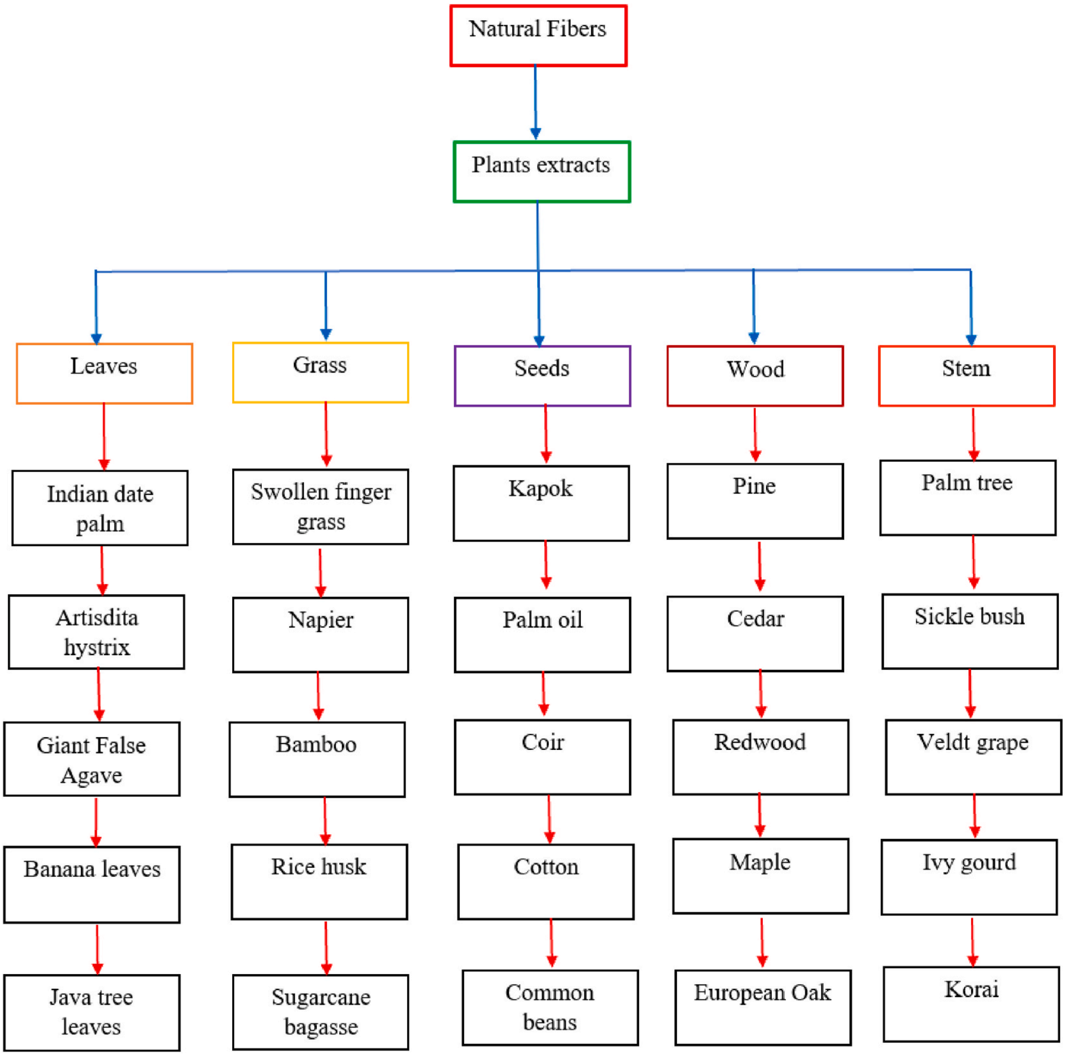

Fig. 1. Classification of plant-based natural fibers [42].

properties of concrete using date palm fibers by varying their amount from 0 to 3% and fumed silica from 0 to 15% to improve the heat resistance of concrete. They concluded that the addition of 1 wt% of date palm fibers and 12.14% of fumed silica gave the best results. Different weight ratios of date palm fibers have also been mixed with recycled polymers, i.e., polyethylene and polypropylene, to develop polymeric composites with enhanced hardness, impact, creep resistance, and ductility [52]. In another study, adding 2 wt% of date palm fibers in concrete and fumed silica mixture improved concrete's flexural strength and water absorption capacity [53]. Furthermore, the optimum dosage of date palm fibers (1.16%) and fumed silica (7.7%) enhanced the tensile and flexural strength of concrete [54].

Noran et al. [55] developed a new green composite based on plasticized polylactic acid mixed with date palm waste for single-use plastics. The hybrid composites made of date palm and bamboo fibers developed by Mohamad et al. [56] exhibit improved mechanical and water-resistance properties. These hybrid composites are biodegradable and have improved tensile, compressive, and flexural strength. In another study, the surface fibers of date palm trees were mixed with cornstarch resin to develop an insulation material. The prepared material has excellent insulation properties compared with commercially available materials, and is cost-effective and environmentally friendly [57]. Basim et al. [58] prepared a green polymeric composite using date palm wood powder and polylactic acid. They claimed the developed composite was thermally stable and could be used as an insulating material for construction applications. Furthermore, the polymeric composite had better compressive strength than commercially available insulation materials.

Tahar et al. [59] reinforced polystyrene waste using date palm leaves. They reported that the prepared material was biodegradable and suitable for use in building construction for thermal insulation and as a component in sandwich structures. Another study used date palm waste-derived biochar to prepare polymer composites from polypropylene, resulting in good electrical, mechanical, thermal, and rheological characteristics [60].

Daifallah et al. [61] investigated how the addition of date palm waste increased the thermal insulation and mechanical performance of bricks. Abolfazl et al. [62] utilized different weight ratios of palm fibers to reinforce adobe bricks, and found that the addition of these fibers improved the structural behavior of adobe bricks. The maximum compressive and tensile strength was achieved with just 0.25% of fiber content. Hamid et al. [63] incorporated modified oil palm fibers and clay particles to reinforce high-density polyethylene, and found that this enhanced the thermal stability of the product.

Lokmane et al. [64] utilized a mixture of alkali-activated palm oil fuel ash and glass fibers for soil stabilization. The final product showed an improvement in shear and tensile strength, a 49% increase in young's modulus, and an 11% increase in tensile strength. Ramlee et al. [65] concluded that oil palm empty fruit bunch (OPEFB) and sugarcane bagasse (SCB) could be effectively utilized as green thermal insulators, as the composites of these fibers have low thermal conductivity. Furthermore, OPEFB and SCB have relatively high sound absorption coefficients.

Taallah et al. [66] investigated the mechanical properties and hygroscopicity of compressed earth blocks filled with date palm fibers. The results of this study revealed that enhanced dry compressive strength could be achieved with 0.05% fiber, 8% cement, and a compaction pressure of 10 MPa. Further investigations showed that adding palm fibers increased the blocks' tensile strength, water absorption capacity, and swelling behavior. Danso et al. [67] studied the effect of the aspect ratio and oil palm fiber content on the strength characteristics of soil blocks. The compressive and tensile strengths of the reinforced soil could be enhanced by increasing the aspect ratio of the oil palm fiber up to an optimum value.

2.2. *Bamboo fibers*

The addition of nano-clay and palm fibers can increase the mechanical properties of polyester composites, although a fiber content above the optimal value is not favorable for durability [68]. Bamboo is a plentiful and sustainable natural resource, with over 1250 species varying in diameter from "reed-like" bamboo to giant "woody" bamboo [69]. Bamboo grows rapidly at 30–100 cm/day throughout the growing season and takes just 3–5 years to reach harvesting maturity. Bamboo has received considerable attention as a civil engineering material because of its high water-absorption capacity, flexibility, intensity, high fiber content, low weight, low price, and fast growth [70]. It has been used as a reinforcing agent in architectural and composite material engineering applications to replace traditional materials such as steel and polymer plastics [62]. Moreover, researchers have focused on improving the behavior of challenging soft clays through the random dispersion of bamboo fibers. Bamboo chips and flakes have been incorporated in soft clay, where their water-absorption capability provides some structural reinforcement. However, the addition of bamboo fibers alone does not improve soil quality because of the absence of a binding material [71,72]. To rectify this, Huang et al. [73] studied soil's tensile strength and ductility after adding bamboo chips and a small amount of cement as a binding agent. Devi et al. [74] studied soil reinforcement by adding bamboo fibers and concluded that an increase in fiber content enhanced the strength of the soil. Furthermore, by increasing the fiber length, the shear strength of the soil could also be increased. In general, the ultimate load-bearing capacity of soft clays can be improved by up to six times compared with conventional soil through the addition of bamboo cells [75]. Various techniques have been adopted for stabilizing soft clays by adding small amounts of cement as a binding agent for the bamboo, thus significantly improving the reinforcing effect.

2.3. *Jute fibers*

Jute plants, which typically grow to heights of 2.5–4.5 m, are one of the world's most widely grown, cost-effective, commercially available natural fiber crops [76]. Jute fibers are promising materials for improving the geotechnical properties of soil. Their excellent surface roughness and high tensile strength have been utilized in various applications, e.g., soft soil consolidation, construction of roads in rural areas, riverbank protection, embankment stabilization, erosion control, and slope management [77,78]. Adding jute fibers improves the mechanical and fracture behavior of clay-modified starch composites [79], and adding 15% jute fibers enhances the tensile strength and modulus of polyethylene and nano-clay composites by 20% and 37%, respectively [80]. The mechanical characteristics of micaceous clay composites can also be enhanced by adding jute fibers and ground-granulated blast furnace slag [81]. Fataha et al. [82] claimed that adding 5 wt% clay and 50% jute fiber to a polypropylene-based composite resulted in increased tensile strength and modulus. Furthermore, the addition of an optimum amount of jute fibers (~1%) to micaceous clay increases the compressive strength, stiffness, and ductility [83].

Chakraborty et al. [84] studied the mechanical characteristics of cement reinforced with chopped jute fibers, and observed that the compressive and flexural strength of the resulting product was increased by 9% and 16%, respectively. Jute fibers and nano-clay combinations are also used to enhance the mechanical properties of epoxy composites. This enhancement is the result of strong bonding between the fiber–matrix interface and less agglomeration of nano-clay platelets [85]. The addition of 5 wt% nano-clay and 15 wt% jute fibers significantly improved polyester-based composites' mechanical and vibration characteristics. However, further addition of nano-clay reduced the mechanical strength because of the agglomeration of nano-clay particles [86,87]. Sujatha et al. [88] demonstrated that adding jute fibers to soil blocks improved strength and durability than adding polypropylene, AR glass, or banana fibers.

2.4. *Sugarcane bagasse fibers*

SCB is the pulpy and fibrous biomass left over after juice extraction from sugarcane. It is generally used for heat generation and biofuel production. Therefore, its utilization represents a sustainable approach for various applications [89,90]. SCB fibers have been identified as promising materials for stabilizing soils [91] and increasing the strength, stability, and durability of adobe bricks [89].

The reinforcement of clay soil using SCB fibers results in improved shrink–swell behavior, with an optimum SCB content of 2%.

Combining bagasse fibers and nano-clay has been used to reinforce high-density polyethylene composites via extrusion injection molding [92]. Adding 2–4 wt.% nano-clay and bagasse fibers increase the adhesion properties, tensile strength and modulus, and other mechanical properties due to the uniform distribution of clay particles and higher contact area in the polymer matrix. Moreover, the combined effect of bagasse and lime enhances the ultimate compressive strength by 145% and reduces the linear shrinkage effect.

2.5. Sisal fibers

Sisal fibers are promising engineering materials because of their flexibility, strength, durability, and resistance to the deterioration [93]. They are commonly used in the manufacturing of twine and rope and for other industrial applications requiring high strength and toughness [94]. Furthermore, adding sisal fibers to silty clay enhances the shear and deformation properties. The addition of sisal fibers significantly increases the ductility of the soil. However, it does not significantly impact the compressive strength of the soil [95]. The combined effect of sisal fibers and nano-clay in a polypropylene matrix, with maleic anhydride-grafted polypropylene used as a compatibilizer, has been studied by Ibrahim et al. [96]. They observed that adding nano-clay and sisal fibers along with the compatibilizer significantly improved the mechanical and thermal characteristics and significantly reduced water absorption rate.

The addition of nano-clay significantly decreases the water absorption capacity of sisal/epoxy composites due to its water-repellent solid tendency [97]. The addition of 3 wt% clay and 25 wt% sisal fibers increases the tensile, impact, and flexural strengths of the polymer matrix through the extra reinforcing effect of the nano-clay [98]. Wu et al. [99] utilized pretreated sisal fibers with 10% NaOH solution to improve the mechanical characteristics of silty clay. They claimed that the mechanical strength of the treated silty clay was 20% higher than that of the untreated material. Mixing sisal fibers with clay as a reinforcement agent forms cementation links between the clay particles, which bounds the movement of soil particles. Therefore, sisal fibers improve the strength properties by producing a uniform stress distribution [100]. Based on the abovementioned studies, it can be concluded that sisal fibers are promising materials for various applications, e.g., earth reinforcement, civil engineering, dam foundation, roadbed engineering, and ground treatment.

2.6. Waste coffee beans

As well as the natural fibers derived from plants discussed above, many other biomaterials have been considered because of their eco-friendly and economical nature. One of the most promising biomaterials is spent or ground coffee beans. Coffee, one of the most popular beverages on the planet, comes with a significant financial and environmental cost in the form of spent coffee grounds (SCGs), the unusable fraction of coffee beans left after brewing. Traditional methods of eliminating SCGs include dumping them as solid trash into landfills and sewage, which can pollute the environment due to poisonous and organic components. The organic waste that has been leached poses a risk to both the environment and human health.

Landfill disposal is ineffective, especially in smaller countries with scarce land. Another method of removal is incineration, which is

Table 2

Summary of reinforcement of various materials using different natural fibers and binding materials.

Type of fiber	Type of matrix	Fiber quantity (wt.%)	Fiber length (mm)	Advantages	Refs.
Date palm fiber	Concrete	2.5–7	50	Enhanced compressive & flexural strength	[112]
	PE & PP	5–20	2.5–10	Increased hardness & impact	[52]
	Concrete & Fumed silica	0–3	20–30	Improved compressive strength, water absorption capacity & heat resistance	[51, 53]
	EPS	70–80	0.1–1	Improved density & thermal conductivity	[59]
	Clay & HDPE	0–25	2–3	Improved thermal stability	[113]
Bamboo chips	Soil	0–5	20–30	Increased shear strength	[74]
Jute fibers	PE & Clay	5–20	3	Better tensile properties	[114]
	GBFS & Clay	0–1.5	15	Better ductility & toughness	[115]
	Lime & Clay	0.5–1.5	15	Improved compressive strength, material stiffness & ductility	[83]
	Nano clay & epoxy composites	0-25 of fiber 1-7 of clay	10–40	Higher tensile, flexural & impact strength	[85]
Bagasse fiber	Adobe bricks	10–50	0–3	Increased compressive strength & water stability	[89]
	Hydrated lime & Expansive soil	0.5–2	0.3–13.8	Increased compressive strength & curing time	[116]
Bagasse ash	Hydrated lime & soil	4.5–13.5	–	Better stability of soil	[117]
Sisal fiber	rPP & nano clay	10-40 of fiber 1-5 of clay	5	Increased tensile, impact strength & tensile modulus	[96]
	Silty clay	0.5–1.5	5–15	20% improved soil strength	[118]
Waste coffee beans	Clay paste	5–20	–	Increased porosity, water absorption capacity & firing temperature	[108]
	PVA	1–3	–	Increased tensile strength & young's modulus	[106]
	Light weight clay	5–17	–	Improved compressive strength	[119]

PE= Polyethylene, PP= Polypropylene, PVA= Polyvinyl alcohol, HDPE= High density polyethylene, GBFS = ground-granulated blast-furnace slag, EPS = Expanded polystyrene wastes, rPP = Recycled polypropylene.

equally undesirable because the particulate matter produced may impact the local air quality. These practices are incredibly harmful to the environment, emphasizing the need for improved SCG waste management [101].

In a study by Wu et al. [102], spent coffee beans (SCBs) were used to enhance the thermal, mechanical, and moisture-absorption properties of polypropylene. Garcia et al. [103] mixed SCBs with polypropylene to develop a wood–plastic composite with enhanced thermal stability, while Zarrinbakhsh et al. [104] made polypropylene composites with SCGs and coffee chaff, and showed that the coffee chaff had better thermal stability, lipid content, and fibrous structural density. The polylactide (PLA) composites and SCB developed by Wu et al. [105] exhibit enhanced mechanical and water-resistance properties and are biodegradable. Polyvinyl alcohol and coffee nanocomposites have a higher tensile strength and Young's modulus than composites created using carbon black, proving that they could be utilized as a replacement [106].

The use of SCGs as an additive in brick manufacturing has also been investigated. Munoz et al. [107] claimed that bricks made from 17% SCB waste had a compressive strength of more than 10 N/mm^2 and could be used structurally. The thermal conductivity of these bricks was also reduced by 50%, making them better insulators than conventional bricks. Sena da Fonseca et al. [108] found that bricks made of 10% SCGs still met the highest mechanical standards, whereas the addition of 20% SCGs reduced the thermal conductivity by 70%. The scope of SCBs is not limited to the applications mentioned above—they have also been utilized to produce biodiesel and bioethanol, sugar recovery, and the preparation of phenolic compounds, antioxidants, and fertilizers [109–111]. The summary of the utilization of different natural fibers for the reinforcement applications of concrete, polymers, natural soil and adobe bricks with varying materials of binder, fibers quantity and the advantages of end products are given in Table 2.

2.7. *Advantages and limitations of natural and synthetic fibers*

Natural fibers are promising feedstocks for the reinforcement of different polymers, clays, and other construction materials. They are cost-effective, environmentally friendly, and biodegradable. However, their utilization for stabilizing and improving the properties of different clays and in 3D/4D printing technology requires further investigation.

Natural fiber-reinforced composites are sometimes less appealing because of their low melting point, weak interfacial adhesion, and poor moisture resistance [5]. Furthermore, clay-based composites are extensively used for the adsorption ofmetal–organic pollutants, dyes, aromatic compounds, and heavy metal ions from wastewater [120]. Increased societal and environmental concerns, complete data availability, and the ubiquitous existence of natural fibers have seen natural fiber composites garner widespread attention. Natural mineral, animal, and plant fibers have been used to make various composites [121]. The natural fibers produced from plant sources are frequently favored for the reinforcement of polymeric composites due to their simplicity of extraction and abundance. In polymer composites, they serve as the primary load-carrying ingredients [122]. The addition of natural fibers improves the technical qualities of polymer matrices while lowering their cost. Plant-based fibers are a worthy reinforcement material for making polymeric composites with low density, high strength, and specific modulus [123,124]. These fibers mainly comprise cellulose, hemicellulose, lignin, pectin, and waxy components. Furthermore, they have high tensile strength due to the presence of H-bonds within cellulose molecules and aligned cellular microfibrils in the fiber direction [125]. Because of their hollowness and lignocellulosic components, natural or bio-based fibers provide extraordinary thermal and acoustic insulation characteristics [126].

Natural fibers are environmentally friendly, biodegradable, harmless, abundant, sustainable, cost-effective, smooth, and visually appealing. Furthermore, compared with their synthetic equivalents, they create fewer health and environmental issues. Their specific strength is comparable to that of synthetic materials, making them suitable for a wide range of industrial applications. However, natural fibers are easily degradable under sunlight and microorganism reactions, have lower compressive strength than synthetic fibers, and are hydrophilic [127]. Synthetic fibers have a high cost, and high density, are challenging to process, and are nonbiodegradable [128,129]. The various advantages and limitations of natural and synthetic fibers are summarized in Table 3.

The chemical composition and mechanical properties of different natural fibers are given in Table 4.

Comparison of chemical composition i.e., percentages of cellulose, hemicellulose, lignin, ash, moisture, and mechanical properties e.g., modulus, tensile strength, and density of cotton, kenaf, alfa, coconut, hard wood, soft wood, jute, flax, sisal, hemp, and bagasse

Table 3
Advantages and limitations of natural and synthetic fibers.

Type	Advantages	Limitations	Refs.
Plant-based or natural fibers	Abundantly available Nontoxic Noncorrosive Lower density Friendly processing e.g., no wearing tools and skin irritation Biodegradable Environmentally friendly Cost-effective	Hydrophilic nature Highly polar surfaces Less adhesion with polymers Degradation due to sunlight and microorganisms Normal strength Shorter service life	[40,130,131]
Synthetic or artificial fibers	Higher thermal stability Water resistant nature Higher chemical resistance	Expensive, Flammable Difficult to handle, Poor insulation capacity, restricted towards hot washing Nonbiodegradable, not ecofriendly, cause microplastic pollution	[129,132]

Table 4
Physical, chemical, and mechanical properties of different natural fibers.

Type of fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Moisture (%)	Ash (%)	Modulus (GPa)	Tensile strength (MPa)	Density (g/cc)	Refs.
Bagasse	45	30	25	55	1–9	17	290	1.25	[133,134]
Date palm leaf	54.75	20	15.30	26–30	1.75	7	203	0.9	[135,136]
Pineapple leaf	69.5	19.5	4.4	13	19.5	11.84	159	1.32	[122,137]
Jute	61–72	18–22.4	12–13	12–14	0.5–2	10–30	393–770	1.46	[138]
Flax	64–72	19–21	2–2.2	8–12	3.4	60–80	800–1500	1.4–1.5	[139]
Sisal	78–80	10–12	8–10	11	1–2	38	600–700	1.45	[140]
Hemp	69.5–73.5	18–22.5	4–6	6.2–12	0.8	70	550–900	1.48	[141]
Date palm wood	24–82	20–22	26–33	15–20	1.5–5.5	3–8.5	90–213	0.16–0.63	[142,143]
Hard wood	43–47	17–38	25–35	8–25	0.56–0.89	5–16	51–121	0.3–0.88	[144,145]
Soft wood	40–44	22–40	25–29	13.7–46.7	2.6–18.3	4–14	46–111	0.3–0.59	[146]
Coconut fiber	22–45	1–3	40–48	60–80	0.5–1.5	3–26	90–175	0.88–1.36	[147,148]
Oil palm fiber	23–65	20–34	14.1–30.5	12–15	4.7	0.44–1.9	65–220	1.24	[67,149]
Kenaf fiber	50–80	21–35	5–20	20	5.4	14.5–73	230–1000	1.2–1.4	[150,151]
Alfa fiber	38.8–47.6	22.1–38.5	14.9–24	13	2–7.2	0.18–0.3	18–25	1.4	[152]
Cotton fiber	88–96	5–12	0.4–1	5.3	1.3	0.29–0.8	5.5–13	1.5–1.6	[153,154]

fibers are described by the floating graphs as shown in Fig. 2(a–h). The percentage ranges of cellulose, hemicellulose, lignin, moisture and ash content of different natural fibers are given in Fig. 2 a, 2 b, 2 c, 2 d and 2 e respectively. Similarly the comaprsion of mechanical properties i.e., tensile strenghth (MPa), modulus (GPa) and density of (g/cc) of different natural fibers are given in Fig. 2 f, 2 g and 2 h, respectively.

2.8. Background study of 3D printing

3D printing is an emerging technology enabling a wide range of novel applications. There are some factors e.g., availability of materials, speed of fabrication, and resolution of 3D printing process must be considered with respect to an individual application [155]. 3D printing should never be considered a stand-alone process; rather, it is evolving into a crucial component of a multi-process system or an integrated process of various techniques to accommodate the creation of innovative materials and new product requirements. Many new materials, including nanomaterials, functional materials, biomaterials, smart materials, and even fast-drying concrete, have been investigated for 3D printability and the use as feed materials for printing actual application parts in recent years due to an increase in demand for both product complexity and multi-functionality.

Ceramics and concrete, for example, are not appropriate for 3D printing because different powders cannot be fused together by applying heat to their melting temperature. In contrast, metal and polymers can be fused together by raising a material's melting or glass transition temperature. One of the most significant difficulties in additive manufacturing is the extremely high melting point of ceramic materials compared to metals and polymers [156]. 3D printing concrete technology is a revolutionary construction process that predominantly employs layered extrusion for material deposition [157]. Without formwork, concrete is extruded through a nozzle and automatically placed in layers per a digitally planned printing route [158]. It has been demonstrated that 3D printing technology has advantages, including high efficiency, flexibility, and environmental benefits, when used for both conventional right-angle wall printing and complex-shaped buildings [159]. Numerous laboratory studies have been conducted on the performance and characterization of concrete containing fine aggregate printed with 3D printers [160–162]. Concrete with coarse aggregate has recently been used in 3D printing technology. Furthermore, large-scale 3D-printed concrete is being developed and used in various construction applications [163,164]. The use of recycled sand in 3D printing construction can boost the cost-effectiveness and environmental friendliness of 3D printed materials [165]. Due to high water absorption capacity, recycled sand can improve the buildability of printing materials. However, recycled aggregate significantly affected tensile splitting strength while having no effect on compressive or flexural strength [166]. Ma et al. [167] tested the printability and mechanical properties of 3D printing mortar using industrial waste copper tailings. They observed that the buildability and compressive strength was increased by increasing the copper tailings content up to an optimum amount i.e., 30%.

Natural fibers continue gaining acceptance and applicability in cementitious composites due to their advantages over other artificial and synthetic fibers as they are more economical, environmentally friendly, biodegradable, and sustainable. Furthermore, replacing synthetic fibers such as glass and carbon fibers, their biodegradability, lightweight, lower density, higher strength-to-weight ratio, and non-toxicity give them some advantages. Moreover, natural fiber production and processing require less energy than other synthetic fibers. As an example, the processing and production of natural jute fiber require approximately 7% of the energy needed to

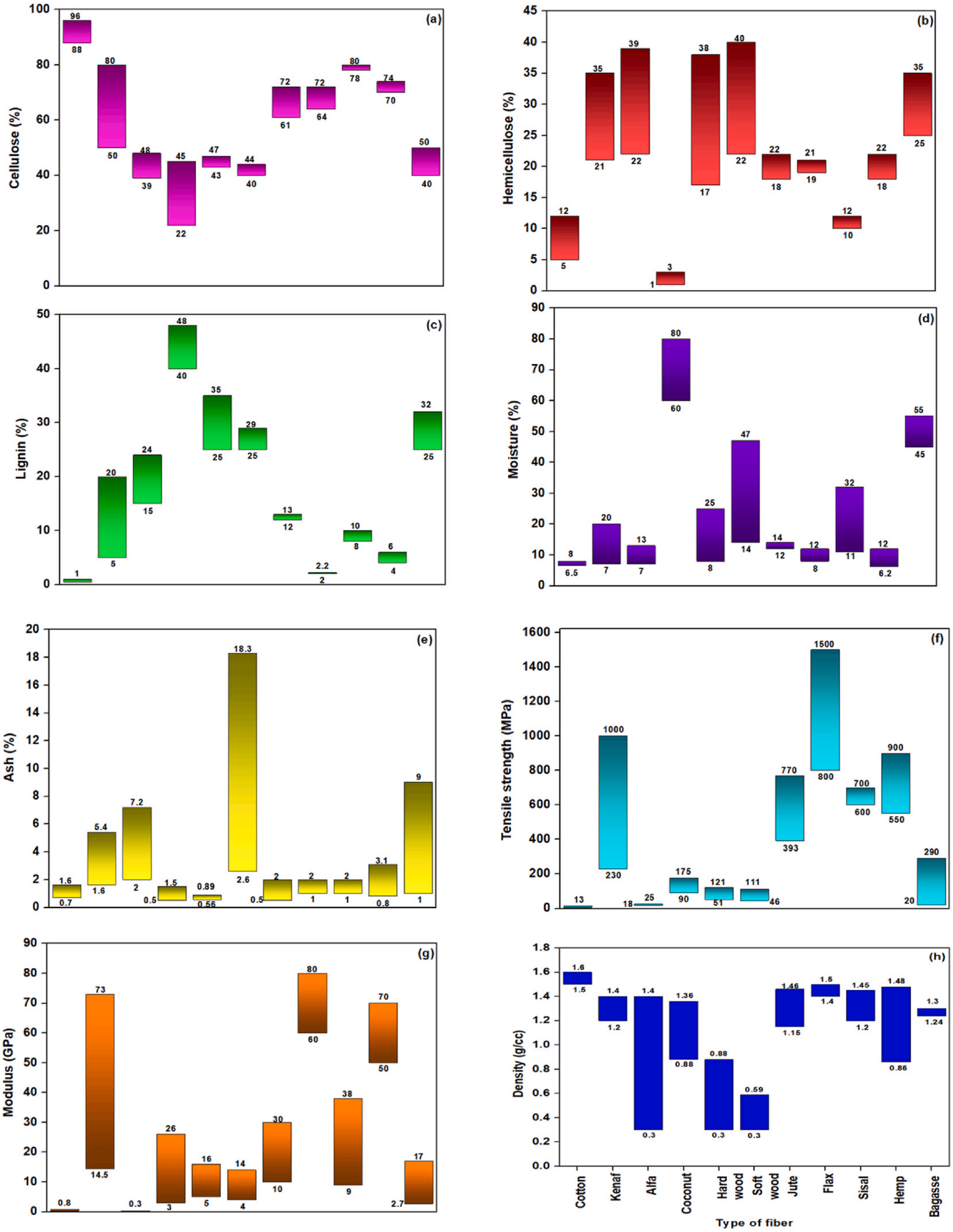

Fig. 2. Summary of mechanical properties and chemical composition of different fibers; (a) Cellulose, (b) Hemicellulose, (c) Lignin, (d) Moisture, (e) Ash, (f) Tensile strength, (g) Modulus, and (h) Density.

produce the same weight of polypropylene artificial fibers [50,168].

However, some limitations are associated with using natural fibers, i.e., their hydrophobic nature. Furthermore, the use of natural fibers in cement composites can significantly alter the properties of cementitious material. These limitations must be resolved for the effective use of fibers and to improve the properties of cementitious composites [169].

2.9. Polymeric composites reinforced with clay and natural fibers for 3D printing

The characteristics of polymer matrix materials can also be significantly improved by fiber reinforcement. Fused deposition modeling (FDM) and direct writing are widely used 3D printing technologies for developing fiber-reinforced polymer composites. Polymer pellets and fibers must first be combined in a blender before being supplied to an extruder to produce filaments for FDM processing. The uniform distribution of fibers can be ensured by applying a second extrusion operation. In the direct writing process, polymer paste and fibers are mixed and then extruded. Powder-based technologies are unsuitable for producing fiber-reinforced composites because it is difficult to create a smooth layer of powder–fiber mixture [170,171]. Scholars have recently focused on additive manufacturing for natural fiber-reinforced polymer composite materials, and numerous studies have examined processing and molding methods, modification approaches, and the mechanical properties of biomass composites. In general, natural fibers are hydrophilic, while the polymer matrix is hydrophobic; because of the two materials' differing polarities, poor bonding is to be expected. The most popular method of enhancing the interfacial bonding qualities involves the surface modification of the material.

Furthermore, choosing the right polymer matrix and regulating the quantity of fiber insertion can help improve the mechanical and interfacial properties [172]. When processing fibers in polymer mixtures, the fiber acts as a nucleating agent, helping to speed up the crystallization process. Increasing the crystallization rate for 3D printing applications is crucial because PLA has a slow crystallization rate and poor crystallization ability under high cooling rates, which is not conducive to rapid curing and molding after melt extrusion printing. Various techniques have been used to improve the performance of the matrix or natural fibers to solve this issue. There are many ways to modify the interface between the matrix and fiber, including chemical modification of the fiber surface, fiber size enhancement, appropriate fiber addition, and appropriate modifier addition [173]. Table 5 summarizes several studies on natural fiber-reinforced composite filaments with different weight percentages that have been applied to thermoplastics.

2.10. Literature review methodology

The search engines used for the literature review were Google Scholar, Web of Science, and ScienceDirect. The keywords used for this search were "natural fibers," "polymeric composites," "technologies for the development of composites," "applications of clays," "applications of natural fibers as reinforcement agents," and "3D printing." Only those articles focusing on the reinforcement of polymers and clays using bio-derived materials, i.e., natural fibers from different plants and waste resources, and published from 2010 to 2022 are discussed in this study. A bibliographic mapping of text data in the titles and abstracts, which represents the occurrence of frequently used keywords such as natural fibers, applications of clays, additive manufacturing, 3D printing, and polymeric composites, was generated using the VOS viewer software. This mapping is shown in Fig. 3. Articles on the reinforcement of polymeric composites and other materials using natural fibers and recent advances in developing composite techniques were taken into consideration. The following categories of articles were selected: reviews, clay reinforcement, 3D printing, additive manufacturing, applications of 3D printing, the role of nanoparticles in support, and the general role of natural fibers in enhancing the mechanical, chemical, and physical characteristics of materials. The reviewed articles were retrieved from Elsevier, Springer, MDPI, American Chemical Society, Wiley Online Library, Taylor & Francis, RSC, and Nature.

3. 3D printing technology

Additive manufacturing (AM), often known as 3D printing, allows for creating complicated geometries, consolidating complex components, product customization, and reducing material waste [184]. These benefits have fueled the rapid expansion of 3D printing in recent years. In AM, the material is added to a digital model in consecutive stages to form a 3D item [185,186]. Traditional manufacturing procedures such as machining, grinding, and casting, in which molten material is added to a mold to make a product, can be contrasted with 3D printing. There are several types of 3D printing technology, each having specific uses. According to ASTM standard F-2792, AM technologies can be classified into binder jetting, directed energy deposition, FDM, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization [187].

Table 5

Natural fiber-reinforced 3D-printed composites.

Fiber type	Polymer matrix	Fiber content (wt.%)	Ref.
Hemp	PP & PLA	10–30 & 0–30	[174,175]
Bamboo	PLA	20	[176]
Sugarcane	PLA	3–15	[177]
Flax	PLA	15	[178]
Rice straw	ABS	0–15	[179]
Lignin	ABS	0–40	[180]
Wood	PLA	40	[181]
Thermomechanical pulp	Bio-PE	10–20	[182]
Cardboard dust	HDPE	20, 50, & 70	[183]

ABS = Acrylonitrile butadiene styrene, PLA = polylactide acid, PP = polypropylene, HDPE = High-density polyethylene.

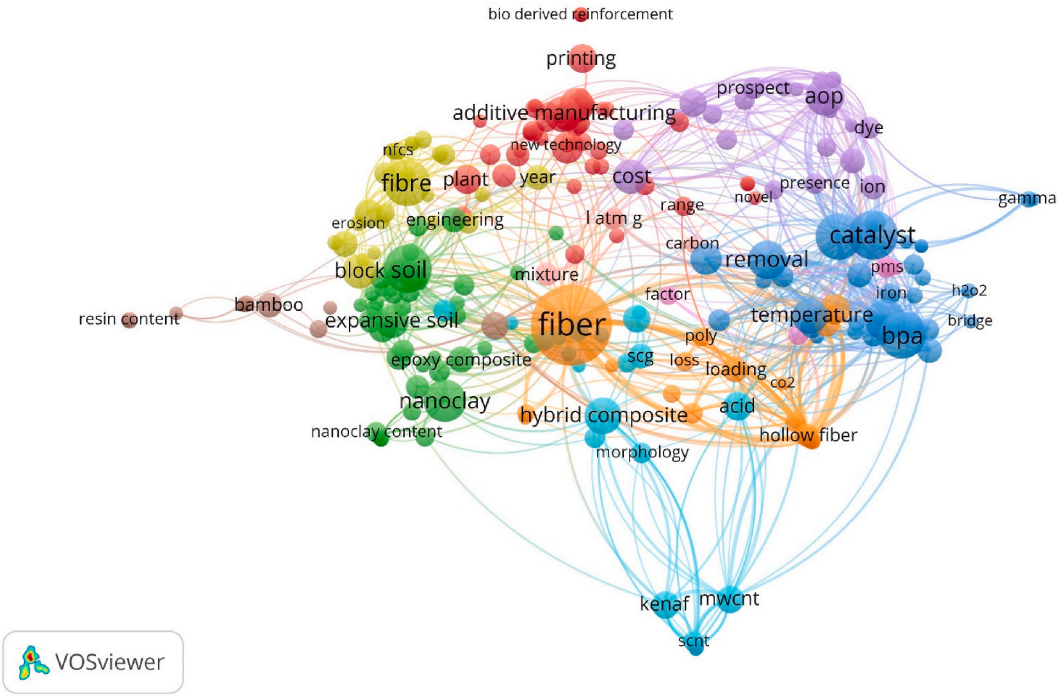

Fig. 3. Bibliographic mapping of occurrence of keywords based on title and abstract text.

3.1. *Binder jetting*

This method is a modified version of the Inkjet technique. It was firstly introduced by the Massachusetts Institute of Technology (MIT). This method uses inkjet for binding objects instead of laser beams [188]. The binder jetting method is cost-effective, and energy-efficient as no heat is required to bind the materials. Furthermore, the extra material is completely recyclable as it is not heated. The most widely used materials in this process are metals, polymers, and ceramics [189,190].

3.2. *Directed energy deposition*

This method is used for repairing and maintaining the present products instead of developing new ones. The directed energy deposition technique utilizes heat as a laser or electron beam, with materials typically in the form of wire or powder [191]. This fast method enables complex materials to be produced with enhanced flexibility. However, the parts made from this method have relatively low resolution and rough surfaces, and this technique is not cost-effective due to the very high equipment costs [192].

3.3. *Material jetting*

The material jetting technique is advantageous at the nanoscale, producing ultra-thin layers compared with other AM techniques. In this method objects are developed like a two-dimensional ink jet printer. A product with high accuracy and good surface finish having multiple materials can be acquired through this technique. However, additional material in the form of filler is required to obtain desired shape of end-product which may remove after the process [193]. However, the limitation of this process is that it uses limited polymers, ceramics, hybrid materials, and waxes as feedstock [194].

3.4. *Powder bed diffusion*

The powder bed fusion technique uses a high-power energy source to develop a single object. This technique has been divided into direct metal laser melting, direct metal laser sintering, electron beam melting, selective laser melting, and selective laser sintering. Various metals, synthetic polymers, and ceramics can be used for powder bed diffusion. The significant advantage of this method is that little waste is produced. However, printing the objects takes a long time [195].

3.5. *Sheet lamination*

Sheet lamination is another type of 3D printing in which the feedstock is sheets instead of powder or wires. This process is cost-effective and energy-efficient because the materials are printed rapidly at low temperatures. Another benefit of this technique is that the material maintains its original state before and after the procedure, making handling relatively easy. However, this process has limited uses, requires post-processing to achieve the desired object, and cannot be used to manufacture hollow parts [196,197].

3.6. *Vat photopolymerization*

Vat photopolymerization is a relatively fast 3D printing technique in which photoreactive materials are cured and controlled using a light source or ultraviolet radiation to make 3D objects with potentially huge sizes and volumes. This technique can be further classified into stereolithography and digital light processing. The main difference between these two types is the source of light used. Digital light processing uses an arc lamp, whereas ultraviolet rays are used as a light source for stereolithography [198]. Stereolithography is the most precise AM technique for developing high-quality prototypes with complicated and concise geometrical designs. Furthermore, products with excellent surface polish and high dimensional tolerance can be manufactured by this technique. However, stereolithography is a high-cost technique because of the required resins [199].

3.7. *Fused deposition modeling*

FDM is a material extrusion technique. Thermoplastic filaments are first heated and then extruded via a nozzle tip. According to a digital model of the component, extruded molten material is then added layer by layer. FDM is mainly used to develop concept models in the early stages of product development. The significant benefit of this technique is that the filament materials are readily available. Furthermore, there are various FDM filaments with different strengths and temperature characteristics. This technique has several advantages over other AM methods: its low cost, reusable filaments, cloud server printing, ease of implementation, realistic ergonomics, wide variety of materials, and portability. However, FDM has relatively long printing times and gives a rough surface finish [200,201]. Although most 3D printing methods employ a layer-by-layer production approach, 3D freeform printing can be used to produce complicated shapes in open space using a robotic arm with an extrusion chamber. To create the finished item, the robotic arm extrudes and places material where it is needed in 3D space [202]. From 2010 to 2021, our literature search found the most studies related to FDM for 3D printing. Metals, polymers, resins, and powders can be used in FDM 3D printing [203].

Thermoplastics, thermosets, hydrogels, functional polymers, and polymer-based composites are the most-utilized materials [204]. There is a high demand for sustainable alternatives to these materials in the 3D printing business. The most frequently used 3D printing materials are thermoplastics. However, relying heavily on thermoplastics made from petrochemicals does not support the development of a circular economy [205]. Consequently, there has been considerable interest in adopting naturally derived polymers and their composites as replacements for conventional oil-based polymers to make the AM sector more sustainable. The most popular material

Table 6
Mechanical properties of commonly used polymers for 3D printing [207–209].

Type & nature of polymer	AM method	Tensile strength (MPa)	Flexural strength (MPa)	Young's modulus (GPa)	Flexural modulus (GPa)	Elongation (%)	Refs.
Polylactide (Biodegradable)	FDM, SLS, Jetting	50–89	120–150	3–4	3.5–5	2–9	[210]
Polyamide (Non-biodegradable)	FDM, Multi-jet fusion	52–54	150–162	1.7–1.8	1.2	28	[211]
Polyethylene (Non-biodegradable)	FDM	18–19	18.7–19.8	1.4–1.9	0.8–1.01	5–7	[212]
Polycarbonate (Non-biodegradable)	FDM	70–75	93	2.3–2.5	2.4	17–94	[213]
Polycarbonate (fossil fuel blend)	FDM	28–62	93.1	2.3	2.34	10	[214]
Polyhydroxy alkanoates (Biodegradable)	FDM	15–40	17–61	1–2	1.4–3.2	1–15	[215]
PEF (Non-biodegradable)	FDM	67–77	–	2.7–2.9	–	2–4	[215,216]
ABS	FDM, Stereolithography, Jetting	35–38	0.379–593	1.79–3.2	1.6–2.4	1.7–6	[217]
PEEK	FDM, SLA	58–85	172	3.76–3.95	4.13	0.3–1.5	[218]
PETG	FDM, SLA, Inkjet, Extrusion	38–40	70	2.01–2.11	2.1	1.02–1.18	[219]
Biocompatible nylon	SLS	44	85	1.8–5.1	2.3	10	[220]
Polyphenylsulfone	FDM	55	108	3.6	4.7	3	[221]
Veroclear	Polyjet	50–65	75–110	2–3	2.2–3.2	10	[222]
Polyethylenimine	FDM	105	152	3.3–3.6	3.31	7	[223]
Nylon 12	SLS	43–48	50	1.5–1.8	0.4	1.4–2.4	[224]
Protogen	SLA	42.2–43.8	66.7–70.5	2.1	1.9–2.1	8–16	[225]
Polystyrene	SLS	5.5	70	1.6	2.5	0.4	[226]

*PEF: Polyethylene-2,5-furandicarboxylate, PEEK: Polyether ether ketone, ABS: Acrylonitrile butadiene styrene, PETG: Polyethylene terephthalate glycol, FDM: Fused deposition modeling, SLS: Selective laser sintering, SLA: Stereolithography.

for 3D printing globally is polylactic acid, a bio-derived and biodegradable polymer. Naturally derived polyhydroxy alkanoates, polyethylene, polyethylene-2,5 furandicarboxylate, polycarbonate, and polyamide are other bio-derived polymers utilized in 3D printing [206]. AM processes also use acrylonitrile butadiene styrene (ABS), poly ether ester ketone (PEEK), polyethylene terephthalate glycol (PETG), polyetherimide (ULTEM), and nylon. The mechanical characteristics of several bio-derived and commercial thermoplastics used in 3D printing technologies are listed in Table 6.

Summary of mechanical properties i.e., tensile strength, flexural strength, Young's modulus, elongation at break and flexural modulus of most commonly used polymers e.g., polylactic acid (PLA), polyamide (PA), polyethylene (PE), polyether ether ketone (PEEK), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG) and polyhydroxyalkanoate (PHA) used in 3D printing process is described by the floating graphs as shown in Fig. 4(a–e). Comparison of tensile strength, flexural strength, young's modulus, elongation at break and flexural of different polymers are given in Fig. 4 a, 4 b, 4 c, 4 d and 4 e respectively. PLA has the highest tensile strength, young's modulus and flexural modulus as shown in Fig. 2(a–e). Furthermore, PEEK showed the highest flexural strength and PA has the highest elongation at break as shown in Fig. 4 b and 4 d, respectively.

PLA has a higher tensile and flexural strength than other bio-derived thermoplastics. It is also favored because it is widely

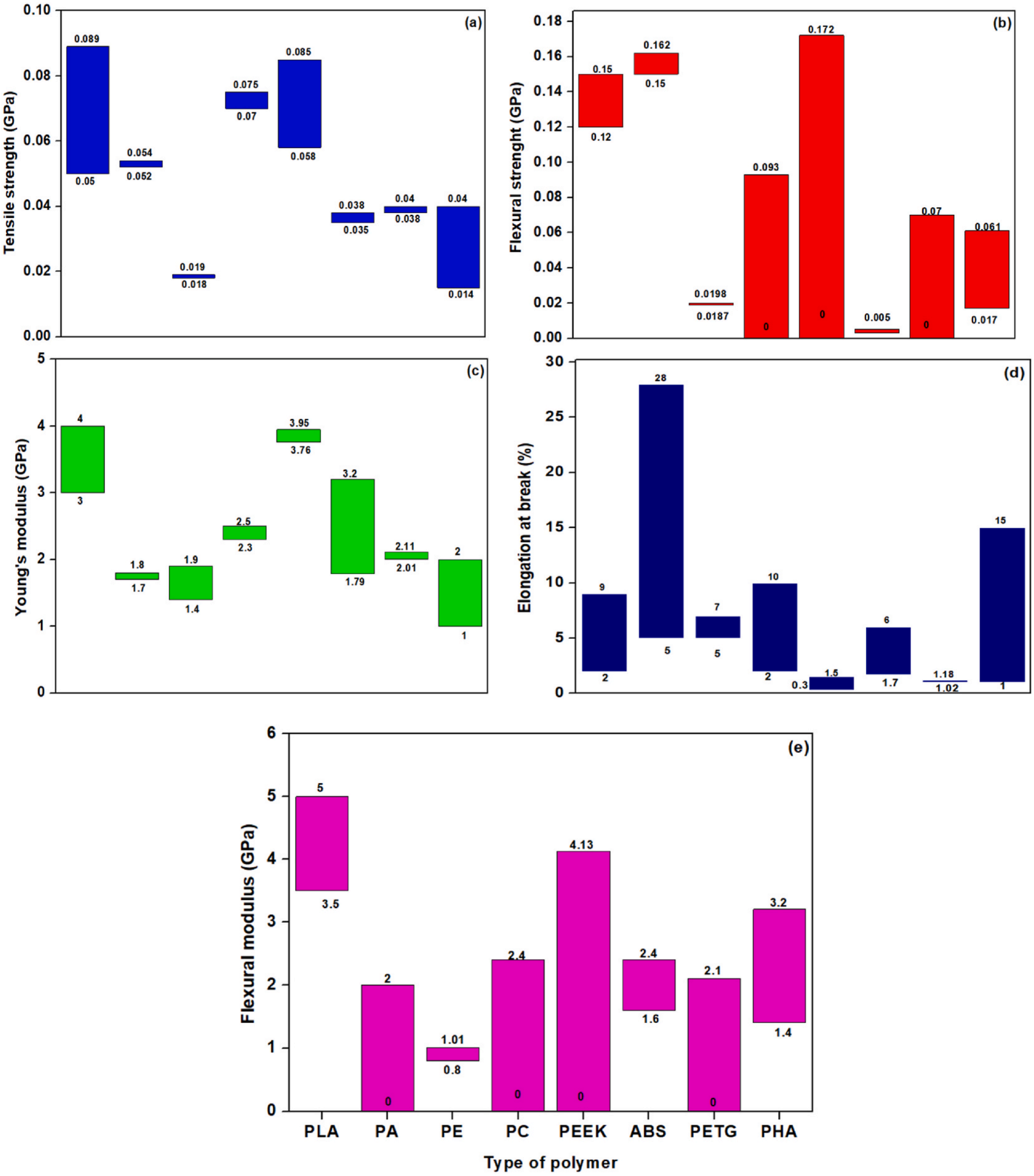

Fig. 4. Mechanical properties of polymers, (a) Tensile strength, (b) Flexural strength, (c) Young's modulus, (d) Elongation at break, (e) Flexural modulus.

accessible. For FDM 3D printing, PLA composites have been used to produce better mechanical properties and enhanced functions that cannot be obtained using PLA directly. Furthermore, it is also used to minimize production costs and increase the sustainability of manufactured goods. PLA composites incorporating bio-derived reinforcements, including flax, hemp, jute, bamboo, and other natural fibers, have been extensively investigated for 3D printing [184,227].

Natural fibers are a renewable resource that represents a new generation of polymer-based material reinforcements and integrators. Natural fiber-reinforced composites require additional processing during assembly to achieve specific design criteria. However, few studies have been on the processing of natural fiber-reinforced composites for use in 3D printing. Different methods have been adopted to develop composite materials, and 3D printing technology using raw materials and clays has gained broad interest as a simple, efficient, and cost-effective technique for developing materials of various shapes, sizes, and dimensions.

The waste from date palm trees has been utilized in many ways for different valuable applications, and other polymeric composites, e.g., MOFs, filters, and membranes, have been developed using 3D printing technology, resulting in materials of better quality and greater efficiency. Filters created using 3D printing can achieve excellent wastewater treatment performance [228].

Although the literature supports using various materials based on natural resources, e.g., sand, clay, and fibers, there is a solid need to study new pathways and develop novel materials for 3D printing. Furthermore, other silica, clay, sand, and polymer-based composites, and the fibers developed through 3D printing, result in enhanced CO_2 adsorption from flue gas compared with conventionally produced materials. Moreover, these materials can be used for numerous applications e.g., drug delivery, food packaging, interior decoration, antimicrobial devices, light sensing materials, textiles, hydrogels for medical implants, tissue engineering, and biomedical equipment, aerogels for tissue engineering, and thermal insulation, electrodes for membranes and batteries etc. [229–231]. Table 7 summarizes the previous studies on using various natural fibers and biomass wastes for 3D printing applications.

3.8. *Practical applications of 3D printing*

In general, 3D printing technology is significantly helpful for developing novel materials and products in minimum time with the least amount of waste. Furthermore, the processes facilitate the formation of complex structures of exceptional quality with great ease. With the help of 3D printing, industries are being modernized and revolutionized. Manufacturing processes are gradually shifting from traditional to non-conventional 3D printing. There is a dire need of thorough understanding of materials and their properties. With current knowledge of materials and processes, some modifications to traditional techniques using 3D printing have been made. In this section, we will discuss the applications of various processes.

- Stereolithography is used for the tissue engineering of heart valves which are biodegradable and biocompatible compared to mechanical ones. Furthermore, these tissues are same as the actual tissues and capable of growing inside the human body [188].
- Fused deposition modeling 3D printing technology is used in drug delivery systems to manufacture individualized tablets because it is cost-effective, easy to process, and distributes dosage types [249]. This technique is effectively used to produce cost-effective wax for in industrial casting. Furthermore, castings, vent gates and molds are made by FDM 3D printing for foundry operations.

Table 7

Summary of biomass wastes and natural fibers utilization for 3D printing applications.

Printing Technique	Type of fiber & biomass	Type of polymer	Fiber & biomass wt.%	Dimensions of fibers & biomass	Refs.
Fused deposition modeling	Phosphor	PLA	2	500 µm	[232]
	CNF		0–5	1 µm	[233]
	Wheat straw powder		1–5	70–150 µm	[234]
	Spruce		0–20	0.4–1.55 mm	[235]
	Flax			20 mm	[236]
	Sugarcane		0–15	450 µm	[177]
	Rice husk powder		10	≥20 µm	[237]
	Grass		–	20–40 µm	[238]
	Jute		–	2 mm	[239]
	Oil palm	ABS	5	1.75 mm	[240]
	Coconut		15	0.5–2 mm	[241]
	Rice straw		0–20	0.105–0.149 mm	[242]
Twin screw extruder	Lignin & carbon		40-60 lignin & 4–16 carbon	–	[243]
FDM	Nutshell		19–29	–	[244]
	Hemp	PP	10–30	10 mm	[174]
Single screw extruder	CNC	PVA	0–20	1.7 mm diameter	[245]
LDM	Microalgal biomass & Lignin	Metakaolin & bentonite	37.6–47.7 of metakaolin, 10.4–22.6 of bentonite, 0.6–3.1 of microalgal biomass, & 0.6–2.8 of lignin	–	[246]
FDM	Poplar wood	Polyurethane	10–40	150 µm	[247]
Extrusion	Natural cellulose	CMC	35–50	100–200 µm	[248]

FDM= Fused deposition modeling, LDM = Liquid deposition modeling, CMC= Carbon micro crystals, PVA= Polyvinyl alcohol, CNC= Carbon nano crystals.

- Powder bed fusion produces lightweight robotic structural parts with desired shapes and mechanical properties in a single-stage process [250]. Sensitive parts of the sensors which are exposed to high temperatures with enhanced efficiency, are produced using this technology [251].
- The direct energy deposition technique is used to produce stainless steel parts with strong metallurgical bonds, minimum dilution, smaller heat affected region, and higher micro hardness of the deposition zone. Repairing engine parts of vehicles done by this method is more effective and long-lasting than conventional tungsten welding [252].
- The selective laser sintering technique is used for rapid prototyping to manufacture different parts e.g., hinges, chips etc., with improved functionality. This technique produces complex macro-micro scaffolds for biomedical and tissue engineering applications [188].
- The binder jetting technique is used in pharmaceutical industries to produce oral dosage forms with a wide range of release characteristics. This technique is also used for bone scaffolds and implant applications [253].

The comparison of advantages, limitations, applications and materials used in different 3D printing techniques is given below in Table 8.

4. Conclusion and future recommendations

Natural fibers and other biomass residues have become one of the most frequently utilized materials for 3D printing. Plants-derived natural fibers are considered appropriate for processing with polymer matrix and other materials in 3D printing for different applications because of their high aspect ratio, thermal stability, and mechanical strength. Therefore, to get the appropriate results and characteristics in the product, fibers should be prepared with modification methods specific to the application requirement while employing 3D printing technology for processing and the following points should be considered in this regard.

- Polymers are not desirable alone due to their high cost and other limitations. Therefore, various bio-based green materials such as natural fibers and biomass residues are mixed with them as activators or additives to enhance their structural properties and make them suitable for printing on large-scale and industrial applications. This study provides an overview of optimum conditions to obtain desired characteristics for 3D printing of different materials using natural fibers. However, these conditions are only suitable for a particular application described in their research.
- Interfacial adhesion, mechanical properties, and surface modifications of natural fibers and their derivatives or modifications in polymer matrixes and mixing materials are standard techniques to improve the interfacial bonding between two phases.
- The effect of thermal characteristics on the laminate properties of composite materials by mixing natural fibers as nucleating agents with polymer matrixes would alter the properties of composites, and an appropriate product will be obtained with excellent thermal stability after cooling and curing.

Although the 3D printing of fibers and their derivatives has been intensively studied on a broad scale in the sectors of intelligent manufacturing, biomedicine, and electronic devices, several drawbacks still prevent its widespread use in actual production [265–267]. 3D printed bio-composites have inferior mechanical characteristics to commercially available composites. They typically suffer from weak interlayer adhesion, lack of fiber in FDM filaments, a low aspect ratio of bio-derived fibers, and porosity of the printed objects. The weak mechanical strength of 3D printed composites comes from residual stresses, uneven fiber distribution, and poor bonding between the fiber and the matrix [264]. Despite various achievements, there are still many limitations in applying polymer 3D printing to construction applications. Despite the recent development of several 3D-printed polymer materials, choosing materials for applications is not always easy. The choice of material is crucial to producing a print with the desired features. Still, this may be not easy because the performance of 3D-printed polymers varies depending on the printing technique and other factors.

3D printing equipment has a complex structure, expensive, and requires extensive. Therefore, ordinary consumers cannot afford it. However, the existing problems can be divided into material, process, and design categories, as they overlap significantly. For instance, the process parameters affect the material attributes, and the fabrication consistency can affect the design performance. The performance of 3D printed polymers for construction and applications must thus be improved by developing innovative, integrated design techniques and computational methods that holistically incorporate materials, processes, and design in developing new products. Existing studies have discussed the use of polymeric composites. Still, limited data are available for the reinforcement of clays and concrete using natural fibers and their fabrication using 3D printing technology for construction applications. For example, using natural waste fibers for soil and concrete reinforcement through 3D printing would be cost-effective. This field can be further explored to make the construction industry more sustainable and environmentally friendly.

Reinforced clay and concrete with natural fibers or clay composites provide a potential feedstock in 3D printing technology for construction applications. There is tremendous space to investigate new approaches that would fully harness the possibilities of 3D polymer printing. Future design advancements must support nonlinear and integrated decision-making across materials and processes for specific applications. Based on the findings presented in this review, it can be concluded that, despite thorough analyses of printable composites with added natural fibers, information about the toughened characteristics of 3D printed composites is still scarce. While some information on the mechanical properties of clay and polymeric composites is accessible, the durability properties of mixes, including nanoparticles, are largely unknown because minimal information is available on the reinforcement of clay using these natural fibers and their applications using 3D printing technology. Therefore, further research is needed to comprehend how natural fibers and other waste materials affect the technical characteristics of the various types of clay that may be used for 3D printing

Table 8
Summary of advantages, limitations, and applications of different 3D printing techniques.

Method	Materials	Applications	Advantages	Limitations	Refs.
Fused Deposition Modelling	Thermoplastic polymers, ceramics, food pastes, slurries, clays, fiber reinforced composites, metals, and biological materials	Aerospace and aerodynamic applications Fast prototyping of composite parts and toys	Cost-effective High surface finish Less waste generation Suitable for manufacturing complex parts	Relatively slow process Poor mechanical properties	[254, 255]
Selective Laser Sintering	Polymers, ceramics, and metals	Automobile parts, hardware, glass filters, casting of jewelry patterns, and biomedical devices	Higher accuracy and precision, no additional support, product durability	High cost, post processing, shrinking, and wrapping of fabricated parts	[256, 257]
Direct energy Deposition	Metals, alloys, ceramics, and polymers	Aerospace industry, biomedical applications, repairing of automotive parts	Good mechanical properties, and cost effective, development of denser parts with improved properties	Limited material availability for usage, Time taking, Not suitable for complex printing	[155, 191]
Powder bed fusion	Ceramics, limited polymers, metals, and alloys	Automotive, marine, jewelry, and aerospace industries	Cost effective, no additional support required, waste recycling, and wide choices of materials	Post processing Long processing time Week structural properties	[258, 259]
Binder jetting	Metals, sands, and ceramics	Mold casting, turbine blades, repairing of automotive parts, and drilling equipment	Cost effective, less processing time, easy operation, high quality products, no post processing	Weaker strength of parts, less density, shrinkage problem, limited material availability	[260, 261]
Sheet lamination	Polymers, composites, paper, metal rolls and tapes, composites	Smart structures, paper, forging, and foundry industries	No additional support, fast process, cost effective, suitable for bigger parts	Post processing required, not suitable for complex parts	[262, 263]

applications.

Compared to conventional methods for manufacturing objects, 3D printing is overly time intensive and complicated, making it challenging to develop massive structures. In conclusion, potential applications of fibers and their derivatives in the field of 3D printing have not been thoroughly explored [268], which can elevate the additive manufacturing technology of 3D printing to a new level through the joint advancement of both technology and materials [269,270]. We predict that this evaluation will encourage other academics and researchers to investigate fibers and their derivatives for possible uses in 3D printing.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Declaration of competing interest

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

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