Enhancing the Fracture Toughness of Biomimetic Composite Through 3D Printing

Sugumari Vallinayagam, Karthikeyan Rajendran, A. K. Ramya, R. R. Remya, and Leeba Balan

Abstract Strength, toughness, and anisotropy are all important mechanical features in 3D printing. Unfortunately, strength and toughness are frequently antagonistic, making it difficult to improve both at the same time. Here, a biomimetic composite is proposed to increase both the strength and toughness with in-plane isotropy. The optimal rotational angle, ultimate strength and toughness can be improved around 100%, respectively, along with good in-plane isotropy. The mechanics of the improvement, the fracture surface is investigated, and a finite element (FE) simulation is carried out. By keeping the stress at a modest level and maximising the fracture surface during its propagation, ideal mechanical characteristics can be achieved at a specific rotational angle. This approach is straightforward, adaptable, and has the potential to provide good mechanical reinforcement in extrusion-based 3D printing. This paper provides a critical view of the state of the 3D printing of composites of natural fibre or biocomposites for mechanical purposes and an overview of their use in 4D printing in stimulating applications. Due to unique process advantages such as rising porosity, Natural discontinuous, improved polymers with a low fibre content and very low fibre aspect ratio (L/d) have mild mechanical properties in comparison with standard composites. Fibre material, fibre control and fibre quality are defined in response to established diagnostic problems.

S. Vallinayagam (✉) · K. Rajendran
Department of Biotechnology, Mepco Schlenk Engineering College, Sivakasi, Tamilnadu 626005, India
e-mail: sugumari@mepcoeng.ac.in

A. K. Ramya
Veridian Micro Lab Pvt Ltd, OMR, Chennai, Tamil Nadu, India

R. R. Remya
Department of Industrial Biotechnology, Bharath Institute of Science and Technology, Selaiyur, Tamil Nadu, India

L. Balan
Bionyme Laboratories, No.109, 1st Cross Street, Shanthi Nagar, Chrompet, Chennai, Tamil Nadu 6000 044, India

A. Praveen Kumar et al. (eds.), *High-Performance Composite Structures*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-7377-1_10

Keywords Composites · Natural fibre · 3D printing · Hygromorphic printing · 4D printing

1 Introduction

Due to its ability to achieve complex Geometry, 3D printing technology is commonly used in aerospace, automotive and biomedical applications. Although it is used for making parts beyond the prototyping stage, the less mechanical characteristics of 3d printed parts have convert an important challenge for industry, especially for 3d printing technologies like FDM and ink writing (DIW) [1–5]. For these technologies, poor interfacial bonding, low infill density, and the anisotropy of the extruded filament cause inadequate strength and strength which are greatly affected by the direction of infill [6]. Arbitrary geometry potential microstructures and have encouraged an increase in the analysis of biomimetic composites. For example, staggered bone-inspired microstructures were printed with a multi-material printer which increased fracture energy by over 10 times under a static tensile load. The function of osteo-shape, interfacial waviness and mineral bridges was examined using similar methods, which uncovered the design motives of biomaterials [7–9].

Creatures consist of basic and complex organic materials organised in a complex hierarchy of nano to microeconomic dimensions. The biological materials' parametric structure has been developed and is basically multifunctional. The beings in nature after millions of years have almost perfect structures and functions. The Arapaima gigas fish scale for example is a synthetic body arms with excellent mechanical characteristics and high flexibility. Spider silk, nacre, and collagen, such as Bouligand, are all showing very good structures in shrimp claws [10–12]. Different plants (building pads, Flowers) and animals also have significant survival form changes and reproductive properties. In addition to thermal conductivity, many animals have other physical properties critical for their survival. The shark-skin surface morphology decreases drag forces in water dramatically, for example, from a hydrodynamic point of view, while the thermoplastic composition of the egg-beater surface in South East Brazil, Salvinia Molesta, ensures that the free-floating plant keeps booming in water. Animal vascular systems consist of efficient, multi-faceted blood vessel networks that carry oxygenated tissue blood, as well as the removal of CO_2 and industrial waste (Fig. 1).

Multifunctional biological systems and materials create an extraordinary variety of sensory skills in living organisms [13–15]. For instance, composite insect lips, in terms of visual sensory organs, concentrate on providing a wrapping view to allow people to look at each action, while an eagle's eyesight is four to eight times better than the average human. The human epidermis is very sensitive to movement, temperature and humidity [16, 17]. From an electro-chemical (galvanic) reaction point of view. An example of advanced ultrasonic condenser detection in bats reveals a highly precise environmental echolocation capability. These Biological

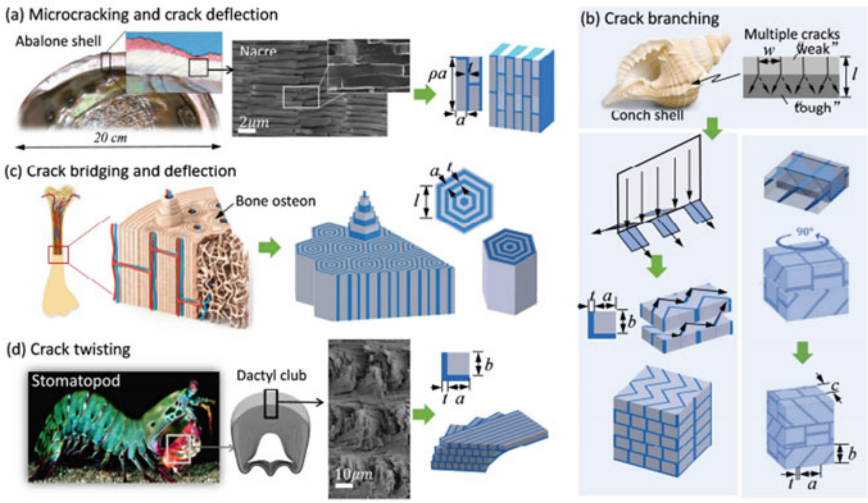

Fig. 1 Biomimetic microstructure architecture. **a** Brick and mortar microstructure in the abalone shell's nacreous layer. **b** The crack mechanism found in the conch shells is seen in the top. Underneath is the branch-lamellar (left) and the cross-lamella (right) Microstructures that imitate the shell's tough layer. **c** The concentrated hexagonal microstructure that simulates the structure of the bone osteon. **d** The stomatopod dactyl club rotating plywood microstructure. The photos of **a**, **c** and **d** can be adapted respectively. The grey and blue colors in the schemes reflect both the hard and the soft step. The geometric parameters defining the unit cells are also labelled

abilities and characteristics go beyond conventional engineering frameworks [18–21]. In addition to 3D polymers. In a selected process of laser melting, metals with dislocations arranged in hexagonal networks are printed, simultaneously increasing strength and ductility. Furthermore, magnetic fields and nozzle rotation are used to control fibre directions. To organize concentration, layered and spiral patterns that give tuneable stiffness and > 100% strength enhancement. In recent times, a number of bioinspired micro structures have been incorporated in one specimen using hierarchical/hybrid design techniques to increase impact resistance and customized dynamic performance combinations six times [22–25].

In this paper, we propose using a parallel-scan approach to improve the mechanical properties of 3D printed parts. Uniaxial tensile tests are a useful tool for determining mechanical properties, especially strength and toughness [26]. The toughness mechanism is then explained using various fracture surface analyses, which may aid in a better understanding of the tool-path optimization strategy. With the information presented in this chapter, both strength and toughness can be significantly improved simply by altering the rotation angles in the printing tool path; no special equipment or complicated material treatment is necessary [27–30]. This could be a very practical, low-cost, and broadly applicable technique for improving mechanical characteristics in 3D printing.

2 Composites Using Fields-Assisted 3D Printing

The excellent mechanical properties in anatomic tissues are described by mineralized polymers. These composite materials consist of mineral enhancements like Calcium or silica Hydroxyapatite, biopolymer cell layer, such as collagen or chitin. Additive manufacturing grows for structural applications, from single materials and multimaterials to nanocomposites and 3D multipurpose printing. To reinforce the 3D impressed structures the addition of microfillers (e.g. ceramic platelets, micro-fibres) and nano-fillers (e.g. carbon nanotubes, graphenes, etc.) was developed [31–35] (Fig. 2).

The combination of shear, electrical and magnetic field methods and 3D printing has been developed to imitate biological structures in order to achieve anisotropic mechanical features with controlled filled coordination. These are classified as '3D Field Printing' and discussed in the following pages [36].

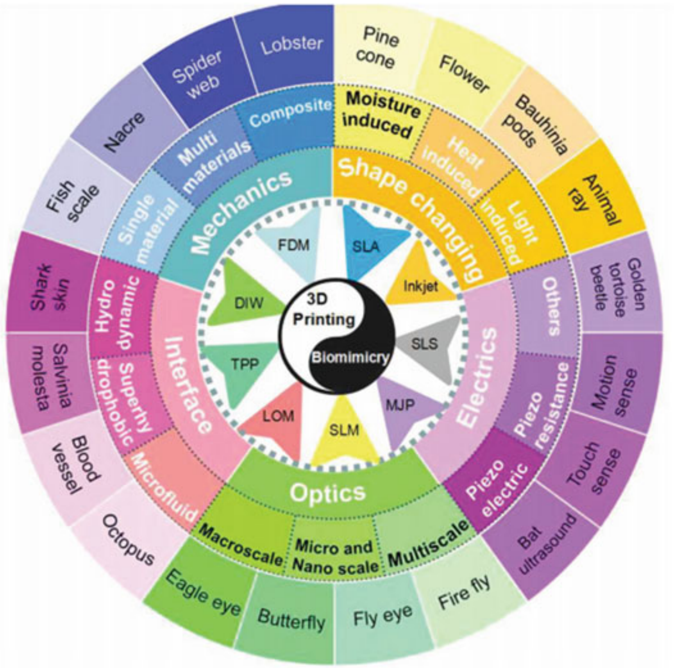

Fig. 2 3D printing and biomimicry integration, with 3D printing technology categories shown in the Figure

3 Supported Shear Force 3D Printing

The cellular water architecture is supported by rigid fibres and the low balsa weight of the pore web are two main buildings or installations in the environment. The shear strength was developed to reproduce these structures to obtain polymer resin aligned silicon carbide whiskers and carbon fibres. Force alignment was used to stabilise each wall Because of shear stress when extruding [37–41]. A class of composite enhanced carbon fibre aligned with DIW technology was also developed. Carbon fibres are aligned by the regulated micro-extrusion with epoxy or thermal aromatic resin and then transformed into complex geometric compounds. Similarly filled composites with uniformly oriented fibres outperform the carbon-fiber composites. The production of the FDM for continuously fibre reinforced thermoplastics supplied the head of the printing machine with polylactic acident and carbon fibres (or natural jute fibres) separately and the fibre filaments were fathered directly prior to printing [42–45]. The aligned carbon fibre sections had stronger mechanical characteristics than jute-enforced and non-reinforced thermoplastics. In a hydrogel with shear strength for Special biomimetic structures with changes in shape, 3D cellulose-related fibrils were printed. This leads to the generation of anisotropic modules that means that the Filament readily extends radially (40%) but not longitudinally (10%) [46] (Fig. 3).

The different growth rates contribute to the programmable folding behaviour of artificial flowers manufactured. Direct ink writing was also employed to build solid polymer composites made of aluminium oxide nanowires and flak graphemic shear strength [19]. The composite of graph/polylactide-co-glycolide is mechanical robust and multifaceted so that fine printed structures can roll, fold and evenly fusion [47–49]. A further tri-dimensional the shear force alignment printing process is the sintered metal process. The lateral oscillating shear flow and SLA printed image

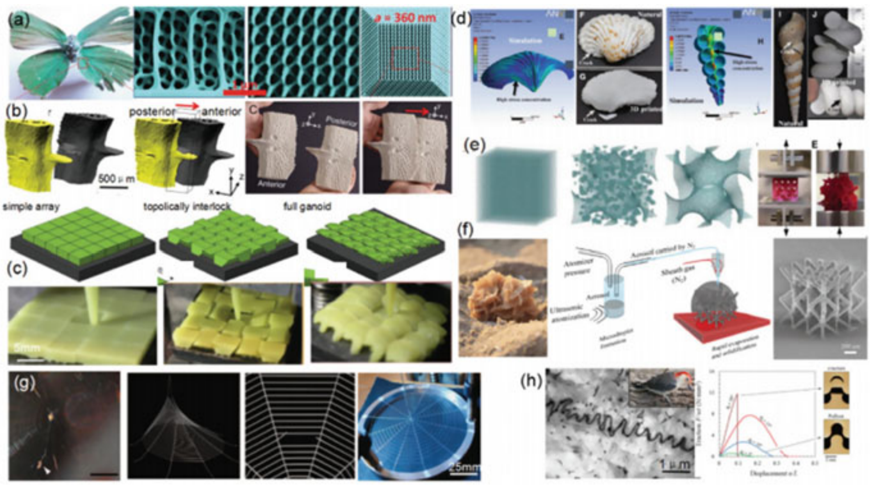

Fig. 3 Bioinspired mechanics reinforced 3D-printing structures with single material

matched the nanowire aluminium oxide [20–22]. The Tensile strength with aligned nanowires of aluminium oxide was increased by 28%. Helped 3D composite shear force printing enables the combination of the required Thermal mechanical, electrical and anisotropic properties with a scalable 3D printing process. This helps engineers to develop design as construction and rigidity Digitally adjusted in a 3D structure [50–53].

4 Bioinspired 3D Printing Magnetic Field

Due to its versatility in regulating the alignment of polymer resin fillers, a magnet field is commonly used in production processes. For example: magnetic templates and graphite electrodes are aligned magnetically to produce Electrodes with high-performance Li-ion battery [54]. The freezing help Magnetic Magnet field process monitors strength and rigidity alignments by doubling and rotating changes in order to create bioinspired ceramic spiralling. The Combined magnetic field and 3D printing was developed as a magnetic 3D printer, successfully using shrimp, bone, mollusc, and mantis-inspired architecture [55–57]. To track magnetic response particle alignment in the resin (decorating with super-paramagnetic iron oxide nanoparticles), Modulation was used [58]. The particle orientation in the individual voxels may be improved or weakened depending on the perpendicular (local) or parallel alignment (cracking). The printed 3D objects have also new mechanical properties such as programmable endurance, which cannot be accessed through homogenous monoliths or conventional production techniques [59]. Made a 3D field-responsive smart polymer composite for a wide range of applications, including soft robotic sensing, biomedical devices and independent systems. Various materials can be printed by simply filling in different syringes in the 3D (MM-3D) microprinting process with inks with various monomer compositions and ultrasound magnetic reaction (UHMR) concentration particles aligned with magnet or electromagnet spins [60]. The magnetic orientation in the directions of applied load of 15wt% (4.4% vol.%) Increases the power and elastic module by 49% and 52% respectively. In comparison to a shear-induced implementation, the magnetic adjustment approach may provide deliberate texture control with limited alignment directions to eliminate local swelling responses [61–65]. A MASC is designed to deposit particles in a layer-based additive cast technique, in order to track the path of the fillers during filtering using advanced gravitationally supported technology [66].

A bio-inspired in order to mimic the shape of the natural dental orientation, the synthetic tooth was made of an outer layer of enamel made of silica nanoparticles and aligned aluminium plates. All results show that alumino-silicate plates are aligned perpendicularly, resulting in a slightly denser and tougher synthetic enamel than the internal dentine layer [33–35]. To produce organic composites, a robust and universal magnetic field-based casting method was developed, which can replicate structures that alter their forms [67]. The controlled alignments produce anisotropic mechanical properties and their swelling/shrinking effects. On the basis of the design, the Stuart group Two forms studied of Composites of polymers. First of all, Controllability alloy oxide platelet alignment in hydrogels helps to imitate pinecones, are wheat and orchids trees seedpods by various plating behaviours. The second is the bioinspired form of the ceramic transformation by aligning the magnetic rotation with magnetised alumina plates [68–70]. Bending, rotating or modifying these two fundamental movements can be efficiently structured to accomplish a number of complex forms [36]. The combination of the magnetic field and direct writing was studied in addition to SLA and glitter casting techniques. Firstly, the fibre length must be small to control the shear force generated by the bucket and the system must be controlled in a low magnetic field [71–74].

4.1 Tariff Rate

Cosmic rays were actively used in the manufacture of reinforced fibre composites to Check the orientation of reinforceable Fillers (e.g. phosphate of calcium) microphones and Microphones of alumina) in epoxy [75]. In the magnetic field around the tip of the syringe, the three orthogonal iron-core solenoids were added. This technology is a successful way forward in the development of composite high-Optimal 3D printing resolution products. Magnetic films have been printed and compared with their magnetic properties with and without the particle alignment [76]. Increased permeability and decreased hysteresis loss were observed in the direction of alignment [42]. This is what we are talking about. Technique helps to prototype and develop new magnetic composites and related components for the application of inductors and antennas [77].

5 Bioinspired 3D Printing Helped Electric Field and Acoustic Wave

Dielectrophoresis (DEP) has been used to balance both AC and DC pottery field fillers, carbon nanotubes, graphite and glass polymer resin fibre. The electric field can be used in selected areas for the development of composites with uniformly oriented structures or locally modified surfaces [78]. Bio-inspired reinforced structure by manipulation of various alignments of multiple electrical field wall-mounted carbon nanotubes (MWCNT). The 3D printed Bouligand MWCNT alloys provide insight into the tough natural mechanism and the guidance in the design of structures for high impact resistance. It is also a workable way to print artificial meniscus that can be used for the reparation of Meniscal and other fibrous tissues defects, with increased mechanical efficiency [79]. Another Laminar composite production process, assisted by electrical field, has been developed to align micro-sized aluminium particulates with an electric field in a chain, for example structures in an ultraviolet photopolymer matrix. On the surface layer are embedded polymer/alumina particulate composites, and the sample is formed layer by layer [80]. For a range of electrical materials and geometries can be managed. The combination of electrical and inkjet printing leads to electrostatic jet printing technology in 3D (E-jet) [81].

For obtaining fine electrode patterns and analogue diagrams, e-jet printing was used [82]. There are several bio-inspired structures produced by the E-jet 3D printing process. E-jet printing in written form of predetermined bio-inspired geometries is possible by synchronising energy supply operations (electric hydrodynamics) with the translation level. Tints consisting of Single Walled Carbon Nanotubes (SWNTs) stabilised in the water are printed on a floral image. The essential dimension of 1 μm has been seen for future uses, including printed electronics and graphics. To generate small, high-resolution OLED pixels with 5 μm, there has been created another E-jet printing process. E-jet technology was also used to create bio-inspired, bio-compatible and mechanically improved scaffolds [83–85]. The results showed that the E-jet scaffolds can direct and boost cell growth and improve the efficiency of wound healing. A near-field electrospinning (NFES) technology has been developed to construct direct 3D paper structures such as walls, hollow cylinders and logos with PVDF fibre. The new technologies will progress in biomedical, microelectronics and MEMS/NMES applications to construct 3D structures. Apart from the electrical sector, there was also 3D assisted ultrasound wave printing [86]. Two sparkling, flat waves were produced using glass fibres in a photocurable resin that Conducts mechanical anisotropic properties of printed objects. An acoustic addition thrilling micro-fluid printer nozzle is used in an epoxy matrix to customise the Printed composite filaments with SiC material, solid $BaTiO_3$ or hollow SiO_2 microstructure sphere [87–90].

The results show that acoustic focusing in mechanical composites is a promising method for controlling microparticles. As a relatively material agnostic approach to micro hardness control, the Acoustic 3D printing extends the library of printed fillers substantially and complements current and modern 3D printing technology [91].

6 Definition of 3D Printing Technology

3D printing is a tool for creating haptic physical object layers of 3D layers based on CAD models. Various printing methods were used to manufacture biodegradable polymers. There are known techniques including Modelling of deposition, selective lasers, 3D jet printing, stereo and 3D printing [92]. Few study groups are either creating or using others. Each technology it has its own composite output advantages and constraints. Depending on the starting materials, speed and resolution parameters, cost and performance requirements of the production process the end product. Modelling fused deposition (FDM) fused repository (FDM) modelling tends to be the most frequently used printers for the production of Composites of polymers [93]. Thermoplastics like PC, ABS, and PLA are widely used because of their low melting point. As shown in the figure, FDM printers operate with thermoplastic filament operated extrusion. FDM melts filaments in semi-liquid mode and Layer by layer, where layers are combined and fastened to the final elements, on the building frame. Printing parameters such as layer thickness, print orientation, raster size, Raster angle and air breakage are used to monitor the consistency of the printed component. One common inconvenience of FDM is that in order to allow extraction operation, titanium alloys must be produced from filaments [94].

During the development of composite filaments, the vacuum produced is difficult to uniformly spread. Another drawback of FDM printers are the materials used are confined to natural materials with the necessary melt viscosity. The viscosity of the molten material should be sufficiently high to help the structure and Low enough for extrusion to be permitted. The support device used during printing can also be difficult to remove completely [95]. Despite these disadvantages, FDM printers still have advantages such as low cost, high speed and simplicity. Another value of FDM printing is ability to deposit various materials simultaneously. Many extrusion nozzles can be programmed for loading different materials in FDM printers so that printed sections of a built-in structure can be multiple [96].

6.1 3D Printing of Powder and Inkjet Head (3DP)

The Massachusetts Institute of Technology created the powder-fluid 3D printing technology as a rapid test technology in 1993. (MIT). This technology is focused on the processing of powder. Powder is first stretched on the platform and then added selectively to a built layer via an ink-jet head, which can go in the direction of XeY [97]. If A 2D pattern will be created, the platform will decrease and the next powder layer will be extended. This process is repeated and unbound powder can be extracted to finish finished products. By altering the deposited binder, the internal structure can be changed. The quality of finished products is dependent on the dust, binder viscosity, binding and powder contact, and binder deposition rate [98]. The main benefits of this technology are the versatility of material selection and the environment for room temperature processing. In principle, this technology could be used to print any polymer material in powder state. With this approach, it is reasonably easy to eliminate the support system. However, other contaminations can be found in the binder used, and the print resolution for this technology is very little [99].

6.2 Stereolithography (SLA)

Stereolithography uses photopolymers in ultraviolet laser therapy. The UV laser is worked in the resin reservoir in the desired direction, while the photocurable resin polymerizes into a designed two-dimensional sheet. The platform is lowered and a further Uncuring resin layer is ready model after each layer has been cured as shown in the figure. The popular SLA polymers are acrylic and epoxy resins. In order to track the consistency of the finished pieces, the curing reactions during polymerisation are important to understand. Laser intensity, scanning speed and exposure period affect the time and resolution of the printing process. In order to monitor the degree of polymerisation, photo initiators and UV absorbers may be added to the resin. The key benefit of SLA printing technology is its ability to print high-resolution components. Moreover, the issue of dust obstruction can be avoided, as SLA is a non-dust technique. The high costs of this method, despite these advantages, are an important industrial application concern. Another concern is the potential cytotoxicity of the untreated resin and the residual photoinitiator [100–105].

6.3 Selective Laser Sintering (SLS)

The technology of direct metal Laser sintering is similar and powder processing based on the above 3DP technology. Rather than using an SLS fluid binder, a laser beam powered route scans the power to heat it, combining adjoining powders with high-energy lasers with mass transfer and processing the next sheet [106]. Unbound powder should be extracted for final products. The resolution depends on the particle size, laser power, scanning distance and scan speed. While a thermoplastic polymer can technically be processed in powder with the SLS process, the complex consolidation and molecular energy distributed by sintering the selection of products used in the SLS process is small. Laser sintering materials are currently widely used in polycaprolactone (PCL) and polyamide (PA) [107–109].

6.4 Direct-Write/3D Plotting

The 3D plotting is based on the extraction of viscous material from a pressurised syringe. The Siren head will move in 3 components and the platform remains stationary when the moulded materials are joined layer by layer. The mixing boxes can dispense two reactive components, or activate them by thermal or UV light. UV light. Material can in some cases be sent to a plotting medium to complete the treatment reaction. The viscosity and deposition speed of the material is related to the consistency of the printed materials. The key value of this approach is the versatility of materials. 3D Plotting Printers are expected to have all loading solutions, pastes and hydrogels. Temporary, ritual sacrificing Material may be necessary to protect the printed structure, because raw viscous materials have a limited rigidity which may break down complex mechanisms [110–112].

6.5 Additional Methods

In recent years, several new 3D concrete printing technologies have been developed, such as PolyJet used to polymerize deposited photopolymer droplets or DLP based on selective polymerization of the whole photopolymer surface by light projection. These methods have either more choice of content than conventional 3D printing techniques or less processing time. However, these new methods are implemented by only a few researchers due to their high costs and difficulties [113].

Polymer materials are widely used in the 3D printing industry due to their low mass, low cost, low-end conditions and versatility of manufacture. While 3D printed polymers can be geometrical, the lack of structural resistance and flexibility is a major challenge for all of their applications. To address these problems the combination of different materials to achieve the desired mechanical and functional properties are promising. Consequently, the production of composite materials compatible with available printers in recent years has attracted considerable attention [114–118]. In the production of new structural printable materials strengthened by particles, fibres or nanomaterials, many promising results have been demonstrated. The reinforcement of particles is also used to improve polymer matrix properties because of its low cost. Particles are easily combined in powder or liquid in SLS with polymers, or are eventually extruded into printable FDM filaments. The Different polymer enhanced particle materials used in 3D printing and the resulting composite properties [119, 120].

The primary considerations for 3D particle prints are the improved tensile/storage module through the addition of glass beads, copper and iron pearls, improved resistance to wear through the addition of aluminium and Al_2O_3 and enhanced dielectric permittivity through the incorporation of ceramic or fragments of tungsten. In these cases, cuboid or cylindrical sections were made with FDM, SLS or SLA and improved properties were observed [121]. An exciting development in the field of 3D printed particle enhanced Composites is the potential for future real-world applications to print structural components [122]. Recently, SLA technology used to produce a composite heat sink structure, as the figure shows. This composite structure is composed of microdiamond acrylate resin particles up to 30% (w/v). When heating the sinks at the same temperature, the temperature of the composite heat sink was above that of pure polymer heat sinks and the added diamond particles indicated an increased heat transfer rate. Printing of barium titanite ($BaTiO_3$)/ABS diamond photonic crystal structures in another piece. Enhanced. The integration of $BaTiO_3$ particles was observed and adjustable dielectric relative permittivity. The relative permittivity of a printed composite increased 240% compared to 70% wt percent of the $BaTiO_3$ charge compared to Pure polymer [123–125].

In order to modify size patterns, the main components of the effective permittivity tensor can also be tuned in this work due to the flexibility of 3D printing technology. It also helps to introduce particulates to polymers to solve these printing problems. The distortion of final printed components because of thermal polymer expansion is an obstacle to FDM printing. The incorporation of Polymer metal particles has proven an effective solution to this problem. ABS composites showed a substantial decrease in the coefficient of thermal expansion in combination with copper and iron particles, which significantly reduces the distortion of the imprint content [126]. The anisotropic 3D printed component properties, which can have advantages or drawbacks depending on the application, are another characteristic feature of FDM printing. In case of isotropic load conditions, the low tensile strength and modulus cause the printed component to fail in a direction perpendicular to the construction orientation. Thermoplastic elastomer is a promising mechanical anisotropic additive reduction (TPE) [83]. The TPEs prepared in two directional perpendicular composites based on ABS and the results of the tensile test showed the difference in tensile strength, thus demonstrating reduced mechanical property anisotropy. In another recent research a new magnetic-assisted 3D printer platform has been designed to monitor particle trajectory by including magnetised alumina platelets into the polymer matrix [127–130].

7 3D Printing Bioinspired Shape Shift Structures

Structures most versatile or receptive still work on a complex basis in the engineering world.

7.1 Modern Types of Actuation and Sensors

This means that the sensors detect stimuli for the environment and send electrical signals to the actuators. The sensing and action of these systems is energy intensive and relies heavily on expensive and failure-prone mechanisms. In comparison to human structures, Nature provides many examples of climactic processes that metabolistically modify their forms. In other words, natural systems change dynamically without active metabolism and fully react to inherent materials and structures. For example, plants such as pine cones and Bauhinia pods display varying moistures in their seed dispersal units. It ensures that seeds can only distributed through the climate when properly hydrated by water. Several attempts have been made to replicate improvements in nature [131]. Because of its versatility in managing the material supply in structures, 3D printing has drawn considerable attention to all available methods. Four-dimensional (4D) printing identifying the class of structural printing technology. Readers searching the new 4D printing will receive excellent reviews. This section mainly discusses the major barriers to the transition of shape and some Recent developments in 3D printing of biologically based structures [132].

The main concepts form change in a large number of plants can be caused by anisotropic cell wall swelling characteristics consisting of steep microfibrils in the direction of the hygroscopic matrix. The composite structures swell ideally towards the microfibrils when exposed to water. The two layers of orthogonal fibre structures will lead to differential water swelling between the top and bottom layers, often leading to bending or twisting motions in two orthogonal directions due to anisotropic contraction. Inspired by these structures, a typical structural design paradigm that changes its form includes receptive materials that change shape in the Architecture anisotropic. This structure is retracted/extensive, or even distorted and twisted. Guided by controlled mode, such as moisture, heat, light, etc. [133–135].

7.2 Classical Indentation-Based Methods

The scheme stated in the Fig is that precise measurement of radial cracks at the edge of a Vickers mark (or Berkovich) indentation tests sharp indentation-based models for toughening fractures [1]. Perhaps the final version reduces image dimensions. The first Lawn-Evans-Marshall (LEM) the famous equation:

$$K_c = \alpha \cdot \sqrt{\frac{E}{H} \cdot \frac{P_{\max}}{c^{3/2}}},$$

where A is the average crack length, H is the material hardness, and P is the whole load applied during the indentation process [136]. The coefficient for a collection of brittle (bulk) materials was calculated experimentally and determined to be 0.016 for the 4-sided pyramidal indenter Vickers. Further research discovered that the original LEM model was only suitable for brittle bulk ceramics because radial crack diameters are typically much bigger than the indentation point, or 'half penny'. Coefficients for various indicator geometries that are specialised. If the crack shape differs substantially from half a penny, using the LEM model can result in a mis-estimated (or at least in exact) fracture. strength estimates [137]. In the last several decades, numerous other models have been proposed to take account of various potential Crack geometries and variations of content property. The choice between the right model for determination toughness of the Indentation fractures depend on the shape of the geometry of the cracking system, e.g. median, radial, half-penny, cone or lateral cracks or the pyramid indenter geometry [138].

CZ-FEM has been employed in more recent research to simulate inelastic densification, plastic deformation, fracture nucleation, and increase after strong indentation. Such studies show that the α coefficient of the LEM model actually depends significantly on the E/H ratio (or, similarly, the E/Factory where production stress is, the Poisson ratio and geometry of the indenter. In particular in broken materials with E/μy ~ 10, mid-crack geometry is prevalent, while the geometry of radials (often known as Palmqvist) is the more likely single Andallic (E/5-0y ~ 100)90. Detailed functions on the coefficient α are found in references for a wide range of material properties and an indenter angle scan that can be effectively utilised in the proper use of indentation-based methods to assess fracture strength [139]. In practical situations, the choice of the best model to use can therefore be extremely difficult due to (a) potential uncertainties in deciding the E/μy ratio and (b) residual material tension. The latter is critical for thin films and coatings in which, following a sharp indentation test, a compressive residual stress could prevent the development of radial cracks. New experimental methodologies were recently suggested to address the apparent limits of the Classical indentation-based fracture toughness test method on a micron scale. Such methods typically utilise a nano inventor to test microscale specimens of various geometries created by the processing of the focused ion beam (FIB). The sample of geometries which include pillars, membranes, micro-inspired specimens, beams with double clamps and single and double beams [140].

The method of division of Pillars based on a sharp micropillar nano indentation. This technique is particularly useful for testing thin ceramic films. The very versatile and important approach to the study of fracturing processes in fragile and semi-breakable materials [141].

8 3D Printed Polymer Composites Application

Biomedical system Three-dimensional tissue and organ representations are available been improved by the improvement of CT and MRI technologies with higher resolution. The 3D printing technology can produce Patient tissues and organs with detailed 3D microarchitecture using image data acquired. Currently working in the field of biomedical materials, the polymeric materials concerned are based on derived natural polymers (gelatine, alginate, collagen, etc.) or on synthetic polymeric molecules (polyethylene, polylactic co-glycolic acid, PLGA), etc. Printability, biocompatibility, mechanical properties and structural characteristics for biomedical applications are the necessary features of printable materials [142–145].

For a good transplant and function it is critical that the printed 3D parts interact with endogamous tissue. Scaffolds are essential for the physical connection between cell penetration and proliferation in tissue engineering. Traditional technology Cannot integrate internal architecture and monitor scaffold porosity. 3D printing solved these problems by testing the pore size and distribution of scaffolds in pores. The inclusion of bioactive particles into polymer has printed composite scaffolds with high biocompatibility [146].

Polymers that are biodegradable and biocompatible can maintain scaffold's resilience and improve biocompatibility through breakage of bio ceramic particles. A highly porous 3D biodegradable PLA/bio glass was produced using a nozzle-based printing system. The microscopy of the scan electron shows a standardised and repetitive 3D frame architecture. The addition of glass particles enhances PLA polymers' adhesion and improve their robustness and hydrophilicity. Tissue engineers also used additional synthetic calcium phosphates like hydroxyapatite (HA) or tricalcium phosphate to develop biocompatible composite scaffolds using 3D variable printing systems (TCP). The materials effectively produce nano-micro-topology in composite rims and improve skirts' hydrophilicity, thus enhancing skirmishes' bioactivity. In vivo experiments with printed composite scaffolds have also been performed. Composite FDM printed PLGA/TCP/HA grooves were successfully implanted in femoral rabbit bone defects to facilitate bone reposition and eventually biodegradation of the grooves for weeks [147].

Biofabrication with live. Another latest paradigm for the 3D print polymer composite applications in the biomedical industry is tissue and organ transplantation cells. Several tissues and organs have been successfully printed to fulfil the requirements for transplant functionality. These include ears, vasculatures, aortic valves, structures of cartilage and structures of the liver tissue. A 3D Bioplotter was used for printing a complex structured ear consisting of PCL and hydrogel seeds. The composite ear fulfils indigenous ear geometry and anatomy. Tissue generations occurred successfully Manufactured in the composite structure. Another example used silver nanoparticles to improve the auditory sensing of the printed ear in the hydrogel seeds matrix [148].

8.1 Electronics

The use of 3D printing would minimise the production time for geometrically acceptable electronic prototypes. 3D printed polymer composites and electric conductive materials may be used for different purposes as electronic devices. Electronic sensors from piezoresistive sensors were developed via FDM carbon black/PCL composites. By changing electric resistances, the piezoresistive sensors could feel mechanical flexing, the capacitive sensors could be printed on customised interfaces or placed into smart vessel for detection of the Presence and water scarcity. For use in printed electronics, the 3D printings of CNT/epoxy nano-composites using the UV-assisted direct writing technique have also been published [149, 150]. This composite material was used to create a highly electro-mechanically sensitive piezoresistive sensor (gauge factor ~ 22). These practical sensors display the promising use of 3D printing on electronic devices. 2D flat surface printing is the base of conventional printed electrical circuits [151]. For instance, silver capsulated composite particles were a conductional toner on flexible substrates for electrostatic printing. The written leading paths are approximately 104 U cm conductive. However, electronic prototypes that must be incorporated into real-world application in more suitable formats so that prototypes are authenticated in the earlier development period. Recently attempts were made to create 3D structural electronics [152].

An optical light processing printer used silver and attached photopolymer created a 3D electrical circuit connector. The 3D porous structure created using water emulsion printing oil was immersed in the scatter of silver nanoparticles and subsequently sintered for conductive percolation pathways. The adjustment of processing parameters can manage the porosity and the entire surface of the printed 3D structures and theoretically manage electrical conductance [153]. The CNT/PLA liquid deposition composite modelling 3D structural electronics was also used. Direct deposition with a high volatility solvent was made of the homogenous PLA CNT dispersion and a rigid 3D microstructure formed following solvent evaporation [154]. The 3D flexible tissue conductive structure printed from this material is used in order to produce a simple circuit which activates a commercial LED and thus shows the usefulness in microelectronics [155].

Three-dimensional electronic devices were also developed during the printing process by encapsulating metal wires in a polymer matrix. This printing approach is comparable to how better continuous fibre composites are made. Copper wires and molten copolymers were delivered separately in styrene blocks. The two-phase composites were used as an open membrane transition which resulted in a pressed touch bending of the membrane and shortening the copper wires on adjacent polymer layers together [156].

8.2 Aerospace Applications

Many components of aerospace Complex geometries that take time and are expensive to make. 3D printing is therefore highly appropriate for the production of these pieces. Most aerospace products, including exhaust engine components and turbine blades, have been printed 3D using metallic materials until now. Because metals are usually stronger and flammable than polymer materials. Several institutes of research have been researching recently ways of applying aeronautical 3D printing of polymer composites Because of the strength of composite polymers. The air foil and propeller were displayed on a 3D printer with glass fibre and photopolymer composites. The use of these aerospace product materials produces high-faith and reproductive replicas from the digital model [157–159].

The strong mechanical property of printed components is favoured by an excellent relation between layers. Polymer composites capable of withstanding high temperatures for aerospace applications were recently printed. The FDM process has been used by the Glenn Research Centre to develop the Ultem 1000 inlets guide and chopped carbon fibre inlet and the This composite structure's operating temperature could exceed 400 F. Unable Unthinkable Artefacts has likewise declared their ability to manufacture aerospace composites for Enhanced polyether ether ketone high-performance carbon fibre (PEEK). The Compounds are heat-resistant to 482F and lighter than regular aluminium components 50% and maintain 2/3rds of aluminium power. This content was printed on air foil, rotor support arm and air intake [160].

8.3 Biomimetics and Its Applications

Peel & Ball (2010) The work currently has an easy and artificial arm, which gives the ability of Rubber muscle Actuators (RMA) a greater strength than usual, and provides

Author (year)	Average particle size	Effect on fracture toughness
Alhareb et al. (2015)[32]	NBR (>150 μm), Al_2O_3 (4.4 μm), YSZ (1.05 μm)	Significant increase
Asar et al. (2013)[31]	ZrO_2 (8.6 μm)	Significant increase
Hosseinalipour et al. (2010)[7]	SiO_2 (20–50 nm)	Significant increase
Watanabe et al. (2008)[40]	SiO_2 (5–20 nm)	Significant increase
Ahmed and Ebrahim (2014)[38]	ZrO_2 (5–15 nm)	Significant increase
Protopapa et al. (2011)[42]	Diamond (4–6 nm), clusters (20–60 nm)	Significant increase
Topouzi et al. (2017)[39]	SiO_2 (12 nm)	Significant increase
Ornaghi et al. (2014)[30]	Glass (1.9 μm)	Increase
Chan et al. (2007)[37]	SiO_2 (40–120 nm)	Increase
Elsaka et al. (2011)[41]	TiO_2 (21 nm)	Increase
Balos et al. (2014)[103]	SiO_2 agglomerates (50 nm)	Increase

Fig. 4 The influence of filler size on dental composite fracture toughness

a portable bracelet wrestling platform for students recruiting. Kingsville Arm One & Two TS actuators are McKibben-like actuators made of composites made of fibre-reinforced elastomers. These actuators are very heavy and contract like a human muscle. RMAs generate higher t strength than typical McKibben actuators and have less-blow-outs due to optimised braid angles and ends which pass burdens across the braid fibres [161] (Fig. 4).

To address feedback from existing prostheses that overlooked many of the lubricant and joint capsule functions, a new artificial joint system with bionic joint capacitor was suggested and created. Medicinal lubricant, prosthetic joints, and artificial joint capsule were all present in the new construction. The grain filtered through a capsule reduces prosthetic joint wear while also preventing wear particles from escaping into the liquid body. As a result, unintended interactions between the wearer's particles and the liquid can be completely avoided. Meanwhile, for the bionic artificial joints with the joint cap, a three-dimensional (3-D) analysed finite element (FEA) model was developed [162–165].

The earthworm-like robot model in the F2MC segments under review of their actuators. It explores a new F2MC application in the field of bionics. First, the general film model of the robot is built with earthworm-like locomotion. On the basis the locomotive function of this model is evaluated to determine output of the F2MC section. Then an F2MC segment analytical model is used Finite deformation under internal pressure to be estimated. This specifies the optimal F2MC segment configuration that meets the needs of an actuator [166].

A conceptual design is proposed for the Earthworm-like F2MC segment robot. Then the robotic gaits are designed with some physical assumptions based on the cinematic locomotive mechanism. Guided locomotive can be accomplished on the basis of the installed gaits. In order to improve the robot's average speed and motion performance, locomotive gaits are programmed. Optimal gaits are obtained that lead to maximum speed and locomotive efficiency respectively [167].

The use of pneumatic artificial muscles (PAMs) for lightweight design and superior static performance in robotics applications. Further PAM advantages include highly specific workload, high strength Density, basic nature and long tiredness. Previous robotic research use of PAMs based on the use of large, systematic PAMs [168].

The non-linear behaviour, influenced by biological systems (for example, human airways), to solve One of developing countries' most important subsistence farmers is the dearth of entree to affordable and water-efficient irrigation systems. An effective way of supplying crops with water is through an emission network with plants consuming 85% of the water supplied. However, only 61 million of 140 million hectares of cultivated land are irrigated in India and only 5 million by drip irrigation. Partly because of the relatively high cost of irrigating the drip. The key costs are Pump water at relatively high pressure (>1 bar), reduce the upshot of irregular ground and gluey fatalities on the system and certify that the identical expanse of water is obtained by every plant [169].

Technology Strategy Board (2008–2011) focuses on the concept of biomaterials as materials used for a biological system or as materials from a biological source. These can be mixed in some situations. Biomaterials can also be viewed under the first Definition as a group of structural, functional, or multifunctional materials that behave in a biological setting. Applications include applications catalysis, biomedical engineering and biodegradable containers and packaging. Biomaterials are also discussed in the KTA and KAA methods of Biosciences and Medicines and Healthcare [170] (Fig. 5).

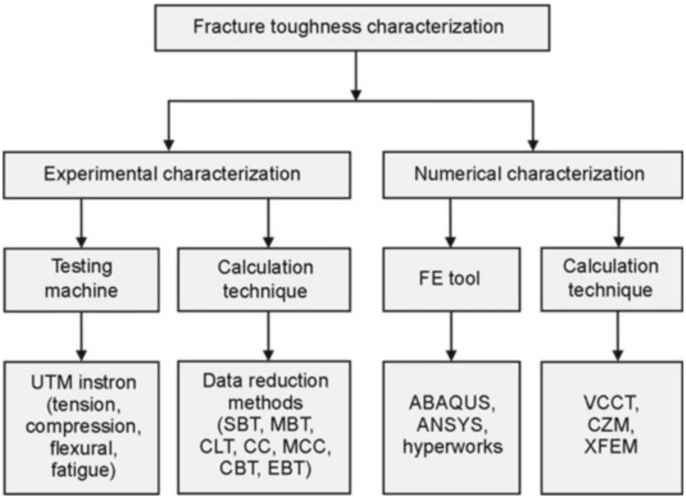

Fig. 5 Characterization of fracture toughness

A new artificial joint system thru bionic cooperative capacitor stayed future besides built by Suet et al. (2005) to solve feedback from existing prosthetics, which ignored many Functions of lubricant and joint capsule. The new construction included pharmaceutical lubricant, prosthetic joints, and an artificial joint capsule. The grain filtered by a capsule minimises prosthetic joint wear while also keeping wear particles out of the liquid body. As a result, unintended interactions between the wearer's particles and the liquid can be completely avoided. Meanwhile, for the artificial bionic joints with the joint capsule, a three-dimensional (3-D) finite element analysis (FEA) model was built [171].

The earthworm-like robot model in the F2MC segments under review of their actuators. It discusses a recent F2MC application in the area of bionics. Next, the robot's general film model has an earthworm-like locomotive. This model evaluates the locomotive mechanism to determine the performance of the F2MC section. An empirical F2MC segment model is then used to estimate finite internal deformation strain [172].

Briefly discussed are the two basic types of biomimetic approaches. The technical plant stem is a biomimetic product with structural and functional qualities similar to those found in plants. The key botanical Models are the stalks of the Rush of the Netherlands (Arundo donax, Poaceae) (Equisetum hyemale, Equisetaceae). The physical concepts were studied, extracted from their structural and mechanical properties and extended eventually to scientific applications [173]. Modern computer-controlled production methods for production of technical textiles and the structuring of the composite materials integrated matrix build unrivalled opportunities transition into technical applications of the complex structures contained in plants frequently optimised at various hierarchical levels. This process is comprehensive for the biomimic, lightweight, fibrous, advanced textile composite material with optimised mechanical properties and a gradient structure [174].

Addressed the creation of modern versatile and mobile collector systems, Based on the polar bear fur and skin solar function. A translucent spacer textile and silicone-coated Fiber polymer are included in the transparent heat insulation material. The unit is translucent when exposed to visible light but opaque when exposed to UV light. Due to its composition, it exhibits less convective heat loss. The emission of long-wave radiation will avoid heat loss by means of an effective low-emission coating. Appropriate silicone surface treatment protects against soiling. Full flexible solar collector systems are being built more isolation products and flow systems in conjunction [175].

Removal of coloured materials was found to be difficult and costly in dye house effluent. Explored a new method using a single oxygen producing material applied to fabric surfaces. These materials produce single oxygen when exposed to light that is able to kill several coloured organisms. The fabrics developed in this process have proven to contain singlet oxygen. In addition, when exposed to visible light, a thionin-containing solution (one of the methylene blue derivative dyes) was decoloured in the presence of these fabrics. Moreover, E. Coli are immune to this medication and thus are not supposed to have a harmful environmental effect [176].

Using material property charts and indications of the materials, the cuticle's amazing mechanical performance and efficiency were examined and compared to that of other materials. There are four in this paper: Young module density (starring by unit weight), Young basic Modular strength (elastic hinges, unit weight elastic energy storage), young modular durability (fracture Resistance and toughness under various load conditions (wear resistance).Together These diagrams help to illustrate the significance of a fibrous composite microstructure (for example, fiber-orienting effects on tendons, joints and sensory organs) and shape (including surface structure) for a certain reason through a cuticles structural analysis [177].

Suggesting a new strategy explaining the Biological and technical approaches have varying degrees of difficulty depending on the quantity of various raw components: many (material dominates) materials or few (form dominates) materials or only one single material (structure dominates). With declining numbers of basic materials, the difficulty of the solution (in biology as well as engineering) increases [178].

Propose to mimic and exploit the natural capabilities of the bat, recognising the relationship between structure, features and function of the wing tissue. The first mechanical biaxial characterization of the skin in the bat wing describes main deformation mechanisms for the manufacture of biomimetic skin. In order to evaluate the relations entre tissue structure, characteristics and functional flight capability, both static mechanical testing of synthetic skins and aerodynamic testing are used [179].

Tries to consider the viability of energy harvesting using active compatible materials from the tail movement of a fish. It is suggested that the underwater vibration model structure of the biomimetic tail be a cantilever beam with rectangular cross section be assimilated. The Fluid effect is characterised by a nonlinear hydrodynamic function. Electromechanical system assesses and models the possibilities of the accumulation of energy from an IPMC connected to the vibrating structure. Experiments are conducted to validate theoretical expectations of biomimetic tail energy harvesting [180].

Via electrospinning techniques, draft a series of new nanostructured 3D biomimetic scaffolds based on carbon nanotubes or biocompatible polymers (PLLA). In particular, a series of electro spun fibrous PLLA scaffolds were developed in this study with regulated fibre dimensions. In vitro hMSC experiments have shown that stem cells tend to bind smaller fibre diameter in scaffolds. Most Significantly, our in vitro diffentiation results have shown that biomimetic carbon nanotubes and polylysine coating can lead to more MSC Chondrogen differentiation than controls that are promising for applications in cartilage tissue technology [181].

A good-oriented nanofabrication array of nanomatrix geometers that can be simple to use for high S/N digital detection, miniaturisation, integrated assays, and single molecule analyses. This describes tethered bilayer membrane nano(submicron) array consisting of a biosensing network [182].

In order to create critical action parameters such as strain distribution, maximal strain and response times, the partial differential equation of IPMC behaviour is calculated using finite element methods. Hosseinipour and Elahinia (2012) 1D the results of the FEM solution are then applied to 2D in order to detect flap actuator tip displacement. A model of a seven-degree IPMC-driven for study, biped robot is then shown. The main motivator for this study was the ability to use IPMC artificial muscles for fast and stable bipedal locomotion. With the limit of the actuator, joint paths for fast and smooth movement are formed. The stability of the gait is evaluated using parameters for ZMP and motion simulation. The manufacturing parameters for each actuator are, for example, weight, platinum (or gold) thickness and the angle of installation [183].

To examine the effect of drag-reduction for four types of surfaces Rib-shaped grooves, V-shaped railings, shield-shaped grooves and straight slot grooves. The new numerical approach at the mescoscopic stage is the Lattice Boltzmann method (LBM) for numerical simulation. The micro-grooved surfaces work as the microstructure affects the flow guides. The vortices in the trenches not only decline the cuts amid fluid and walls, but also the extent of contact amongst the fluid and walls, thus decreasing the pressure loss [184–187].

9 Conclusion

Manufacture of complex biological structures, 3D-printing technology in the future must be further improved. Fresh, multi-scale 3Dprinting technology can be developed with the integration of various 3D prints. Processes designed for various size scales to meet the multiscale encounter of manufacturing of bioinspired structures. Another exciting path is the incorporation of 3D printing with conventional manufacturing technology. The robotic positioning of components and complementary techniques like micromachining, functional ink dispensing and wiring incorporation could also be combined with 3D printing. This integration could allow greater control over multiple materials, geometric scales, and functions in 3D-printed structures.

However, deprived of cross-fertilization amid the various disciplines—biology, chemistry, physics, materials science etc. research into such hybrid production processes is difficult. Natural production itself may be considered as an additive method of production, for example nature begins with a single cell and ends with a living organism by introducing materials progressively by increasing or removing environment. These processes could stimulate new additive manufacturing technology, which could hypothetically produce artefacts more effectively and efficiently close to natural structures. In general, understanding and replicating natural structure can improve the subject of biomimicry by using 3D printing for diverse engineering applications. At the same time, biomimicry's production problems will lead to new biomimetic stabilized manufacturing processes.

The future bio-inspired 3D printing study falls under the sort of multifunctional, multi-scale, multimaterials and multi-dimensional (4D) production. The advancement of biomimetic additive production technology would further contribute to breakthroughs in building materials and erections for future engineering schemes in the next decade. It has many restrictions; 3D polymer composite printing has advanced. Investigators are researching. Latest 3D and new material polymer composite printing, as shown in the above publications. The great potential is the key feature of its growing research. The findings from biomimetics are sustainable so that people look optimistically at biomimetics and continue until solutions are sustainable.

The application of biomimetics must concentrate on research that may contribute to the development of a sustainable environment worldwide in order to create more and more sustainable solutions and design. This paper provides a forum for more researchers. There are new areas of study in materials, process management, process scalability and product performances with 3D printing contains polymer composites.

Acknowledgements We would like to thank the college management for their extended support for doing this. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

1. Stahlberg R, Taya M (2006) What can we learn from nastic plant structures? the phytomimetic potentiality of nastic structures. In: Proceedings of the SPIE 6168, SmartStru
2. Le Duigou A, Castro M (2016) Evaluation of force generation mechanisms in natural, passive hydraulic actuators. Sci Rep:18105
3. Burgert I, Fratzl P (2009) Actuation systems in plants as prototypes for bioinspired devices. Philos Trans R Soc A Math Phys Eng Sci 367:1541–1557
4. Elbaum R, Abraham Y (2014) Insights into the microstructures of hygroscopic movement in plant seed dispersal. Plant Sci 223:124–133
5. Dunlop JWC, Weinkamer R, Fratzl P (2011) Artful interfaces within biological materials. Mater Today 14:70–78
6. Rüggeberg M, Burgert I (2015) Bio-Inspired wooden actuators for large scale applications. PLoS One 10:e0120718
7. Reichert S, Menges A, Correa D (2015) Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. Comput Des 60:50–69
8. Holstov G, Farmer G, Bridgens B (2017) Sustainable materialisation of responsive architecture. Sustainability 9:1–20
9. Vailati C, Bachtiar E, Hass P, Burgert I, Ruggeberg M (2017) An autonomous shading system based on coupled wood bilayer elements. Energy Build
10. Guiducci L, Razghandi K, Bertinetti L, Turcaud S, Ruggeberg M, Weaver JC et al (2016) Honeycomb actuators inspired by the unfolding of ice plant seed capsules. PLoS ONE 11:1–21
11. Lining Y, Jifei O, Guanyun W, Chin-Yi C, Wen W, Helene S, Hiroshi I (2015) BioPrint: a liquid deposition printing system for natural actuators. 3D Print Addit Manuf 2:168–179. Chen X, Mahadevan L, Driks A, Sahin O (2014) Bacillus spores as a building blocks for stimuli-responsive materials and nanogenerators. Nat Nanotechnol Lett 9:137–141
12. Wang Q, Tian X, Huang L, Li D, Malakhov AV, Polilov AN (2018) Programmable morphing composites with embeddedcontinuous fibers by 4D printing. Mater Des 155:404–413
13. Rayate A, Jain P (2018) A review on 4D printing material composites and their applications. Mater Today Commun 5
14. Turcaud S, Guiducci L, Fratzl P, Brechet Y, Dunlop J (2011) An excursion into the design space of biomimetic architectured biphasic actuator. Int J Mater Res 102
15. Reyssat E, Mahadevan L (2009) Hygromorph: from pine cone to biomimetic bilayers. J R Soc 6:951–957

16. Correa D, Papadopoulou A, Guberan C, Jhaveri N, Reichert S, Menges A et al (2015) 3D printing wood: programming hygroscopic material transformations. 3D Print Addit Manuf 2(3):106–116
17. Vazquez E, Gursoy B, Duarte J (2019) Designing for shape change: a case study on 3D printing composite materials for responsive architectures. Conference:391–400
18. Zhang P, Chen P, Wang B, Yu R, Pan H, Wang B (2019) Evaluating the hierarchical, hygroscopic deformation of the Daucus carota umbel through structural characterization and mechanical analysis. Acta Biomater 99:457–468
19. Van Opdenbosch D, Fritz-Popovski G, Wagermaier W, Paris O, Zollfrank C (2016) Moisture-driven ceramic bilayer actuators from a biotemplating approach. Adv Mater 28:5235–5240
20. Zhao Q, Dunlop J, Qiu X, Huang F, Zhang Z, Heyda J et al (2014) An instant multi-responsive porous polymer actuator driven by solvent molecule sorption. Nat Commun 5
21. Vailati C, Hass P, Burgert I, Ruggeberg M (2017) Upscaling of wood bilayers: design principles for controlling shape change and increasing moisture change rate. Mater Struct 50
22. Vazquez E, Gürsoy B, Duarte J (2019) Formalizing shape-change: three-dimensional printed shapes and hygroscopic material transformations. Int J Archit Comput:1–17. Baley C, Kervoëlen A, Lan M, Cartier D, Le Duigou A, Bourmaud A et al (2016) Flax/PP manufacture by automated fibre placement (AFP). Mater Des 94
23. Liang S, Gning P-B, Guillaumat L (2015) Quasi-static behaviour and damage assessment of flax/epoxy composites. Mater Des 67:344–353
24. Lefeuvre A, Bourmaud A, Baley C (2015) Optimization of the mechanical performance of UD flax/epoxy composites by selection of fibres along the stem. Compos Part A Appl Sci Manuf 77:204–208
25. Cadu T, Berges M, Sicot O, Person V, Piezel B, Van Schoors L et al (2018) What are the key parameters to produce a high-grade bio-based composite? application to flax/epoxy UD laminates produced by thermocompression. Compos Part B Eng 150:36–46
26. Van de Weyenberg I, Ivens J, De Coster A, Kino B, Baetens E, Verpoest I (2003) Influence of processing and chemical treatment of flax fibres on their composites. Compos Sci Technol 63:1241–1246
27. Baets J, Plastria D, Ivens J, Verpoest I (2014) Determination of the optimal flax fibre preparation for use in unidirectional flax–epoxy composites. J Reinf Plast Compos 33:493–502
28. Torrado AR, Roberson DA (2016) Failure analysis and anisotropy evaluation of 3D-printed tensile test specimens of different geometries and print raster patterns. J Fail Anal Prev 16:154–164
29. Pyl L, Kalteremidou K-A, Van Hemelrijck D (2018) Exploration of specimens' geometry and tab configuration for tensile testing exploiting the potential of 3D printing freeform shape continuous carbon fibre-reinforced nylon matrix composites. Polym Test 71:318–328
30. Fernandez-Vicente M, Calle W, Ferrandiz S, Conejero A (2016) Effect of infill parameters on tensile mechanical behavior in desktop 3D printing. 3D Print Addit Manuf 3:183–192
31. Goh G, Dikshit V, Nagalingam A, Goh G, Agarwala S, Sing S et al (2018) Characterization of mechanical properties and fracture mode of additively manufactured carbon fiber and glass fiber reinforced thermoplastics. Mater Des 137:79–89
32. Baets J, Plastria D, Ivens J, Verpoest I (2014) Determination of the optimal flax fibre preparation for use in unidirectional flax-epoxy composites. J Reinf Plast Compos 33:493–502
33. Sanandiya N, Vijay Y, Dimopoulou M, Dritsas S, Fernandez J (2018) Large-scale additive manufacturing with bioinspired cellulosic materials. Sci Reports 8:8642
34. Zhou J, Sheiko S (2016) Reversible shape-shifting in polymeric materials. J Polym Sci Part B Polym Phys 54:1365–1380. https://doi.org/10.1002/polb.24014
35. Sun L, Huang W (2010) Mechanisms of the multi-shape memory effect and temperature memory effect in shape memory polymers. Soft Matter 6:4403
36. Sun L, Huang WM, Ding Z, Zhao Y, Wang CC, Purnawali H et al (2012) Stimulus-responsive shape memory materials: a review. Mater Des 33:577–640
37. Mulakkal MC, Trask RS, Ting VP, Seddon AM (2018) Responsive cellulose-hydrogel composite ink for 4D printing. Mater Des 160:108–118

38. Baker A, Bates S, Llewellyn-Jones T, Valori L, Dicker M, Trask R (2019) 4D printing with robust thermoplastic polyurethane hydrogel-elastomer trilayers. Mater Des 167:107544
39. Yuan C, Wang T, Dunn M, Qi H (2017) 3D Printed active origami with complicated folding patterns. Int J Precis Eng Manuf-Gr Technol 4:281–289
40. Ge Q, Dunn C, Qi H, Dunn M (2014) Active origami by 4D printing. Smart Mater Struct 23:15
41. Bodaghi M, Damanpack A, Liao W (2016) Self-expanding/shrinking structures by 4D printing. Smart Mater Struct 25:15
42. Kokkinis D, Schaffner M, Studart A (2015) Multimaterial magnetically assisted 3D printing of composite materials. Nat Commun 6:8643
43. Holstov A, Bridgens B, Farmer G (2015) Hygromorphic materials for sustainable responsive architecture. Constr Build Mater 98:570–582
44. Lin S, Xie Y, Lib Q, Huang X, Zhoua S (2016) On the shape transformation of cone scales. Soft Matter 12:9797–9802
45. Poppinga S, Speck T (2015) New insight into the passive motions of pine cone and false indusia in ferns. Plant Biomech 8
46. Liu Y, Genzer J, Dickey M (2016) 2D or not 2D: shape programming polymer sheets. Prog Polym Sci 52:79–106
47. Le Duigou A, Keryvin V, Beaugrand J, Pernes M, Scarpa F, Castro M (2019) Humidity responsive actuation of bioinspiredhygromorphbiocomposites (HBC) for adaptive structures. Compos Part A 116:36–45
48. Vailati C, Rüggeberg M, Burgert I, Hass P (2018) The kinetics of wooden bilayers is not affected by different wood adhesive systems. Wood Sci Technol 52
49. Wood D, Vailati C, Menges A, Rüggeberg M (2018) Hygroscopically actuated wood elements for weather responsive and self-forming building parts—facilitating upscaling and complex shape changes. Constr Build Mater 165:782–791
50. 4D Printing Market, by Application (Aerospace and defense, Healthcare, Automotive, Construction, Clothing, Utility, Others.), by Region-Global Forecast to 2022. Mark Res Futur2020;ID: MRFR/S.
51. Sullivan F (2014) Advances in 4D printing—next paradigm in manufacturing. Rep D545-TI
52. Tibbits S (2014) 4D printing: multi-material shape change. Archit Des:116–121
53. Pucci MF, Liotier P-J, Drapier S (2016) Capillary wicking in flax fabrics—effects of swelling in water. Colloids Surfaces A Physicochem Eng Asp 498:176–184
54. Deroiné M, Le Duigou A, Corre Y-M, Le Gac P-Y, Davies P, César G, et al (2014) Accelerated ageing of polylactide in aqueous environments: comparative study between distilled water and seawater. Polym Degrad Stab
55. Le Duigou A, Chabaud G, Scarpa F, Castro M (2019) Bioinspired electrotherma-hygro reversible shape changing materials by 4D printing. Adv Funct Mater 1903280. https://doi.org/10.1002/adfm.201903280
56. Lincoln R, Scarpa F, Ting V, Trask R (2019) Multifunctional composites: a metamaterial perspective. Multifonc Mater
57. Poppinga S, Correa D, Bruchmann B, Menges A, Speck T (2020) Plant movements as concept generators for the development of biomimetic compliant mechanisms. Integr Comp Biol
58. Turcaud S (2015). Some patterns of shape change controlled by eigenstrain architectures. Thesis Report-Https:/tel.archives-Ouvertes.fr/tel-01206053
59. Guiducci L, Weaver, Bréchet Y, Fratzl P, Dunlop J (2015) The geometric design and fabrication of actuating cellular structures. Adv Mater Interfaces 2:1500011
60. Parandoush P, Lin D (2017) Review on additive manufacturing of polymer-fiber composites. Compos Struct 182:36–53
61. Le Duigou A, Castro M (2017) HygromorphBioComposites: effect of fibre content and interfacial strength on the actuation performances. Ind Crops Prod 99
62. Cole D, Riddick J, Jaim H, Strawhecker K, Zander N (2016) Interfacial mechanical behavior of 3D printed ABS. J Appl Polym Sci 133:913

63. Brites F, Malça C, Gaspar F, Horat J, Franco M, Biscaia S et al (2017) Cork plastic composite optimization for 3D printing applications. Procedia Manuf 12:156–165
64. Wang X, Jiang M, Zhou Z, Gou JHD (2017) 3D printing of polymer matrix composites: a review and prospective. Compos Part B Eng 110:442–458
65. Khoo Z, Teoh J, Liu Y, Chua C, Yang S, An J et al (2015) 3D printing of smart materials: a review on recent progresses in 4D printing. Virtual Phys Prototyp 10:103–122
66. Boumaud A, Beaugrand J, Shah D, Placet V, Baley C (2018) Towards the design of high performance biocomposites. Prog Mater Sci 97:347–408
67. Sekar V, Fouladi M, Namasivayam S, Sivakumar S (2019) Additive manufacturing: a novel method for developing an acoustic panel made of natural fiber-reinforced composites with enhanced mechanical and acoustical properties. J Eng:1–19
68. Beaugrand J, Berzin F (2013) Lignocellulosic fiber reinforced composites: influence of compounding conditions ondefibrization and mechanical properties. J Appl Polym Sci 128:1227–1238
69. Le Duigou A, Pillin I, Bourmaud A, Davies P, Baley C (2008) Effect of recycling on mechanical behaviour of biocompostable flax/poly(L-lactide) composites. Compos Part A Appl Sci Manuf 39:1471–1478
70. Madsen B, Thygesen A, Lilholt H (2007) Plant fibre composites—porosity and volumetric interaction. Compos Sci Technol 67:1584–1600
71. Coroller G, Lefeuvre A, Le Duigou A, Bourmaud A, Ausias G, Gaudry T et al (2013) Effect of flax fibres individualisation on tensile failure of flax/epoxy unidirectional composite. Compos Part A Appl Sci Manuf 51:62–70
72. Kelly A, Tyson WR (1965) Tensile properties of fibre-reinforced metals: Copper/tungsten and copper/molybdenum. J Mech Phys Solids 13:329–350
73. Badouard C, Traon F, Denoual C, Mayer-Laigle C, Paës G, Bourmaud A (2019) Exploring mechanical properties of fully compostable flax reinforced composite filaments for 3D printing applications. Ind Crops Prod 135:246–250
74. Lefeuvre A, Le DA, Bourmaud A, Kervoelen A, Morvan C, Baley C (2015) Analysis of the role of the main constitutive polysaccharides in the flax fibre mechanical behaviour. Ind Crops Prod 76:1039–1048
75. Hill CAS, Norton A, Newman G (2009) The water vapor sorption behavior of natural fibers. J Appl Polym Sci 112:1524–1537
76. Bismarck A, Mishra S, Lampke T, Mohanty AK, Mishra MDL (2005) Plant fibers as reinforcement for green composites. Nat Fibers, BiopolymBiocomposites Boca Rat CRC Press
77. Pickering K (2008) Properties and performance of natural-fibre composites, 1st edn. Woodhead Publ:576
78. Monti A, Alexopoulou E (eds) (2013) Kenaf: a multi-purpose crop for several industrial applications. Springer, London, London
79. Bledzki AK, Gassan J (1999) Composites reinforced with cellulose based fibres. Prog Polym Sci 24:221–274
80. Dayakar N (2015) Effective properties of randomly oriented kenaf short fiber reinforced by Dayakar Naik L. Thesis Report, Utah State University
81. Akil HM, Omar MF, Mazuki A, Safiee S, Ishak Z, Abu BA (2011) Kenaf fiber reinforced composites: a review. Mater Des 32:4107–4121
82. Mahjoub R, Yatim J, Sam A, Hashemi S (2014) Tensile properties of kenaf fiber due to various conditions of chemical fiber surface modifications. Constr Build Mater 55:103–113
83. Bourmaud A, Le Duigou A, Baley C (2015) Mechanical performance of flax-based biocomposites
84. Komuraiah A, Kumar N, Prasad B (2014) Chemical composition of natural fibers and its influence on their mechanical properties. Mech Compos Mater 50
85. Eder M, Arnould O, Dunlop J, Hornatowska J, Salmen L (2013) Experimental micromechanical characterisation of wood cell walls. Wood Sci Technol 43

86. Marrot L, Lefeuvre A, Pontoire B, Bourmaud A, Baley C (2013) Analysis of the hemp fiber mechanical properties and their scattering (Fedora 17). Ind Crops Prod 51:317–327
87. Placet V, Cisse O, Boubakar ML (2011) Influence of environmental relative humidity on the tensile and rotational behaviour of hemp fibres. J Mater Sci 47:3435–3446
88. Eichhorn S, Young R (2004) Composite micromechanics of hemp fibres and epoxy resin microdroplets. Compos Sci Technol:767–772
89. Kariz M, Sernek M, Obucina M, Kuzman M (2017) Effect of wood content in FDM filament on properties of 3D printed parts. Mater Today
90. Stoof D, Pickering K, Zhang Y (2017) Fused deposition modeling of natural fibre/polylactic acid composites. J Compos Sci 1:8
91. Xie G, Zhang Y, Lin W (2017) Plasticizer combinations and performance of wood flour-poly(lactic acid) 3D printing filaments. BioResources 12:6736–6748
92. Le Duigou A, Requile S, Beaugrand J, Scarpa F, Castro M (2017) Natural fibres actuators for smart bio-inspired hygromorphbiocomposites. Smart Mater Struct 26
93. Faruk O, Bledzki AK, Fink H-P, Sain M (2012) Biocomposites reinforced with natural fibers: 2000–2010. Prog Polym Sci 37:1552–1596
94. Baley C, Gomina M, Breard J, Bourmaud A, Drapier S, Ferreira M, et al (2018) Specific features of flax fibres used to manufacture composite materials. Int J Mater Form:1–30
95. Mohanty A, Misra M, Drzal L (2002) Sustainable bio-composites from renewable resources. J Polym Environ 10:19–26
96. Pickering K, AruanEfendy M, Le T (2015) A review of recent developments in natural fibre composites and their mechanical performance. Compos Part A Appl Sci Manuf 83:98–112
97. de Bruyne N (1939) Plastic progress—Some further developments in the manufacture and use of synthetic materials for aircraft construction. Flight:77–79
98. Tibitts S (2013) The emergence of 4D printing. TED Talks
99. Ge Q, Qi HJ, Dunn ML. Active materials by four-dimension printing. Appl Phys Lett 103
100. Pei E (2014) 4D printing: dawn of an emerging technology cycle. Assem Autom 34:310–314
101. Miao S, Castro N, Nowicki M, Xia L, Cui H, Zhou X et al (2017) 4D printing of polymeric materials for tissue and organ regeneration. Mater Today 20:577–591
102. Gladman S, Matsumoto E, Nuzzo R, Mahadevan L, Lewis J (2016) Biomimetic 4D printing. Nat Mater 15:413–418
103. Le Duigou A, Castro M (2015) Moisture-induced self-shaping flax-reinforced polypropylene biocomposite actuator. Ind Crops Prod 71. https://doi.org/10.1016/j.indcrop.2015.03.077
104. Correa D, Menges A (2017) Fused filament fabrication for multi kinetic state climate resonsive aperture. Fabr Chapter 3 Rethink Addit Startegies, UCL Press, pp 190–195
105. Correa D, Menges A (2015) 3D printed hygroscopic programmable material systems. MRS Online Proceeding Libr Arch 1800
106. Le Duigou A, Castro M, Bevan R, Martin N (2016) 3D printing of wood fibrebiocomposites: from mechanical to actuation functionality. Mater Des 97:347–408
107. Correa D, Papadopoulou A, Guberan C, Jhaveri N, Reichert S, Menges A et al (2015) 3D-Printed wood: programming hygroscopic material transformations. 3D Print Addit Manuf 2:106–116
108. Lee A, An J, Chua C (2017) Two-way 4D printing: a review on the reversibility of 3D-Printed shape memory materials. Eng Mater 3:663–674
109. Momeni F, MedhiHassani S, Liu X, Ni J (2017) A review of 4D printing. Mater Des 122:42–79
110. Vazquez E, Randall C, Duarte J (2019) Shape-Changing architectural skins a review on materials, design and fabrication strategies and performance analysis. J Facade Des Eng 7
111. Zhang Z, Demir K, Gu G (2019) Developments in 4D-Printing: a review on current smart materials, technologies, and applications. Int J Smart Nano Mater 3:1–20
112. Defoirdt N, Biswas S, De VL, Tran LQN, Van AJ, Ahsan Q et al (2010) Assessment of the tensile properties of coir, bamboo and jute fibre. Compos Part A Appl Sci Manuf 41:588–595
113. Fratzl P, Elbaum R, Burgert I (2008) Cellulose fibrils direct plant organ movements. Faraday Discuss 139:275–282

114. Joffre T, Neagu RC, Bardage SL, Gamstedt EK (2014) Modelling of the hygroelasticbehaviour of normal and compression wood tracheids. J Struct Biol 185:89–98
115. Lefeuvre A, Bourmaud A, Morvan C, Baley C (2014) Elementary flax fibre tensile properties: correlation between stress–strain behaviour and fibre composition. Ind Crops Prod 52:762–769
116. le Duigou A, Bourmaud A, Balnois E, Davies P, Baley C (2012) Improving the interfacial properties between flax fibres and PLLA by a water fibre treatment and drying cycle. Ind Crops Prod 39:31–39
117. Baley C, Perrot Y, Busnel F, Guezenoc H, Davies P (2006) Transverse tensile behaviour of unidirectional plies reinforced with flax fibres. Mater Lett 60:2984–2987
118. Baley C (2002) Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase. Compos Part A Appl Sci Manuf 33:939–948. [42] Placet V, Cissé O, LamineBoubakar M (2014) Nonlinear tensile behaviour of elementary hemp fibres. Part I: Investigation of the possible origins using repeated progressive loading with in situ microscopic observations. Compos Part A Appl Sci Manuf 56:319–327
119. Shah D (2015) Damage in biocomposites: stiffness evolution of aligned plant fibre composites during monotonic and cyclic fatigue loading. Compos Part A Appl Sci Manuf
120. Martin N, Mouret N, Davies P, Baley C (2013) Influence of the degree of retting of flax fibers on the tensile properties of single fibers and short fiber/polypropylene composites. Ind Crops Prod 49:755–767
121. Bismarck A, Aranberri-Askargorta I, Springer J, Lampke T, Wielage B, Stamboulis A et al (2002) Surface characterization of flax, hemp and cellulose fibers; Surface properties and the water uptake behavior. Polym Compos 23:872–894
122. Gallos A, Paes G, Allais F, Beaugrand J (2017) Lignocellulosic fibers: a critical review of extrusion process for enhancement of the properties of natural fiber composites. R Soc Chem 7
123. Le Duigou A, Kervoelen A, Le Grand A, Nardin M, Baley C (2014) Interfacial properties of flax fibre-epoxy resin systems: existence of a complex interphase. Compos Sci Technol 100
124. Le Moigne N, Longerey M, Taulemesse J, Bénézet J, Bergeret A (2014) Study of the interface in natural fibres reinforced poly(lactic acid) biocomposites modified by optimized organosilane treatments. Ind Crops Prod 52:481–494
125. Le Duigou A, Baley C, Grohens Y, Davies P, Cognard J-Y, Créach'Cadec R et al (2014) A multi-scale study of the interface between natural fibres and a biopolymer. Compos Part A Appl Sci Manuf 65
126. Bourmaud A, Morvan C, Bouali A, Placet V, Perré P, Baley C (2013) Relationships between micro-fibrillar angle, mechanical properties and biochemical composition of flax fibers. Ind Crops Prod 44. Stoof D, Pickering K (2018) Sustainable composite fused deposition modeling filament using recycled pre-consumerpolypropylene. Compos Part B Eng 135:110–118
127. Filgueira D, Holmen S, Melbø J, Moldes D, Echtermeyer A, Chinga-Carrasco G (2018) 3D printable filaments made of biobased polyethylene biocomposites. Polymers (Basel) 10:314
128. Tran TN, Bayer IS, Heredia-Guerrero JA, Frugone M, Lagomarsino M, Maggio F et al (2017) Cocoa shell waste biofilaments for 3D printing applications. Macromol Mater Eng 1700219:1700219
129. Bi H, Ren Z, Guo R, Xu M, Song Y (2018) Fabrication of flexible wood flour/thermoplastic polyurethane elastomercomposites using fused deposition molding. Ind Crops Prod 122:76–84
130. Parlevliet P, Bersee H, Beukers A (2006) Residual stresses in thermoplastic composites—a study of the literature—part I: formation of residual stresses. Comp Part A Appl Sci Manuf 37:1847–1857
131. Clegg W, Kendall K, Alford NM, Button T, Birchall J (1990) A simple way to make tough ceramics. Nature 347(6292):455e457
132. Munch E, Launey ME, Alsem DH, Saiz E, Tomsia AP, Ritchie RO (2008) Tough, bio-inspired hybrid materials, Science 322 (5907):1516e1520

133. Jia Z, Li T, Chiang F-P, Wang L (2018) An experimental investigation of the temperature effect on the mechanics of carbon fiber reinforced polymer composites. Compos Sci Technol 154:53e63
134. Wu X, Yang M, Yuan F, Wu G, Wei Y, Huang X, Zhu Y, Heterogeneous lamella structure unites ultrafine-grain strength with coarse-grain ductility. Proc Natl Acad Sci Unit States Am 112(47):14501e14505
135. Podsiadlo P, Kaushik AK, Arruda EM, Waas AM, Shim BS, Xu J, Nandivada H, Pumplin BG, Lahann J, Ramamoorthy A (2007) Ultrastrong and stiff layered polymer nanocomposites. Science 318(5847):80e83
136. Shin YA, Yin S, Li X, Lee S, Moon S, Jeong J, Kwon M, Yoo SJ, KimT Y-M (2016) Zhang, Nanotwin-governed toughening mechanism in hierarchically structured biological materials. Nat Commun 7:10772
137. Meza LR, Zelhofer AJ, Clarke N, Mateos AJ, Kochmann DM, Greer JR (2015) Resilient 3D hierarchical architected metamaterials. Proc Natl Acad Sci Unit States Am 112(37):11502e11507
138. Wang L, Lau J, Thomas EL, Boyce MC (2011) Co-continuous composite materials for stiffness, strength, and energy dissipation. Adv Mater 23(13):1524e1529
139. Raney JR, Compton BG, Mueller J, Ober TJ, Shea K, Lewis JA (2018) Rotational 3D printing of damage-tolerant composites with programmable mechanics. Proc Natl Acad Sci Unit States Am:201715157
140. Dimas LS, Bratzel GH, Eylon I, Buehler MJ (2013) Tough composites inspired by mineralized natural materials: computation, 3D printing, and testing. Adv Funct Mater 23(36):4629e4638
141. Martin JH, Yahata BD, Hundley JM, Mayer JA, Schaedler TA, Pollock TM (2017) 3D printing of high-strength aluminium alloys. Nature 549(7672):365
142. Libonati F, Gu GX, Qin Z, Vergani L, Buehler MJ (2016) Bone-inspired materials by design: toughness amplification observed using 3D printing and testing. Adv Eng Mater 18(8):1354e1363
143. Liu L, Li Y (2018) Predicting the mixed-mode I/II spatial damage propagation along 3D-printed soft interfacial layer via a hyperelastic softening model. J Mech Phys Solids 116:17e32
144. Gu GX, Libonati F, Wettermark SD, Buehler MJ, Printing nature: unraveling the role of nacre's mineral bridges. J Mech Behav Biomed Mater 76:135e144
145. Liu L, Ding Q, Zhong Y, Zou J, Wu J, Chiu Y-L, Li J, Zhang Z, Yu Q, Shen Z (2017) Dislocation network in additive manufactured steel breaks strengtheductility trade-off, Mater. Today 21(4):354e361
146. Martin JJ, Fiore BE, Erb RM (2015) Designing bioinspired composite reinforcement architectures via 3D magnetic printing. Nat Commun 6:8641
147. Compton BG, Lewis JA (2014) 3D-printing of lightweight cellular composites. Adv Mater 26(34):5930e5935
148. Jia Z, Yu Y, Hou S, Wang L (2019) Biomimetic architected materials with improved dynamic performance. J Mech Phys Solids 125:178e197
149. Ming-Yuan H, Hutchinson JW (1989) Crack deflection at an interface between dissimilar elastic materials. Int J Solids Struct 25(9):1053e1067
150. Fratzl P, Gupta HS, Fischer FD, Kolednik O (2007) Hindered crack propagation in materials with periodically varying Young's modulusdlessons from biological materials. Adv Mater 19(18):2657e2661
151. Toribio J, Kharin V (1999) Role of fatigue crack closure stresses in hydrogen-assisted cracking. In: Advances in fatigue crack closure measurement and analysis, vol 2, ASTM International
152. Suo Z (1990) Singularities, interfaces and cracks in dissimilar anisotropic media. Proc Roy Soc Lond A 427:331e358
153. Suo Z, Bao G, Fan B, Wang T (1991) Orthotropy rescaling and implications for fracture in composites. Int J Solids Struct 28(2):235e248
154. Hutchinson JW, Suo Z (1991) Mixed mode cracking in layered materials. Adv Appl Mech:63e191. Elsevier

155. He MY, Evans AG, Hutchinson JW (1994) Crack deflection at an interface between dissimilar elastic materials: role of residual stresses. Int J Solids Struct 31(24):3443e3455
156. Kolednik O, Predan J, Fischer F, Fratzl P (2014) Improvements of strength and fracture resistance by spatial material property variations. Acta Mater 68:279e294
157. Faber KT, Evans AG (1983) Crack deflection processesdI, Theory. Acta Metall 31(4):565e576
158. Suksangpanya N, Yaraghi NA, Kisailus D, Zavattieri P (2017) Twisting cracks in Bouligand structures. J Mech Behav Biomed Mater 76:38e57
159. Wei Y, Gao H, Bower AF (2009) Numerical simulations of crack deflection at a twist-misoriented grain boundary between two ideally brittle crystals. J Mech Phys Solids 57(11):1865e1879
160. Gao Y, Guo Z, Song Z, Yao H (2017) Spiral interface: a reinforcing mechanism for laminated composite materials learned from nature. J Mech Phys Solids 109:252e263
161. Barthelat F, Tang H, Zavattieri P, Li C-M, Espinosa H (2007) On the mechanics of mother-of-pearl: a key feature in the material hierarchical structure. J Mech Phys Solids 55(2):306e337
162. Wegst UG, Bai H, Saiz E, Tomsia AP, Ritchie RO (2015) Bioinspired structural materials. Nat Mater 14(1):23
163. Grunenfelder L, Suksangpanya N, Salinas C, Milliron G, Yaraghi N, Herrera S, Evans-Lutterodt K, Nutt S, Zavattieri P, Kisailus D (2014) Bio-inspired impact-resistant composites. Acta Biomater 10(9):3997e4008
164. Gu GX, Takaffoli M, Buehler MJ (2017) Hierarchically enhanced impact resistance of bioinspired composites. Adv Mater 29(28)
165. Weaver JC, Milliron GW, Miserez A, Evans-Lutterodt K, Herrera S, Gallana I, Mershon WJ, Swanson B, Zavattieri P, DiMasi E (2012) The stomatopod dactyl club: a formidable damage-tolerant biological hammer. Science 336(6086):1275e1280
166. Bigi A, Burghammer M, Falconi R, Koch MH, Panzavolta S, Riekel C (2001) Twisted plywood pattern of collagen fibrils in teleost scales: an X-ray diffraction investigation. J Struct Biol 136(2):137e143
167. Yamamoto T, Domon T, Takahashi S, Islam N, Suzuki R (2000) Twisted plywood structure of an alternating lamellar pattern in cellular cementum of human teeth. Anat Embryol 202(1):25e30
168. Zhang Z, Zhang Y-W, Gao H (2011) On optimal hierarchy of load-bearing biological materials. Proc R Soc Lond B Biol Sci 278 (1705):519e525
169. Kruzic J, Kuskowski S, Ritchie R (2005) Simple and accurate fracture toughness testing methods for pyrolytic carbon/graphite composites used in heart-valve prostheses. J Biomed Mater Res A 74(3):461e464
170. Chen Y, Li T, Jia Z, Scarpa F., Yao C-W, Wang L (2018) 3D printed hierarchical honeycombs with shape integrity under large compressive deformations. Mater Des 137:226e234
171. Yao H, Song Z, Xu Z, Gao H (2013) Cracks fail to intensify stress in nacreous composites. Compos Sci Technol 81:24e29
172. Song F, Soh A, Bai Y (2003) Structural and mechanical properties of the organic matrix layers of nacre. Biomaterials 24(20):3623e3631
173. O'Masta MR, Dong L, St-Pierre L, Wadley H, Deshpande VS (2017) The fracture toughness of octet-truss lattices. J Mech Phys Solids 98:271e289
174. Li T, Chen Y, Wang L (2018) Enhanced fracture toughness in architected interpenetrating phase composites by 3D printing. Compos Sci Technol 167:251e259
175. Barthelat F, Espinosa H (2007) An experimental investigation of deformation and fracture of nacreemother of pearl. Exp Mech 47(3):311e324
176. Sih GC, Paris P, Irwin GR (1965) On cracks in rectilinearly anisotropic bodies. Int J Fract Mech 1(3):189e203
177. Wang R, Suo Z, Evans A, Yao N, Aksay I (2001) Deformation mechanisms in nacre. J Mater Res 16(9):2485e2493
178. Askarinejad S, Rahbar N (2015) Toughening mechanisms in bioinspired multilayered materials. J R Soc Interface 12(102):20140855

179. Yang H-M, Chan Y-C, Hsu T-H, Chen H-W, Lee J-W, Duh J-G, Chen P-Y (2015) Synthesis and characterization of nacre-inspired zirconia/polyimide multilayer coatings by a hybrid sputtering and pulsed laser deposition technique. Surf Coating Technol 284:118e128
180. Begley MR, Philips NR, Compton BG, Wilbrink DV, Ritchie RO, Utz M (2012) Micromechanical models to guide the development of synthetic brick and mortar composites. J Mech Phys Solids 60(8):1545e1560
181. Barthelat F, Dastjerdi AK, Rabiei R (2013) An improved failure criterion for biological and engineered staggered composites. J R Soc Interface 10(79):20120849
182. Gao H (2006) Application of fracture mechanics concepts to hierarchical biomechanics of bone and bone-like materials. Int J Fract 138(1e4):101
183. Xie Z, Yao H (2014) Crack deflection and flaw tolerance in brick-and-mortar structured composites. Int J Appl Mech 6(02):1450017
184. Evans AG, Hutchinson JW (1989) Effects of non-planarity on the mixed mode fracture resistance of bimaterial interfaces. Acta Metall 37(3):909e916
185. Kamat S, Kessler H, Ballarini R, Nassirou M, Heuer AH (2004) Fracture mechanisms of the Strombus gigas conch shell: II-micromechanics analyses of multiple cracking and large-scale crack bridging. Acta Mater 52(8):2395e2406
186. Kamat S, Su X, Ballarini R, Heuer A (2000) Structural basis for the fracture toughness of the shell of the conch Strombus gigas. Nature 405(6790):1036
187. Gu GX, Takaffoli M, Buehler MJ (2017) Hierarchically enhanced impact resistance of bioinspired composites. Adv Mater 29(28):1700060