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Review of advanced techniques for manufacturing biocomposites: non-destructive evaluation and artificial intelligence assisted modeling

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Abstract

Natural fiber reinforced polymer composites (NFRPCs) are being widely used in aerospace, marine, automotive, and healthcare applications due to their sustainability, low cost and ecofriendly nature. The NFRPCs manufactured through conventional, and computer controlled intelligent manufacturing techniques may contain internal and external defects. Traditionally, the microstructure of NFRPCs at different stages of manufacturing was obtained using destructive techniques which have stringent sample size restrictions and may cause decrease in residual properties of composites due to destructive scanning. However, these complications can be overcome by using non-destructive evaluation (NDE) and artificial intelligence (AI) techniques. This review highlights the impact of NDE and AI on the improvement of emerging manufacturing systems. We have discussed the classification of biocomposites, their manufacturing techniques, recyclability and strategies to improve mechanical properties. Further, the use of different types of contact and non-contact NDE techniques in understanding the microstructural variations during manufacturing, machining and the parameters that effects the mechanical performance of NFRPCs are discussed. The use of NDE images in developing the geometrical and computational models of NFRPCs are presented. We have highlighted the importance of AI technology in enhancing the quality of NDE images, improving the microstructural information before post-processing the data, and minimizing the analysis time, and identifying the defects and damages in NFRPCs. In the end, we presented the application of NDE techniques and AI technology in efficient generation of digital material twins of NFRPCs, which will be useful to design next generation biocomposites.

Keywords: Biocomposites; natural fiber; modern manufacturing techniques; non-destructive evaluation; machine learning; deep learning.

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1. Introduction

NFRPCs possess several advantages over synthetic fiber reinforced polymer composites (SFRPCs), which include low cost, environment friendly, biodegradability, recyclability, sustainability, reductions in CO_2, etc., [1, 2]. In particular, bamboo fiber reinforced composites absorb approximately up to 12 tons of CO_2 per hectare per annum, which are highly renewable construction materials and protect the pollution generated from the construction industry and fight against global warming [3]. Therefore, these composites have been widely used in civil construction applications [4] and offer a reduction in industrial waste as compared to the use of steel, aluminum, cement, etc. [5]. The production of natural fibers requires low energy, for example, the production of flax fiber requires approximately 9.55 MJ/kg compared to synthetic glass fibers (approximately 54.7 MJ/kg) [6]. Chandgude and Salunkhee [7] reported that the energy required for the production of carbon and glass fibers are 355000 and 31700 MJ/t, respectively, while the production of hemp, flax and sisal fibers requires 4170, 2752 and 2488 MJ/t, respectively. In the last decade, the production rate of NFRPCs has increased for manufacturing various interior and exterior automotive structural parts such as Audi, BMW, Toyota, etc., door panels, outdoor furniture, etc., [8, 9]. It was reported in recent literature that the compound annual growth rate has been estimated at approximately 11.8% for NFRPCs during the period 2016 to 2021 [10, 11].

The structural and environmental performance of conventional and biocomposite panels have been recently compared under various conditions [12]. It was reported that NFRPCs exhibited promising environmental and structural performance, and encouraged the use of NFRPCs in automotive and aerospace applications [13]. However, there are several limitations of natural fibers, such as lower water absorption resistance, poor weather resistance, high moisture sensitivity, poor thermal stability and fire resistance, low melting temperature, etc., [14]. As a result, sometimes burning of fibers can be occurred during manufacturing. Therefore, it is recommended to use curing temperatures lower than 200°C in manufacturing NFRPCs [15]. More importantly, most of the natural fibers are inherently incompatible with the resin due to their hydroxyl functionality of fiber cell walls, which ensures that the fibers are hydrophilic [16]. However, usually, most of the polymers (thermoset, thermoplastic and elastomer) are hydrophobic [17, 18]. Therefore, wetting of fibers is difficult in that case, which lead to poor interfacial bonding between fiber and matrix and also causes several defects. All these factors affect the mechanical performance of composites.

Several authors have proposed different approaches to overcome the above-discussed limitations of NFRPCs. Recently, Vigneshwaran et al. [15], Zhang et al. [19] and Prabhakar et al. [20] reported novel strategies to improve the thermal stability and fire resistance of NFRPCs via chemical treatments or treatment with coupling agents of fibers. To improve the mechanical properties of NFRPCs, it was suggested to use a compatible fiber/matrix system, optimum weaving pattern, high aspect (length to diameter ratio), the volume fraction of the fiber [21], and low bulk factors in prepregs to avoid fiber waviness, etc., [22]. However, there is a certain limit in choosing a high fiber volume fraction based on the rule of mixtures, beyond that value, poor interfacial bonding occurs, owing to low matrix volume fraction which leads to higher percentage of voids and brittle failure of the structure [23]. Therefore, it is important to perform the microstructural studies without destroying the specimens during investigation.

In the past, several researchers [24, 25, 26] investigated the failure mechanisms of SFRPCs using non-destructive evaluation (NDE) techniques. Performing NDE techniques in understanding the failure mechanisms of NFRPCs is difficult and challenging owing to lower density of fibers, which are closer to the density of polymers [27, 28]. Moreover, NFRPCs are susceptible to defect formation during manufacturing and machining, owing to high surface roughness and lower failure strain compared to SFRPCs [29, 30]. For example, delamination is the commonly occurred failure while drilling composites [31], it increases with the increase of feed rate while it decreases with the increase of speed and point angle [32]. Nasaar et al. [33] reported that various delamination parameters of NFRPCs can be measured using NDE techniques.

In conventional composite manufacturing techniques, there is a large tendency to form voids through the hand lay-up technique followed by the compression molding technique, however, the possibility of voids through the filament winding technique would be lower. However, identifying the optimum fiber roving angle is essential in the filament winding technique to minimize the voids. Therefore, it is essential to investigate the NFRPCs using NDE techniques to control the quality and to fully access the structural integrity [34].

There are certain limitations of NDE techniques, such as several artifacts can be occurred during data acquisition using NDE techniques, therefore, several filters and algorithms have to be used to enhance the quality of obtained data [35]. Also, the data of most NDE techniques are huge (several gigabytes) [36, 37], and contain several thousands of images to process [35, 37, 38]. Artificial intelligence (AI) technology can be used to improve the processing of NDE images. The automated defect classification is possible using machine and deep learning algorithms, which minimizes the size of the data and reduces the post-processing time [39, 40]. Caglar et al. [41] reported that the computational time for permeability predictions of fibrous microstructures was reduced to less than 10 seconds through the deep learning convolutional neural network algorithms, from several 1000 seconds of their counterparts through 3D flow simulations.

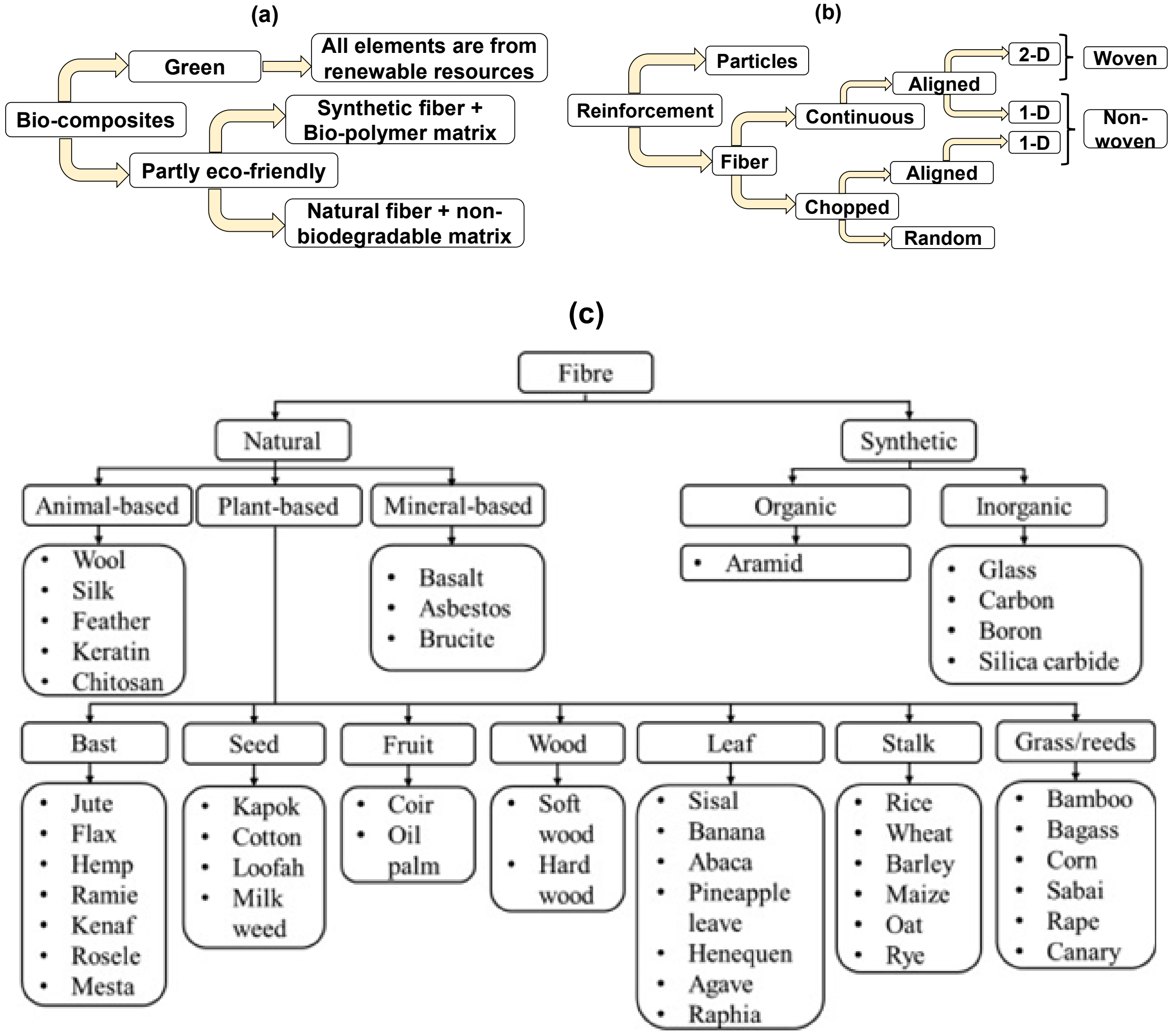
Modeling and simulation of NFRPCs are useful to minimize the number of experiments and labor costs and to enhance the product quality and performance of composites [42, 43, 44]. NDE techniques are useful to provide the input data for modeling and simulation of NFRPCs [45]. Moreover, the digital twins of NFRPCs manufactured through modern manufacturing techniques can be generated with the help of NDE techniques [35, 46] and used to validate the experimental results [47]. Strohrmann and Hejek et al. [48] validated the finite element analysis (FEA) results of tensile properties of LINEO FlaxPreg T-UD 110 with digital image correlation and found good agreement. Joffre et al. [45] validated the FEA results of moisture induced swelling (relative humidity of 80%) properties of wood fiber with the X-ray computed tomography results and found excellent agreement.

In this review article, the classification of biocomposites, manufacturing of natural and synthetic fiber, and their recyclability have been discussed. Next, several conventional and modern manufacturing techniques are described. Further, the use of different types of contact and non-contact NDE techniques in understanding the microstructural variations during manufacturing, machining and testing of NFRPCs are discussed in detail. The comparison of NDE-aided geometrical models data with the numerical simulation (finite element analysis and computational fluid dynamics) results of NFRPCs are presented. Also, the importance of artificial intelligence (AI) technology in enhancing the quality of NDE images and minimizing the analysis time, is discussed. In the literature, there is no such review available that discusses in detail the application of NDE techniques and Artificial intelligence technology in NFRPCs. Therefore, new research directions in the field of NFRPCs related to Industry 4.0 which include AM, robotics, big data, the internet of things, AI, etc., can be identified through this review article. These details are essential to utilize currently available new technologies for designing and manufacturing high-quality and eco-friendly structural components.

2. Biocomposites:

In a composite material if one constituent (fiber or matrix) is bio-based then it is called as bio-composites [2]. Biocomposites can be divided into two groups, as shown in Fig. 1(a). (i) Green composites, in which both fiber and matrix are biodegradable [49] and (ii) Partly eco-friendly, in which either fiber or matrix would be bio-degradable. Partly eco-friendly composites are classified into two groups. (i) Natural fibers (flax, hemp, ramie, pineapple, banana, etc.) reinforced with petroleum based non-biodegradable polymers (epoxy, polyester, vinyl ester, etc.) and (ii) synthetic fibers (aramid, carbon, glass, etc.) reinforced with biodegradable polymers (polylactic acid (PLA), Polyhydroxybutyrate (PHB), polycaprolactone (PCL), poly butylene succinate (PBS), etc.) [50].

The classifications of synthetic and natural fiber composites are shown in Fig. 1(c). Natural fibers can be classified into three groups, based on animal, plant and mineral fibers [51]. Fig. 1(c) shows the sub-classifications of these three groups. These fibers are reinforced with thermoset and thermoplastic polymers [21]. Recently, several plant and animal fibers inspired structures are manufactured for various applications, e.g: bamboo-inspired structures are used for leg applications, as shown in Fig. 1(d). The plant fibers consist of cellulose, hemicellulose, lignin and pectin [52]. The chemical structure of plant fiber constituents is shown in Fig. 1(e) [53]. The degradation temperature range of cellulose, hemicellulose and lignin is approximately between 260ºC to 350ºC, 200ºC to 260ºC and 160ºC to 400ºC, respectively [54]. Hence, lignin has a higher degradation temperature compared to cellulose and hemicellulose [55], therefore, it can be used as a filler along with flame retardants for enhancing the thermal stability of NFRPCs [56]. The glass transition temperature and viscoelastic properties of NFRPCs can be studied as a function of temperature and frequency using a dynamic mechanical analyzer [57], and the thermal stability of NFRPCs can be studied using a thermogravimetric analyzer [58].



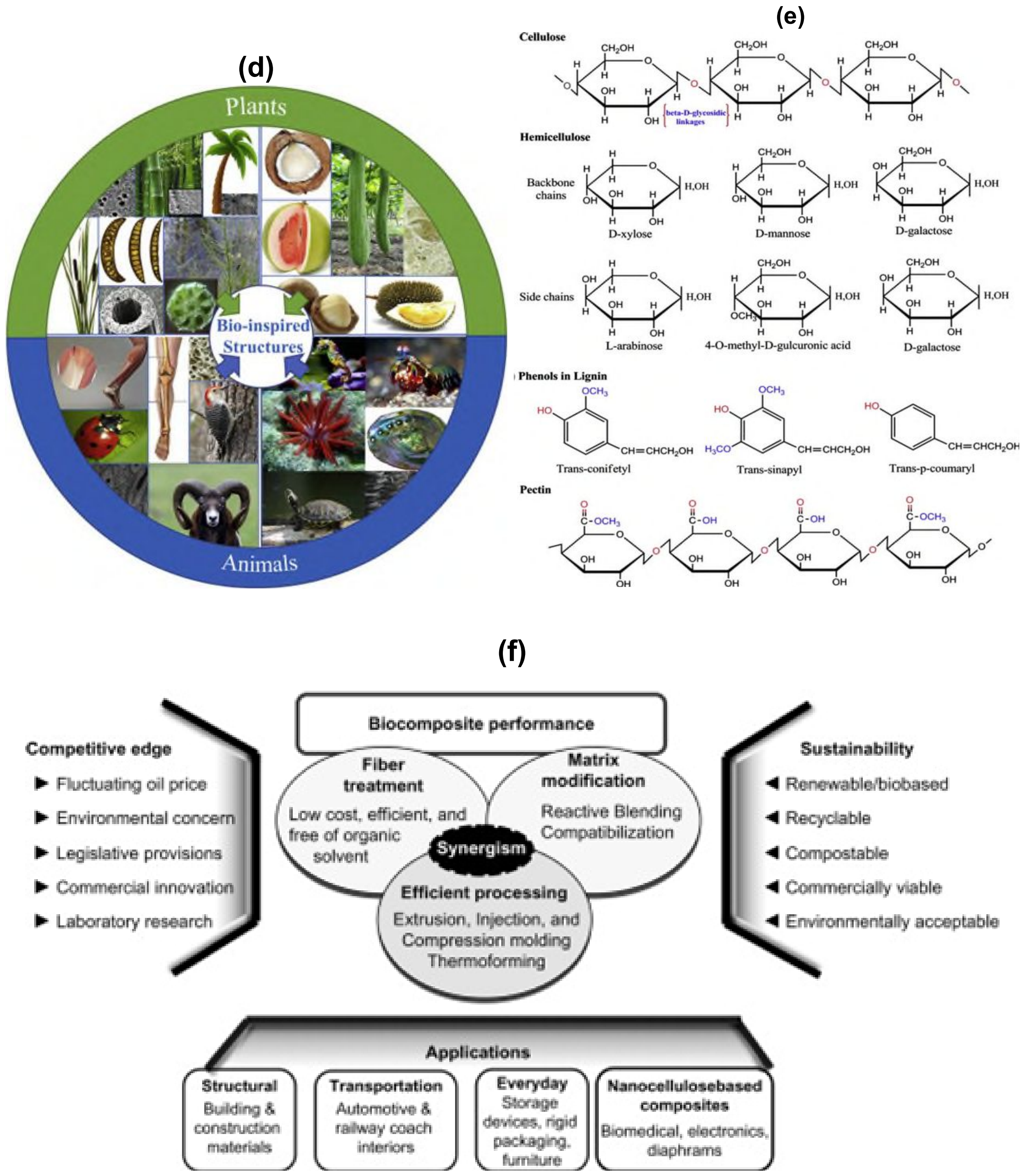


Fig. 1 Classifications of biocomposites (a) and classification of reinforcement in NFRPCs based on its dimensions (b) Adapted from MDPI [59], Copyright MDPI 2018; classifications of natural and synthetic fibers (c) Adapted with permission from Elsevier [60], Copyright Elsevier 2021; bio-inspired structures from plant and animal fibers (d) Adapted with permission from Elsevier [61], Copyright Elsevier 2020; chemical structure of plant fiber constituents (e) Adapted with permission from Elsevier [53], Copyright

Elsevier 2015; Performance and Applications of biocomposites (f) Adapted with permission from Elsevier [62], Copyright Elsevier 2015.

The bio-based biodegradable polymers are manufactured from renewable sources, which require lower Energy and produce low carbon emissions compared to petrobased non-biodegradable polymers [63, 64]. Therefore, these polymers are being increasingly considered in many medical and engineering fields [65, 66]. Recently, several researchers using bio-degradable polymers for reinforcing fibers, in that PLA is a promising thermoplastic bio-polymer, it is extracted from renewable resources, such as corn, sugar beets, etc., [67]. More details about PLA based NFRPCs can be found in recent papers [56, 68].

2.1 Comparison of natural and synthetic fibers:

Fig. 2(a) and (b) show the comparison of cost per weight, density, environmental compatibility and work safety of natural and synthetic fibers. From these figures, it is observed that natural fibers are cheaper and safer to handle than synthetic fibers. In addition, the density of natural fibers and NFRPCs is lower than E-glass fiber and its composites [2, 69]. Therefore, these materials can be used for numerous applications [70, 71], as shown in Fig. 2(c).

Basalt fiber is a promising fiber among the other natural fibers that possess superior physical and mechanical properties [72]. Basalt fiber is a natural rock fiber, it has higher aluminum oxide and iron oxide content compared to E-glass fiber [73]. As a result, the former has greater chemical degradation resistance and superior mechanical, thermal, impact and vibrational properties compared to the latter [74, 75]. Moreover, the cost of basalt fiber is several times lower and %elongation and impact resistance are higher than that of carbon fiber [76]. Therefore, basalt fiber bridges the gap between E-glass fiber and carbon fiber, and potential to replace E-glass fiber in almost all aerospace, automotive and marine structural applications [72, 76]. However, the density and cost of flax fiber are lower than the basalt fiber [77], even though the mechanical performance of basalt fiber is superior to that of flax [78]. Therefore, recently, several other researchers performed life cycle assessments on the production and transportation of flax fiber, and reported that flax fiber is the emerging and potential material to replace E-glass fiber in the automotive and aerospace sectors [79].

In general, many other natural fibers possess lower physical and mechanical properties compared to synthetic fibers. Moreover, the natural fibers are easily aged compared to synthetic fibers, when exposed to environmental effects such as moisture and ultraviolet (UV) absorption, temperature and other climate effects, etc., which affect the durability and life span of natural fibers [72, 80]. Therefore, to improve the low desirable properties of both natural and synthetic fibers, the hybridization approach can be used by stacking both the fibers in a polymer matrix [70] or by adding nanofillers in the NFRPCs [74, 76]. The mechanical properties of natural fiber reinforced polymer nanocomposites are higher than GFRP and almost closer to CFRP, as shown in Fig. 2(d). In particular, graphene-oxide, carbon nanotubes, polyethylene terephthalate char and MMT clay are compatible with polymer matrices [81, 82, 83, 84]. These nanofillers can be added in NFRPCs to enhance mechanical and thermal performance. More details about this hybridization approach on various physical and mechanical properties of NFRPCs and SFRPCs are discussed elaborately in recent articles by Gupta et al. [85] and Vigneshwaran et al. [15]. In that way also, natural fibers are playing a vital role in reducing global warming by decreasing the non-biodegradability of synthetic fibers and polymers.

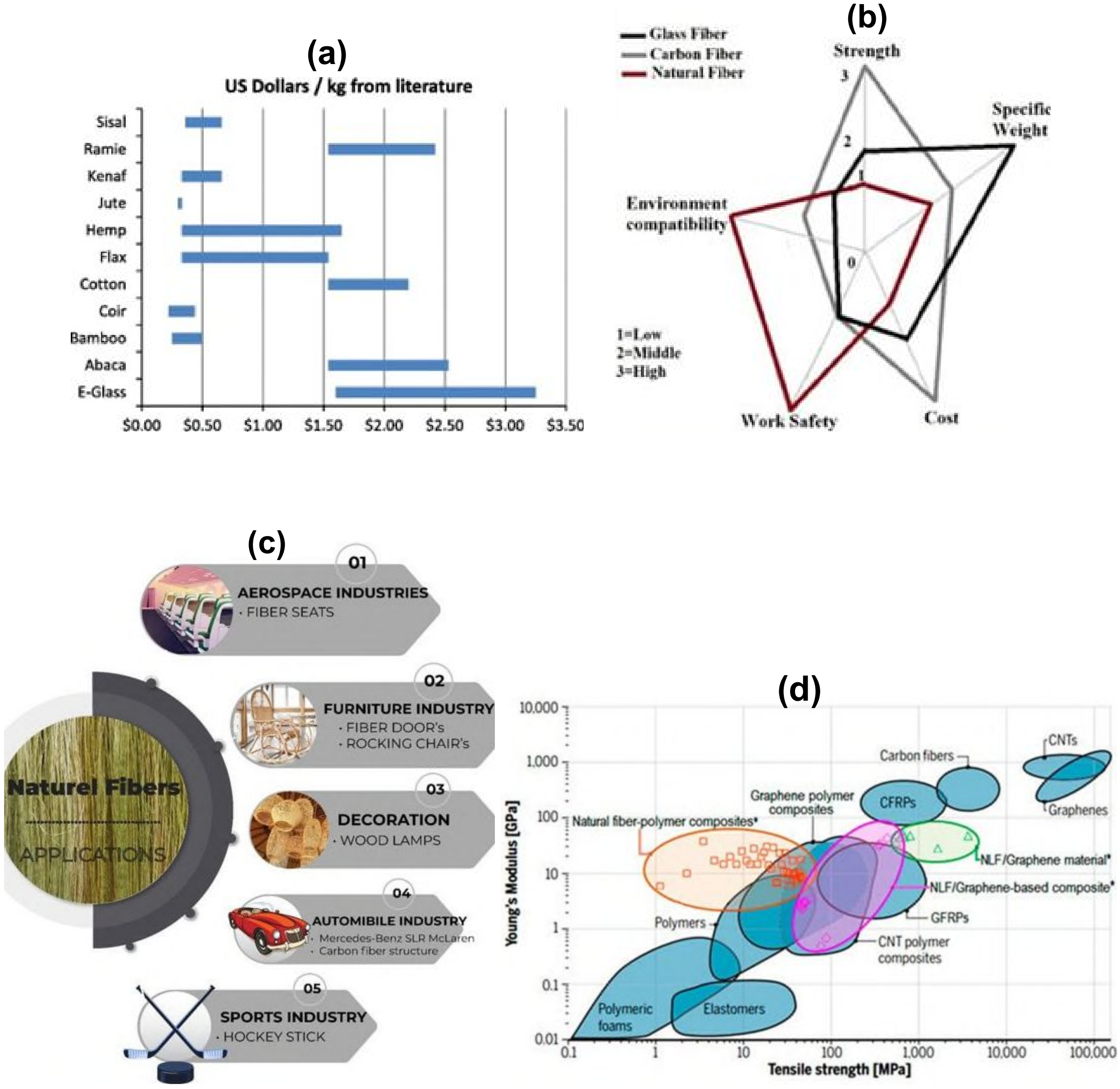


Fig. 2 Comparison of cost per weight, density, environmental compatibility and work safety of natural and synthetic fibers (a, b) Adapted with permission from [86, 87], Copyright Elsevier 2012, Copyright MDPI 2021; Applications of natural fibers and their composites (c) Adapted from MDPI [88], Copyright MDPI 2021; Comparison of mechanical properties of natural and synthetic fibers and their composites (d) Adapted from MDPI [89], Copyright MDPI 2020.

2.2 Recycling and surface treatment of biocomposites

The polymer matrix can be divided into petrobased (non-biodegradable and biodegradable) and biobased (non-biodegradable and biodegradable), as shown in Fig. 3(a). Comparison of the mechanical properties of these polymers is shown in Fig. 3(b). The thermoset polymers (epoxy, polyester, vinyl ester, etc.,) are non-biodegradable whereas several thermoplastic polymers are biodegradable. From Fig. 3(b), it is observed that the elongation at break (%) of thermoset polymers is lower and Young's modulus is higher compared to most thermoplastic polymers. Among the biodegradable polymers, PLA and PHB have higher Young's modulus and lower elongation at break (%) compared to PBS and PCL. The energy requirement and CO_2 emission are lower with biobased polymers compared to petrobased thermoplastic polymers, as shown in Fig. 3(c).

Recyclability is possible with wood and non-wood natural fiber reinforced thermoplastic polymer composites [90, 91, 92], as shown in Fig. 3(d). This is one of the advantages of using thermoplastic polymers over thermoset polymers. Recently, Manral et al. [21] reported in detail about the processing of natural fiber reinforced thermoplastic polymer composites. Biocomposites can be recycled approximately four to six times until their mechanical properties decrease. The decrease in mechanical properties upon recycling is due to polymer degradation, fiber shortening, decrease in viscosity, poor fiber-matrix adhesion, etc., [93]. Choosing appropriate fiber and matrix materials is necessary to maintain or enhance the mechanical properties of these composites after several reprocessing cycles. It was reported recently [94, 95] that coriander straw fiber and polypropylene (PP) and high density polyethylene (HDPE) matrices are the best materials to maintain the mechanical performance for several reprocessing cycles. Through the chemical treatment of fibers or by adding coupling agents in NFRPCs, the mechanical performance of NFRPCs increases after multiple reprocessing cycles, which resolve the compatibility issues between fiber and matrix [96]. There are different types of chemical treatment (Sodium hydroxide, Acetic acid, Silane, Benzoyl peroxide, Potassium permanganate, Stearic acid, Cellulose powder, etc.) and surface treatment (plasma, vacuum ultraviolet irradiation, ozone, corona, γ –Ray and laser) methods of natural fibers are available [96, 97]. In general, lignin, pectin, waxy substances, and natural oils are covering the external surfaces of natural plant fiber cell walls, these can be removed through the chemical treatment of fibers. Sodium hydroxide (NaOH) is being widely used chemical treatment to bleach or clean the plant fiber surface [98, 99]. Also, through the process of alkalization, the NaOH reacts with cellulose for changing the fine structure of the native cellulose I to cellulose II. As a result, the surface roughness of the fiber is enhanced, i.e., this network of fibrils exhibits a greater surface area than regular cellulose fibers [100]. Moreover, to increase the adhesion between the natural fibers and the polymer matrix, silane and alkali treatments can be used. These treatments reduce the hydroxyl (OH) functional groups present on the fiber surface, as shown in Fig. 3(e). Therefore, incompatibility issues between fiber and matrix can be resolved and the void content can be reduced [101, 102]. Further details about different chemical treatments used to treat different types of natural fibers are elaborately reported in a recent review article by Ighalo et al. [103].

Surface treatment of fibers helped to improve the mechanical properties [99]. For example, the flexural strength and modulus of Sugarcane bagasse/PP composites increased by 4 and 14%, respectively, after surface treatment of Sugarcane bagasse fiber with the combination of NaOH and silane. The failure strain of hemp/PP composites increases (22%) after six cycles, by adding maleic anhydride grafted polypropylene (MAPP). Similarly, the flexural modulus of Kenaf/PP composites increases (20%) after two cycles, by adding MAPP in it [92]. More details about challenges and opportunities in the recycling of NFRPCs are discussed recently by Zhao et al. [93].

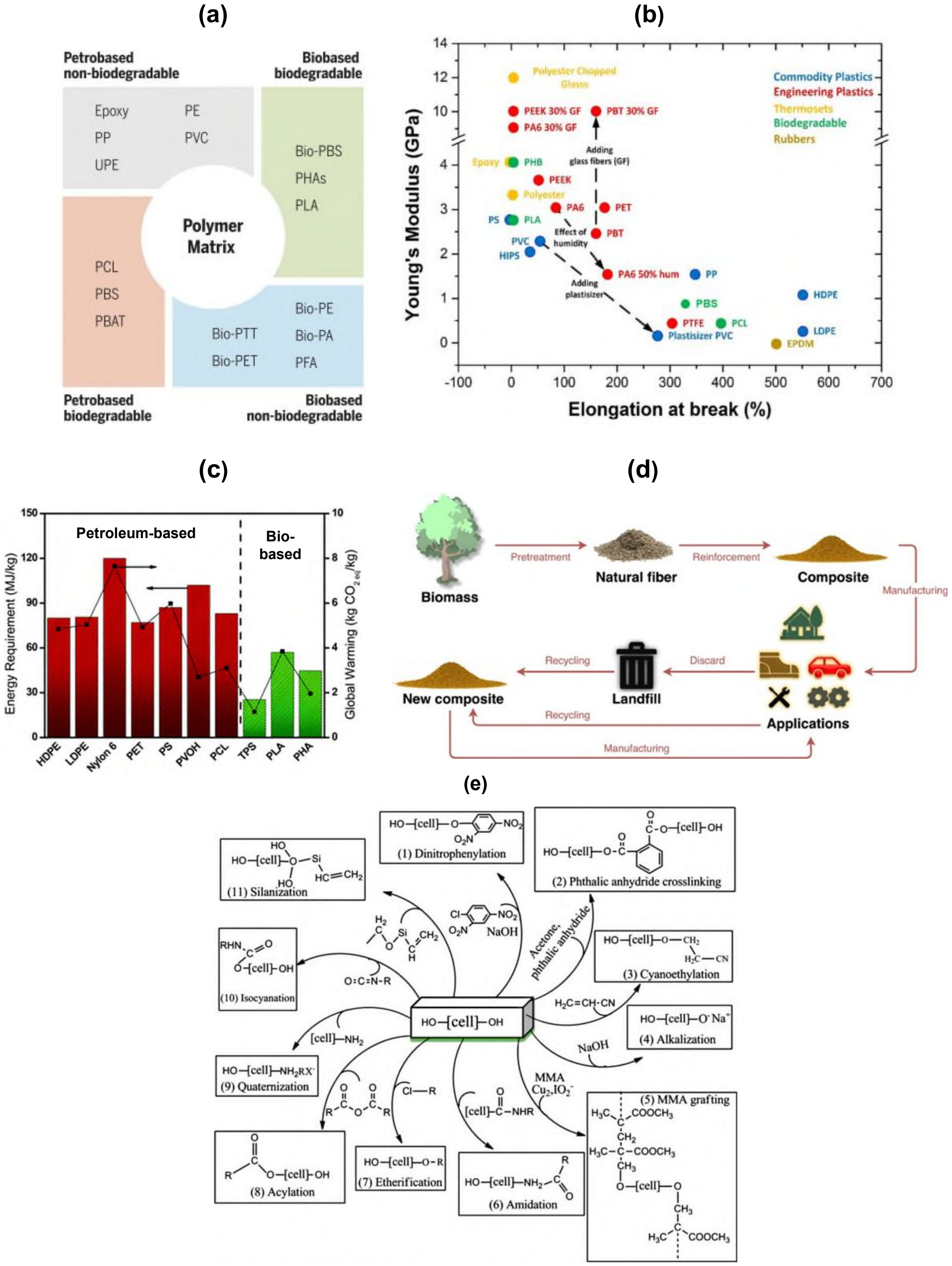


Fig. 3 Different types of petro- and bio-based polymers (a) Adapted from Science [104], Copyright Science 2018, Young's modulus and Elongation at break (%) of different polymers (b) Adapted from MDPI [105], Copyright MDPI 2015; comparison of Energy requirement and carbon emission of petro- and bio-based polymers (c) Adapted from RSC [63], Copyright RSC 2020; recycling of NFRPCs (d) Adapted with

permission from Elsevier [93], Copyright Elsevier 2022; and chemical treatment of natural fibers (e) Adapted with permission from Elsevier [53], Copyright Elsevier 2015.

3. Processing and Mechanical Performance of NFRPCs

The mechanical performance of NFRPCs depends on many parameters such as raw materials, manufacturing techniques and cure cycle process parameters, etc. Choosing raw materials (fiber and matrix) and their properties for a particular application is the essential first step in the processing of NFRPCs [23]. The second step in the processing of NFRPCs is choosing the manufacturing technique. The third step is choosing appropriate cure cycle parameters, e.g., degree of cure, pressure, temperature, etc.

There are several manufacturing techniques available for the fabrication of NFRPCs based on the size and shape of the component, which can be categorized as conventional and modern manufacturing techniques. There are several conventional techniques (hand-lay-up followed by autoclave or out-of-autoclave) [106, 107] which have been used from several decades in fabricating NFRPCs. However, in recent years, modern manufacturing techniques such as automated fiber placement (AFP) and automated tape lay-up (ATL) followed by autoclave or out of autoclave [35, 108], additive manufacturing (AM), etc. [109] have been increasingly used. The component can be fabricated based on the shape of the mold in conventional manufacturing techniques. However, mold is not required in modern manufacturing techniques, these are computer-aided intelligent manufacturing techniques [110]. here, based on the dimensions of the 3D solid model (.standard file format (.STL) file), the component can be printed [111].

3.1. Conventional manufacturing techniques

There are two types of conventional manufacturing techniques, namely out-of-autoclave (OoA) and autoclave techniques [112]. OoA technique can be classified as hand lay-up, spray lay-up, filament winding (FW), compression molding (CM), injection molding (IM), liquid molding (resin infusion (RI) or vacuum assisted resin infusion (VARI) and resin transfer molding (RTM)), vacuum bag only (VBO) prepregs process, pultrusion, etc., [2]. Pultruded products have high stiffness and high fiber volume fraction (closer to 70%) compared to other OoA techniques [113]. In the OoA technique, the first two techniques are open molding processes while the remaining techniques are closed molding processes. The cost of these OoA techniques is relatively cheaper than the autoclave technique. The higher cost and energy required for processing (~21.9 MJ/kg) and size restrictions of the component are the major drawback of the autoclave technique, even though the lowest void content can be obtained [7]. In these conventional manufacturing techniques (OoA and autoclave techniques), the hand-lay-up process is used for stacking the fabric layers with the resin. Further, the manufacturer's recommended cure cycle can be used in curing the samples using either any of the OoA techniques or the autoclave technique [35]. Moreover, the mechanical performance of components fabricated using these techniques rely on post-cure time. Table 1 shows the main process parameters which control the void content in components manufactured using conventional techniques.

Table 1 Main process parameters and applications of conventional techniques

Conventional manufacturing techniques	Main process parameters	Energy (MJ/kg)	Applications	References
Hand layup	Applied pressure, curing time, post-curing temperature and time, etc.	-	All thermoset and thermoplastic	[114]

Spray layup	Spray gun pressure, the mixing ratios of fiber and resin, etc.	15	Chopped strand mat and short fiber reinforced thermoset	[7, 115]
FM	Winding angle, revolution per minute of the mandrel, etc.	3	Thermoset pipes, tubes, shafts, etc.	[74, 76, 116]
CM	Pressure, isothermal dwell temperature, dwell period, etc.	-	Small size thermoset and thermoplastic.	[8, 117, 118, 119]
IM	Injection speed and pressure, temperature, holding pressure, etc.	-	Short fiber reinforced thermoplastic	[21]
RI and VBO prepreg processes	Vacuum pressure, debulking time, dwell temperature and dwell period, etc.	10	Large size thermoset and thermoplastic	[120, 121, 122].
RTM	Pressure, temperature, etc.	15	Small size thermoset	[17, 115]
Pultrusion	Pressure, pull speed, temperature, etc.	3.1	Large size thermoset and thermoplastic	[7, 123, 124]
Autoclave	Pressure, temperature, dwell period, etc.	21.9	Small size thermoset and thermoplastic	[35, 121]

3.2. Modern manufacturing techniques:

Automated or modern manufacturing techniques can be classified as automatic fiber placement (AFP), automatic tape lay-up (ATL) and tailored fiber placement (TFP), additive manufacturing (AM), etc., [108]. More complex geometrical components can be fabricated using these techniques without the requirement of mold, which is the major advantage of these techniques over conventional manufacturing techniques [125, 126]. Chansoda et al. [127] compared the tensile properties of wood-based PLA manufactured using compression molding and AM techniques, and found that the tensile strength values of AM manufactured components are higher, while the compression molded components exhibited higher elongation at break (%) values. Numerous studies related to manufacturing and property characterization of NFRPCs are available with AM techniques [11, 128, 129, 130, 131] and, limited studies have been found with AFP related to NFRPCs [132, 133, 134]. Different advantages and limitations of the AFP technique over conventional techniques are shown in Fig. 4.

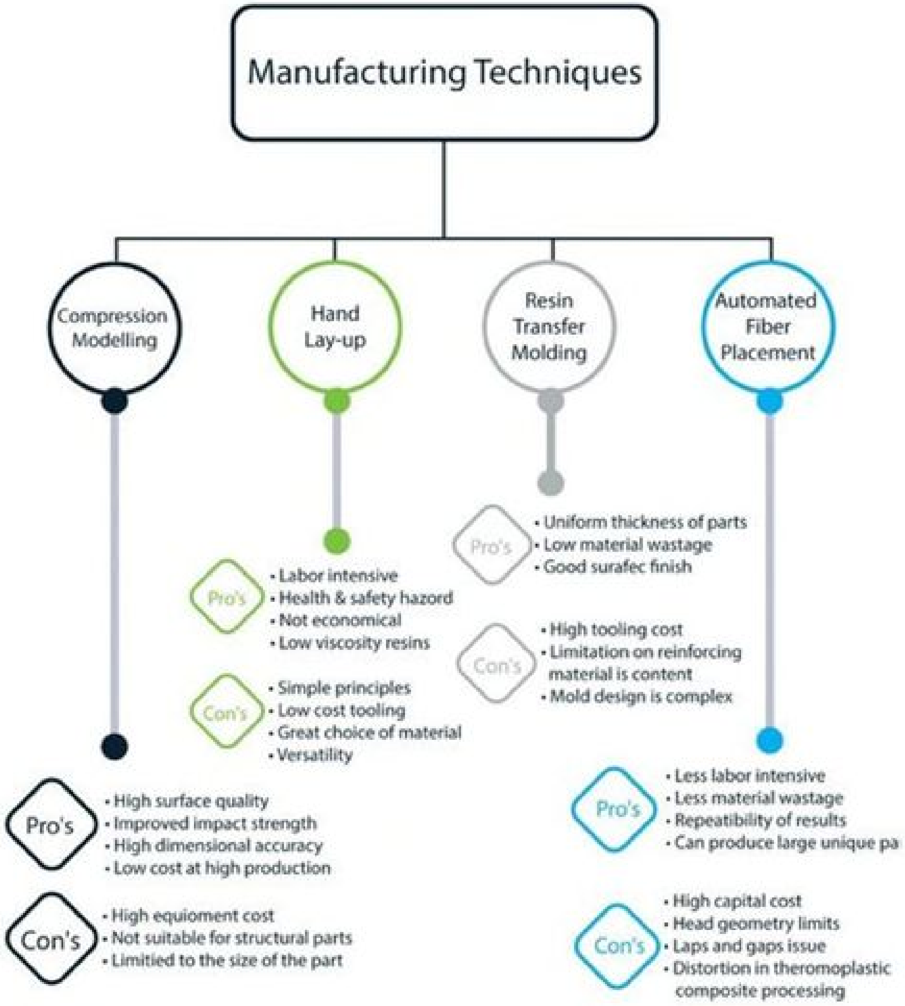


Fig. 4 Comparison of conventional techniques with AFP technique. Adapted from MDPI [88]. Copyright MDPI 2021.

3.2.1 AFP and ATL techniques

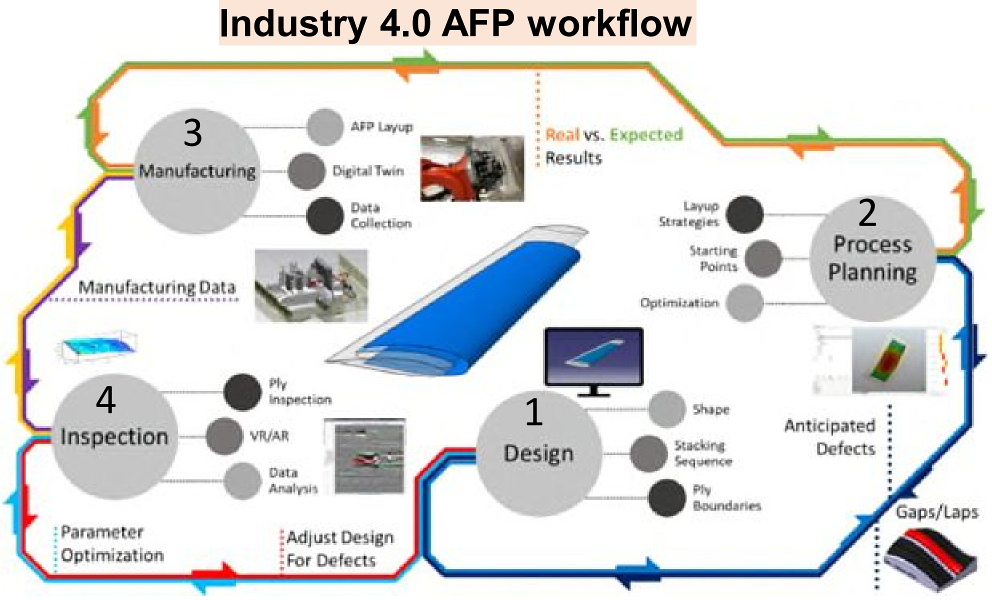
AFP and ATL techniques operate with the help of standard industrial robots [135]. The number of publications related to AFP and ATL is limited until 2010. However, Lukaszewicz et al. [108] and Kim et al. [136] reported about AFP and ATL techniques, after that, these techniques are growing enormously. The application of ATL is different from AFP. The former is mainly useful for flat surfaces with small curvature while laying defects (tape folds or tears) can occur when dealing with complex surfaces with high curvature [137]. Therefore, compared to the ATL technique, AFP provides better structural performance in manufacturing concave or double curvature and variable angle tow laminates with curvilinear fiber paths, owing to the multiple degrees of freedom of its fiber placement head [138]. More importantly, almost all AFP systems can deposit composites approximately at the rate of 6000 cm/min, however, even these can go up to 7500 cm/min, by optimizing the process parameters [87]. Because of these many merits, AFP is being widely used in fabricating numerous large spacecraft structural applications, such as satellites, solid rockets, etc., [139], in addition to primary aircraft structural applications, such as wing, fuselage, etc., [35].

3.2.2 Working principle of AFP

Fiber sliding and fiber bridging are the major problems associated with the conventional filament winding technique, owing to manually operating and changing the fiber orientation angles by humans [140, 141]. These problems can be overcome with the AFP. Fig. 5(a and b) shows the Industry 4.0 stepwise workflow to anticipate defects in AFP manufactured composites, which include mold design, process planning, manufacturing, and inspection based on CAD (computer-aided design)/CAM (computer-aided manufacturing). Mold design includes creating the drawing using CAD software and then importing the file into AFP software [142]. Process planning includes placement path planning and post-processing, in this stage, layup strategies, desired fiber orientation paths and optimizing the position and attitude of the AFP head can be carried out for checking each axis and outputting the motion control file. Further, the AFP head follows the motion paths through the motion simulation software. The motion simulation software reduces material wastage by adjusting the parameters at the right time and continuously optimizes the AFP head paths [143]. The key advantage of running the simulation virtually is to ensure there is no collision or damage to the AFP head and tooling, which could be detrimental.

In general, consolidation of composites using AFP or ATL alone would not provide better results. Instead of that, these techniques can be used only for laying the fibers and then consolidation of composites can be performed using the autoclave or OoA techniques for obtaining better performance. Christophe et al. [133] reported that NFRPCs can be fabricated using the AFP technique. However, the low void content and high fiber volume fraction were obtained using AFP followed by compression molding technique (Fig. 5(d)) as compared to AFP alone (Fig. 5(c)). Sanandiya et al. [134] fabricated a large-scale wind turbine blade made up of fungal-like adhesive material using infused AFP and AM techniques, as shown in Fig. 5(e).

(a)



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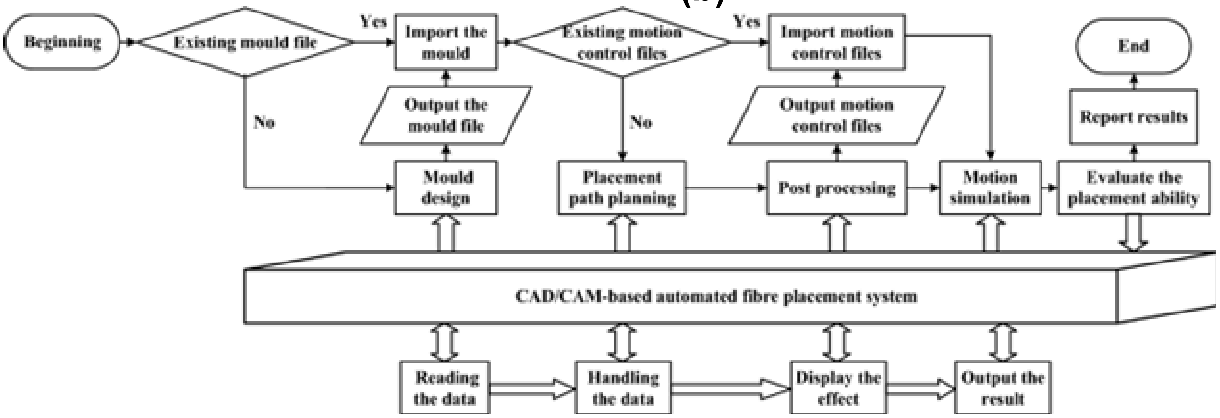


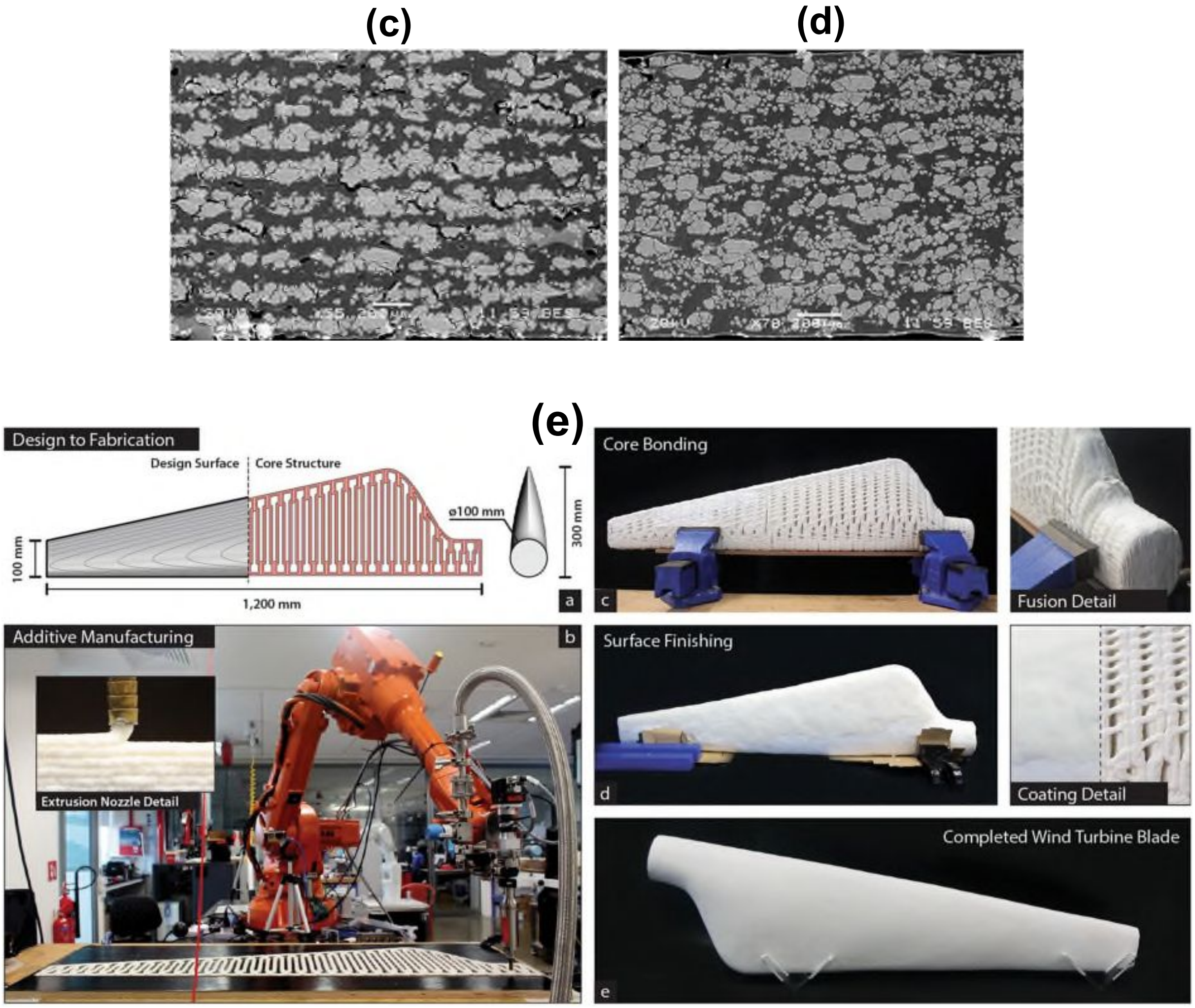


Fig. 5 Working principle of AFP manufactured composites based on CAD/CAM (a) Adapted with permission from Elsevier [144], Copyright Elsevier 2021 and Adapted from Springer [137] (b); Flax/PP composites manufactured using AFP (c) and AFP + Compression molding (d) Adapted from Elsevier [133], Copyright Elsevier 2016; Large scale wind turbine biocomposite blade made up of fungal-like adhesive material(s) (FLAM) using AFP (e) Adapted from Scientific reports [134], Copyright Scientific reports 2018.

3.2.3 Additive Manufacturing techniques

Different types of AM techniques, such as fused deposition modeling (FDM) or fused filament fabrication (FFF), stereolithography (SLA), digital light processing (DLP), two-photon polymerization (TPP), powder bed fusion (PBF), selective laser melting (SLM), binder jetting (BJ), selective laser sintering (SLS), laminated object manufacturing (LOM), sheet lamination

(SL), material jetting (ML), liquid deposition modeling (LDM), etc., [145, 146], are shown in Fig. 6(i)(a) and (b). These techniques fabricate the component based on the dimensions of the 3D solid model (.standard file format (.STL) file [11, 147]. FDM is suitable for thermoplastic composites while photo-curing AM techniques (SLA, TPP, direct ink writing, etc.) can be used in UV-curable thermosets. Also, the accuracy and resolution of photo-curing techniques are higher and mechanical properties are lower compared to FDM [148]. The working principle, advantages and disadvantages of these different types of AM techniques are reported in detail [11, 149]. Different types of fibers and matrix materials are suitable to use in different AM techniques for various applications, which are reported in detail by Fidan et al. [150]. AM market has been growing continuously in the past decades and has reached 21 billion U.S. dollars in 2021, as shown in Fig. 6(i)(c).

(a)

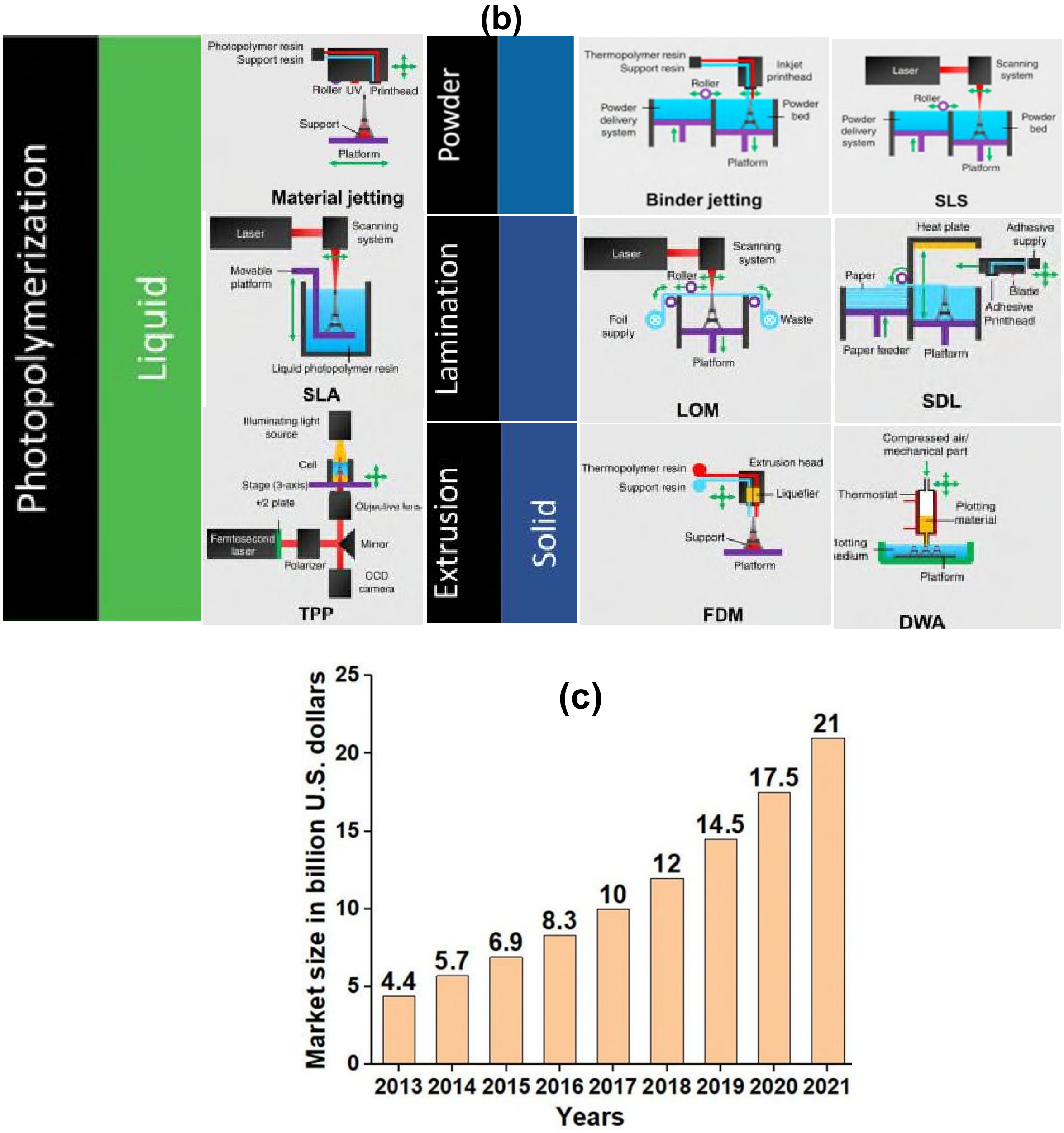
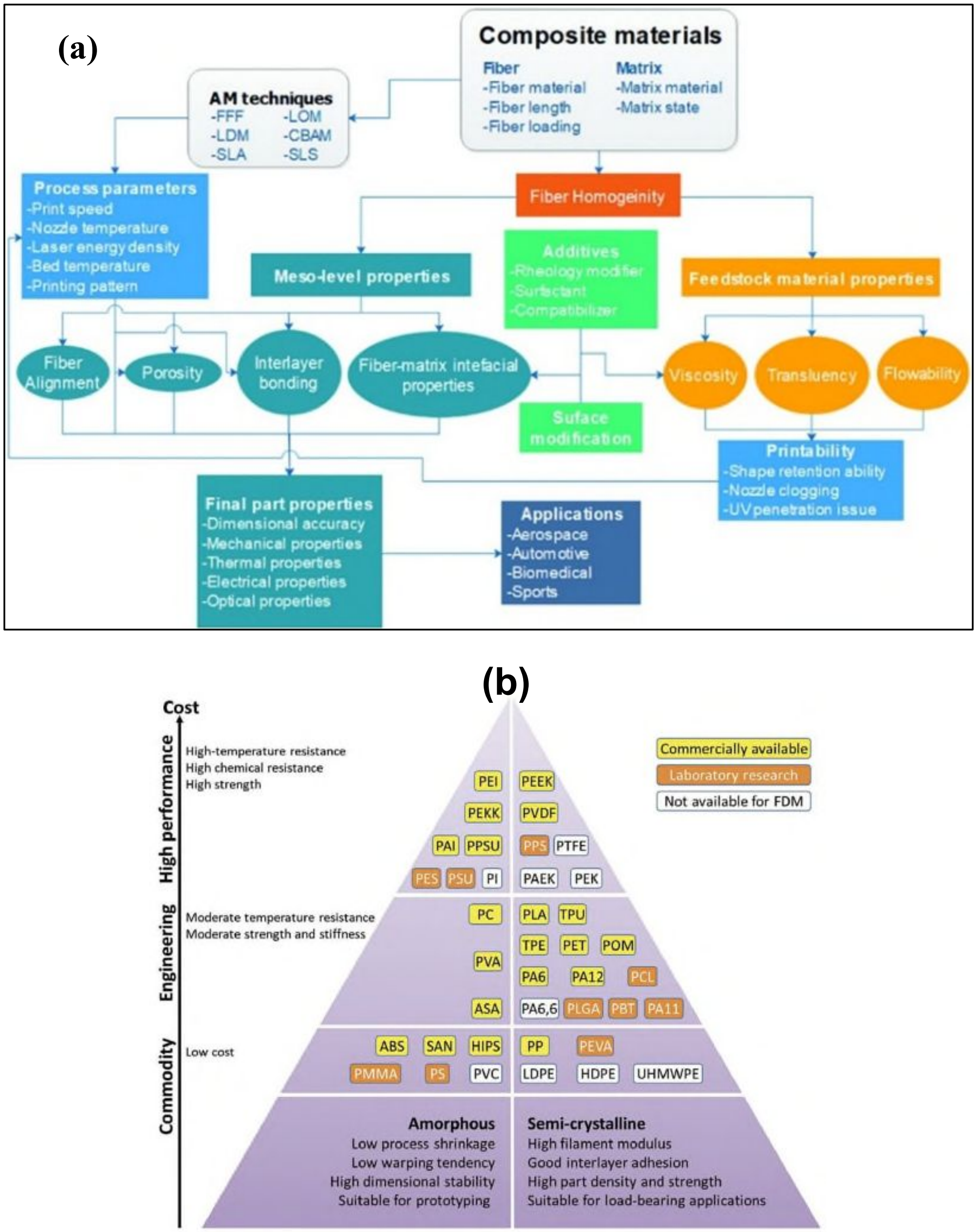


Fig. 6(i) Applications and types of AM techniques (a, b) Adopted from [151, 152]; AM Market size (c) Adopted from MDPI [153], Copyright MDPI 2022.

3.2.4 Processing parameters in modern manufacturing techniques

Modern manufacturing techniques contain higher processing parameters compared to conventional manufacturing techniques [35, 154]. For example, in AFP and ATL techniques, the processing parameters include but are not limited to temperature, compaction force or pressure, fiber placement head, lay-up speed, etc., [155, 156]. The process parameters in AM techniques include but are not limited to print speed, nozzle and bed temperature, printing pattern, build orientation that includes flat, on-edge and upright, etc., [149, 157], as shown in Fig. 6(ii) (a). Optimizing these process parameters are time-consuming, moreover, the quality of the final product relies not only on printing parameters but also on factors related to preparatory parameters and machining [158, 159]. As a result, the possibility of defects owing to these several process parameters is high in additive manufacturing techniques [160]. Moreover, owing to the layer-by-layer printing process, the possibility of forming voids is higher in AM techniques [125, 161]. Further challenges (thermal degradation, water or moisture absorption, distribution of fibers in the resin, fiber breakage, uneven surface finish, etc.) associated during and post-manufacturing of NFRPCs using AM techniques are reported in recent articles [11, 111, 162]. These all are the main reasons for the limited studies available in fabricating of NFRPCs. Among the various AM techniques, the FDM technique is one of the most widely used techniques in fabricating NFRPCs in literature [130]. This is owing to low cost, easy operating procedure and low material wastage and shortening the design-manufacturing time [163]. However, the cost and operating procedure of FDM printed components rely on the type of thermoplastic polymer used for fabrication [147]. Different types of thermoplastic polymers can be used in FDM based on the application of the component, as shown in Fig. 6(ii)(b). However, still, several challenges are existing in the processing and development of high-temperature polymer feedstocks for FDM [125].

On the other hand, the processing of natural fiber reinforced thermoplastic composites using the injection molding technique is easy and the quality of the component is more reliable compared to the FDM technique [61]. Moreover, the specimen fabrication time is very less in this technique compared to the FDM technique. Therefore, the injection molding technique is the best suitable one for mass production applications [126]. However, the major drawback is the higher capital investments, which require both extruder and injection molding machines to fabricate composites, as shown in Fig. 6(ii)(c). Also, complex geometrical components are difficult to fabricate using this technique, it demands separate molds.



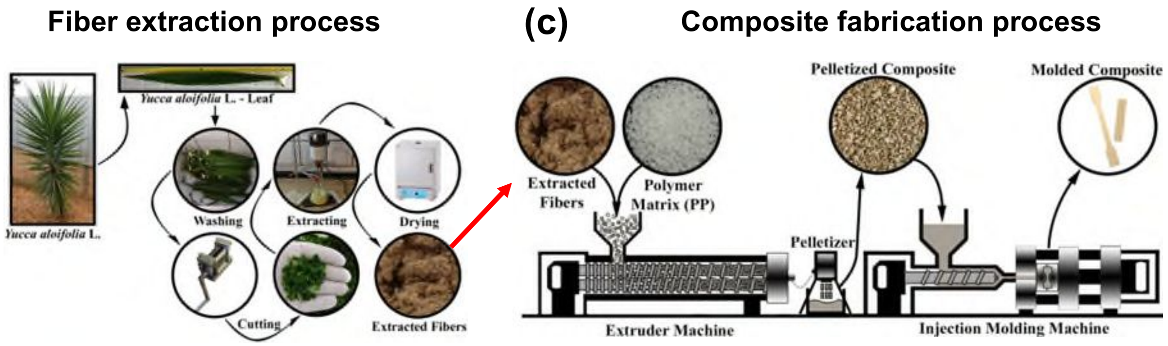
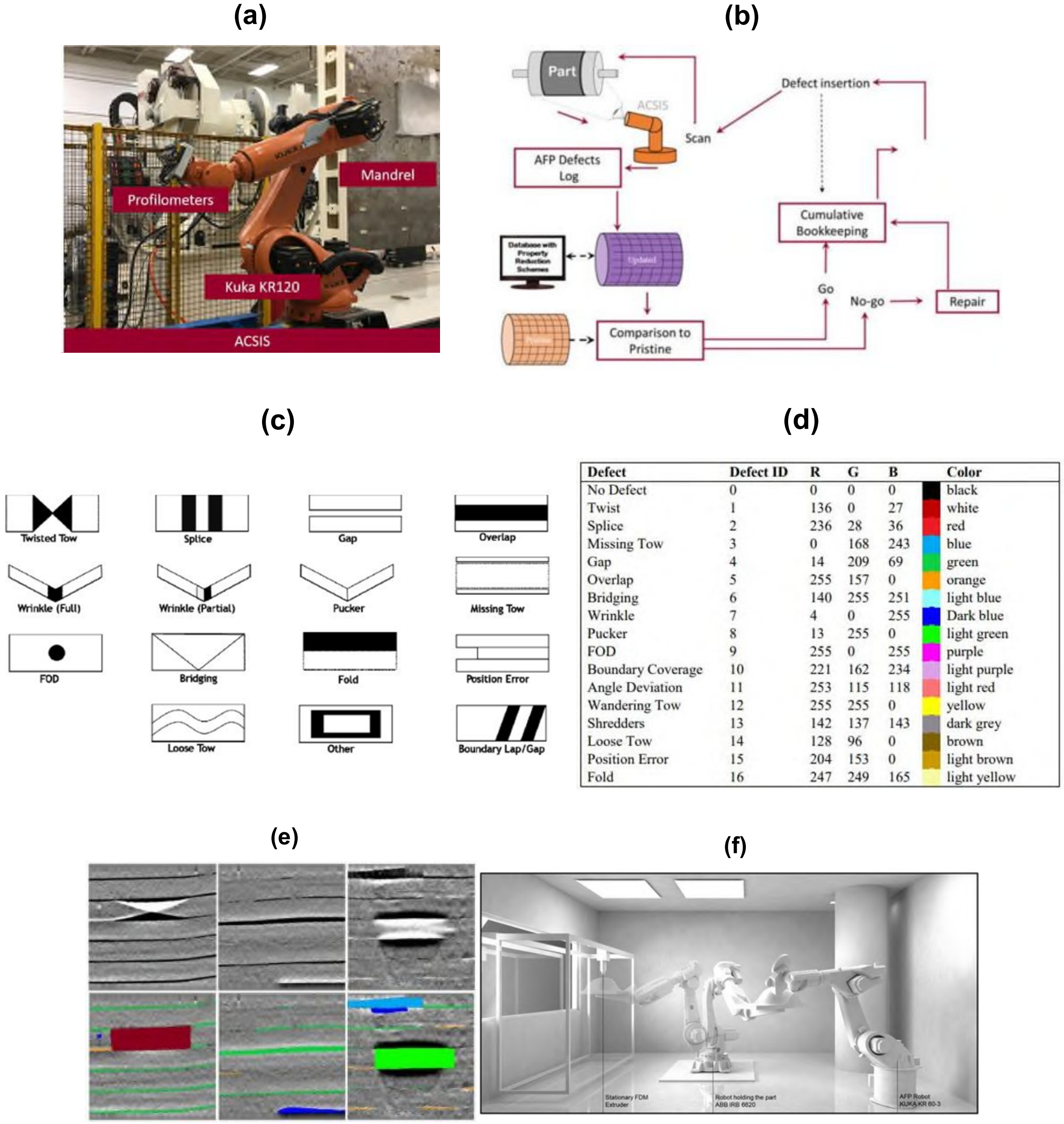


Fig. 6(ii) Process parameters of AM composite techniques (a) Adopted from MDPI [164], Copyright MDPI 2021; types of polymers available for FFF (b) Adopted from Oxford Open Materials Science [165]; Yucca aloifolia L/PP fabricated using twin-screw extruder followed by injection molding (c) Adapted with permission from Elsevier [166], Copyright Elsevier 2021.

3.2.5 Remedies to overcome the challenges of modern manufacturing techniques

The biggest challenge with modern manufacturing techniques is controlling the formation of defects during the manufacturing of NFRPCs. The remedies to control the formation of defects are: studying several process parameters and optimizing the best parameters, however, this approach is time-consuming. The other remedies are discussed below.

(i) In-situ inspection is the best possible way to control defects during the manufacturing of composites. Ingersoll Machine Tools (IMT) at the McNair Center developed the Advanced Composite Structures Inspection System (ACSIS) AFP, as shown in Fig. 7(a) [167]. ACSIS is a layer-by-layer in-situ monitoring system that consists of Kuka KR120 robotic arm with 4 laser profilometers, i.e., each layer could be scanned completely by ACSIS through the high resolution profilometer, immediately after laying down each layer by the AFP machine. After completing the scan for the first layer, the layup of a new layer can be carried out by moving the AFP mandrel back to its original position. This procedure can be continued for layup and scanning of each layer. The ability of ACSIS software is that it automatically operates the robotic arm and stores all captured images [168]. More importantly, AI-based algorithms are in-built into the software which identifies layer-wise defects, as shown in Fig. 7(b). The defects captured are initially trained to the machine learning (ML) software with different color coding, as shown in Fig. 7(c, d). Further, the defects in the composites can be detected automatically using ML methods, as shown in Fig. 7(e). Further details about the ACSIS in-situ monitoring technique are discussed in recent articles [167, 168, 169].



Defect	Defect ID	R	G	B		Color
No Defect	0	0	0	0	⬛	black
Twist	1	136	0	27	🟥	white
Splice	2	236	28	36	🟥	red
Missing Tow	3	0	168	243	🟦	blue
Gap	4	14	209	69	🟩	green
Overlap	5	255	157	0	🟧	orange
Bridging	6	140	255	251	🟦	light blue
Wrinkle	7	4	0	255	🟦	Dark blue
Pucker	8	13	255	0	🟩	light green
FOD	9	255	0	255	🟪	purple
Boundary Coverage	10	221	162	234	🟪	light purple
Angle Deviation	11	253	115	118	🟥	light red
Wandering Tow	12	255	255	0	🟨	yellow
Shredders	13	142	137	143	⬛	dark grey
Loose Tow	14	128	96	0	🟫	brown
Position Error	15	204	153	0	🟫	light brown
Fold	16	247	249	165	🟨	light yellow

Fig. 7 In-situ defect monitoring in AFP using ACSIS (a) Adapted with permission from Elsevier [167, 169], Copyright Elsevier 2020 and Adapted from NASA Technical Reports (b) [170]; training defect data in ML

(c-d) Adapted from thesis [171]; automatic defect detecting using ML methods (e) Adapted from Elsevier [144]; fusing modern manufacturing techniques (AFP and AM) (f) Adapted from Taylor & Francis [172].

(ii) The AFP manufacturing time can be reduced by optimizing the process parameters through numerical simulation tools. Several software packages are available to perform AFP numerical simulations. Vistagy Inc [173] has developed Fibre SIM software, through this material wastage can be minimized and product quality can be enhanced by optimizing placement path planning, machine parameter setting and error analysis, etc. Also, Coriolis Composites [174] has developed CAD Fibre and CAT Fibre, which consist of programming, simulation and post-processing modules of AFP. AFP simulation with CAD Fibre software works based on CATIA version 5, it can be used for designing molds and then importing the mold files into the simulation interface [175]. In addition to these, FiberGrafiX was developed by Entech [176] to perform AFP simulation in studying the various process parameters.

(iii) Integration of AFP and FDM could reduce the time consumption for optimizing the process parameters. The other advantage of this technique is that the composites can be fabricated even using FDM alone or AFP alone or combinedly (integrated approach), as shown in Fig. 7(f). This approach was employed by Raspall et al. [172], and fabricated the composites at a lower time. Also, this integrated approach was employed by few researchers to fabricate large-scale biocomposite components [175, 177]. The in-situ defect monitoring system, ACSIS can be built in this integrated technique to study the layer-wise defects, such that the manufacturing defects can be reduced [178].

(iv) Replacing the AFP technique with the tailored fiber placement (TFP) technique:

Several defects such as local fiber buckling and wrinkling, gaps and overlaps, etc., are associated during the lay-up process with the AFP (Fig. 7(d)) technique [22]. However, to replace this technique for overcoming these defects [179, 180], recently, numerous researchers have been employing the TFP technique to fabricate highly curvilinear NFRPCs parts [181, 182, 183]. TFP makes use of an embroidery machine that continuously lays the dry fiber filaments and stitches them to the textile substrate [180]. This technique works based on the desired fiber placement program generated by a CAD file, which is imported to the embroidery machine to tailor the fiber orientations. The stitch length and stitch width are the main parameters of the TFP technique [183]. The angle of fiber placement using this technique can be varied easily between 0º to 360º [182, 183]. After creating a desired structural pattern of fabric architecture through stitching and bending, based on the CAD file imported into the embroidery machine, the resin can be impregnated using the autoclave or any one of the OoA techniques [183, 184]. TFP technology has been used effectively, not only in thermoset polymer composite applications but also in thermoplastic polymer composite applications [185, 186].

TFP can be used in all manufacturing techniques of AFP could be used, with fewer defects [180, 187]. This technology is being widely used in the buckling optimization of composite cylinders with the filament winding technique [188]. Uhlig et al. [187] reported that the TFP technique is well suited for fabricating the variable axial (variable angle tow and stiffness) composites. These variable axial composites are well suited for improving the buckling and post-buckling response of composite plates [189]. Further details about these composites can be found in [180].

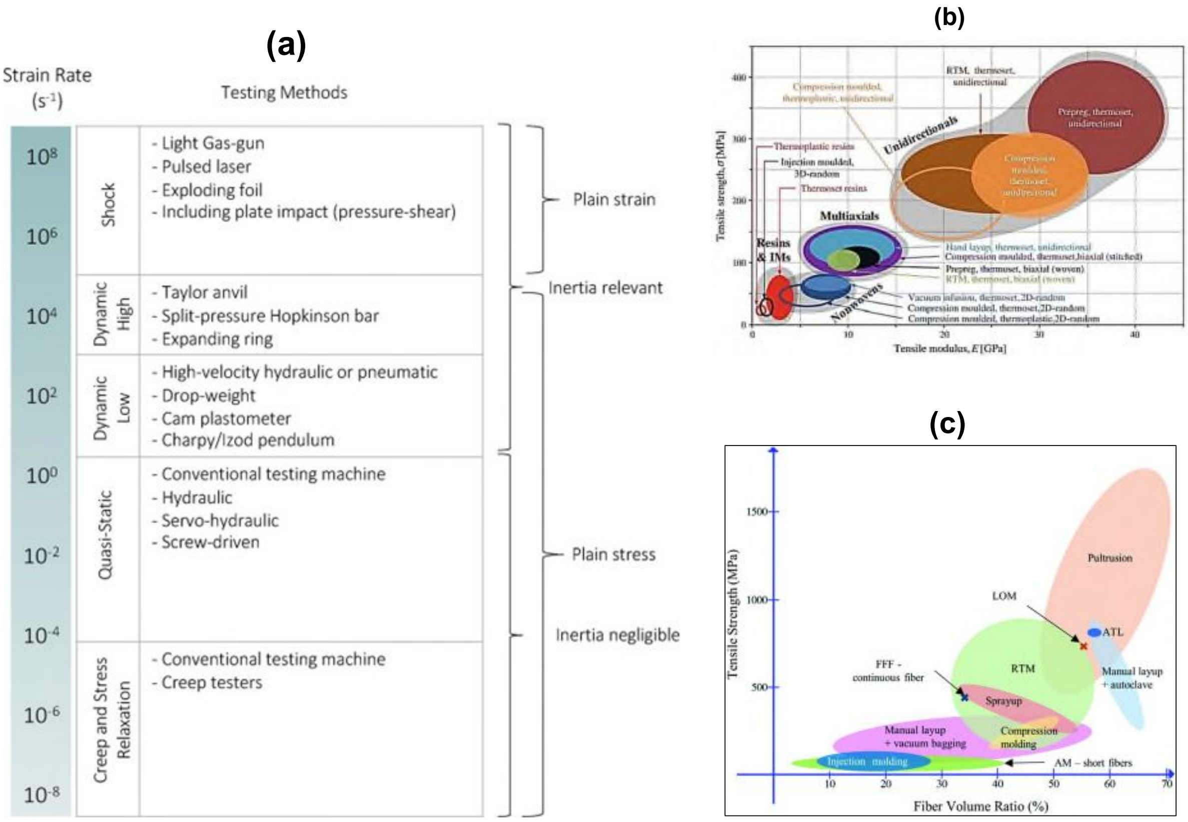
3.3 Machining of NFRPCs:

Machining is an important step before performing the mechanical tests on composites. Mechanical properties of composites depend on the machining characteristics of composites. There are two types of machining: (i) conventional machining, which includes turning, drilling, milling, grinding, etc., and (ii) Unconventional machining, which includes water jet machining, laser machining, ultrasonic machining, electric discharge machining, etc., [190].

Machining induced defects and damages are higher in NFRPCs compared to SFRPCs, owing to high surface roughness and rapid occurrence of damage mechanisms (delamination, fiber-matrix debonding, fiber pull out, etc.) during the machining process [191]. Therefore, it is important to study the machining characteristics of NFRPCs, however, the challenges associated with these are higher [192]. The studies related to machining characteristics of NFRPCs are limited compared to SFRPCs [132, 193]. Raj et al. [190] reported in detail the challenges associated with the machining characteristics of NFRPCs. It is important to use NDE techniques for online monitoring of NFRPCs during machining for reducing defects [33, 194] and the digital twin models can be developed in minimizing the challenges associated with the machining of NFRPCs [195]. Different NDE techniques can be used, which are discussed in Section 4.1.

3.4 Mechanical property characterization of NFRPCs

Different types of mechanical tests can be performed on NFRPCs by varying the strain rates from 10^{-8} to 10^{8} s^{-1}, as shown in Fig. 8(a) [196]. The tensile properties of different fiber weaving architectures of composites, with different conventional OoA manufacturing techniques are shown in Fig. 8(b). From the figure, it is observed that unidirectional fiber reinforced polymer composites (FRPCs) exhibited the highest tensile properties followed by woven roving mat FRPCs. RTM, CM and RI are the commonly used manufacturing techniques in fabricating continuous FRPCs. Among these techniques, RTM exhibited better tensile properties compared to compression molding and RI. This is due to the possibility of a higher fiber volume fraction of RTM compared to the other techniques. Injection molding is mainly used for manufacturing short random FRPCs, it exhibited the least properties. The mechanical properties of woven NFRPCs are better and more stable compared to random NFRPCs [197]. In particular, intraply composites are gaining interest in recent days, owing to their excellent impact resistance capability compared to interply composites [14, 198, 199]. From Fig. 8(c), it can be seen that the modern manufacturing techniques ATL + autoclave exhibited higher tensile strength than conventional manufacturing techniques. Moreover, FFF exhibited higher strength and fiber volume fraction than injection molding and hand lay-up + RI processes. Although the requirement of mold is not required in these techniques, higher strength and fiber volume fraction can be attained in these modern manufacturing techniques. Moreover, Fig. 8(d) shows the lower scrap rate of modern manufacturing techniques, compared to conventional manufacturing techniques. The lower the scrap rate, the higher would be the sustainability and lower would be the product cost [200].



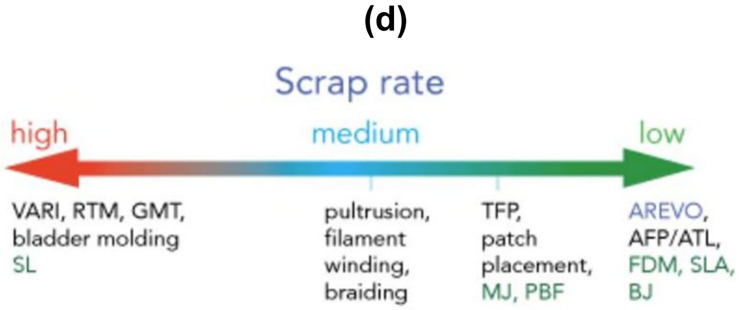


Fig. 8 Effect of strain rate on different mechanical tests of biocomposites (a) Adopted from Elsevier [196]; Comparison of tensile properties of polymers and different fiber weaving structures of composites using different manufacturing techniques (b) Adapted with permission from Elsevier [201], Copyright Elsevier 2014; comparison of tensile strength vs. fiber volume fraction between conventional and modern manufacturing techniques (c) Adopted from [149]; comparison of scrap rate between conventional and modern manufacturing techniques (d) Adopted from [200].

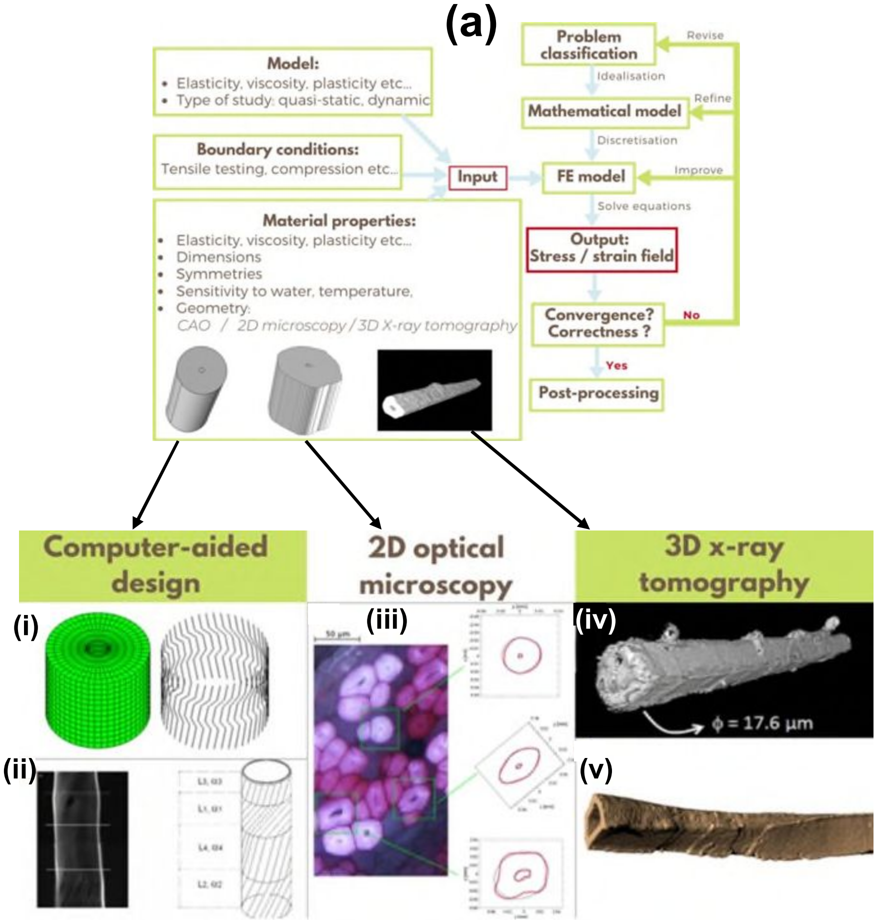
Mechanical (tensile, flexural, water absorption, vibration, low velocity impact (LVI), etc.,), thermal and fire resistance properties of NFRPCs fabricated using conventional [70, 72, 114, 202, 203, 204] and automated manufacturing [11, 109, 126, 130] techniques, are reported and discussed by several researchers. However, the studies related to medium or high velocity impact loading of NFRPCs are limited [52], except very few papers [205, 206, 207, 208, 209, 210]. High velocity impact (HVI) studies can be performed using the air gun [210, 211]. Moreover, the studies related to high strain rate studies of NFRPCs are limited, except very few papers [198, 212]. High strain rate studies can be performed using a drop mass tower [213], Split-Hopkinson Pressure Bar (SHPB) [214], etc. It is important to perform further studies related to HVI and high strain rate properties of NFRPCs to understand the material behavior under dynamic loading events. For example, bird strikes the aircraft, hailstones hit the wind turbine blades, etc., to protect the structure from catastrophic failure [215, 216].

The present work is not aimed at reporting the physical and mechanical properties of NFRPCs fabricated using different manufacturing techniques. Rather, the focus of this review paper is to discuss in detail for effective utilization of NDE techniques in understanding the process of defects generation that occurred at different stages of manufacturing. Subsequently, utilize NDE results to enhance the mechanical performance of NFRPCs. It is essential to investigate the microstructure of NFRPCs using NDE techniques for verifying the final component quality. Also, post characterization, investigating the microstructure of tested NFRPCs using NDE techniques is equally important to understand the failure mechanisms of composites such that the residual properties of composites cannot be degraded [217, 218]. Different types of NDE techniques will be discussed in Section 4.1.

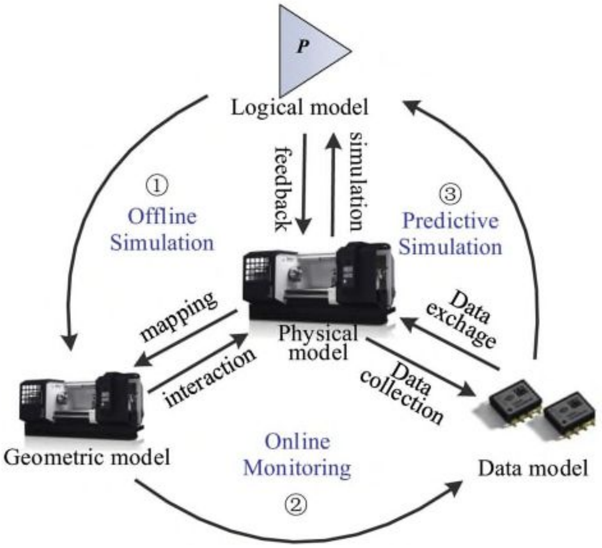
4. Destructive and non-destructive evaluation techniques and generation of digital twins

In general, surface defects and dislocations or microfibrils (kink-bands, slips, etc.) in cell walls of natural fibers can be investigated using destructive techniques, such as microscopy (Normal light microscope, Polarized light microscope and Fluorescence microscope) and scanning electron microscopy. As compared to destructive techniques, NDE techniques can provide clear information and would not affect the residual properties of NFRPCs [35]. However, both destructive and NDE techniques are used as input parameters in modeling of NFRPCs using finite element (FE) analysis for studying the mechanical properties [36, 43, 219], as shown in Fig. 9(a). However, the present review article is mainly focusing on NDE techniques of NFRPCs. Figs. 9(b) shows the NDE inspection and its aided real and geometric modeling and Fig. 9(c) shows the digital twin (DT) concept in smart manufacturing and its applications in various fields.

(a)


Model:
Elasticity, viscosity, plasticity etc...
Type of study: quasi-static, dynamic
Boundary conditions:
Tensile testing, compression etc...
Material properties:
Elasticity, viscosity, plasticity etc...
Dimensions
Symmetries
Sensitivity to water, temperature,
Geometry:
CAO / 2D microscopy / 3D X-ray tomography
Input
Problem classification
Revise
Idealisation
Mathematical model
Refine
Discretisation
FE model
Improve
Solve equations
Output: Stress / strain field
Convergence? Correctness ?
No
Yes
Post-processing
Computer-aided design
2D optical microscopy
3D x-ray tomography
(i)
(ii)
(iii)
(iv)
(v)
50 µm
ϕ = 17.6 µm

(b)


P
Logical model
feedback
simulation
①
Offline Simulation
③
Predictive Simulation
mapping
interaction
Physical model
Data exchange
Data collection
Geometric model
Online Monitoring
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Data model

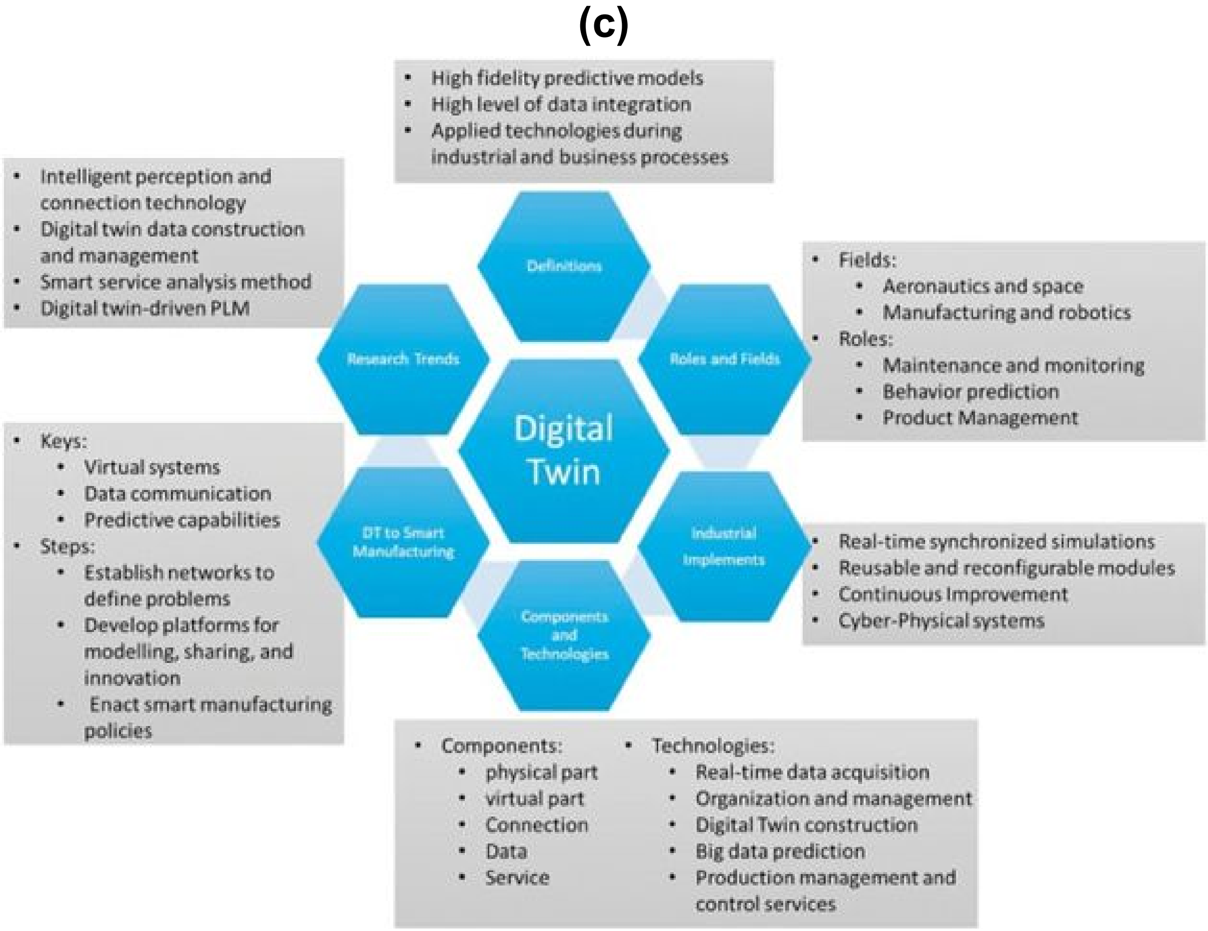
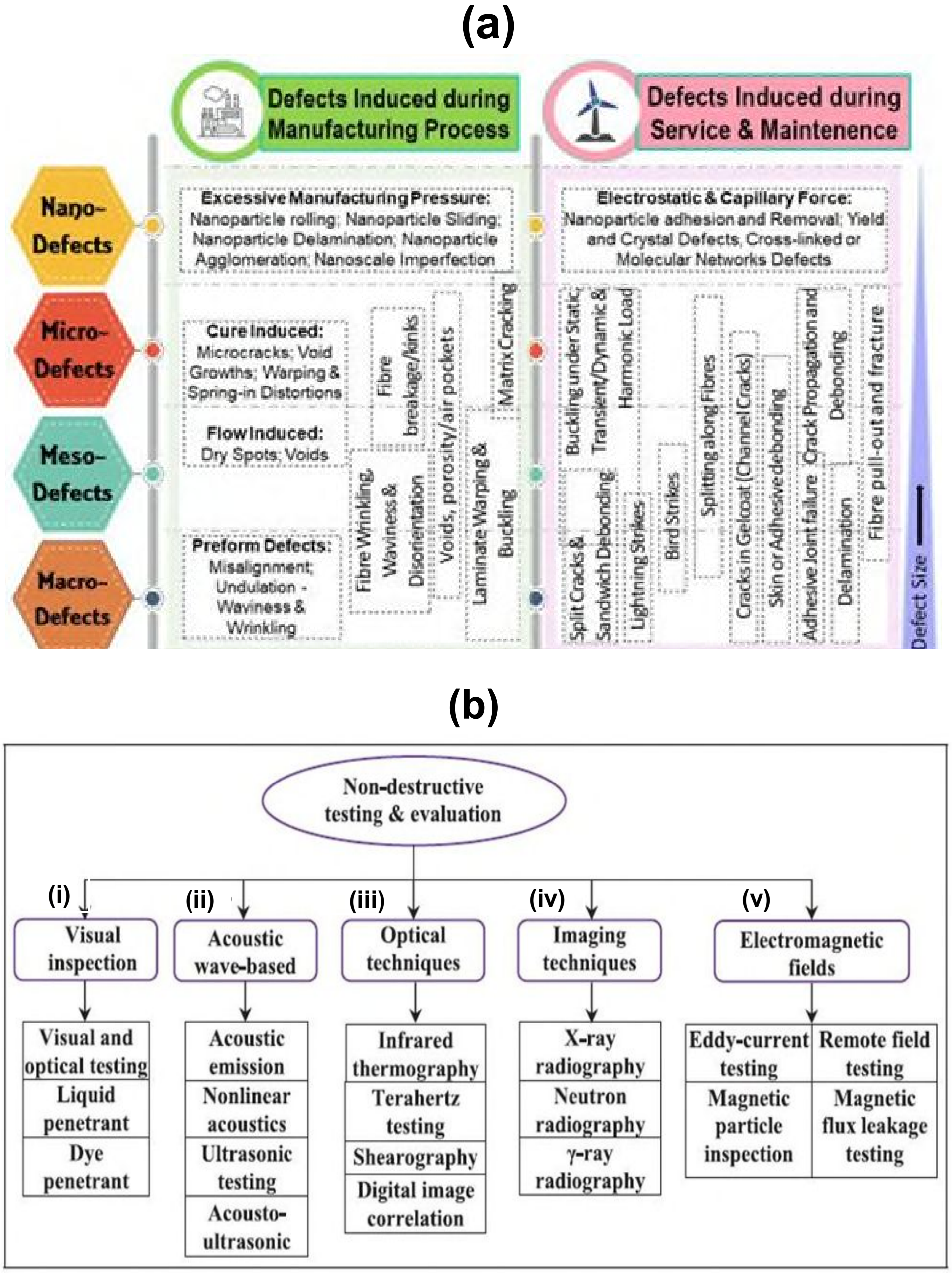


Fig. 9 Estimation of stress-strain fields in hemp/pp composites using FE modeling based on microstructural properties as input obtained using destructive and NDE techniques (a) Adapted with permission from Elsevier [43], Copyright Elsevier 2022; NDE aided real and geometric modeling (b) Adapted with permission from Elsevier [220], Copyright Elsevier 2020; digital twin concept and its application in various fields (c) Adapted with permission from Elsevier [221], Copyright Elsevier 2021.

4.1 Types of non-destructive evaluation techniques

Different sizes of defects can be induced in composites at different stages, such as manufacturing, in-service and maintenance, as shown in Fig. 10(a). These defects can be identified using NDE techniques [222]. From Fig. 10(b)(i), NDE techniques in inspecting composites manufactured using conventional and modern manufacturing techniques are divided into five groups. These techniques can be further divided into contact and non-contact techniques [223, 224]. Fig. 10(b)(i, ii and v) are corresponding to contact NDE techniques whereas Fig. 10(b)(iii and iv) are corresponding to non-contact NDE techniques. Fig. 10(c) shows the ability of different NDE techniques to capture the damage mechanism at different scales in composite specimens. It is clear from the figure that the tomography technique has the good ability to capture the finest damage mechanisms in composite specimens compared to other NDE techniques while the finest damage mechanisms could not be identified using visual inspection techniques.



(c)

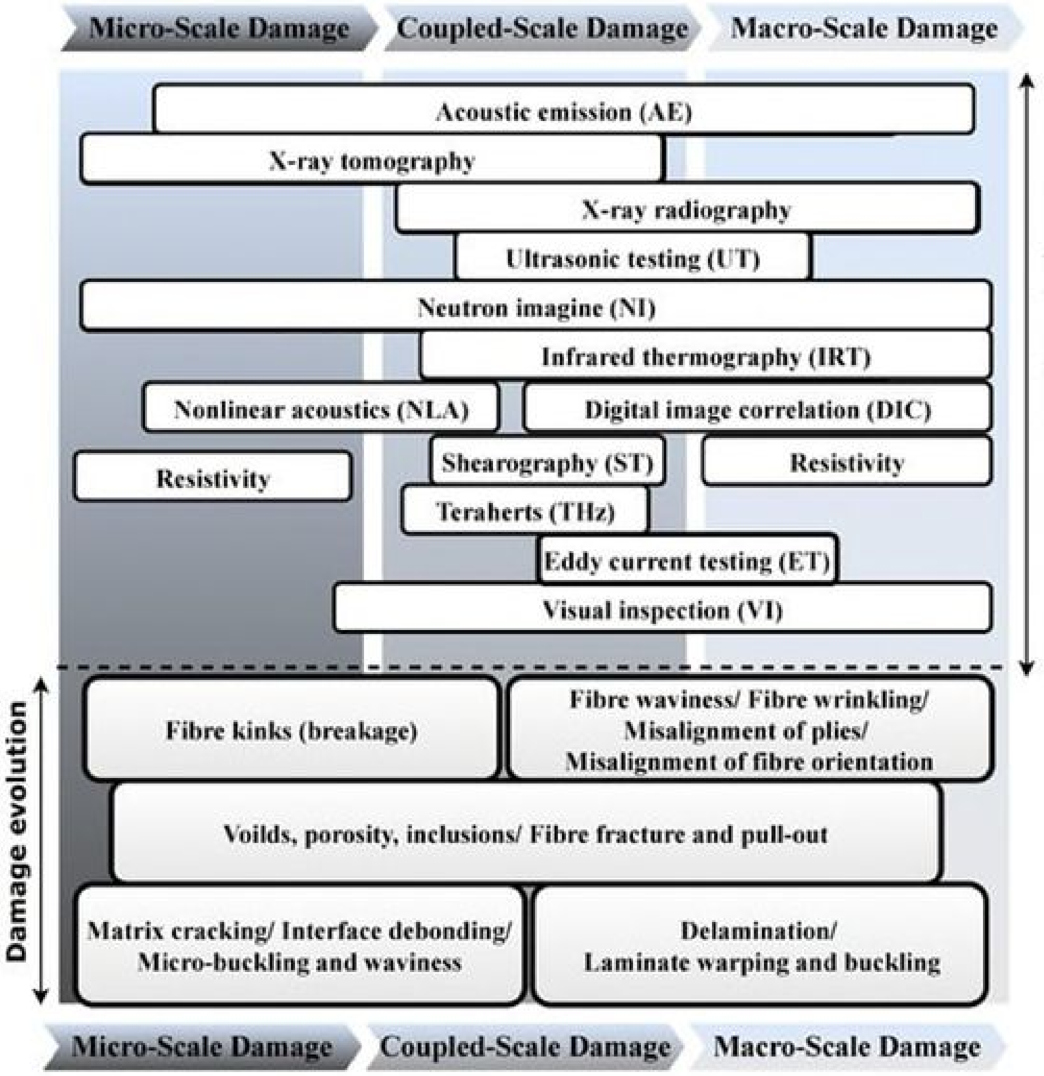


Fig. 10 Different scales of defects occurred during manufacturing and service and maintenance (a) Adopted from [225]; Schematic representation of different types of NDE techniques (b) Adopted from [226]; Identifying the different damage mechanisms in composite specimens using different NDE techniques (c) Adopted from [227].

(i) Visual inspection:

The failure mechanisms can be identified using the human eye. This is the cheapest noncontact technique compared to other NDE techniques. It can be classified as visual and optical testing, liquid penetrant and dye penetrant [228].

(ii) Acoustic wave-based techniques:

Acoustic Emission (AE):

AE is a contact NDE technique and is being widely used technique in detecting commonly occurred failure mechanisms such as fiber breakage, fiber pull out, delamination, etc., in FRPCs [229]. The defect information through this technique can be captured using an AE sensor that is attached to the specimen. AE technique is different compared to other NDE techniques. This technique receives AE energy in the form of a waveform from the failure mechanisms of the specimen, instead of sending energy to the specimen. The failure mechanisms of long-term loading (fatigue) and dynamic loading (impact) events can be captured using this technique [230]. Therefore, this technique is increasingly used in aircraft structural components. Moreover, the AE technique is the most widely used in studying the machining of NFRPCs, owing to its ability to capture various process conditions which include a change in cutting speed and fiber orientation, etc., [132, 231]. Wang et al. [232] have employed the AE technique for monitoring machining characteristics of flax/PP composites to understand process conditions during orthogonal cutting using a random forecast machine learning model. Applications of the AE technique in various fields of NFRPCs are reported by Sarasini and Santulli [233].

Ultrasonic Testing (UT):

UT is a contact NDE technique that consists of transmitter, receiver and, computer for storing and pre-and post-processing the data. In this technique, the signals can be propagated into the specimen from the transmitter and the defect information will be captured by the receiver [234]. It is one of the most commonly used NDE techniques in NFRPCs [235]. The defect of failure mechanisms such as porosity, fiber misalignment, crack size and orientation can be detected using this technique [229]. This technique is best suitable for investigating small size flat specimens while using this instrument it is difficult to investigate curved or cylindrical specimens. The ultrasonic 'C' scan technique is being widely used in understanding the impact failure mechanisms of both thermoset and thermoplastic polymer composites [236, 237]. Different types of ultrasonic techniques (immersion, air-coupled, contact guided wave and air-coupled excitation and contact reception guided wave) and their advantages and limitations are discussed by Yilmaz et al. [238].

Acousto-ultrasonic (AU):

AU is a contact NDE technique that is based on a combination of acoustic and ultrasonic testing technology. This technique can detect internal imperfections and inhomogeneity in composites, these characteristics are especially higher in plant fibers [239]. This technique has proven to be an accurate one based on optimal economy, and sensitivity [240]. It detects the accumulated damage present in the specimen subjected to impact and fatigue loading.

(iii) Optical techniques:

Optical techniques are camera based non-contact NDE techniques. Several researchers are being used optical techniques in investigating NFRPCs [241]. Lopato et al. [242] investigated the different stages of failure mechanisms in thin basalt fiber reinforced composites by using two different NDE techniques combined terahertz and infrared thermography techniques. Sfarra et al. [239] reported that investigation of the plant fiber composites using different NDE techniques is required owing to inherent irregularities present in the fibers. The presence of damage, resin-rich regions and defects in the jute/hemp/epoxy hybrid composites were investigated and reported in detail. In another study, the indentation damage mechanisms of jute/hemp/epoxy hybrid composites were studied using optical and infrared NDE techniques [243].

Infrared thermography (IRT):

In this technique, the thermal radiation emitted by the surface of the specimen can be recorded using the infrared camera [234]. It is an accurate technique to determine the crack size and shape of the specimen. It measures the damages in a shorter time. Boccardi et al. [244] studied the microstructure of thermoplastic resin reinforced basalt fiber composites using UT and IRT techniques. It was reported that UT and IRT techniques are in good agreement in capturing failure mechanisms of basalt/polyamide composites. However, the IRT technique is found to be a better one to detect the failure mechanisms in basalt/polypropylene composites. However, gel-based UT could not capture the failure mechanisms in basalt/polyester composites owing to hydrophilic characteristics of composites, these would be soaked with the coupling agent. In another study, Zhang et al. [245] investigated the impact damage mechanisms of basalt/vinyl ester composites using UT and IRT techniques. From Fig. 11(a), it is clear that using the UT technique both delamination and resin-rich regions (shown in Red color) can be detected while IRT provides only delamination (Fig. 11(b)) in basalt/vinyl ester composites. Therefore, further studies are required related to NFRPCs to identify the best technique out of these two techniques. Brasington et al. [144] compared different NDE techniques (profilometry, thermography and eddy current) in inspecting the defects (gap, overlap, wrinkle, twist, etc.) in the AFP manufactured component and reported that the thermography technique is the best to capture all defects compared to other NDE techniques. IRT technique is also useful in studying the machining of NFRPCs. Wang et al. [246] have investigated the drilling performance of hemp/vinyl ester composites using conventional drilling (CD) and ultrasonically-assisted drilling (UAD) approaches through the infra red camera. It was reported that higher magnitude of cutting forces and energy are required and drilling induced damage was higher with CD approach compared to those with of UAD approach. Moreover, UAD approach exhibited better surface finish and quality of holes compared with those of UD approach.

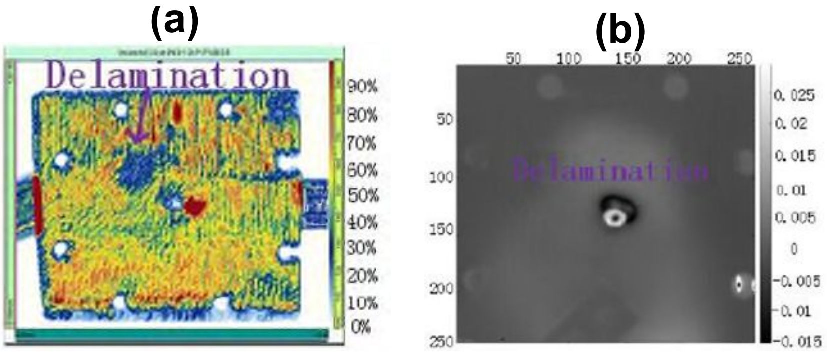


Fig. 11 Comparison of impact damage mechanisms in basalt/vinyl ester composites subjected to 15 J, using UT (a) and IRT (b) Adapted from MDPI [245].+

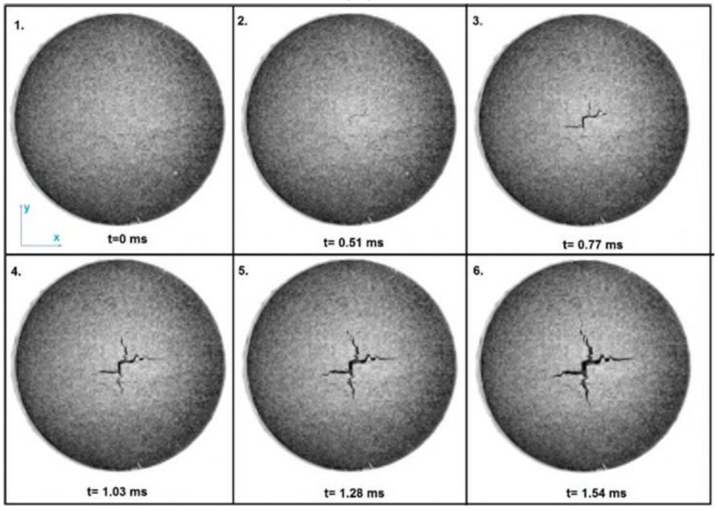
Shearography:

Shearography is a non-contact optical NDE technique. It consists of a laser light source, optical shearing device, charge-coupled camera (CCD), etc. The main advantage of this technique is that it is less susceptible to noise compared to many other techniques. It is mainly useful to detect delamination in composites. Further details about this technique are given in literature [229, 234].

Digital Image Correlation (DIC):

DIC is a widely used NDE technique to measure the in-situ strain and capture the failure mechanisms at different fiber orientations [117, 247]. It is a non-interferometric technique. The deformation of the specimen can be detected by comparing gray intensity variations of the reference and deformed images. DIC technique is useful to capture the deformation history in both quasi-static and high strain rate loadings [212]. Further details about this technique and working principle are given in our recent articles [213, 248]. Begum et al. [98] employed the DIC technique to measure the in-plane strain in-situ in flax/glass/epoxy and jute/glass/epoxy hybrid composites. Habibi and Laperriere [249] investigated the tensile properties of flax/epoxy composites using DIC and acoustic emission techniques. It was reported that the number of acoustic events noted was lower in open hole tensile experiments owing to formations of stress concentrations and crack initiation near to open hole, which lead to premature failure in composites. The major drawback of DIC is that it suits to capture the displacement fields before the failure of the sample and it fails to identify the displacement fields when there are discontinuities that occur after the initiation of the failure. The discontinuities occur in the sample due to the cracks and fiber failures. For example, in Fig. 12(a), the DIC approach can be used when time (t) = 0.51 ms. The DIC approach cannot be used from time (t) = 0.77 ms. Moreover, the DIC approach may not be accurate for very high impact energy experiments. To overcome these drawbacks, Ramakrishnan et al. [250] proposed the crack-tracking approach to identify the crack length using Image J software, at any stage above or below t = 0.77 ms, by developing an algorithm. Through this algorithm, initially, a combination of median and Gaussian blur filters can be applied to the reference (undamaged) image, and then each image can be treated with the same filters, as shown in Fig. 12(b). Further, the deformed image can be subtracted with the reference image, such that the cracks can be isolated from the deformed image. However, at this stage, the cracks may not be visible clearly. Therefore, the subtracted image can be converted to mask and binarized to clearly measure the crack length. This crack-tracking approach can be used to any impact tests, irrespective of any impact energy for measuring the crack size.

(a)



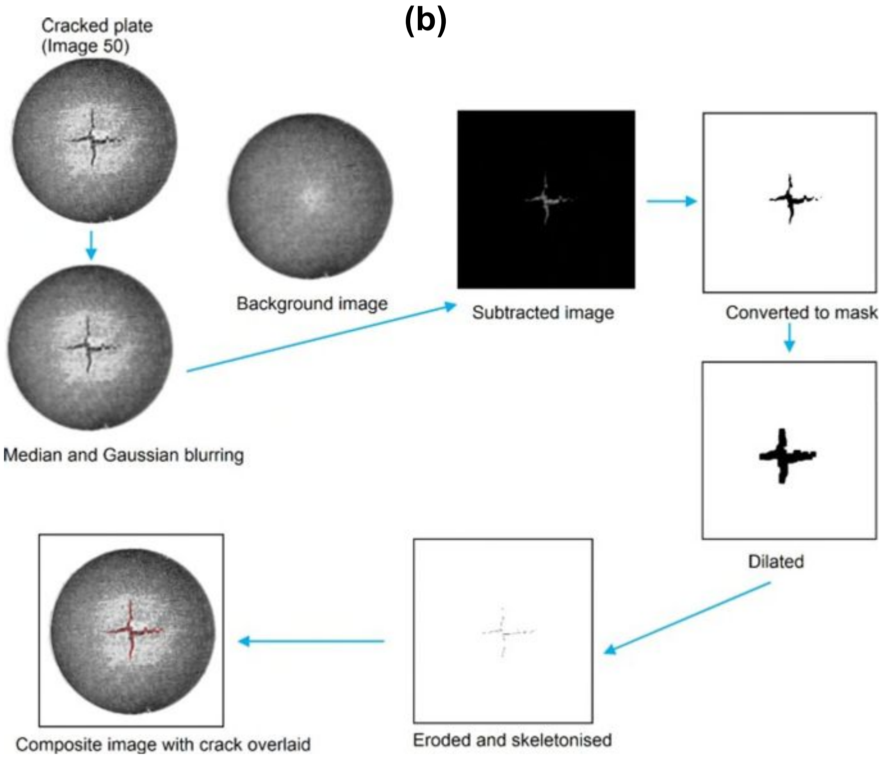


Fig. 12 In-situ observation of initiation and propagation of macro-cracks in flax/PP composites subjected to LVI at 6J using high speed camera (a) and procedure to measure the crack length in high speed camera images Adapted with permission from Elsevier [250], Copyright Elsevier 2021.

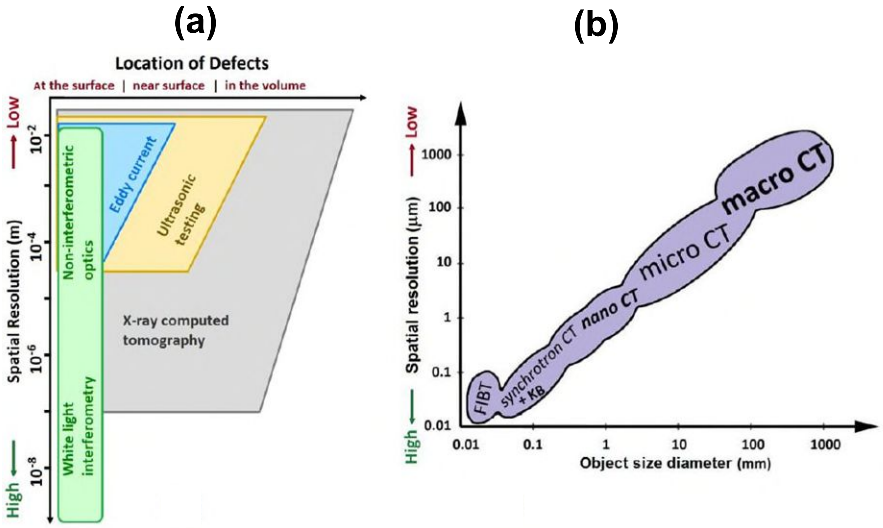
(iv) Electromagnetic fields

Electromagnetic techniques induce electric currents, magnetic fields, or a combination of both into a sample, in order to detect fractures, defects, etc., in composites and observe the electromagnetic response. Electromagnetic techniques are classified as eddy current testing, magnetic particle inspection, remote field testing, magnetic flux leakage testing. Further details about these techniques are elaborated in detail in literature [229, 234].

(v) Imaging techniques:

In recent times, X-ray computed tomography (XCT) is being widely used in medical, engineering and defence fields compared to other imaging techniques [24, 35]. This is owing to its high accuracy and it can provide information in both 2D and 3D [251]. However, the cost of XCT is very high compared to other imaging techniques. Recently, the use of XCT is gaining more interest in studying natural fiber based wood [252, 253, 254] and non-wood [28, 255, 256] composites. Three dimensional voxel models can be created after reconstruction, using different software packages (Volume graphics (VG) Studio max, Fiji, Geodict, Avizo, etc.,) [35, 257, 258]. Mutiargo et al. [259] have reported that capturing microstructural information in complex geometrical components fabricated by AM is difficult with ultrasonic testing and eddy current, owing to presence of insurmountable difficulties. These challenges can be overcome by using XCT owing to its ability to capture the data during a 360° rotation of a sample [35, 121]. Also, the spatial resolution of XCT is higher than the ultrasonic testing and eddy current, as shown in Fig. 2. Typical spatial resolutions could be achieved with different XCT instruments based on the size of the sample size [260]. It is clear from Fig. 3(b) that spatial resolution could be achieved with conventional or macro XCT is low (>10 μm) and it increases gradually with micro XCT (>3 μm), nano XCT (>0.4 μm), synchrotron XCT (>0.2 μm), synchrotron XCT with Kirkpatrick–Baez mirrors (>0.04 μm), and focused ion beam tomography (FIBT) >0.01 μm.

Bensadoun et al. [261] reported that the use of XCT has several advantages in inspecting the fiber orientation, void content, delamination, etc. However, this can be possible only if the X-ray absorption coefficient of natural fiber and matrix are different, otherwise, difficult to identify the internal structure. Giuseppe et al. [262] measured the fiber length and diameter in NFRPCs using different approaches, namely 2D scanner, MorFi Compact® fiber analyzer (automated analyzer) and XCT, as shown in Fig. 13(c). It was reported that the techniques of 2D scanner and automated analyzer need specific treatments to separate the fiber from the polymer, while the separation of fiber from the polymer is not required in XCT. Moreover, XCT has several advantages and it can capture images with good resolution and measure the fiber length and diameter precisely, over other two techniques. Bossio et al. [263] investigated the void volume fraction in hemp fiber reinforced with two different bio-resins (the first one is epoxy, which is derived from 25% of eggshells and the other one is Ecopoxy, which is derived from soybeans) braided composites using XCT, and reported that XCT is useful in optimizing the interaction between the cellulose yarns and bio-resins. Rask et al. [264] have performed in-situ tensile experiments on unidirectional flax/pp composites and monitored the microstructural changes during testing. Therefore, it is clear that XCT can be used effectively in observing microstructural changes in NFRPCs in-situ. These in-situ studies are limited related to NFRPCs, even though several studies are available with SFRPCs. The reason for limited studies available on NFRPCs is due to the lower density of natural fibers, which are closer to the density of polymers, therefore, performing XCT tests are difficult to achieve good resolution, compared to synthetic fibers [28]. The resolution of the NFRPCs can be enhanced by placing the sample closer to the X-ray tube during scanning. Further details to enhance the resolution of the sample are discussed in literature [35, 251]. Moreover, there are several other challenges are associated while inspecting NFRPCs, in that, particularly important to know the scanning parameters (voltage, current, intensity, etc.) [261, 265], which can be withstood by natural fibers without affecting the properties.



(c)

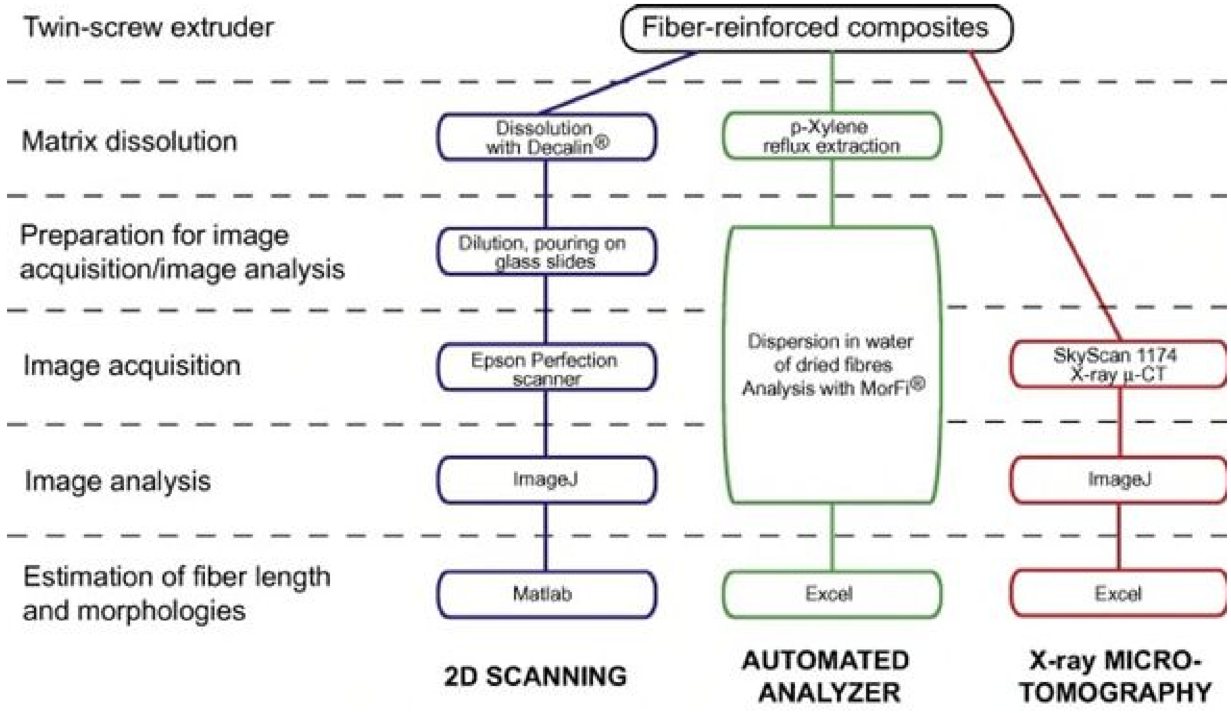


Fig. 13 Comparison of spatial resolution with XCT and other NDE techniques (a, b) Adapted with permission from Elsevier [266], Copyright Elsevier 2019; Comparison of different techniques for measuring fiber dimensions in polymer-lignocellulose fiber composites (c) Adapted with permission from Elsevier [262], Copyright Elsevier 2016.

4.2. XCT aided models in NFRPCs

(a) Void based models:

XCT based void models are useful to estimate the void volume fraction in NFRPCs. Yu et al. [267] investigated the void volume fraction in different fiber orientations of FDM printed basalt/polylactic acid (PLA) composites using XCT and found a lower void volume fraction of 7.92% in $[0/90]_6$ laminates and a higher void volume fraction of 8.23% in $[45/135]_3$ laminates, as shown in Fig. 14. Fig. 15 shows the XCT aided void analysis maps of injection molded basalt/polyamide composites. The void volume fraction of 1.2% is observed from the void analysis maps.

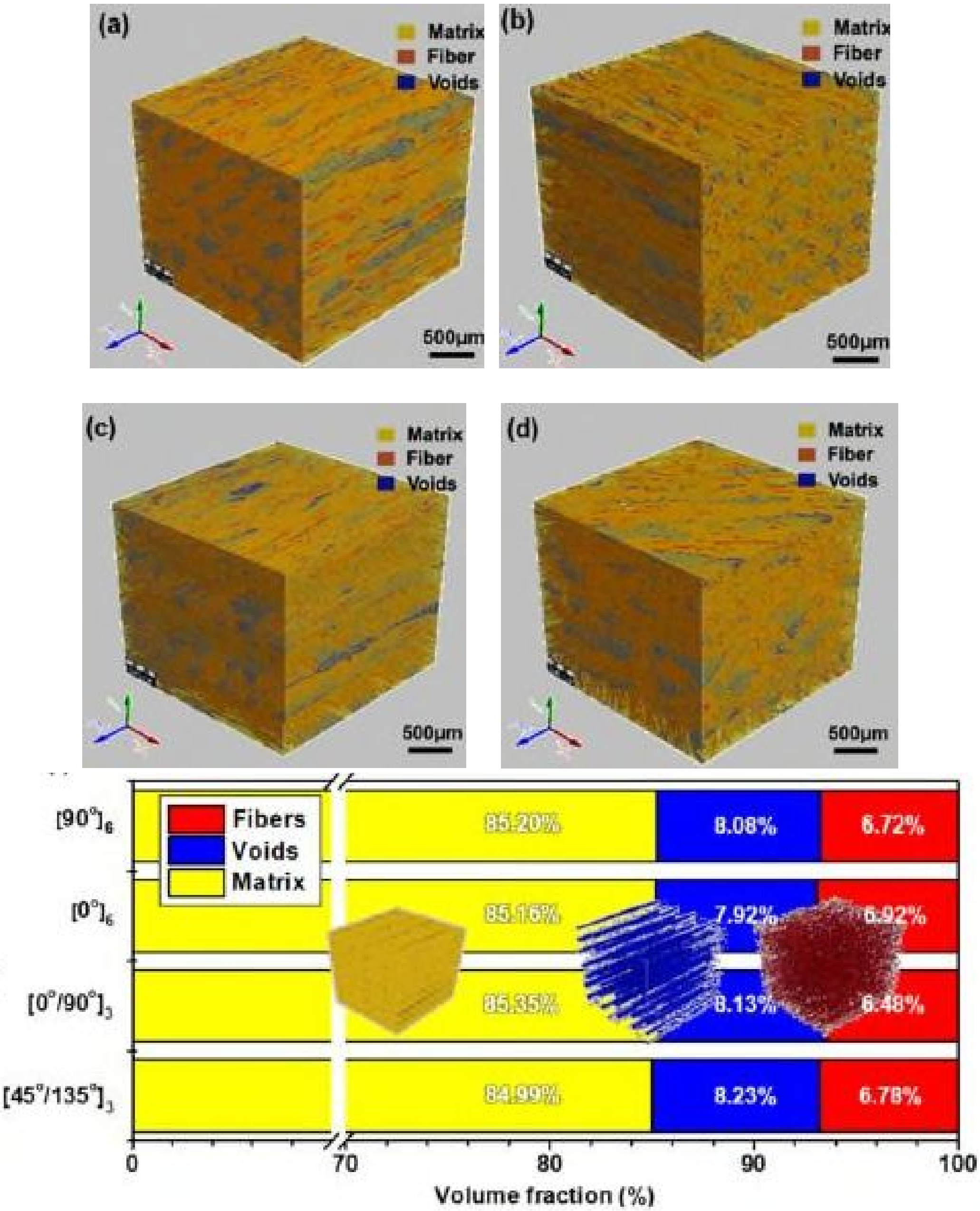


Fig. 14 XCT images of FDM printed basalt/PLA composites: (a) $[0/90]_6$; (b) $[0]_6$; (c) $[0/90]_3$; (d) $[45/135]_3$ Adapted with permission from Elsevier [267], Copyright Elsevier 2021.

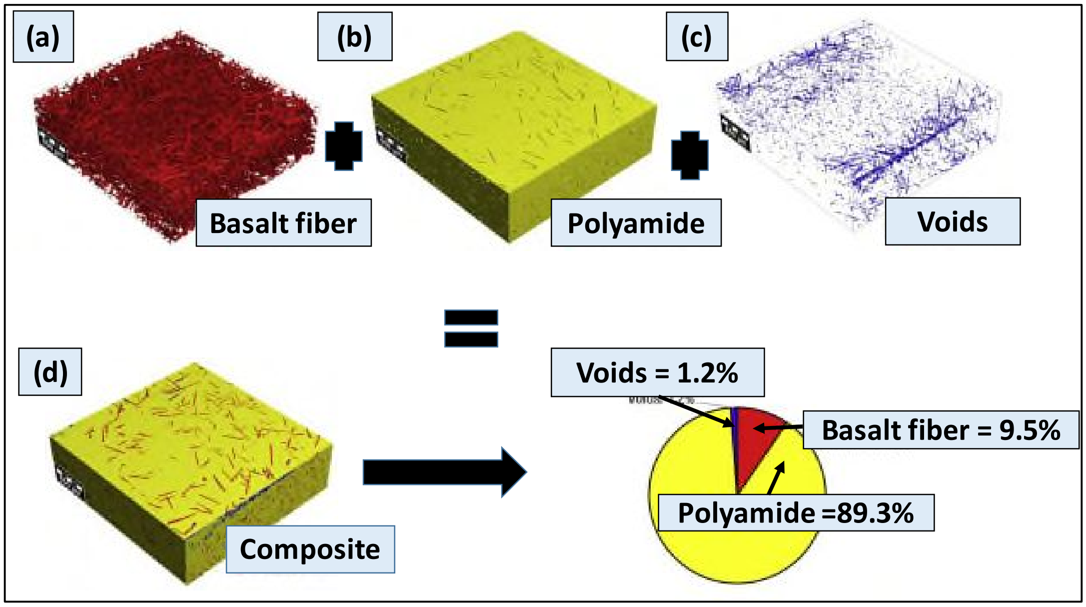


Fig. 15 Void analysis in injection molded short basalt fiber/Polyamide 6,6 using XCT. Adapted with permission from Elsevier [268], Copyright Elsevier 2020.

(b) XCT aided statistical models:

The statistical analytical models can be used to study the morphological characteristics of different constituents (size, shape and distribution of fibers and voids) in NFRPCs based on data provided through the XCT aided models [257]. XCT data can be presented statistically using VG Studio Max software [121], Avizo [269], Geodict [270], etc. Fracz et al. [28] investigated the distribution of hemp fibers in hemp biocomposites statistically, which are manufactured at different injection molding rates, 10, 35 and 75 cm^3/s, as shown in Fig. 16(a-c), respectively. It was reported that the clustering of fibers is lower at the highest injection molding rate. Normal distribution and two-parameter Weibull distribution models are the most widely used statistical models to study these morphological characteristics [121]. Giuseppe et al. [271] reported that the Log-normal distribution model fits well with the data compared to two parameter Weibull distribution.

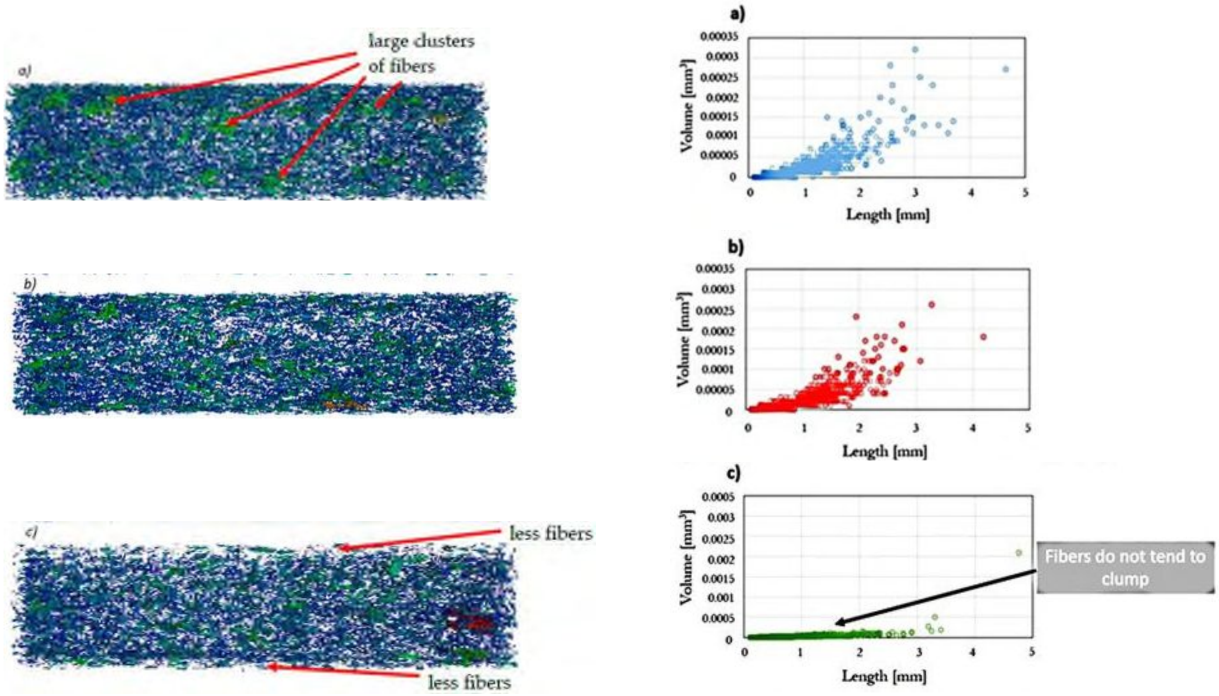


Fig. 16 Fiber distributions in 3D at different injection molding rates, 10, 35 and 75 cm^3/s (a-c) and corresponding statistical analysis of hemp fiber clusters as a function of length. Adapted from MDPI [28].

4.3 XCT aided real and virtual geometry-based simulations in generating digital twins

Generating XCT aided real geometry is straightforward from 2D XCT scanned images after reconstruction, using software packages, such as WiseTex, Avizo, VG Studio Max, Geodict, etc., [269, 271]. However, XCT scanned data can be used to create the virtual geometry, as shown in Fig. 17(a), using software packages, such as TexGen, WiseTex, etc., to predict mechanical properties [272]. Compaction based simulations can be performed using FEA software packages, such as Ansys, Abaqus, Voxtex, etc., while permeability based simulations can be performed using computational fluid dynamics (CFD) software packages, such as Geodict, Ansys, Paraview, Flowsquare, etc., [35, 269]. Fig. 17(b)-(c) show the comparison of compaction simulation results of real and virtual geometry modeling while Fig. 17(d) shows the comparison of permeability simulation results of real and virtual geometry modeling. From these figures, it can be observed that both results are correlating well. Therefore, it is clear that XCT can be used effectively for generating geometrical models of NFRPCs for various digital twin applications.

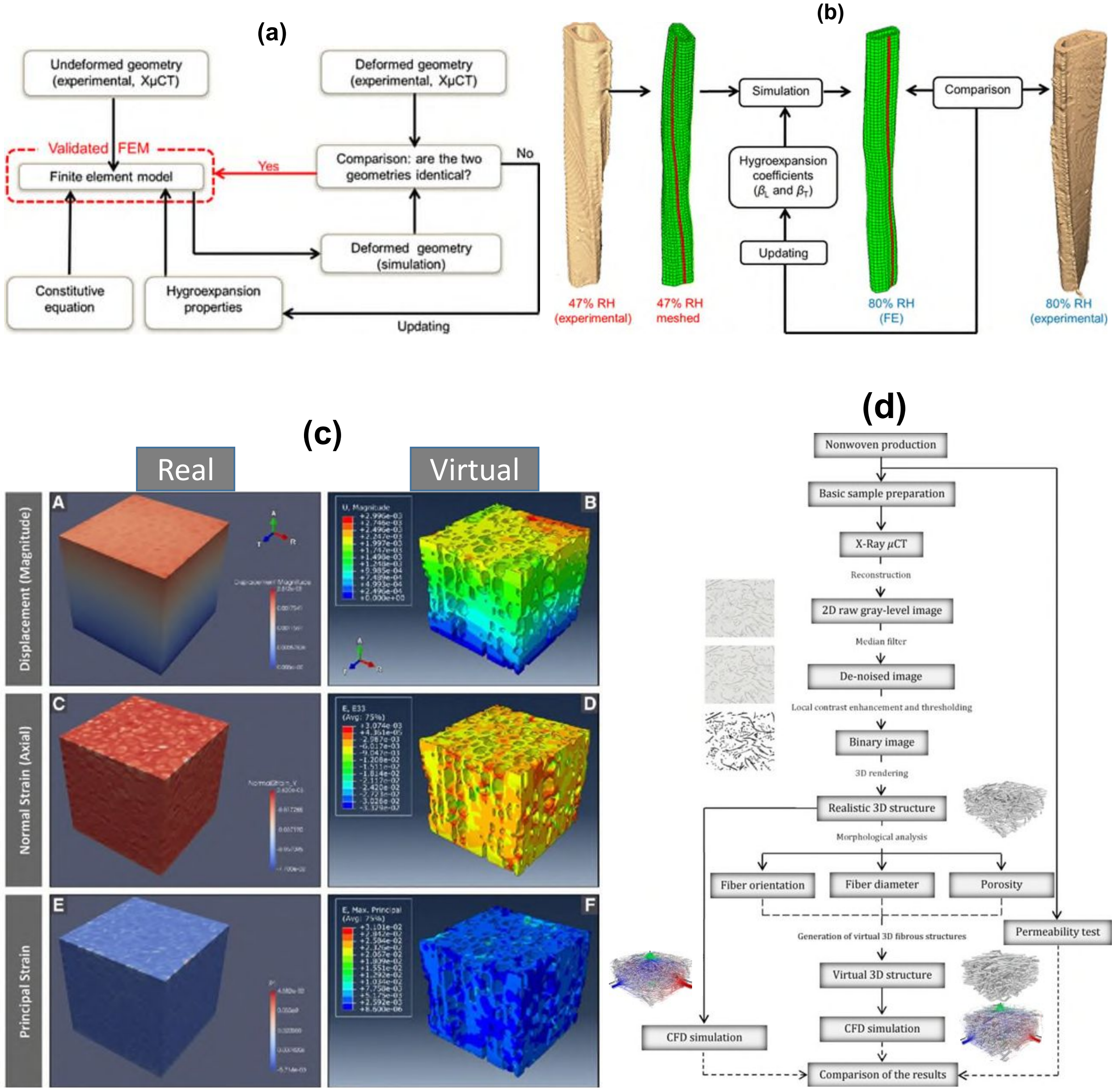


Fig. 17 Procedure for validating XCT aided virtual geometry modeling results with XCT aided real geometry modeling results (a) Adapted from Springer [45]; Comparison of XCT aided real and virtual geometry FEA simulations of wood composites (b) Adapted from Springer [45] and (c) Adapted from Springer [36]; Prediction of permeability in nonwoven fabrics using different approaches: experimental and XCT aided real and virtual geometry CFD simulations. Adapted with permission from Elsevier [273], Copyright Elsevier 2017.

The advantages, limitations and potential applications of each non-contact and contact NDE techniques are discussed in a recent article [224]. Table 2 shows the microstructure investigation details in NFRPCs subjected to different loading, which are measured using different NDE Techniques. Most of the studies presented in Table 2 were carried out recently.

Table 2 Microstructure investigation in NFRPCs using different NDE Techniques

NFRPCs	Manufacturing technique	Characterization	NDE Technique	Year	Reference
Basalt/polypropylene (PP) Hemp/ PP	CM	Tensile, flexural and fracture toughness	AE	2006	[274]
Flax/epoxy	CM	Tensile, bending and fatigue	AE, IRT, DIC, XCT	2022	[275]
Luffa/epoxy	RTM	LVI	AE, DIC	2022	[276]
Flax/epoxy	Autoclave	LVI	XCT	2021	[277]
Bamboo/ poly-benzoxazine	CM	High strain rate	High speed camera and DIC	2022	[212]
Hemp/PP Wood/PP	IM	Microstructure	XCT	2008	[278]
Palm/Phenolic	CM	Tensile and impact	IRT, UT	2021	[27]
Basalt/vinylester Jute/hemp/vinylester	RTM	LVI, quasi-static indentation	IRT, UT	2018	[245]
basalt/polyamide basalt/PP	CM	LVI	IRT, UT	2019	[244]
Flax/CORAL (bio-epoxy)	CM	Tensile	DIC, AE	2020	[249]
Basalt/PLA	FDM	Tensile and Void analysis	XCT	2019, 2021	[255, 267]
All-cellulose	CM	Tensile	DIC	2021	[241]
Jute/epoxy, Jute/glass/epoxy Flax/epoxy Flax/glass/epoxy	Manual molding	Tensile	DIC	2019	[279]
Jute/hemp/epoxy	CM	Static indentation	All optical techniques	2016	[239, 243]
Hemp/bio-resin	RI	Void analysis	XCT	2019	[263]
Hemp/PLA	FDM	Tensile	XCT	2019	[280]
Hemp bast fibers	-	Microstructure	XCT	2019	[47]
Kenaf/Jute		LVI and CAI	C-scan	2021	[281]
Basalt/epoxy	RI	LVI	C-scan	2021	[237]
Flax/PLA-PP	CM	Tensile, flexural and LVI	Laser UR, Profilometry, XCT	2019	[282]
Flax/carbon/epoxy	Autoclave	LVI	Laser vibrometry	2019	[283]
Basalt/epoxy	RTM	LVI	IRT, C-scan and terahertz imaging	2017	[284]
Basalt/Polyamide 6,6	IM	Void analysis	XCT	2020	[268]
Flax/epoxy and Flax vinyl ester	RI	Mechanical properties	XCT	2018	[285]
Silkworm cocoons	-	Tensile and microstructure	XCT	2021	[286]

Kenaf/epoxy/X-ray film	Hand lay-up	Tensile, flexural and HVI	Die penetrant	2018	[208]
Kenaf/Aramid/Polyvinyl butyral	CM	HVI	Visual	2016	[206]
Non woven Kenaf/PLA/clay	Resin casting	HVI	High speed camera	2020	[205, 207]
Glass/jute/flax/epoxy	RI	LVI and CAI	Visaul inspection	2020	[287]
Basalt/Kevlar/epoxy	RTM	Flexural and LVI	AE	2013	[288]
Basalt/carbon/epoxy	Autoclave	Flexural and Laser shock wave	XCT and AE	2015	[289]
Basalt/hemp/polyester	CM	Flexural and LVI	AE	2015	[290]
Basalt/flax/epoxy	RI	Tensile and Fatigue	IRT	2020	[291]
Carbon/flax/epoxy	Autoclave	Tensile, Flexural and LVI	DIC and XCT	2016	[292]
Basalt/glass/epoxy based vinylester	RTM	LVI	IRT	2013	[293]
Basalt/vinylester	RTM	LVI	IRT	2016	[294]
Jute/glass/polyester	RTM	Impact and post impact	AE and IRT	2009	[295]
Flax/ epoxidized pine oil	Hand lay-up	Compression	DIC	2020	[296]
Abaca/glass/polyester	RI	Tensile and flexural	XCT	2021	[297]
Basalt/epoxy, basalt/vinylester	RI	LVI	C-scan	2021	[237]
Short Palm fiber/Phenolic	CM	Tensile and LVI	IRT and C- scan	2021	[27]
Jute/PLA	CM	LVI	C-scan	2017	[298]
Jute/vinylester	RI	LVI	C-scan	2006	[299]
Hemp/polyester	CM	LVI	C-scan	2012	[300]
Flax/epoxy	RTM	Four point bending and fatigue	Fibre Bragg Grating and DIC	2020	[301]
Flax/PP	FW	Tensile	XCT	2012	[264]
Hemp/ Poly(3-hydroxybutyric-co-3-hydroxyvaleric acid) (PHBV)	IM	Microstructure assessment	XCT	2021	[28]
Flax/PLA	CM	Microstructure assessment	XCT	2021	[256]
Bamboo scrimber	CM	Compression	DIC	2021	[302]
LINEO FlaxPreg T-UD 110	Autoclave	Tensile	DIC	2018	[48]
Flax/PP and Flax/epoxy	CM	LVI	High speed camera and DIC	2021	[250]
Hemp fiber	-	Microstructure assessment and tensile	XCT and DIC	2017	[265]
Bamboo node	-	Tensile	AE	2020	[303]
Flax/PP	CM	Machining	AE	2020	[232]
Hemp/vinyelster	CM	Machining	IRT	2019	[246]
Banana/epoxy	Hand lay-up	Machining	C-scan	2014	[194]

From Fig. 18 it is clear that the number of publications related to NDE techniques has been increased every year. The number of papers published in 1996 is approximately 100 and in 2019 is approximately above 700. Also, it is interesting to note that the number of papers published from 2015 to now, related to X-ray imaging is higher followed by digital image correlation compared to other NDE techniques, which can be seen in Table 1.

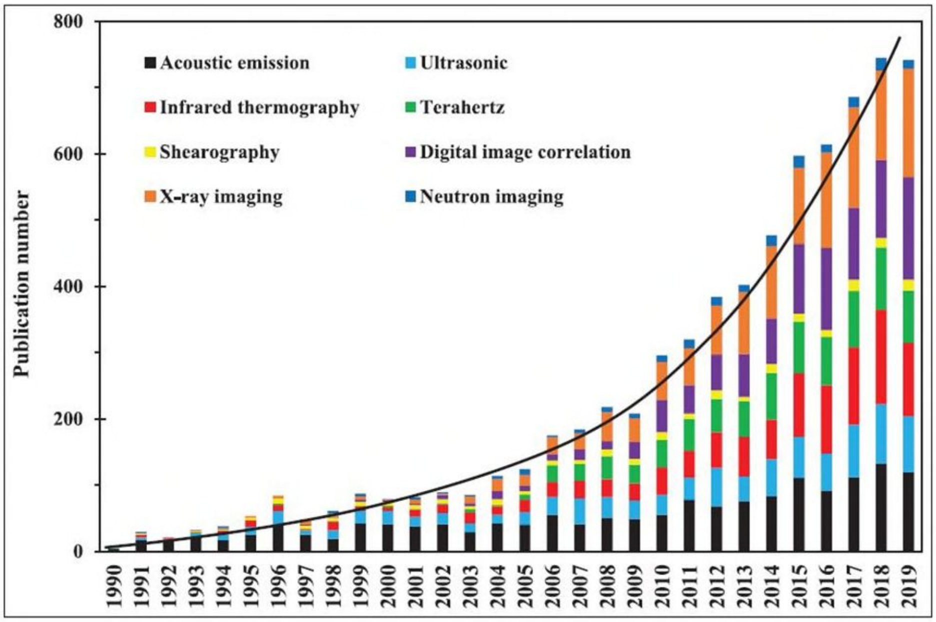


Fig. 18 Number of publications related to NDE techniques of composite materials or structures in the past 30 years. Adapted from Sage, open access [226].

5. Artificial Intelligence approach in polymer composites

Performing several experiments require many costly instruments and require more time and manpower. Therefore, it is necessary to minimize the number of experiments and obtain the data using advanced technology. Although several numerical software packages are commercially available in the market to predict the properties of composites, however, these require severe computational resources. In recent years, the use of AI approach is being increasingly used in designing, manufacturing and inspecting and post-processing data [304]. The idea of AI is inspired by the biological nervous system and it is useful to solve complex mathematical problems based on the available data. The AI-aided approach requires limited experimental data, which minimizes the time and labor cost. AI is subdivided into Machine Learning (ML) and Deep Learning (DL), as shown in Fig. 19(a-b). AI technology is being widely used for smart manufacturing, as shown in Fig. 19(c). As compared to ML, the role of human participants is less in DL [305]. Moreover, ML is used in predicting the properties of composites [306] while DL architecture contains many hidden layers with non-linear combinations of multi-layers. In general, ML requires step-by-step training in each module, while many parameters can be trained combinedly in DL.

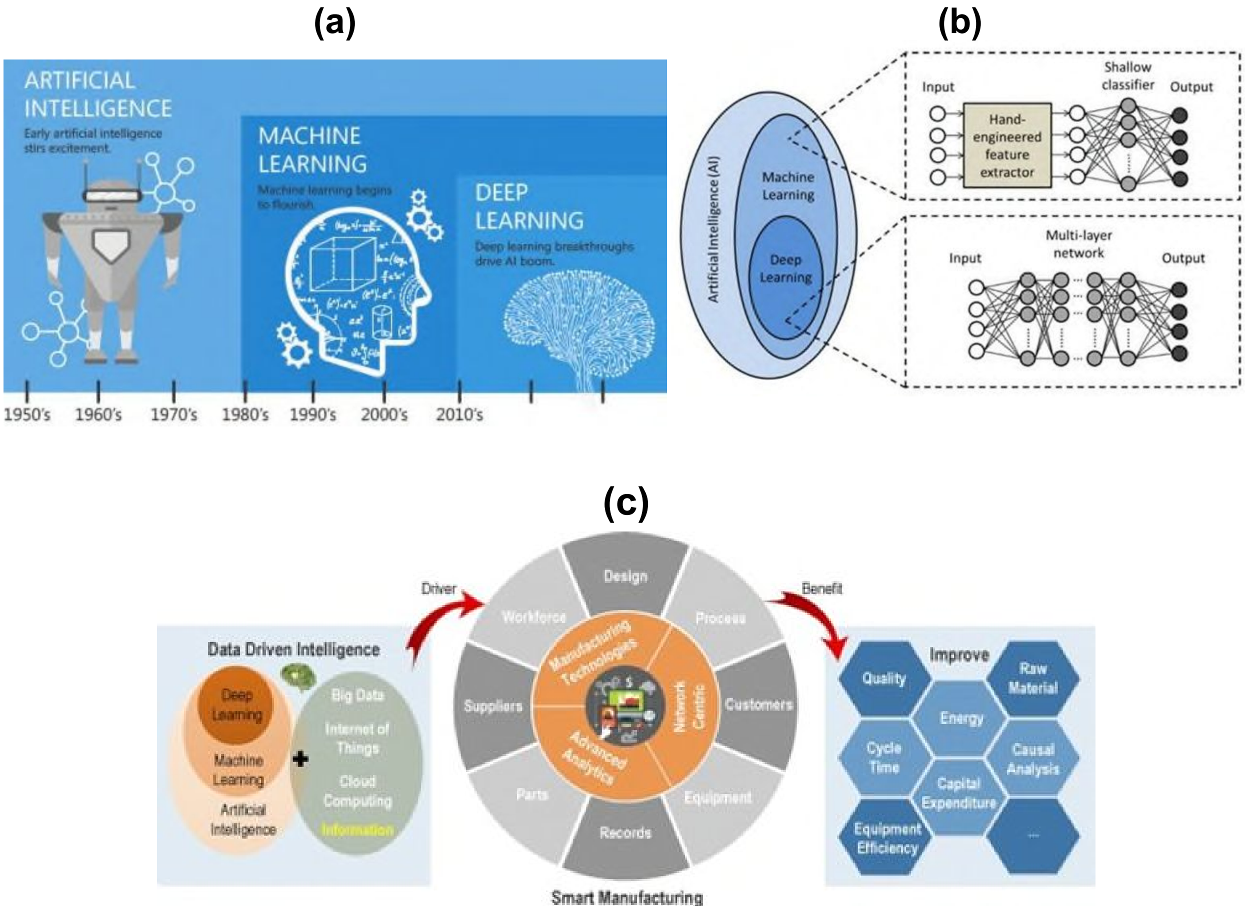


Fig. 19 Progression of AI, ML and deep learning (a) Adapted from thesis [307]; the relationship between AI, ML and deep learning (b) Adapted from MDPI [308] and data driven intelligence approach for smart manufacturing (c) Adapted with permission from Elsevier [309], Copyright Elsevier 2018.

5.1 Machine learning

The branches of ML are shown in Fig. 20(a). Further, ML algorithms can be divided into supervised, unsupervised and reinforcement learning, as shown in Fig. 20(b) [310]. In the training stage, the correct value has to be given for each input signal, this is called as supervised training, as shown in Fig. 21(a). The calculated output value is then compared with the correct value to check the error (%). In general, the output determined through the ML is the class of the sample presented in the input layer, as shown in Fig. 21(b). If the output value is not relying directly on the given input parameter, this kind of approach is called as unsupervised learning. The third one is reinforcement learning, it is useful to solve real-time problems based on iterations [311].

ML is useful in designing, manufacturing and predicting multifunctional properties of composites, as shown in Fig. 21(c-d). A faster convergence with better control could achieve by optimizing the process parameters through the ML approach, which replaces the traditional numeric optimization paradigm. Liu et al. reported that the ANN approach can be the best optimization technique for all stages of composites recycling [312]. Li [313] has outlined a fuzzy neural network approach in replacing conventional PID control in the filament winding technique and obtained better results in adjusting the parameters. Sacco et al. [167] reported that ML is useful in controlling and optimizing many process parameters in the AFP technique. Heider et al. [314] used five hidden layers neural network approach in optimizing process parameters in the automated thermoplastic tow-placement process and optimized better process parameters. The results obtained through this approach was matching with the numerical simulations.

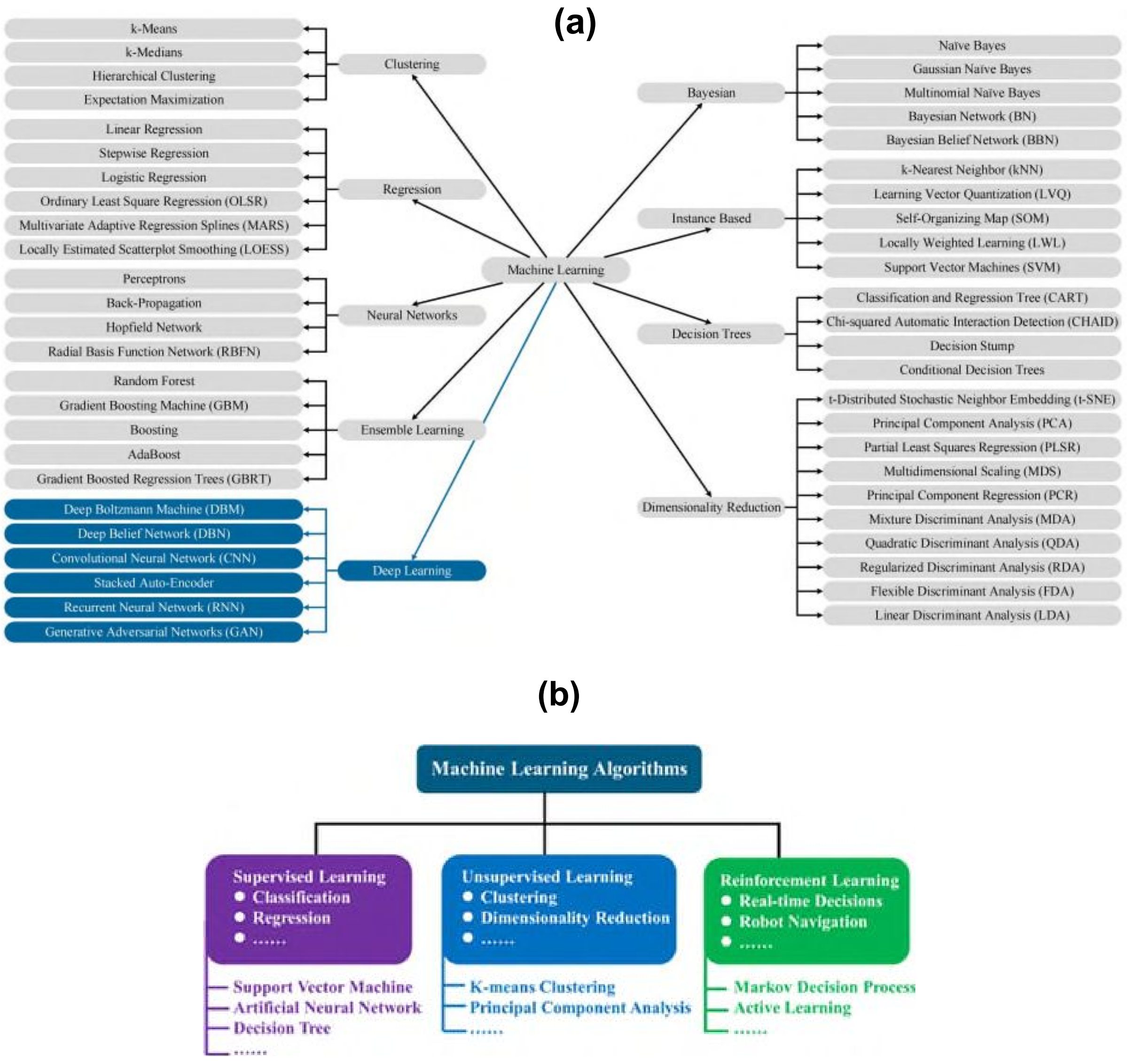
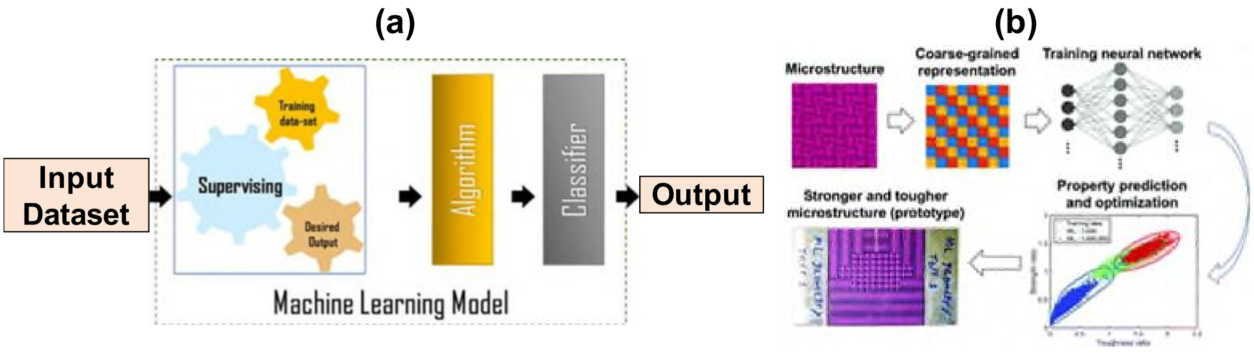


Fig. 20 Branches of Machine learning (a) Adapted from MDPI [315]; types of ML algorithms (b) Adapted from Wiley, open access [311].



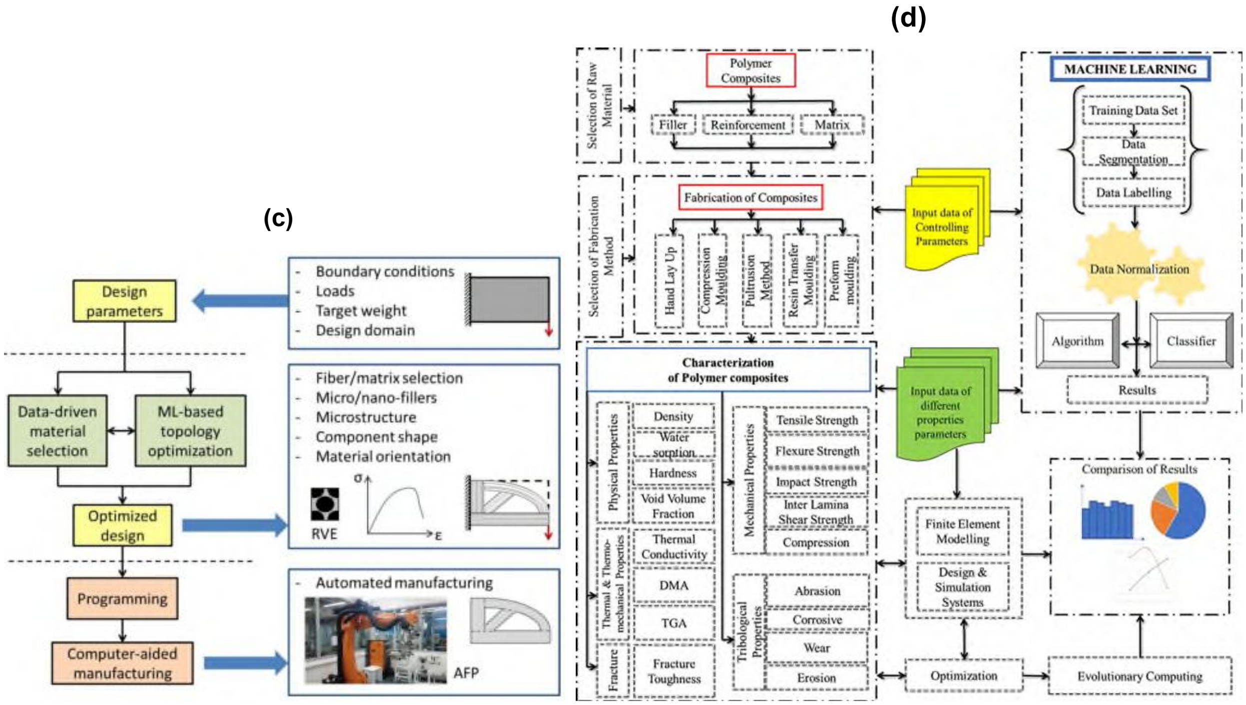


Fig. 21 Supervised training in ML (a, b) and application of ML in designing, manufacturing and predicting multi-functional properties of polymer composites (c, d). Adapted from MDPI, RSC and Elsevier with permission.[308, 316, 317].

Recently, Fernandes et al. [318] have employed the ML approach in processed Infrared Thermography images to identify the fiber orientation of randomly oriented strands. These kinds of ANN approaches can be used in determining the defects and damages in composites which are recorded using other NDE techniques. IRT NDE combined with a machine learning tool is useful to detect the defects automatically in NFRPCs [39].

5.2. Deep learning

Deep learning models can be divided into convolutional neural networks (CNN), deep belief networks (DBN), autoencoder (AE), recurrent neural networks (RNN), etc., [309, 319]. The application of these models for inspecting faults in machines, prediction of analytical problems in various domains, etc.

5.2.1 Convolutional Neural Networks

The working principle of CNN is based on a deep learning algorithm. Nowadays, CNN approaches have been widely used in processing images and videos [115]. CNN requires the input data in the form of the image, such that the set of variables based on pixel values can be reduced greatly for faster processing by adjustable weight. The various pieces of information in the image can be trained and enhanced with multiple filters, therefore, it can distinguish one from the other. CNN contains three types of layers, namely Convolution, Pooling and Fully connected layers. The key features in the input image are extracted through the convolution layer. The width and size of the output can be reduced using the Pooling layer and then the reduced data can be transferred into a column vector as an input to the fully connected layer. A fully connected layer works similarly to ANN, it consists of three layers, which are input, hidden and output layers (Fig. 22(a)). In that, each neuron in the layer can be connected to all neurons in the previous layer for predicting the output [307], as shown in Fig. 22(b). Fig. 22(c) shows the schematic representation of CNN employed by Ramkumar et al. [40] to predict the mechanical properties of NFRPCs. The total computational (CPU) time (including loading the network and the images, etc.) for predicting the permeability would be less than 10 seconds for 800 images, as shown in Fig, 22(d) [41]. The CPU time of CNN is very low compared to FEA or CFD flow simulation tools, which required several thousand seconds to predict the permeability. These findings confirm the advantages of employing CNN.

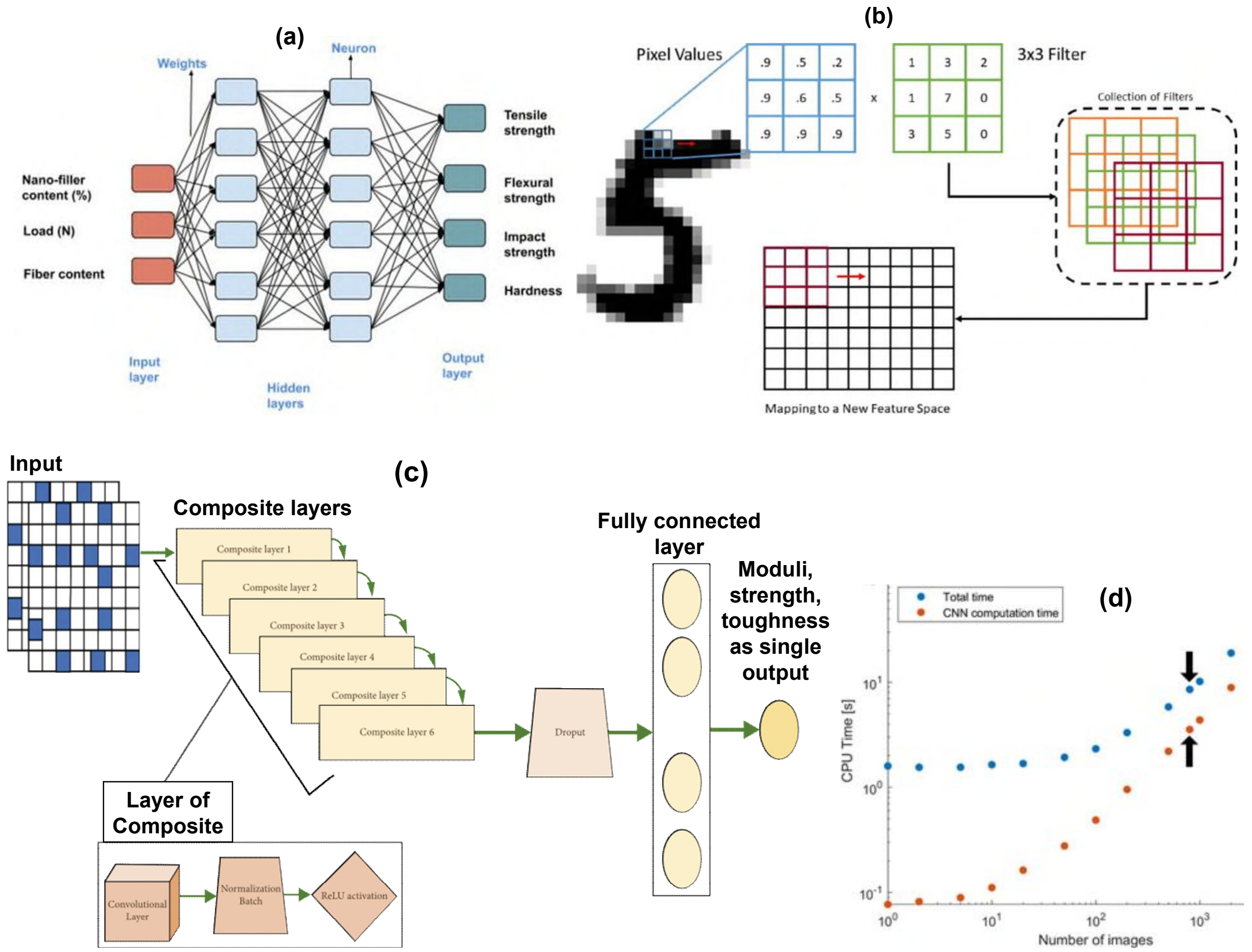


Fig. 22 ANN approach to predict mechanical properties of NFRPCs (a) Adapted from MDPI [320]; Procedure for mapping of CNN (b) Adapted with permission from Elsevier [167], Copyright Elsevier 2020; Schematic representation of CNN to predict mechanical properties of NFRPCs (c) Adapted from Hindawi [40] and its computational (CPU) time to predict permeability of fibrous structures. Adapted from Else5vier, open access [41].

In general, the microstructural information of most of the NDE recorded or scanned images are not clearly visible in the preprocessing stage. Therefore, it is essential to use reconstruction software packages to identify the information in recorded images before post-processing the data [35]. In recent times, trained deep learning tools are used for segmenting the NDE images to create digital material twins of fibers and composites [321, 322]. Also, it is useful in enhancing the image quality of NDE techniques by reducing the noise in the images, for clearly identifying the defects and damages in composites [38, 319, 323], as shown in Fig. 23. Mutiargo et al. [259] have used

U-Net, it is a deep learning architecture, to enhance the image quality of XCT scanned images and accurately detect the porosity in AM built samples. Jiang et al. [319] have predicted compression after impact properties of composites using CNN.

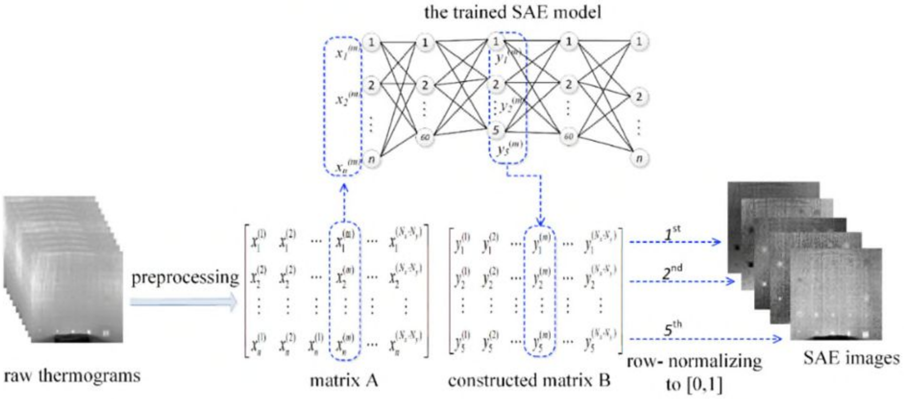


Fig. 23 Enhancement of image quality using stacked autoencoder (SAE) deep learning approach. Adapted from MDPI [324].

6. Future perspectives

- Limited studies have been found in manufacturing NFRPCs using AFP, ATL and TFP techniques. Further studies are required with these advanced fiber placement techniques, as the shape and dimensions of many natural fibers are not uniform, which lead to many defects.
- The studies related to 4D printing of NFRPCs are limited, except very few papers [129, 130, 153, 325]. However, these studies are important to understand the shape memory effect with respect to time.
- Modeling of NFRPCs using in-situ NDE techniques are limited compared to SFRPCs [270, 275]. In particular, these studies are very limited on plant FRPCs compared to wood composites [53], as shown in Fig. 24. These studies are important to conduct, which minimize the number of experiments and reduce the cost and process time, and

enhance the product quality by minimizing the defects [337]. Future demand for NDE techniques in different countries is shown in Fig. 25.

- Recently, researchers are being increasingly performing mechanical tests on SFRPCs by combining XCT and the digital volume correlation technique [326, 327]. These combined advanced techniques are useful to measure the deformations in 3D and minimize the defects in composites. However, these studies are very limited on NFRPCs [252], which will be useful to compare the microstructure in 3D and develop numerical models.
- The expensive XCT technique can be replaced with a hybrid approach (combining two NDE techniques (E.g. IRT and UT)), to obtain the same qualitative results for a very cheaper price [222].
- In recent times, European Union focus on Industry 4.0 which includes artificial intelligence, additive manufacturing, robotics, big data, etc., [46, 109, 328]. However, it is essential to apply the Industry 4.0 concept in adopting new technologies in designing, manufacturing and analyzing NFRPCS to develop high-quality environmentally friendly components in a shorter time. In particular, the adoption of digital twins with the help of NDE techniques in NFRPCS manufactured using modern techniques (AFP, ATL, TFP, AM, etc.,) adds extra benefit in maintaining residual properties of components. The service life of the component depends on residual properties of the component [276].
- In the past, the AI approach was used by several authors to predict the mechanical properties of NFRPCs [329]. However, to the best knowledge of the authors, there are no studies available to explore the best use of NDE combined with the artificial

intelligence approach (ML and DL). This combined approach will be useful in designing and manufacturing high-quality and environmentally friendly NFRPCs.

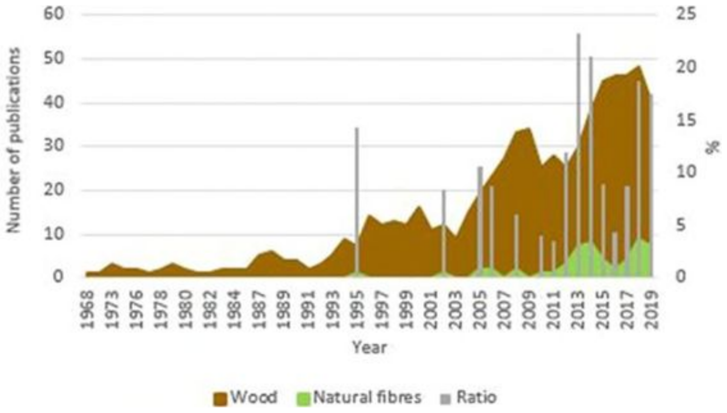


Fig. 24 Modeling of wood and plant fibers. Adapted with permission from Elsevier [43]. Copyright Elsevier 2022.

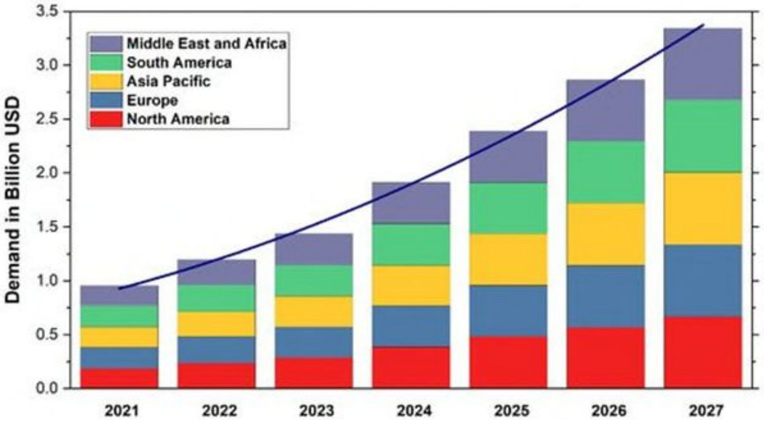


Fig. 25 Future demand for the use of NDE techniques in different countries. Adapted from MDPI [225].

7. Conclusions

In this review article, the important steps in the processing of NFRPCs using conventional and automated manufacturing techniques (ATL, AFP, TFP and AM) were presented. The advantages of automated manufacturing techniques over conventional manufacturing techniques were highlighted. Moreover, the challenges associated with the automated manufacturing techniques and the remedies to overcome those challenges were identified that could enhance the mechanical performance of NFRPCs. Further, we discussed the use of NDE techniques in understanding the evolution of defects generation at different stages of manufacturing, inspecting the defects and determining the cause of multi-scale damage and failure in manufactured NFRPCs. The applications and limitations of both contact and non-contact NDE techniques in obtaining the microstructural information were presented. It was shown that in the last 5 recent years, the higher number of published articles were related to XCT followed by digital image correlation.

The application of AI technology for designing, smart manufacturing, inspecting and post-processing the data was presented. We discussed the importance of artificial intelligence (AI) technology and different methods of ML and DL in enhancing the quality of NDE images before post-processing the data, and minimizing the analysis time through automatic defect detection techniques. Moreover, different ML techniques were discussed to reduce the size of the NDE data, which would be several gigabytes. The application of NDE techniques and Artificial intelligence technology for segmenting the NDE images to create digital material twins of NFRPCs were also highlighted.

It was concluded that the 4D printing of NFPRCs has not been thoroughly investigated, therefore, it is essential to conduct research in this area and utilized the full potential of NFPRCs in biomedical and robotic applications. The studies related to the comparison of XCT results of NFRPCs with the digital volume correlation technique are also limited, these studies provide the validation of XCT results and detailed deformation information of specimens in 3D, even though these studies are available for SFRPCs. Therefore, further studies are essential to potentially utilize the NFRPCs in manufacturing several eco-friendly components for various engineering applications.

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