Fish scale inspired structures - a review of materials, manufacturing and models

Fish scale inspired structures - A review of materials, manufacturing and models

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Abstract. Fish scales inspired materials platform can provide advanced mechanical properties and functionalities. These materials, inspired from fish scales take the form of either composite materials or multi-material discrete exoskeleton type structures. Over the last decade, they have been under intense scrutiny for generating tailorable and tunable stiffness, penetration and fracture resistance, buckling prevention, nonlinear damping, hydrodynamic and camouflaging functions. Such programmable behavior emerges from leveraging their unique morphology and structure-property relationships. Several advanced tools of characterization, manufacturing, modeling and computation have been employed to understand and discover their behavior. With the rapid proliferation of additive manufacturing (AM) techniques, and advancing envelope of modeling and computational methods, this field is seeing renewed efforts to realize even more ambitious designs. We present a review and recapitulation of the state-of-the art in fish scale inspired materials in this paper.

Key words: Biomimetics, Fish scales, Variable stiffness, Smart materials, Additive manufacturing (AM), Metamaterials

1. Introduction

Fish scale inspired structures have attracted considerable scrutiny over the past decade as high-performance materials platforms due to their promising mechanical and multifunctional properties. The fundamental origins of many of these properties lies on the intricate interplay of material and geometry of the scales at multiple length scales Fig. 1(a). The scales themselves are composite materials with intricate hierarchical organization of polymeric materials that provide resistance to damage and fracture.

At the same time, many other unusual properties arise at the structural length scale, which encompasses an array of scales, Fig. 1(b) . Such periodic arrays allow for scales interactions resulting in nonlinear strain stiffening, indentation resistance, locking, buckling resistance and anomalous frictional behavior. These later responses are primarily due to the emergent behavior arising from the intricate interactions between the periodically arranged plate-like scales on a deforming substrate Fig. 1(c) [1–7].

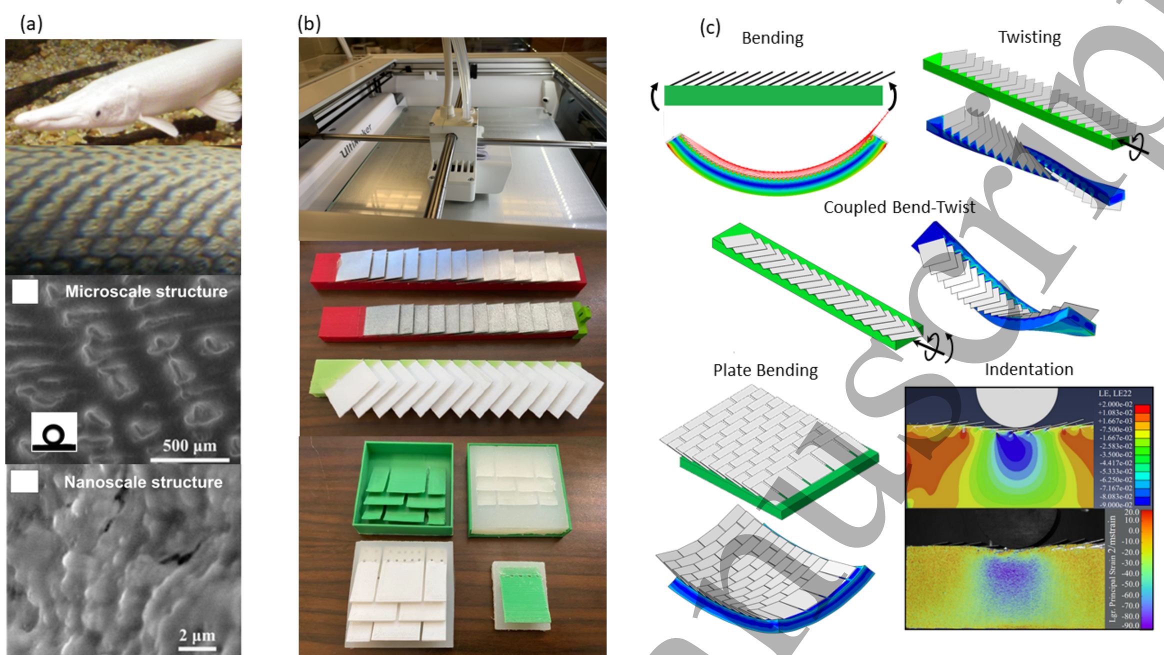

Figure 1. From fish scales to engineering desing. (a) Alligator Gar fish (adopted under CC BY 2.0) [8], and scales of Alligator Gar (adopted under CC BY 2.0) [9] (top), SEM images of the surface of fish scales at microscale and nanoscale structure level [10], (bottom). (owned by IOP) (b) 3D printer nozzle head and various types of biomimetic scales that were fabricated with the assistance of 3D printing [11]. (c) Different types of loading and scales engagement that can be considered for different analyses [11].

Two types of designs are possible – one where the scales are protruding from the surface Fig. 1(b), embedded partially on the substrate and the other where they are completely covered like composites. The partially embedded scale type design most closely mimics the actual scales of fish or reptiles [12–19]. In such cases, it is the sliding contact kinematics that leads to the most unusual nonlinear properties. Alternatively, other fish scale inspired composite-type designs also exist, where the scales are fully embedded within the top layer of the substrate [20–22]. Here, there is no explicit sliding between scales, but the stress profiles are altered on the top layer of substrate due to the constriction of the substrate's material between the stiff scales during loading [20–22].

Early interests in adopting scales for structural modifications were directed at their apparent armor-like functions, also observed in nature where the scales played a role in distributing the indenting force [23–27]. However, more recent efforts have expended towards a deeper understanding of the material behavior of the scales themselves [28–31] to design better materials [20, 22, 25], or to come up with "coatings" that prevent penetration [32]. Parallelly, efforts are underway for using scales' sliding behavior to geometrically enhance the overall functions of the slender substrate [11, 33]. This can provide potential applications for smart structures and soft robotics due to variable and tunable stiffness. However, with ever expanding interests, many challenges arise typical of a maturing field of materials. These include manufacturing, testing, modeling, and computations. Addressing these challenges are critical to enhance the potential of these structures and make their use more widespread.

In this review, first we recapitulate the body of knowledge in mechanics and material properties of natural fish scales. We then highlight the route taken towards adopting the scales for enhanced structural properties that include nonlinear elasticity, drag reduction, and camouflage. Then, we discuss the advances in the fabrication and testing. Finally, we outline the advances made in the area of modeling and simulation. We conclude this paper by discussing the challenges and outlook in this area.

2. Mechanical characterization of natural fish scales

Fish scales found in nature have hierarchical and heterogenous microstructures. These structural features are believed to be essential for their mechanically superior behavior. Typically studied scales in the biomimetic literature are of the types placoid, ganoid, elasmoid, dermal plates and scutes [34–37]. Placoid scales are found in cartilaginous fishes such as sharks and rays. Ganoids are peg-and-socket interlocking type scales with an outer layer of ganoine and typically of rhomboidal shape, typically with little overlap. They are found in fishes such as bichirs (Polypteridae), Bowfin (Amia calva), paddlefishes (Polyodontidae), gars (Lepisosteidae), and sturgeons (Acipenseridae). Elasmoid scales are thin, imbricated scales with a layer of dense, lamellar collagen bone (isopedine), underneath another layer of tubercles (typically composed of bone). Other popularly studied types include cycloid and stenoid types, which have significant overlap. A detailed description of scale type and morphology can be found in prior literature [38–40]. Various sophisticated imaging techniques have been used to study the microstructure of fish scales. These techniques include transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), CM-Toyoperal 650M column chromatography, and microcomputed tomography (μ-CT). In this section we discuss the mechanical characterization of actual fish scales.

Early studies on Goldfish's scale discovered the structures of the constituent fibers electron microscopic analysis [41]. The microstructure of the elasmoid scales of *Carassius auratus* was analyzed using Philips EM 300 electron microscope with a cooled anticontamination device to find the microstructure of scales [42]. In another study by Zylberg et al. (1992), in-situ and in-vitro characterization was performed on the scales of *Carassius auratus L.* (*Cyprinidae*) to investigate the characteristics of fibrillar collagens of scales. The investigations were performed using electron microscopy, immunofluorescence, electrophoretic and HPLC analysis, immunoprecipitation, and RNA analysis. The authors outlined the influence of the environment on the actual fish scale's biological cell behavior, which effects the mechanical properties of the fish scales such as stress absorption and plastic deformation [43]. In a study by Giraud-Guille, et al. (2000) [44], fish scales were extracted from *Soleidae* flat fish, and imaging was done using X-ray diffraction, differential scanning calorimetry (DSC), polarized light microscopy, flow measurement, and transmission electron microscopy. This study, like a similar earlier study [45], was concerned with the biomedical application of fish scales from an amino acid perspective. Further studies have also been carried out focusing on the biocompatibility and potential bone regenerative properties of fish scales such as those of *Sparus aurata* [19, 46–48]. Similarly, fish scales and decalcified scaffolds collected from *Crisp flesh grass carps* were tested using SEM, FTIR, energy-dispersive X-ray spectroscopy (EDX or EDS), and tensile test. Also, the biodegradability of the scaffold has been examined to ascertain its potential for tissue regeneration [49].

The compositional differences between fish scales were contrasted with porcine dermis using FT-Raman spectra on the scales of *Pagrus major* and *Oreochromis niloticas* [50]. The study used dehydrated and demineralized *Pagrus major*'s scales, and performed further characterization using SEM, TEM, EDS, FITR, and tensile testing. Similar material properties were confirmed in later studies of *Pagrus major*'s scales [24]. An in-situ study on *Longnose gar* with the sequential alteration of scales was done for measuring the flexural stiffness, which influences the swimming condition [51]. The hierarchical microstructure and electrochemical properties of *Longnose gar*'s scales were revealed with optical microscope, SEM, and EDS, which confirmed the potential application of such materials for high performance porous carbon material [52].

In a study done by Feng et al. (2020), *Grass carp*'s scales were characterized using SEM, XRD, and atomic force spectroscopy (AFM), to reveal the lamellar structural arrangement of collagen fibers in the scales, and tensile test was done to determine their strength [53]. The authors reported that *Grass carp*'s scale matrix has a textured structure made up of several collagen sheets. Moreover, the matrix had excellent mechanical properties, in-vitro anti-enzymatic abilities, and compatibility with human corneal epithelial cells [53]. The study was done by a micro-CT scan to acquire the body dimension data, junction overlap, and body mineral density. In this study, Mercury porosimetry was performed to find the pore size distribution and volume percent porosity. SEM and micro-CT determined porous and sandwich structure. SEM and surface profilometry were used to characterize the interior and exterior surface topography. Moreover, back-scattered electron microscopy and energy dispersive X-ray analysis helped quantify the weight percent mineral content [54]. In-situ synchrotron small-angle X-ray scattering test was performed during the mechanical tensile tests to find out the deformation behavior of the collagen fibril lamellae in *Arapaima gigas*'s scales. This study showed that Bouligand-type structure of the fish scale contributes in the resistance against bending of the full scale and helps prevent fracture [55]. X-ray microcomputed tomography was used to generate digital 3D reconstructions of the mineralized scales of *P. senegalus* [56].

Mechanical properties of *Cyprinus carpio*'s scales were also investigated by uniaxial tension experiment [57]. The authors found the tangent modulus (instantaneous modulus), strength, modulus of toughness, and strain to failure. The full-field deformation behavior was quantified by performing Digital Image Correlation (DIC).

The authors also revealed the microstructures of fish scales using a series of sophisticated microscopies along with FTIR spectroscopy. This study found that fully hydrated head scales have twice strength than the tail scales, but the dehydrated scales do not have significant differences [57]. Similar study [58] was performed to find the mechanical properties of fish scales under tensile test, and the DIC and microscopic images showed that the tensile strength of carp's scales was dependent on the number of collagen fiber layers in their inner layers [58]. A black carp's (*Mylopharyngodon piceus*) scales was analyzed with tensile testing and DIC for finding the mechanical properties and the effects of different position (head or tail) of scales with its mineralization and dehydration [59].

In another study [24], SEM, EDX, TEM, and FTIR were done to identify the properties including the chemical and physical properties of the mineralized and demineralized fish scales. Tensile strength measurement was undertaken where *Pagrus major*'s scales represented an average of 93±1.8 MPa and showed that the mineral content has significant impacts on the strength of fish scales. The tensile strength was measured using a texture analyzer (TA-XT2i; EKO) [24]. Tensile and puncture test on the scales were done by Ghods et al. (2019) [60], using a commercial universal testing machine, SEM analysis, and microCT. Furthermore, imaging of puncture test on the samples were conducted to analyze the dynamic loading response on elasmoid scales of *Cyprinus carpio*. This study found the significant difference in tensile properties, and puncture resistance among specimens from different locations in a fish (head, tail, and middle bodies), because of the differences in physical (such as thickness) and chemical properties (such as mineralized content). During the puncture test, the strain rate sensitivity was found to depend on the lamination and delamination properties of the microstructural layers. Details of the scale microstructure and the experimental methods shown in the figure 2 [60].

Mechanical properties such as elastic modulus, ultimate tensile strength, strain at failure, modulus of toughness, and stiffness were also evaluated by uniaxial tensile test and transverse puncture test on the scales of *Cyprinus carpio* [61]. Here, scales were obtained from near the head, middle, and tail region of multiple fish, and then evaluated after fully hydrated in water or after exposure to a polar solvent (ethanol), for finding the effect of the polar solvent on the mechanical properties of scales. This study found that polar solvents can increase the resistance to failure of the scales, which is uncommon with the polar solvent in structural material [61]. In another study, tensile test, micro and nano indentation test (using a Vickers indenter), SEM, EDS, X-ray diffraction, and FTIR was done on *Arapaima Gigas*'s scales [62]. This study found the presence of amide I, II, and III, and characteristics and orientation of type I collagen can influence the mechanical properties such as tensile strength [62].

SEM analysis and nanoindentation was also done on *Alligator gar*'s scale specimens to determine the interfacial geometric structure between ganoine and bone [63]. Nanoindentation was performed to determine the elastic moduli's spatial variations and this nanoindentation data was also used to map the fish scale's cross-section, which shows

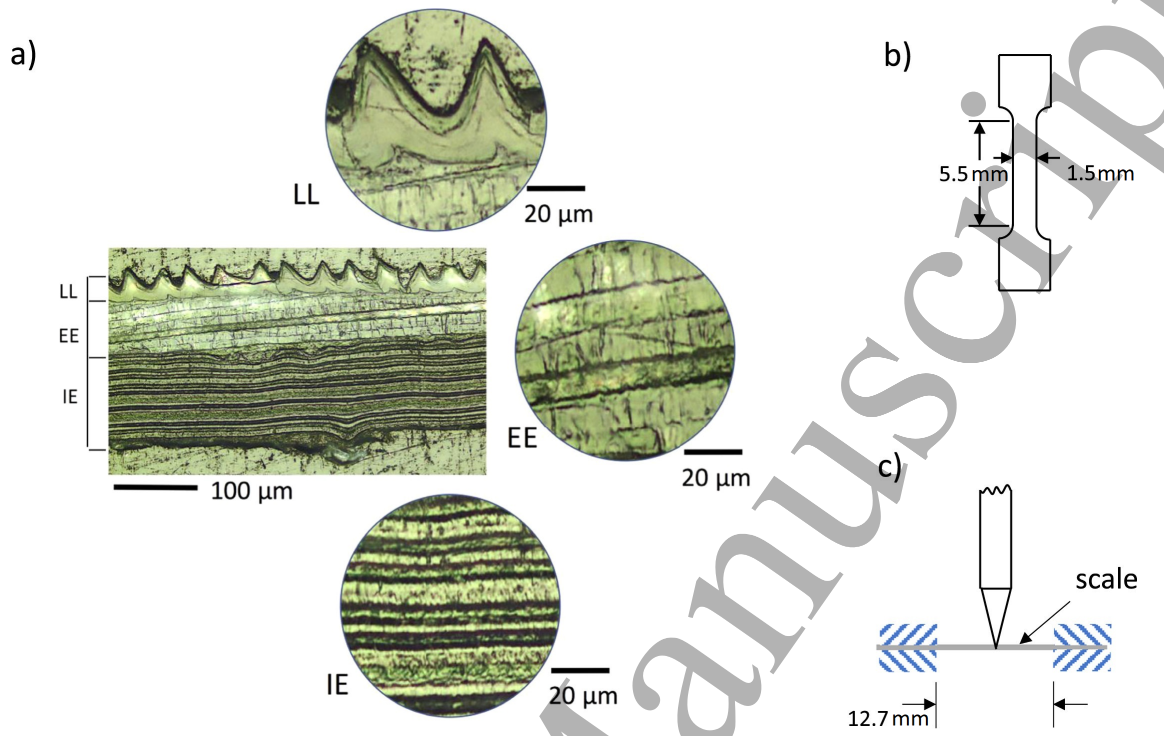

Figure 2. (a) Carp's scale cross-sections for representative head and tail scales with showing three principal layers: the limiting layer (LL), external elasmodine (EE) and internal elasmodine (IE). (b) Tensile testing specimen, which is a conventional dog-bone shaped tensile specimens, sectioned from the scales using punch and stamping process. (c) Clamped puncture testing sample schematic [60]. (Copyright permission has been adopted.)

convergence of the elastic modulus for the ganoine and bone region. Additionally, SEM images of the microstructure and nanoindentation experiments qualitatively showed significant heterogeneity [63]. Scales of *C. Carpio* have been investigated with a puncture test (V-shape indenter) to find the flexural properties and the effectiveness of scales to resist puncture. In this study, nanoindentation test was performed on elasmoid and mineralized layers to determine the elastic modulus of each layer, and significant variation was found among the spatial scales. Thus, the scale distribution could be used in designing flexible puncture-resistant materials for instance in gloves. Both energy and load to puncture have significantly increased with the scale placed as a layer on top of the glove material [64].

Further studies on perforation tests on the scales of a striped bass (*Morone saxatilis*) was done where it shows that the scales have high resistance to penetration. This study also observed the cause of high performance, which mainly is due to the fine balance between the stiffness and hardness of the outside layer as well as the softness and strength of the outer layer [65]. For this case study, the scale thickness was around 200-300 μm and perforation test was done with a sharp needle. In addition to the microstructure of the scales, puncture tests with a sharp needle (tip radius 35 μm) on the striped bass also highlighted the critical role of scales arrangement in enhancing the puncture resistance by distributing the force on the surface [66]. It was found that the individual scales provide a remarkable barrier against sharp puncture, although friction between the scales was negligible. Then, it was surmised that friction does not contribute to the increment of the puncture force [66]. Another penetration test on *Morone saxatilis* to replicate the biting attack with a sharp needle (tip radius $\approx 30\ \mu$m) confirmed that the presence of fish scales significantly increased the penetration resistance [67].

Another experimental investigation [68] with tensile testing, microstructure analysis, and Raman spectroscopy was done on the ontogenetic and regenerated scales of *C. Carpio*. Strength, modulus of toughness, and strain to fracture show the significant difference between the two kinds of scales [68]. An experimental study [69] was done to characterize the Arapaima's (*Arapaima Gigas*) scales through the penetration test, tensile test, in-situ SEM monitoring under tensile loading, small-angle X-ray scattering, and TEM test. This study has provided the details of the mechanism of deformation, delamination, and rotation of the lamellae, and showed how the scales restrict the penetration of external material or force [69]. The penetration resistance, which was measured by the instrumented nanoindentation technique, has been used to reveal the elastic and plastic properties of the scales [24]. An investigation was performed on the teleost fish skin to determine the role of skin bending through pinching test, and it was confirmed that the engagement of scales brought about a much higher bending resistance [17]. Tensile test, surface morphology, and microstructural analysis was made on five types of fish from the members of the family *Lutjanidae* to determine the mechanical properties and scales structure. It found that the mechanical performance of fish scales is influenced by the shape, array pattern, and compactness of strips on the posterior edges of a scale. This study helps to find the best structure for mechanical loading [70].

Interestingly, scales of *Labeo rohita* were studied to find the effect of Pb (II) biosorption and different pretreatment has been done before the analysis with FTIR spectroscopy. This study has been done by Nadeem et al. (2008) and found that pretreatment using HCl, H_3PO_4, and $Ca(OH)_2$ enhance the sorption capacity of fish scales, and pretreatment using H_2SO_4, NaOH, and $Al(OH)_3$ has reduce the sorption capacity. This study suggests that this fish scales could be an inexpensive solution for toxic metal sequestration [71]. All of the discussed experimental studies on different fish scales have been summarized in the Table 1.

In addition to scales, recent interests in suture-type structures have also increased. Suture interfaces are common in biological systems which is the connection of rigid or stiff elements (such as scales) by a compliant seam along the geometrically complex interfaces, with or without significant overlap among the stiff elements or scales. Suture structures are found in the exoskeletons of pangolin, armadillo, osteoderms, and boxfish [2, 72, 73]. Such structures have high resistance ability and flexibility without the critical decrease in stiffness and material strength [74–76]. Wang et al. (2016) studied the nanoscale suture structure found in the scales of different types of pangolin by optical microscopy, Fluorescence microscopy, SEM, TEM, micro-indentation, tensile

Table 1. Summary of experimental studies done on different fish type and their findings, for the purpose of characterization of natural fish scale.

Fish type	Experimental Method	Key Discoveries
Carassius Auratus [41–43]	Immunofluorescence, Electrophoretic, HPLC Analysis, RNA Analysis, and Immunoprecipitation	- Influence of the environment on fish scale's biological cell was revealed. - The structures of the constituent fibers were revealed.
Soleidae Flat Fish [44]	X-ray Diffraction, Differential Scanning Calorimetry (DSC), Polarized Light Microscopy, and Flow Measurement	- Biochemical and biophysical properties were analyzed.
Sparus Aurata [19, 46–48]	FTIR, TG–DTA Analysis, SDS–PAGE Analysis, and Polarized Light Microscopy	- Biomedical application, biocompatibility and potential bone regenerative were analyzed.
Crisp Flesh Grass Carps [49, 53]	FTIR, AFM, and Tensile Test	- Potential use of tissue regeneration was revealed. - Mechanical properties and lamellar structure of scales were revealed. - In-vitro anti-enzymatic abilities and compatibility with human corneal epithelial cells were analyzed.
Pagrus Major [24, 50]	FT-Raman Spectra, FITR, TEM, Tensile Testing, and Instrumented Nanoindentation Technique	- Material properties, chemical and physical properties were extracted. - Penetration resistance was studied to reveal the elastic and plastic properties of the scales.
Oreochromis Niloticus [50]	FT-Raman Spectra	- Chemical compositional differences with other fish scale were revealed.
Longnose Gar [51, 52]	Stiffness Test	- Flexural stiffness was measured, and confirmed the potential application for high performance porous carbon material.
Arapaima Gigas [55, 62, 69]	In-situ Synchrotron Small Angle X-ray Scattering, Micro and Nano Indentation Test, Tensile Test, X-ray Diffraction, Penetration Test, FTIR, and In-situ SEM Monitoring under Tensile Loading	- Deformation behavior of the collagen fibril lamellae was revealed. - Characteristics and orientation of type I collagen influence the mechanical properties. - Scales restrict the penetration by mechanisms of deformation, delamination, and rotation of the lamellae.
P. Senegalus [56]	X-ray Microcomputed Tomography	- Digital 3D reconstructions of mineralized scales were generated.
Cyprinus Carpio [57, 60, 61, 64, 68]	FTIR Spectroscopy, DIC, Tensile Test, Puncture Test, MicroCT, Nanoindentation Test, and Raman Spectroscopy	- Fully hydrated head scales have twice strength than the tail scales. - Mechanical properties differs among the scales of different place of body, and between ontogenetic and regenerated scales. - Polar solvents increase the resistance to failure and puncture, and flexural properties.
Common Carp [58]	Tensile Testing and DIC	- Tensile strength of carp's scales was found dependent on the number of collagen fiber layers in their inner layers.
Mylopharyn-godon Piceus [59]	Tensile Testing and DIC	- Effects of different position (head or tail) of scales with its mineralization and dehydration on mechanical properties were analyzed.
Alligator Gar [63]	Nanoindentation	- Interfacial geometric structure between ganoine and bone were revealed. - Spatial variations of mechanical properties were analyzed.
Striped Bass (Morone Saxatilis) [65–67]	Perforation Tests, Puncture Tests, and Penetration Test	- Fish scales shows resistance to penetration and puncture. - Stiffness and hardness of the outside layer as well as the softness and strength of the outer layer were analyzed. - Friction does not contribute to the puncture force increment.
Teleost Fish Skin [17]	Pinching Test	- The engagement of scales increased the bending resistance.
Lutjanidae [70]	Tensile Test, and Surface Morphology	- Mechanical properties of fish scales is influenced by the shape, array pattern, and compactness of strips on the posterior edges of a scale.
Labeo Rohita [71]	FTIR Spectroscopy	- This fish scales could be used as a solution for toxic metal sequestration.
Gasterosteus Aculeatus [54]	MicroCT Scan, Mercury Porosimetry, Surface Profilometry, and BSEM	- The study obtained the body dimension data, junction overlap, body mineral density, mineral content, and other physical properties of the scales.
All Above Fish Types	Optical Microscope, Electron Microscope, SEM, EDS/EDX, and TEM	- These experiments were done on different natural fish scales for finding the surface structure, microstructure, and chemical properties of fish scales.

testing, and compression testing. It has been shown that the studied suture structure has interlocking behavior, improved bonding and shear resistance [2].

In addition to fish, Pangolins possess striking scales pattern that must balance locomotion with protection. The fracture resistance of an African pangolin's scale is examined using three-point bend fracture testing in order to understand the toughening mechanisms [77]. In this study, the influence of material orientation and hydration level were examined, and other analyses were performed using a combination of optical and electron microscopy, and X-ray computerized tomography. The results showed that, similar to fish scales, the inherent structure of pangolin scales offers a pathway for crack deflection and fracture toughening [77]. Similarly, the pangolin scale's structure, mechanical properties, deformation, and damage behaviors were systematically investigated for finding the effect of hydration and orientation of scales. Hardness test, tensile test, and microscope analysis were done and found the properties of the scales varies with the orientation and hydration [78]. These studies have shown that the fundamental origins of enhanced behavior of fish scales are a result of complex microstructure as well as their action in concert with each other when impressed with external forces. These principles are essentially distilled to produce biomimetic materials with high performance.

3. Biomimetic scale systems

3.1. Arrangement effects in biomimetic scales system

The previous section outlined the critical importance of scale microstructure for high performance mechanical properties. Such microstructural topology can be used to design composites. For instance, a biomimetic Carbon Fiber Reinforced Polymer (CFRP) with a microstructure inspired by fish scales was designed and tested under the quasi-static indentation on a soft backing material [79]. This study showed that the design was effective in redistributing forces from a point load, thus improving its penetration resistance for the biomimetic fish scale structure [79]. The indentation resistance under quasi-static penetration testing was conducted on the replicated teleost fish skin [18]. Biologically relevant parameters of scale surface morphology, scale friction, and epidermal cover were changed in combination to assess their contribution to penetration resistance. Results from this research also suggest that optimized surface treatment can be applied to bioinspired fish skins to increase the resistance [18, 80].

In addition to the microstructure of the scales themselves, their arrangement is also a critical parameter in the enhanced function of overall structure. It is well known that even within a single organism, scales distribution and shape changes with location reflecting their functions [81]. Here, the role of organized geometry comes into play, which leads to emergent mechanical behavior, like metamaterials [15].

Indentation test and three-point bending test with cylindrical indenter were done to test the penetration resistance and flexibility, which can be used for finding the proper configuration of scale/substrate and material for the biomimetic armor [22]. The bending response of scaled and plain beams was measured by Instron universal testing machine. It was found that the stiffness of the scaled sample is higher, and even before the engagement of the scales due to the inclusion effect of scales [4]. Indentation studies on exposed scales sample were also carried out with 3D DIC for tracking the distribution of stress and strain across the samples along with comparisons with finite element (FE) modeling [82]. DIC revealed the global deformation and local contours of logarithmic strain fields in the composite design [20]. Stab-test was performed on the plain samples and scaled samples, which are similar to the knife penetration, and it found that scales samples were highly effective that can be suitable for body armor [83–85]. Another study was done focusing on the unstable tilting of individual scales subjected to off-centered point forces to enhance penetration resistance [86]. The puncture test was performed using two configurations, and pictures of the sample were acquired with a digital camera (Olympus Camedia C-5060) in micro-focus mode. The sample pictures were captured prior to the test to measure the offset distance accurately. Thereafter, images were captured at regular intervals during the test to monitor the tilt angles of the plate. Here, a failure mode was reported where the plate while remaining intact, suddenly tilts under the action of a localized force. The study found that the location of the point force on the plate, friction at the surface, size of the plate, and the stiffness of the substrate governs the stability of individual plates. A combination of scales with desired mechanical properties and these parameters can be used for optimal design [86].

An indentation test was also performed for the puncture examination, where two types of radii were used for the indenters with quasi-static and static loading. From the test, it was found that the synthetic fish skin possessed many of the advantageous attributes of its biological counterpart. This underscores the possibility of obtaining an attractive combination of flexibility and protection found in natural materials with different combination scales and substrate [87]. Tensile test and three-point bending test were done on a biomimetic scales sample using an MTS Sintech machine. These tests evaluated the stability of the specimens which could be used as highly effective protection layers for wearable electronic devices and soft robotic [88].

Impact test was done on a biomimetic composite structure to verify the effects of helical stacking angle, which were found from an analytical model. It was observed that impact resistance decreases with the increase of helical stacking angle. SEM analysis was also done to find the relevant microstructure, which shows the biological structural effectiveness against the force for the composite structure (silicone and Kevlar fiber) [89]. The biomimetic armor was tested under dynamic impact using an ElectroForce 3300 equipment (TA Instruments), and ballistic test using a handgun. The sample design was inspired from the fish scale hierarchical structure (from one to six hierarchy levels), where the ultra-high-molecular-weight polyethylene (UHMWPE) was used as a base material. It has been discovered that these materials can absorb a higher level of energy, which are useful as high impact resistant materials [90]. The quasi-static and impact loading conditions were applied to the panels of biomimetic ceramic building blocks, which is having different interlocking angle where is placed on a aluminum frame. The panels' performance in terms of stiffness, strength, and energy absorption, improved with increasing the interlocking angle up to 20 degrees. The increased interlocking between the blocks, which restricted their relative motion were shown to be responsible for this [91].

In a study for assessment of bio-inspired stab-resistant armor, the test specimen was manufactured from a mix of virgin and recycled Duraform with different sizes and configurations, and it was stab-tested using an Instron 9250HV drop tower. All tests demonstrated successful levels of stab resistance, below the 7.00 mm permissible limit as defined by the CAST KR1 body armor standard, therefore validating the established body armor suitable for both survivability and maximum user mobility and comfort [84]. To study the 3D carved glass, biomimetic glass panels with different interlocking angles were studied using a universal testing machine (5 kN MTS Dual column loading stage). Additionally, the performance of the panels was assessed at high deformation rates by impacting them with a steel ball with the diameter equal to diameter of the ball used for the quasi-static tests. Deformation and fracture of the architectured panel were also shown to be a function of the geometry, size, arrangement of the blocks, and also of the degree of confinement imposed by the external frame [3]. Puncture tests were also performed to determine the resistance of the continuous glass (non-engraved) and engraved glass. The engraved glass was glued to the silicon rubber that was used as a substrate. It was found that the puncture resistance improved with a higher percentage in the engraved samples inspired from the fish scale compared to continuous plate. The technique of the testing sample is shown in figure 3 [92].

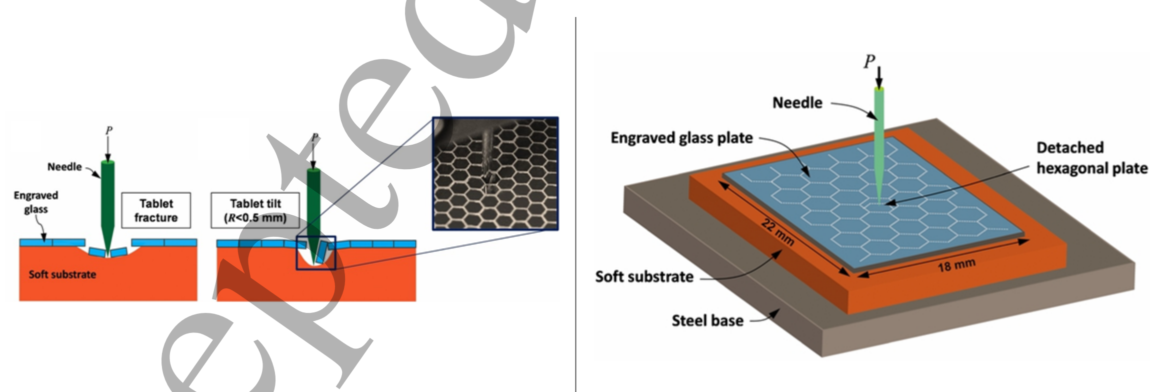

Figure 3. Puncture test illustration on engraved samples, showing two possible condition, fracture and tilting (left), showing structure of engraved glass and shear of hexagon (right) [92]. (Already published and owned by IOP Publishing.)

A test for finding the puncture resistance properties was done using an ABS needle, which leads to a small contact area. It is observed that scale-scale interactions significantly increase puncture resistance, while also decreasing flexural compliance. Some geometries and arrangement of scales have shown better performance than others. For instance, simple arrays show the worst performance and the geometry similar to the natural teleost and ganoid scales show the best performance [25]. The alumina scales with the soft substrate were tested using an MTS testing machine for the sharp needle puncture test with different combinations of the length of scales and overlap ratio. It was found that the size and overlap ratio affect the performance of the puncture test. The scaly skin is always stiffer than the silicone membrane, but more compliant than the continuous alumina strip. The samples were tested under a four-point bending configuration. The results demonstrate the capability of the proposed technique to cover large and complex surfaces, and it shows that the bio-inspired scaled skin can bend up to relatively large curvatures [93]. Earlier, for a fully embedded composite design of biomimetic scales, plane strain compression test was performed with varying geometric conditions, and the image of the test was captured by a DIC camera [20]. The authors quantified the geometry and distribution of the embedded scales on the skin deformation behavior [20].

In addition to indentation studies, buckling experiments on a scaled skin were performed using a dual column universal testing machine (ADMET, Model eXpert 5000) to investigate the effects of biomimetic scales in the buckling modes and stability. The study found that scales can induce a stable mode II buckling which increases the overall flexural compliance and agility. The figure 4 shows the testing results of the buckling test to compare the experimental method and discrete element method (DEM) [94, 95]. The scales themselves can also be tuned from stiff to soft using a stimulus sensitive material such as low melting point alloy (LMPA) [96]. Here, specifically engineered scales were used to design a metamaterial capable of transitioning from stiff to soft behavior. The samples were tested under three-point bending at various controlled temperatures. Results show the pronounced and reversible tunability in bending behavior and complex mechanical response in cyclical loading [96].

The influence of scales in tailoring the global deformation of slender substrates such as beams and plates are also of great significance for designing smart skins/structures and soft robotic structures [4–7, 12–14, 97]. Three-point bending experiments were performed using an MTS Insight machine on the scaled and unscaled samples to find the flexural response of the structure, and it demonstrated the differences in the stiffening response between scaled and unscaled samples, especially highlighting the dependence on the scale overlap ratio [4]. The stiffening response of scale-covered beam remains universal across bending of the uniformly distributed scales [4], bending of functionally graded scale in the scales spacing and in the initial inclination angles of the scales [14], and twisting of the uniformly distributed scales [6]. The experimental investigations showed a noticeable difference in deflection between uniform distribution of biomimetic scales and linear functionally graded scale–covered beam, under their own weight [14]. Also for torsional loading, the effects of scales engagement were investigated using an MTS Bionix EM (Electromechanical Torsion 45 Nm), which showed significant stiffness gains in scale-covered beams in comparison with the plane beam [6]. Furthermore, this study discussed the significance of the scale's oblique angle with respect to the direction of the beam for twisting case as one of the most important differences between the

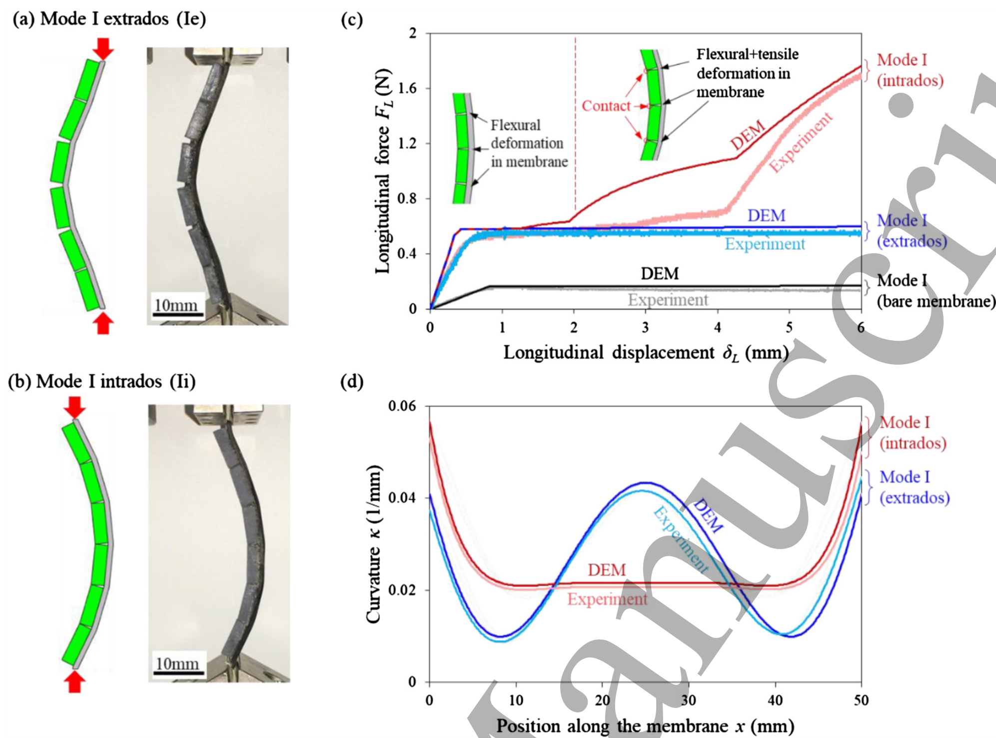

Figure 4. Experimental and DEM buckling test on a scaled polyurethene strip where the system buckles into (a) mode I-extrados and (b) mode I-intrados; (c) longitudinal force-longitudinal displacement curves showing a good agreement between the experimental and DEM results; (d) Curvature of the membrane as a function of the position along the membrane in the mode I-extrados and mode I-intrados configurations at loading point δL = 6 mm [94]. (Already published and owned by IOP Publishing.)

bending case and twisting case in 1D scale-covered beams [4, 6]. These studies outlined the highly non-linear, reversible, and tailorable properties of biomimetic scale-covered materials in both bending and twisting loads [4–7, 12–14, 97].

3.2. Surface effects in biomimetic scales system

In addition to mechanics, biomimetic shark skin has been tested inside a water tunnel for studying the drag reduction effect and found significant results [98]. The fish scales' superoleophobic properties have been studied using SEM and optical contact angle goniometers (OCA20). These artificial superoleophobic interfaces were manufactured from the inspiration of fish scales [99]. Biomimetic 3D printed fish scales were investigated to find their influence on the laminar-to-turbulent transition in the boundary layer of a laminar water channel. This study found the drag reduction properties of the surface, which can be used in bioinspired surfaces for flow control [100].

Wettability and drag reduction performance test using a pressure resistance test device was performed on a biomimetic fish scale Al-alloy sample to find the hydrophobic, superhydrophobic, low adhesion, and draft-reduction behavior. Microstructure of the sample observed with SEM and the surface morphology was observed by laser confocal scanning microscope (LSM700-ZEISS-Germany) and ultra-depth of field microscope (SmartZoom5), and the 3d contour of the sample surface was obtained. This study provides an effective method for fabricating bionic fish scales, which provides superhydrophobic surface and drag reduction properties [101]. Biomimetic shark skin samples were tested to determine the hydrodynamic properties in both static and dynamic moving conditions in a controlled environment through robotic devices [102]. The result shows that the effect of shark skin surface denticles on swimming performance relative to a smooth control is determined by the motion of the skin [102].

Biomimetic skin based on shark skin were tested to determine the swimming performance. Two samples were prepared for this swimming performance test, one sample is based on ribbed rubber material and the other sample is based on the Speedo Fastskin®. It found that the biomimetic skin affects swimming performance [103]. In addition, different bioinspired materials were also used for studying the surfaces with superhydrophobicity, superoleophobicity, drag reduction, and superhydrophilicity which can be used as self-cleaning material. The comparison was also done by different investigation techniques between different types of scales existing in nature [104–107]. In a study by Bixler et al. (2013), the oil drag reduction on the actual fish scale and the biomimetic replica sample was measured for different kinds of natural scales. During the test, a sample was lined rectangular closed channels with the laminar oil flow, to evaluate the performance of the biomimetic structure [108].

Fish scales surface properties such as surface friction has significant effect in biomimetic scales engagement. Friction can advance the locking envelope, significantly larger friction coefficient can create static locking condition [5]. In the dynamic study it is found that frictional effects can create viscous damping behavior [13]. Also, under twisting of the biomimetic fish scales systems, the Coulomb friction between the scales can lead to static locking condition [7].

4. Techniques and advances in fabrication of biomimetic scales

There are different technique for the fabrication of biomimetic fish scales. Among various technique, these can be divided into two main categories such as 3D printing assisted technique [109], and conventional manufacturing method such as stress-and-release fabrication [93] and laser cutting technique [92]. Depending on the requirement of the mechanical properties, implementation of the fabricated system, and testing requirement, different techniques are selected by the researchers [87, 92, 102, 110, 111]. For high performance response, various parameters need to be controlled, such as size and shape of the scales, scale's aspect ratio, spacing between the scales, and scale angles. More significantly, the scales are often made of the same or different kind of materials, different sizes and shapes, which need to be attached to a substrate with much lower stiffness, requiring different joining techniques such as gluing. Fabrication of fish scale structures can be significantly leveraged by additive manufacturing (AM) due to the geometric nature of their organization. Despite this, several challenges remain unique to this system [26, 112, 113]. AM can also be used to fabricate different customized shapes, sizes, root geometry, and molds, which can be used to mimic various kinds of natural scales to endow tailorable properties. Since a combinatoric variety in the materials of scales and substrate can lead to a greater tailorability, multimaterial AM can be of special use. Multimaterial AM also removes the need of glues and complex mold making. In addition to AM, spraying technique is a new technique that can be introduced for the fabrication of biomimetic scales which is already studied for some other biomimetic applications [114–116].

4.1. Techniques based on partial or full AM

Despite the wide range of scope of design in AM and ongoing work [117], there are still limits for the biomimetic design through this technology. In many cases, AM is used for the partial fabrication of the biomimetic parts [90, 109, 118–120]. An overview of AM manufacturing process, which are used currently, is shown in figure 5.

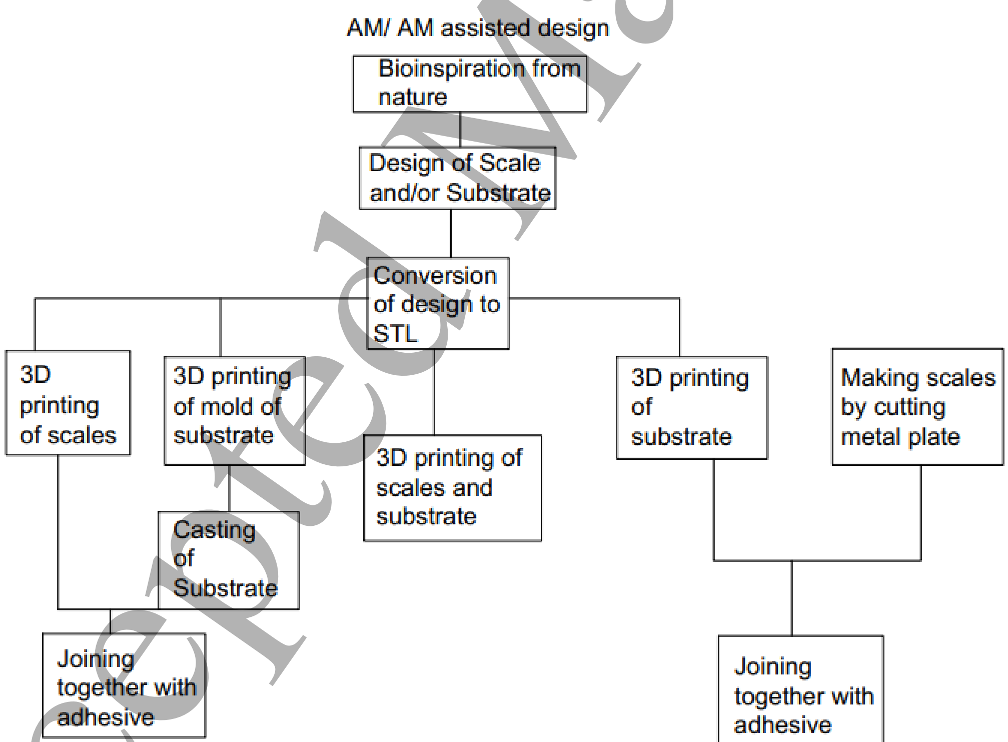

Figure 5. Typical AM assisted fabrication process flow of Biomimetic of fish scale.

Single material AM can be used in some parts of the biomimetic scale fabrication process. This typically involves either or both scales and mold fabrication using AM. When AM is used to create a mold for the substrate with groove-shape features for placing and inclusion of scales into the substrate, a soft polymeric resin such as silicone can be poured in it and cured to obtain desirable substrate properties [121]. After the substrate is made with grooves, glue is used to attach the scales to the substrate. In an early study [122] in this field, the fabrication of biomimetic fish scale prototypes was done in few steps where 3D scanned biological geometry was initially achieved by micro-computed tomography scanning, then converted to surface mesh geometry, and finally converted to stereolithography (STL) file format for additive manufacturing. Then, using the scale-up of the design to avoid low wall thickness failure, an AM machine (or a 3D printer) was used for the fabrication of the scales [122].

Inspired from the previous design techniques, multimaterial AM was used for the fabrication of the rigid (VeroWhite), and soft (TangoPlus) components separately. The ratio between the stiffness of materials selected for the scales and the substrate has significant effect on the mechanical behavior of the system [111, 122]. A similar approach was used with micro-CT scanning of samples, where 3D conversion of image data and modeling was done [102]. This study used multiple nozzle 3D printers to replicate different material properties with rigid and flexible structures and carefully consider the postprocessing of the 3D printed parts. Because of the limitation of the 3D printer for creating smaller parts, this technique created a scale-up denticle design [102]. Another study also used micro-CT to acquire the shark denticle structure, which was then converted to an STL file optimized with Netfabb software to design the denticles' mold. Then this mold was used to fabricate the denticles, which at the end trimmed and manually assembled [123]. By using a multimaterial 3D printer, composite materials of the stiff plate (VeroWhite) and soft matrix (TangoPlus) prototype were fabricated with different inclination angles and volume fractions (between stiff phase and soft material) [22]. In another study, 3D printing of the scales and substrate was done separately and assembled using glue [124].

Another method for fabricating biomimetic scales is by design and fabrication of a mold using 3D printing. Then this 3D printed mold can be used for making the flexible substrate. Finally, 3D-printed or non-3D-printed scales can be partially embedded into the structure with glue while keeping the required distance and overlap ratio [7, 14, 20, 82, 96, 121]. A typical fabrication process of biomimetic scales with mold and scales design is shown in Figure 6, including the mold and scales fabrication in 3D printer, substrate fabrication by adding curing agent, and finally insertion of scales into substrate.

Another study [91] used a 3D printed block to create a silicon mold. Then a ceramic slurry (calcium sulfate powder + 19 wt % water) was pressure cast into the mold to create a ceramic building block, and finally the building block was tape transferred into the aluminum frame. The gap between the edges of the panel and the frame was filled with calcium sulfate paste to maintain uniform force transfer from the frame to the peripheral block. Here, the block was built with different inner and outer angles for material testing [91]. The scales were built with a high-resolution 3D printer, and the scales were then glued onto the surface of the polyurethane membrane using cyanoacrylate and with a gap of 0.5 mm between scales [94].

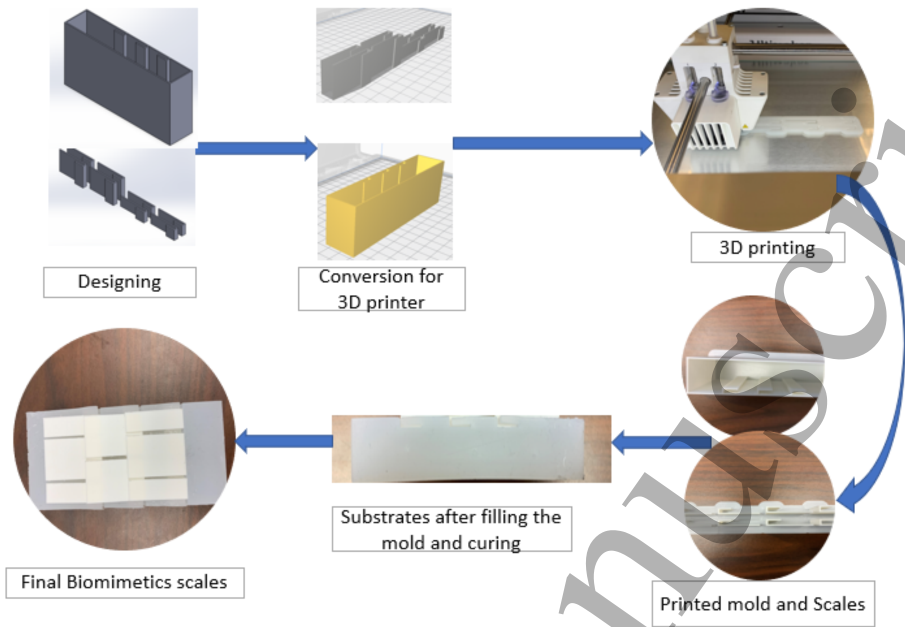

Figure 6. Fabrication process of biomimectic scales with molding concept.

Laser-sintering 3D printing technique was used for fabricating armor, where the CAD model was transferred into the 3D printing machine and finally, additively manufactured samples were achieved [84, 85, 125]. Another technique described in literature is using the 3D printed scales (ABS photopolymer) fabricated with a direct light projector (DLP) printer [25]. After removing the support material, the array of scales was compressed using a biaxial vice system to minimize the gap between the scales, which was intentionally created during the 3D printing process. Then after gluing on the samples, the biaxial force was removed, and finally the scales were glued on a polyurethane membrane using adhesive [25]. A multimaterial 3D printer was used for the fabrication of biomimetic chiton scales, which started from the CAD design conversion to STL file and then transferring to the 3D printer. In this process, both soft and rigid materials were simultaneously printed at each layer [126]. For the study of scales effects on the body drag, biomimetic fish scale samples with different rows and thickness were made using 3D printed scales from CAD model directly [100]. Another approach was used where the substrate was 3D printed with soft material, and then the metallic scales were glued on the substrate [127].

4.2. Other techniques

In this section, we discuss the techniques rather than AM-assisted methods. The shark skin (*Carcharhinus brachyurous*) [98] was chosen as the bio-replicated template with the proper treatment and the replication of the scales done with hot embossing with four steps: substrate heating, stacking and isostatic pressing, flexibility demolding, and mold replicating where polymethyl methacrylate (PMMA) flat plate was selected as the substrate. Mold replicating was done with a casting process where a specific ratio of curing agent was mixed and finally demolding provided the biomimetic skin. The manufacturing technique used the process flow shown in figure 7 [98]. Among the various fabrication method, molding [128] and hot embossing [98] are the two main techniques for fabrication of biomimetics shark skin. Compared with other manufacturing method, 3D printing has many advantages. 3D printing makes multimaterial printing within a single step, also helps large area fabrication within a short period of time, and it allows denticles to be placed on the membrane accurately [102]. This technique also has controlled over the mechanical properties, size, arrangement of the scales, distance between the scales, and having undercut between denticle crown and the membrane surface. Despite all the advantages, 3D printing has one major disadvantage. Using current 3D printing technology, it is not possible to fabricate mako shark denticles that has complex surface characteristics of natural denticles [102].

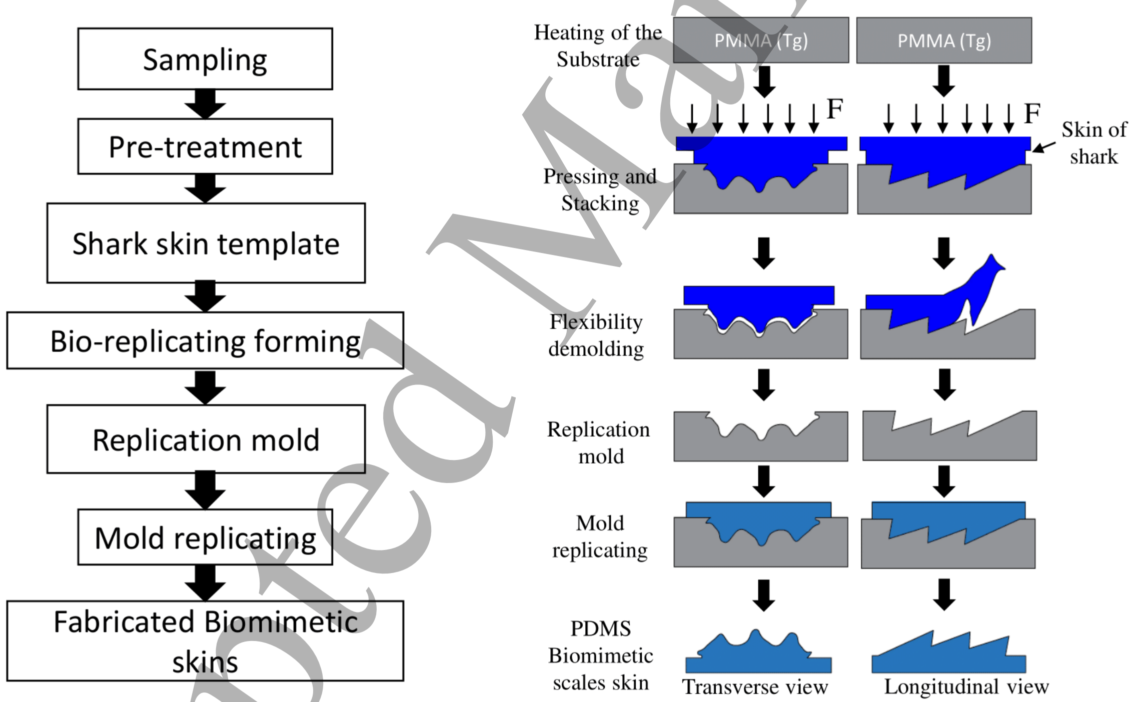

Figure 7. Manufacturing process flow of biomimectic shark skin [98].

A similar casting technique was used to fabricate the biomimetic fish scales, where polydimethylsiloxane (PDMS) precursor liquid was mixed with the curing agent for creating the template, and finally fish-scale structures were made from the polyacrylamide hydrogel films [99]. For designing a biomimetic armor, rigid protective plates (glass) with defined size and shape are placed over a soft substrate (flexible rubber), and this was achieved by laser engraving technique on the glass to gain the natural protective system characteristics [92].

The laser engraving technique is also used with interlocking mechanism inspired by nature-like fish scales on the glass, for increasing the impact resistance of the glass surface. The engraved glass panel was separated and finally put into the aluminum frame for making the samples ready for testing [3]. The synthetic fish skin material has been designed to duplicate the material properties of teleost fish skin consisting of leptoid-like scales. Rectangular scales with fixed size were cut with a controlled mesh from a large cellulose acetate butyrate sheet. The scales were inserted into a polypropylene netting with one-half of scale under the mesh, and finally they were connected with three stitches and a single knot with prefabricated holes [87].

A unique technique was developed where the alumina strip (used as a row of scales) was engraved using a focused laser beam [93]. This engraved alumina was glued to a pre-stretched polyurethane strip, and after releasing the stretch of strip, the scales slide on each other and make an overlap pattern of scales. Then, the prepared overlapped scales pattern was glued on a flexible membrane, and finally the polyurethane strip peeled off to obtain the flexible armor-like structure. This step-by-step fabrication has been shown in figure 8 [93].

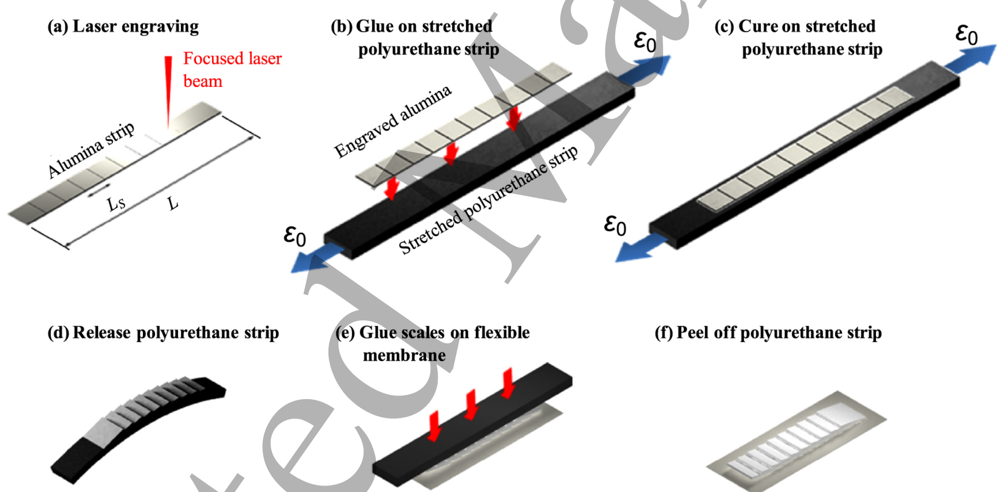

Figure 8. Stretch-and-release step by step fabrication of biomimectic scales [93]. (Already published and owned by IOP Publishing.)

In a recent study, inspired from carp's (*Cyprinus carpio*) scales, the nylon sheet was laser cut and a silicon substrate was cast over scales, which was embedded in the female mold of substrate. After the demolding, the scales were embedded in the substrate, and the final sample was achieved for testing [80]. For creating hierarchical structural materials, ultra-high-molecular-weight polyethylene (UHMWPE) plates (as base material) and fibers were used for the manufacturing of protecto-flexible (Pf) armor in different configurations ranging from monolithic (one level of structural hierarchy H-1) up to six levels of structural hierarchy (H-6). This was specially prepared with a specific fabrication process (described in the supplemental material of [90]), and finally these samples were cut with laser engraving for the preparation of the hierarchical structure. The structure of this newly constructed material resembles the geometrical patterns found in armadillo's osteoderms and the flexible impact-tolerant configuration found in fish scales [90].

In a bioinspired armor design [79], a perforation resistant carbon fiber reinforced polymer (CFRP) was developed inspired from the ratios in teleost fish skin. This CFRP composite structure is consisted of the quasi-isotropic laminated base plate and cross-ply scales configuration. Rows of scales were sequentially attached to the base plate, having 1.5 mm inserted into the base plate, and placing a nonstick film between each layer of the scales to keep them separated during curing [79]. A different method was carried out for fabricating by using decellularized and decalcified fish scale derived scaffolds. Three different kinds of scaffolds were made by using decellularization and decalcification treatments. This samples were used to test the usability for tissue regeneration engineering [49]. Biomimetic flexible composite structures using silicone (silicon with curing agent) and Kevlar fibers were made firstly by mixing both the composite materials. Then, vacuum pump was used for removing the air bubbles, and after pouring the required amount of material into a rectangular mold, again vacuum was used for more assuring of removing the bubbles. After that, the mold is placed in the oven for curing. In next step, Kevlar fibers were included in the solidified mold, covered it with another part of the mixture, and repeated the same curing process. Each sample had five layers of fibers and had a constant helical angle [89].

Aluminum alloys were used as the base material to fabricate the biomimetic oblique groove structure of *Sciaenops ocellatus*'s scale. The process was started with the electrical discharge machining (EDM) cut for cutting the Aluminum alloy, then a laser device (YLP - ST20E) was used for fabricating the multiple curves on the scales. Finally, the samples postprocessing was done using ultrasonic cleaning and drying [101]. Polydimethylsiloxane (PDMS) was used for the fabrication of stretchable armor by pouring it on a PMMA-coated silicon wafer after mixing with the curing agent. Then, spin-casting at 200 rpm generated a temporary substrate as a support for a sheet of fiberglass epoxy placed on top. Finally, the cleaning was done with laser cutting and isopropyl alcohol, and the scales and substrate were connected together [88].

5. Advances in analytical and computational modeling

Fish scale inspired systems have diverse and often unique material design challenges. First, the combination of materials and geometry pose a combinatoric design space of vast parameters. In addition, the contact mechanics of scales make the problem highly nonlinear even for small strains. These periodic nonlinearities can result in unprecedented emergent behavior in dynamic loads, presence of friction, or cross curvature coupling. Therefore, simple hand calculations or strength of material type approach is insufficient to understand, design or optimize these systems. At the same time, high contrast of material behavior between the substrate and scales, large number of contacts and geometric nonlinearity of the slender substrate pose substantial challenges to traditional FE. Thus, modeling and simulation form an equally significant part of fish scale research. One of the earliest simulation studies related to fish scales has been done by Bruet et al. (2008) using finite element analysis (FEA) to develop a computational model for comparing the indentation modulus and yield stress of individual ganoid scales with experimental results and found it almost similar between the simulation and experimental data [24]. The authors described the mechanistic origins of penetration resistance as the juxtaposition of multiple distinct reinforcing composite layers in a ganoid scale. Therefore, each of these layers undergo their own unique deformation mechanisms under the penetrative load, and functionally gradation in mechanical properties of different regions of the scale [24].

In another early research, Zhu et al. [65, 66] studied the puncture resistance of scaled skin from striped bass as an inspiration for flexible wearable armor under experimental efforts. They also developed an axisymmetric finite element model with a bilayer scale to model the outer bony layer and the softer collagen layer of the scales and studied the effect of scales pattern and friction between the scales under a local indentation load. It observed that the surrounding scales contribute to redistribute the puncture force over a larger area to limit local penetrative deflections in the soft tissues [66]. Also, the analytical "Four Flaps" model has been developed to describe crack failure in the bony layer of the scales [65]. By developing the bioinspired analogues of fish scales, this field of interest has been extended from studying natural scales to fabricated bioinspired composites and metamaterials [4, 20, 22, 25, 94]. In the earlier prototypes, the scales were considered fully embedded [20–22]. Through experimental analysis and numerical simulations for these kinds of prototypes, some protective mechanisms have been observed in the biomimetic scales composite, including the scale bending, scale rotation, and shear and constraint in the substrate [20]. Also, this protective response can be tailored by geometrical parameters including scale's angle, scale's overlap ratio, scale's volume fraction, aspect ratio of the scales, and material properties of scales and substrate [20]. Also for fully embedded scale composites, exact analytical solutions were developed under compressive and bending loads with finite deformation assumption [21], which leads to rigorous response tailorability with respect to geometrical parameters similar to earlier study on fully embedded scale composites [21].

In addition to the fully embedded scales composites, the exposed biomimetic scales metamaterials have been studied as well [4, 6, 12, 25, 94, 129, 130]. Exposed scales can be plate like, placed horizontally on a substrate [17, 25, 67, 94, 95, 99, 129], or partially embedded protruding scales [4–7, 12–14, 16]. In the exposed scales system, at a certain deformation of the substrate, the exposed parts of the scales start to contact or engage with each other. This engagement will add geometrical nonlinearity to the system leading to additional stiffening of the system. These large number of contact pairs through the whole biomimetic scale system and significant contact nonlinearity cause limitation in the commercial FE software for the convergence of numerical solution and critically reduce the speed of simulation. Therefore, in addition to the need for major advances in numerical modeling, analytical modeling is of importance, which can acquit the need for numerical simulations.

A basic micromechanical model, which correlate the flexural response, material properties of the substrates and the geometrical parameters of the scaled skin was introduced assuming periodic engagement[129]. This study revealed that scaled structures present inherent strain-stiffening response, which can be tailored by the scales design, scales spatial density, scale-dermis attachment stiffness, scales arrangement or pattern, and their material properties. They also find that in the absence of rigidity assumption for the scales, the scale's shear deformation makes reduction in the average stiffness and strain-stiffening characteristics of the scaled structure [129]. In another later study [17], they improved the introduced micromechanical model by establishing a more rigorous geometrical model between scales rotation and skin curvature. They also investigated the stiffening response of a scaled structure under buckling analysis in addition to the pure bending deformation. This investigation was resulted in the enhancing role of rigid scales to postpone the critical buckling load of the structure due to the resistance of the scales against out-of-plane rotation [17].

In other research works [4, 5, 16] a biomimetic scales metamaterial was considered with equally spaced rigid scales, which partially embedded on a deformable substrate, as shown in Figure 9 (a) that also developed specific rotational stiffness relationships. By assuming periodicity in scale engagement after bending deformation, the authors established a kinematic micro-model for the representative volume element (RVE) level, between the scale's inclination angle θ and the substrate's local bending angle ψ, as follows:

$$\eta\psi \cos\psi/2 - \sin(\theta + \psi/2) = 0 \tag{1}$$

Here, d, l, $\eta = l/d$, and $\kappa = \psi/d$ are the scales spacing, scales exposed length, scales overlap ratio, and beam curvature, respectively [4, 5]. This nonlinear relationship leads to a kinematic performance map as shown in Figure 9 (b), with three regimes of operations: (1) Linear performance before the scale engagement (horizontal section of each η's curve). (2) Nonlinear stiffening after the scale engagement (ascending curved section of each η's curve). (3) Kinematic locking, which is the singular point of equation (1) for each η's curve and connecting these points for all curves leads to the kinematic locking border (black line in Figure 9 (b)).

Then, by developing a micro-macro energy balance (Hill-Mandel Condition) [15, 131], the coupling between the kinematic and mechanic model has been established, which leads to the moment–curvature response of the system as shown in Figure 9 (c). These studies revealed that the frictionless scales engagement will add highly nonlinear stiffening to the system, which at a certain curvature will leads to the kinematic locking of system. Kinematic locking is because that further deformation in the system needs excessive deformation in the scales, which is against the rigidity of scales. They also showed that the friction force between the scales has a dual contribution including advancing the locking mechanism by changing the mechanism depending on purely kinematic configuration to the interfacial behavior, and stiffening the bending moment response due to the increase in the engagement forces [5].

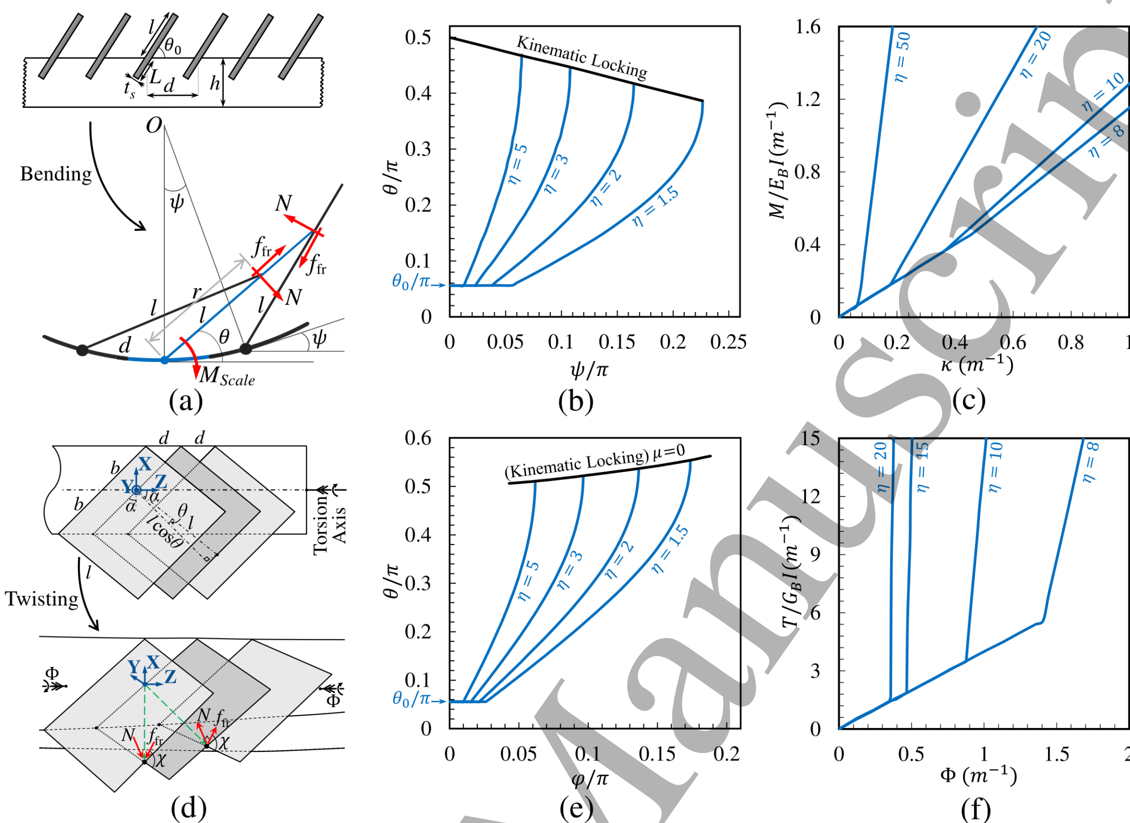

Figure 9. (a) Isolated RVE and free body diagram for bending case. (b) Kinematic performance map for bending case. (c) Moment–curvature response for bending case. (d) Isolated RVE and free body diagram for twisting case. (e) Kinematic performance map for twisting case. (f) Torque–twist rate response for twisting case.

Later researches [12, 14, 16] revealed that the essential characteristics of a scaled structure under bending deformation including strain stiffening, and the locked condition are universally valid even when the scales are not rigid [16, 129], or when periodicity is not valid as scales are not uniformly distributed (e.g. functionally graded [14]) or loading is not uniform bending [12]. For when the periodicity is not satisfied, a discrete non-periodic model have been developed instead of equation (1) [12, 14]. Recent studies in twisting of biomimetic scales have also indicated the universality of locking and strain stiffening under pure torsion [6, 7]. For the twisting case, scales are considered with oblique angle α with respect to the torsion axis (in addition to the inclination angle θ with respect to the substrate surface) [6], as shown in the RVE in Figure 9 (d). This is because that in early studies on the scaled system under twisting, no significant stiffening was indicated despite the bending case for the scales arrangement as parallel to the torsion axis [67]. However, there are striking differences between bending and twisting. For instance, the kinematic locking border is nonlinear functions of geometry as shown in Figure 9 (e), unlike the bending case which is linear as shown in Figure 9 (b). Moreover, the torque–twist response of the system has been shown in Figure 9 (f). By including the friction for twisting case [7], frictional locking is found universal as well, but as a highly nonlinear curve, without any closed form solution, unlike the bending case. Also, in the twisting, the relative energy dissipation is increasing monotonically with μ, which in the bending case increasing in the μ may not necessarily increase the relative energy dissipation of the system [5, 7].

Most of these studies for modeling or simulation of biomimetic scaled systems are under static loads including indentation, bending, and twisting. There are limited studies on the modeling or simulation of dynamic loading on biomimetic scales systems [13, 130, 132]. Liu et al. [130] developed biomimetic composite scale to investigate under ballistic impact, by inspiration from the two-layer structure and overlapping pattern of fish scales using silicon carbide (SiC) ceramic as the outer layer, and aluminum as the inner layer of the scales, respectively. Through the numerical simulation, they found the optimal thickness ratio of SiC/Al to reduce the area density of bio-inspired composite scale with the same ballistic performance at a certain impact velocity. Additionally, with a comparative simulation analysis with of overlapped bioinspired composite scales, an optimal overlapping ratio has been discovered [130]. Recently, the emergent dynamical behavior in a biomimetic scaled system has been studied using the variational energy equation, delivered from Hamilton principle for a simply supported scaled beam with initial velocity condition [13]. The equation of motion has been solved numerically using the direct numerical integration method. The free oscillation response shows that the system oscillates with exponential decay due to the interfacial friction between scales, unlike the spring-mass system with dry friction, which indicates a linear decay. In scaled biomimetic system, the decay will not lead to a totally damping mode unlike the conventional damped oscillation, but it continues rather until the deflection is small enough when the scales don't engage anymore [13]. Also, few recent studies [132, 133] have been studied numerically the ballistic behavior of bioinspired ceramic armors based on ganoid and placoid fish scales. The main conclusion is related to the improved efficiency of a modular armor against multiple shots exhibiting more localized damage and crack arrest properties. Moreover, its potential ergonomic is a promising characteristic justifying a deeper study. These modular armors showed improved efficiency against multiple ballistic shots by providing more localized damage and crack arrest behavior [132].

6. Conclusions, challenges, and future outlook

In spite of impressive advances covering design, fabrication and simulations, several gaps and scope for new scientific discoveries remain. For example, still relatively little is known about the behavior of scale-covered 2D systems like a scale-covered plate and shell systems with more general variations scale geometry, distribution, scale surface morphology and material properties. Also in spite of early advances in using shark skin concept for drag reduction [101, 128], the fluid structure interaction of flow with property programmable scales are relatively unexplored. One of the major challenges remain understanding the multiple-scale fluid-structure interaction problem specific to these problems. The recent work on buckling behavior [94, 134], also points to potential future research on the enriching effects of the scales geometry and nonuniform scales distribution to reach to additional buckling modes and generating localized deformation as combinations of deformation and constraints [94, 126].

Furthermore, nearly all discussed works on the biomimetic scales systems, consider perfectly bonded scales on the substrate, and the substrate without any imperfections. Other than some previous work exploring this topic [16], much more is needed to quantify the effects of imperfections of the substrate or bonding of the scales with the substrate. Such knowledge could be effective for the additional tailorability of material response [94, 134]. The bonding of the scales with substrates is often done using powerful glues. The strength of this bond is critical towards enhancing the overall performance of this system. Such bonding can also be improved using mechanical joints or hierarchical root-like topology. Such joints engineering is an important area of further development.

Mechanics and dynamics behavior of 2D scales such as scales distribution, synergistic behavior, and metamaterials behavior under different load conditions is one of the major field for future scope. Time dependent behavior of biomimetic scales is also one of the promising filed that need to be investigated to understand the time dependent properties of dynamically changing scales structure [15]. Also, less explored is development of multi-functional biomimetic surface, which can include self-repairing and self-cleaning behavior, mechanically and chemically protective coatings, and advanced optical properties. For example, shark skin, which has some topological surface features like scales, has self-cleaning properties and low fluid drag behavior, and these novel properties could be applicable to coating of the aircraft fuselage and the hull of ship. Very few studies have been conducted in the past focusing on this aspect, even though this can increase the usage of biomimetic fish scales in various emerging sectors [135–138]. Among various advantages of teleost fish scales, they have such mechanical properties that prevent from penetration. Even, the scales of *Archispirostreptus gigas* provide protection against counter ballistic projectile from samller bullets [1, 139, 140]. In future the development of rapid prototyping technology may allow the 3D printing of microstructure of scales with desired mechanical properties that can widen the use and performance of biomimetic fish scales [1]. The schematic diagram summarizing such possibilities is shown in figure 10 [137].

Numerical simulations of these metmaterials have encountered some limitations of the commercial FE software because of to the large number of contact pairs between the scales and the significant contact nonlinearity brought to the FE models. Therefore, major advance in numerical simulations and multiscale modeling is needed [15]. Also, other novel behaviors can be obtained by using the phase change materials as tailorable stiffening scales, and color changing materials to provide unprecedented on-demand change of stiffness and optical response as a functional programmability properties [96, 141]. It seems that there are no significant number of research on this type of time dependent behavior and dynamically changing scales systems, because of the necessary needs of advancement in the fabrication techniques and multiphysics modeling. Also,

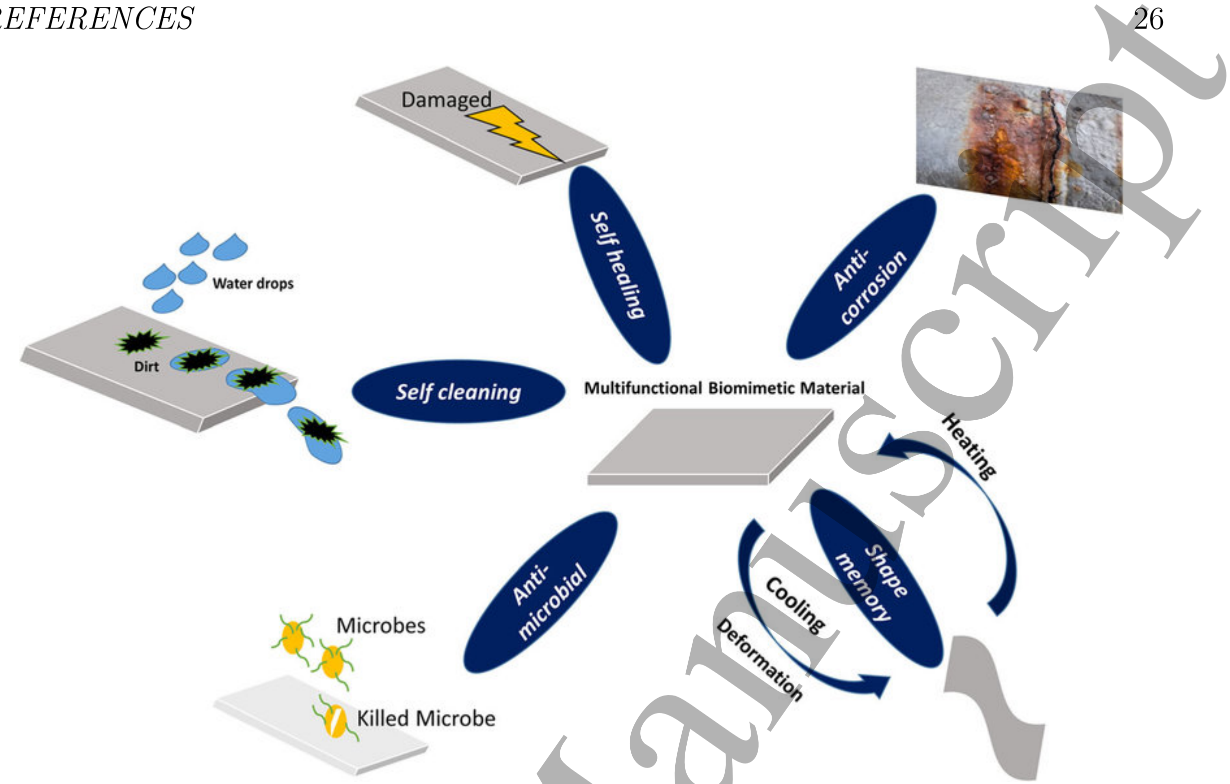

Figure 10. Schematic diagram showing the possible integration of multiple biomimetic functionality [137]. (Copyright permission has been adopted.)

studies on the thermal or electromagnetic behavior of these metamaterials have not been considered yet, which could be a key future frontier in this field. Such complexities in the material, fabrication, and modeling of these system can give rise to new and potentially unanticipated challenges, which is needed to be addressed in future efforts.

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