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TOPICAL REVIEW

Characterization of shark skin properties and biomimetic replication

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Abstract

This review explores the present knowledge of the unique properties of shark skin and possible applications of its functionalities, including drag reduction and swimming efficiency. Tooth-like denticles, with varied morphologies, sizes, and densities across the shark's body, significantly influence the flow and interaction of fluids. Examining dermal denticle morphology, this study unveils the functional properties of real shark skin, including mechanical properties such as stiffness, stress–strain characteristics, and denticle density's impact on tensile properties. The adaptive capabilities of the Mako shark scales, especially in high-speed swimming, are explored, emphasizing their passive flow-actuated dynamic micro-roughness. This research contains an overview of various studies on real shark skin, categorizing them into skin properties, morphology, and hydrodynamics. The paper extends exploration into industrial applications, detailing fabrication techniques and potential uses in vessels, aircraft, and water pipes for friction reduction. Three manufacturing approaches, bio-replicated forming, direct fabrication, and indirect manufacturing, are examined, with 3D printing and photoconfiguration technology emerging as promising alternatives. Investigations into the mechanical properties of shark skin fabrics reveal the impact of denticle size on tensile strength, stress, and strain. Beyond drag reduction, the study highlights the shark skin's role in enhancing thrust and lift during locomotion. The paper identifies future research directions, emphasizing live shark testing and developing synthetic skin with the help of 3D printing incorporating the bristling effect.

1. Introduction

During the evolutionary journey, the shark experienced numerous transformations in key aspects of its anatomy and physiology. These changes encompass adaptations such as acquiring a sleek body shape and the emergence of dermal denticles (Donley *et al* 2004). Shark skin has been an interesting source of inspiration for research because of its unique features that make the skin special in multiple ways. The complex resistive structure of shark skin has fascinated physicists, engineers, and biologists for decades. The skin is decorated with tiny denticles in the dermis, often described as tooth-like structures, that extend from the flexible epidermis. These denticles come in different sizes and shapes, depending on their location on the body, and typically have a width of 0.1 mm to 1 mm (Reif 1978, Reif and Dinkelacker 1982, Lloyd *et al* 2021). One of the functions of the denticles is disrupting the boundary layer of water next to the skin, reducing turbulence around the body and, as a result, reducing resistance during swimming (Diez *et al* 2015). This functionality of the shark skin is explained by several components, such as morphology, hydrodynamics, the material properties of the skin, and the locomotion of the shark itself, as the shark's shape dynamically alters the spacing between the denticles. Another remarkable capability of fast-swimming sharks is the bristling effect, an ability to erect each denticle, which has raised the interest of researchers.

The Mako shark (*Isurus oxyrinchus*) is a widely studied species and known as one of the fastest swimmers among sharks. In addition to its streamlined profile, the Mako shark possesses this unique bristling ability that allows it to control the separation of currents, further enhancing its hydrodynamic performance (Lang *et al* 2014).

Understanding these noteworthy features of shark skin has not only provided insights into the evolutionary adaptations of these marine predators but has also ignited interest in the field of biomimetics. Researchers and engineers have sought ways to replicate the drag-reducing properties of shark skin to enhance the design of various applications, from swimming suits to the fuselages of aircrafts (Oeffner and Lauder 2012, Pu *et al* 2016).

In this comprehensive review, we explored the unique properties of the skin of several species of sharks. We delve into the mechanisms underlying the resistance-reducing properties of shark skin and the role of denticles. This review also discusses the underlying principles for the transition from biology to biomimetics and shows how the sharks' blueprints are translated into breakthrough technologies.

Current research has also focused on exploring the multifaceted functionalities of shark skin denticles, as exemplified by Ghimire *et al* (2024) recent publication 'Shark Skin Denticles: From Morphological Diversity to Multi-functional Adaptations and Applications.' Although there are overlaps in our research on shark skin properties, such as the recognition of drag reduction and denticle morphology, our research differs in some areas. Ghimire *et al* (2024) highlights advances in antifouling studies and bioluminescent adaptations, whereas this research investigates multiple studies that gathered shark skin samples from various locations on the body while delineating the methodology employed.

Overall, this study seeks to answer the following research question:

What is the current state of scientific knowledge regarding the unique properties of shark skin, the diverse testing methodologies utilized to analyze the skin, and the potential interdisciplinary applications such as biomimetic surfaces for ships or aircrafts and materials science?

2. Method

2.1. Systematic search

In the course of this review, a systematic search was conducted on Scopus and ScienceDirect databases utilizing the following search strings: 'Shark AND (skin* OR denticle* OR scale*) AND (drag OR Stiffness OR material*)',

'Shark AND (skin* OR denticle* OR scale*) AND (biomimetic* OR bio-inspir* OR mimic*)' and

'Shark AND (skin* OR denticle* OR scale*) AND (flow* OR morphology OR hydrodynamic*) AND (locomotion OR swim OR movement)'.

The search, which included keywords related to shark anatomy, biomimetics, hydrodynamics, and locomotion, resulted in the identification of a total of 509 relevant papers. After an initial review of titles and abstracts, a total of 67 documents were identified that met the criteria for further research. While acknowledging that sharkskin serves purposes beyond drag reduction, such as its antibacterial properties, this review does not delve into these aspects extensively. Additionally, although longstanding bio-inspired riblets are considered, they are not the primary focus, as more attention is given to biomimetic skins that try to recreate the entire denticle shape. Further, a two-step screening process was performed, comprising title and abstract screening and full-text assessment using predefined eligibility criteria:

- The content of the study should provide information about shark skin morphology.
- The study should address the hydrodynamic properties of shark skin.
- The study should provide information about the manufacturing process of the biomimetic shark skin.
- The content of the study should offer a deeper understanding of the characterization methods for shark skin.
- Studies that cover topics beyond drag reduction, such as antibacterial properties, are excluded.
- Studies presenting the longstanding bio-inspired riblets are not the primary focus of this work.

After full-text examination, another 26 papers were excluded, resulting in a refined selection of 41 documents that were considered relevant and were included in this study. The PRISMA flowchart for a systematic review is given below in figure 1(Page *et al* 2021).

3. Structure and properties of biological shark skin

This chapter focuses on the microstructure of the shark skin. When viewed from a distance, shark skin looks like a smooth, streamlined surface designed to swim efficiently. But at the microscopic level tiny structures, known as denticles, encroach on the skin, offer unparalleled insights into the evolution of resistance reduction and hydrodynamics. We discuss and compare the morphology of denticles at different locations on the skin. In addition, we review the stiffness, roughness, and density of the shark skin. Finally, a comparison is made between results from the included studies and an illustration is provided showing the different tests that were performed at different locations on the torso.

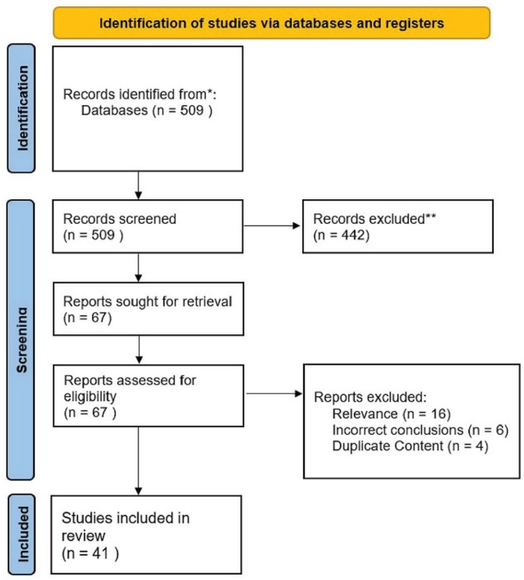


Figure 1. PRISMA flowchart systematic review (Page *et al* 2021).

3.1. Morphology and size of shark skin denticles

Dermal denticles are an essential part of shark skin's dermal layer. Meyer and Seegers (2012) state that each denticle is coated with enamel and dentine, which are two distinct tissues found in the structure of teeth. The denticles have a longitudinally oriented pattern of riblets arranged in rows in the same direction as the water flow and contribute to reduced skin resistance (Bushnell and Moore 1991). In certain places throughout the body, the denticles exhibit ridges exclusively on their leading surface. Even the rounded and widely spaced denticles of some shark species, as shown in figure 2(a), show ridges on their anterior edges. The ridge's height varies depending on the species and the position in the body. The bases of the denticles are extended and firmly anchored to fibers in the lower stratum compactum layer of the dermis (Creager and Porter 2018). Figure 3 shows four different perspectives of a three-dimensional model of an individual denticle, providing insight into its appearance. Different heights of the ridges are shown, with the central ridge being higher than those on the sides. It is noteworthy that the presented model contains three ridges, which serve as an illustrative example since denticle morphology shows many variations in terms of shape, size, and number of ridges.

Feld *et al* (2019) analyzed microscope images of the denticles of a small-spotted catshark. They documented data on the length of selected denticles as well as the total number of denticles present in each frame. Their research revealed that crown lengths for the dermal denticles range from 300 μm to 1 mm. Smaller dermal denticles were predominantly observed on the fins and in close proximity to the gills, while larger dermal denticles were mainly distributed on the body. According to Zhang *et al* (2022), who conducted research on the Shortfin Mako shark, the length of the denticles ranges between 105 $\pm$ 7 μm and 286 $\pm$ 25 μm and the width of the denticles between 87 $\pm$ 4 μm and 255 $\pm$ 22 μm. The length-to-width ratio ranged from 1.02 to 1.45. In addition, Diez *et al* (2015) found that the average height is between 90 μm and 110 μm, which includes the height of the peduncle (the base of the denticle) that connects the crown to the skin. Shark denticles, unlike those of other bony fish, do not increase in size as the shark grows. Instead, their structure and size are primarily determined by their growth position and the specific species of the shark (Pu *et al* 2016).

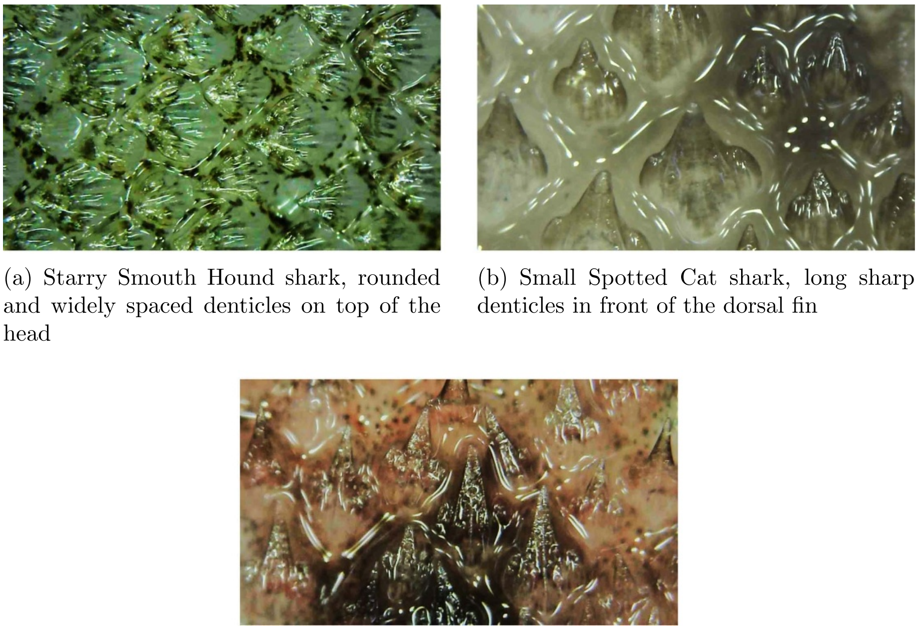
3.1.1. Arrangement and density of shark skin denticles

The structural composition, shape, and density of the denticles of the shark skin show differences among different parts of the shark's body. Figure 2 shows the lattice structures and shapes in different areas of the skin from head to tail of two different species of sharks (Small Spotted Cat shark and Starry smoothhound shark). This figure clearly shows significant differences between species, but also differences within one species since the two pictures of the Cat shark were taken in front of and behind the first dorsal fin, respectively.

According to Diez *et al* (2015), the denticle density along both the longitudinal and vertical axes of the Shortfin Mako shark (*Isurus oxyrinchus*) revealed a noteworthy increase in the number of denticles per square millimeter in the dorsal and ventral regions compared to other areas. This density gradually decreased when moving toward the shark's central body, with the lowest density observed along the central longitudinal axis. Additionally, a statistically significant higher denticle density was observed in the anterior region compared to the central region. Towards the posterior region of the shark, the density showed to increase again.

3.2. Functional properties of shark skin

The versatility of the shark's skin goes beyond its primary role in reducing drag. In addition, the skin serves as an antibacterial barrier and prevents the attachment of marine life to the surface because the placement of the scales alters the turbulent boundary of the water at the surface and generates numerous small eddies as the water flows over the skin. Additionally, another mechanism that may hinder bacterial attachment is super hydrophobia, which results from air trapped in the rough features of the skin, hindering both initial wetting and subsequent attachment (Zhao *et al* 2014, Chien *et al* 2020). The increased shear stress in this turbulent flow is critical. This fluid dynamic process makes it challenging for benthic diatoms and mussels to attach because the shear stress exceeds their ability to attach (Peng *et al*

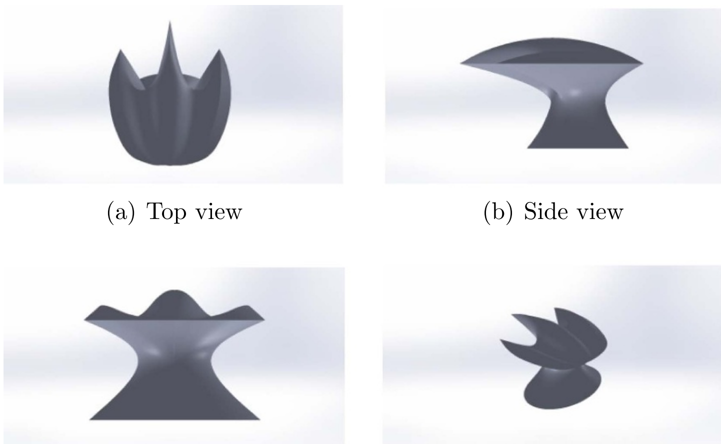


(a) Starry Smooth Hound shark, rounded and widely spaced denticles on top of the head

(b) Small Spotted Cat shark, long sharp denticles in front of the dorsal fin

(c) Small Spotted Cat shark, long sharp denticles behind the dorsal fin

Figure 2. Microscopic pictures of structure and arrangement of the denticles of the Starry smoothhound shark and Small Spotted Cat shark.



(a) Top view (b) Side view

(c) Front view (d) Iso view

Figure 3. Top, side, front and iso view of a 3D reconstructed model of a single denticle of the shark skin.

2009). The shark skin may even offer protection from predators (Creager and Porter 2018).

A special feature was documented by Southall and Sims (2003), and they describe a scenario in which a shark species strategically uses its skin structure while feeding in their paper. Juvenile dogfish use dermal denticles to manipulate and process food, attaching it to the lateral-caudal body region. Southall and Sims (2003) named this behavior pattern scale rasping. These movements keep the food 'hooked' in backward-facing denticles, pulling the prey tight.

Another aspect of the skin that has been studied is material properties, including stiffness and how the skin responds to tension and stretch. In a study of Naresh *et al* (1997) the stress–strain characteristics of shark skin were analyzed, revealing directional effects in the stress–strain curves. Dumbbell-shaped samples of skinned raw skin were used for testing. The study involved dissection of samples in four different directions: 1) parallel to the longitudinal axis of the shark, 2) perpendicular at a 90° angle to the latitudinal axis, and 3,4) two diagonal directions (at a 45° angle to the longitudinal axis) at two different locations both anterior and posterior. The study used a measurement length of 12 mm, a strain rate of 0.4167 per minute, and an Instron universal tensile bench with

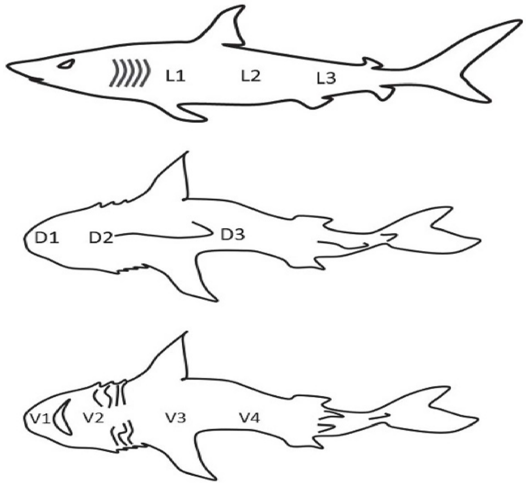


Figure 4. Regions where samples were taken from the mid-lateral (L), dorsal (D) and ventral (V).

a fluid cell. A minimum of 12 samples were tested for each direction at both locations, and average stress–strain curves were plotted, with sample thicknesses ranging from 1.5 mm to 2.0 mm. Final stress ranged from 24 to 32 MPa. Parallel samples showed higher strain rates. Regional differences were more apparent in diagonal samples, with posterior samples showing greater stiffness. These differences can be explained by the orientation and curvy or wavy structure of the fibers. When force is applied, a significant portion of that force is used to straighten out these wavy fibers, influencing the material's response to mechanical stress. In the anterior region, the orientation compared to the stress axis is a significant 120°, while the deviation in the posterior region is less pronounced, at 15° (Naresh *et al* 1997).

The study of Creager and Porter (2018) argues that an increase in denticle density will improve the tensile mechanical properties (stiffness, strength, and toughness) of shark skin. Denticle density, measured in number of denticles per square millimeter, was quantified along with quasi-static mechanical properties, including ultimate strength, yield strength, stiffness and toughness, at ten different locations on five different species of shark. The focus was specifically on quasi-static tensile tests-to-failure to determine the ultimate limits of shark skin mechanical properties. Dumbbell-shaped samples of dissected skin were clamped between stainless steel fixtures and were extended in the cranial to caudal direction at a strain rate of 2 mm s^{-1} until failure. In figure 4, the mid-lateral, dorsal, and ventral regions are shown, which are distinguished in a study of Creager and Porter (2018). The study revealed significant differences in ultimate tensile strength (UTS), with the bonnethead shark (Sphyrna tiburo) displaying the highest UTS at 47 MPa in the caudal region (L3) and the lowest at 9 MPa in the ventral region (V2). Other species, including the scalloped hammerhead, Blacktip, bull term embryos, and Shortfin Mako sharks, exhibited the greatest UTS values in the dorsal cranial (D1) region. There were notable species and region effects for stiffness, with the highest stiffness consistently found in the dorsal-cranial (D1) region across all species. Toughness varied significantly among species and regions, with the greatest toughness observed in the cranial (D1) region of Scalloped Hammerhead and Blacktip sharks, caudal (L3) region of Bonnethead sharks and bull term embryos, and dorsal (D3) region of Shortfin Mako. Denticle density did not significantly correlate with ultimate tensile strength, but stiffness increased and toughness decreased with denticle density (Creager and Porter 2018).

Research on the effect of bristling has discovered that Mako sharks have the ability to finely adjust their scales when swimming at high speeds. This adaptation is rooted in the stratum compactum, which consists of numerous layers of collagen fibers, forming the shark's exoskeleton. This unique structure allows the shark to maintain a balance between longitudinal and hoop stresses, keeping it flexible and storing elastic energy to swim efficiently (Lang *et al* 2008).

Motta *et al* (2012) compared the Shortfin Mako shark and the Blacktip shark and concluded that the scales of the Mako shark are shorter, narrower, and have a shallower ribbing pattern. The scales on the sides of the Mako shark's body are triangular, allowing them to rotate easily around their broad but short base, while the scales on other parts of the body of the Mako shark and those of the Blacktip shark are broader and rhomboid-shaped. The lateral sides of the body, from behind the gills to the tail, have the most flexible scales. It is possible to lift these scales to angles greater than 50° easily, even in dead specimens (Lang *et al* 2011).

Table 1. Summary of profilometry data.

Variable	Maximum	Minimum
Sq (mm)	42.1	3.5
Ssk	20.86	20.25
Sku	8.2	2.8
Sz (mm)	323.3	38.0
Average Length (mm)	554.7	125.9
Average Width (mm)	459.6	126.6

Initially, it was believed that there were multiple ways for the scales to become erect, such as changes in skin tension at higher swimming speeds or the potential for scales to bristle in areas with concave body curvature during swimming (Lang *et al* 2008). Later on, Lang *et al* (2014) showed that the scales are able to erect only by the reversal of the water current, without requiring body movement or an active muscular contraction mechanism. As a result, the skin surface of the shark serves as a passive, flow-actuated dynamic micro-roughness. This was also later proven by Du Clos *et al* (2018), who analyzed video footage of water flow over the skin of a shortfin Mako shark.

3.3. Roughness and hydrodynamic properties of shark skin

In order to gain a more detailed understanding of the exact morphology of a denticle, Ankhelyi *et al* (2018) has performed research on skin samples at 20 different locations on the body of the Dusky smoothhound shark (*Mustelus canis*). The study involved calculating metrology variables, including roughness (Sq), skew (Ssk), kurtosis (Sku), and max height (Sz), for entire sample images of three individual smoothhound sharks. Additionally, the average length and width of three denticles for each region on each individual shark were measured. Spacing between adjacent denticle ridges and denticle ridge height for five denticles on one individual were also measured. Skew values above or below zero signified more peaks or valleys, respectively. Kurtosis values above three indicated surfaces with high peaks and low valleys, while values below three suggested less extreme surface variation. To provide an idea of the range of profilometry variables, table 1 shows the minimum and maximum values of all the different variables.

The maximum of the average length and width of a denticle was at the tip of the shark's nose, while the minimum of both is just behind the pectoral fin. The highest roughness was measured just before the first dorsal fin, and the lowest value of roughness was measured behind the pectoral fin.

When a shark swims, it encounters two primary sources of drag: (1) skin friction drag and (2) form drag (Lang *et al* 2015). Skin friction drag, arising from the friction between water and the shark's body, is associated with the flow moving over the shark. This type of drag results from the no-slip boundary condition between the water and the shark, forming a boundary layer. High swimming speeds result in a high Reynolds number, leading to turbulent flow across the shark's body and a substantial increase in skin friction. The second type of drag, form drag, is more crucial to control. It originates from pressure differences around the body and depends on whether the flow remains attached or separates during swimming (Lang *et al* 2015). The water flow experiences a favorable pressure gradient from the nose to the point of maximum girth (near the gills), while unfavorable pressure gradients occur downstream of this point, causing a substantial increase in drag. Lang *et al* (2011). This aligns with the observation that for the fast-swimming Mako shark, the most flexible scales are situated on the body's flanks and downstream of the gills, regulating flow separation (Lang *et al* 2011).

The study of Miyazaki *et al* (2018) discusses the morphology of a single denticle of the Galapagos shark and highlights a structure with five ridges and four grooves. This feature, referred to as non-uniform grooves in the study, is defined by distinct differences in height or spacing between the ridges on top of the denticle. The research observes strong longitudinal vortices concentrating at the ridges of shark skin denticles, particularly near the side ridges. Weak longitudinal vortices are noted in the valley of the grooves, suggesting that the multiple-ridge denticles play a role in disrupting longitudinal vortices and weakening secondary flows. This disruption may isolate high shear stress across the grooves, reducing the exposure of a significant portion of the denticle surface to high mean shear. The non-uniform grooves, specifically the unique five-ridge denticles, are highlighted for their morphological significance in passive flow control near shark skin. A systematic computational fluid dynamics (CFD) study explores how the morphology of multi-sharp-ridge denticles, characterized by non-uniform grooves, affects passive turbulent flow control (Miyazaki *et al* 2018). The investigation focuses on the hydrodynamic effects of height-to-spacing ratios of mid-ridge and side-ridges. The study found that an increase in non-uniform height-to-height and spacing-to-spacing ratios enhances the strength of longitudinal vortices, clarifying how non-uniform grooves enhance secondary flows better than uniform grooves.

Overall, the results of the study of Miyazaki *et al* (2018) confirm the morphological significance of multiple-ridged non-uniform grooves in passive turbulent flow control near shark skin denticles.

As mentioned before, the Shortfin Mako shark has loosely anchored denticles across its body that, through a flow-activated mechanism, can control the separation of the flow, thereby reducing resistance

(Patricia *et al* 2019). The study of Afroz *et al* (2017) tested the skin of Shortfin Mako sharks, specifically from the flank region with highly movable scales, under various adverse pressure gradients (APG) to assess its ability to control separation in fluid flow. The results showed that shark skin can effectively control both laminar and turbulent separation on a flat, non-moving surface. Furthermore, the presence of shark skin on the flat plate resulted in a smaller separation region and a delayed separation point under different magnitudes of APG. Santos *et al* (2021) even compared different bristling angles observed at the Mako shark, including 50 degrees and 30 degrees. The results indicated that denticles with a 50-degree angle were most effective in reducing and possibly eliminating flow separation.

3.4. Insights into shark skin research: Samples, methodologies, and species diversity

Figure 6 illustrates the location where the skin samples were taken, and the color indicates what research was done. A distinction is made between research focused on skin properties (red), morphology (yellow), and hydrodynamics (blue). These are the three main areas of research shown in table B in figure 6. In table C, the various studies that have investigated real shark skin are listed. Unfortunately, not all studies mentioned the body location, providing only the quantity of samples taken. Some studies have been executed at the same location. In total 21 studies were included and compared. Upon examining the shark and the areas under research, it becomes evident that extensive research has been done on the fins and tail area, focusing on morphology and hydrodynamics. These aspects also contribute significantly to locomotion and maintaining stability for the fin area and to thrust for locomotion for the tail area. Furthermore, it is evident that the studies which examined the properties of the skin were exclusively conducted on the mid-lateral area (L1, L2, L3).

In all of the 21 studies, a total of 19 different species of sharks were examined. The Shortfin Mako shark was by far the most frequently sampled, with the Blacktip and Hammerhead sharks in second and third place, respectively. With over 10 studies having collected samples of the Mako shark, researchers have extensively investigated the distinctive characteristics of this shark species. Shark samples are typically preserved by freezing or immersing them in a solution with a high ethanol percentage to ensure proper preservation. Two papers utilized freshly dead samples. However, no studies were conducted on live animals.

To determine the morphology of denticles, scanning electron microscopy (SEM) and gel-based profilometry together with micro-CT imaging are consistently used to create 3D maps of denticles, which help in their detailed analysis.

Hydrodynamic analysis is usually performed using two distinct methods. Particle image velocimetry (PIV) is an optical measurement technique used in fluid mechanics to visualize and quantify the flow patterns and velocities of fluids to assess the hydrodynamics of the denticle in a given setup. Alternatively, computer models, primarily using CFD, which employs numerical methods and algorithms to simulate and analyze the behavior of fluid flows around the denticle, were used. Tensile tests were conducted using hourglass-shaped or dumbbell-shaped specimens to assess the tensile strength, stress, and strain of the skin.

4. Biomimetic shark skin

4.1. Fabrication methods towards replicating shark skin

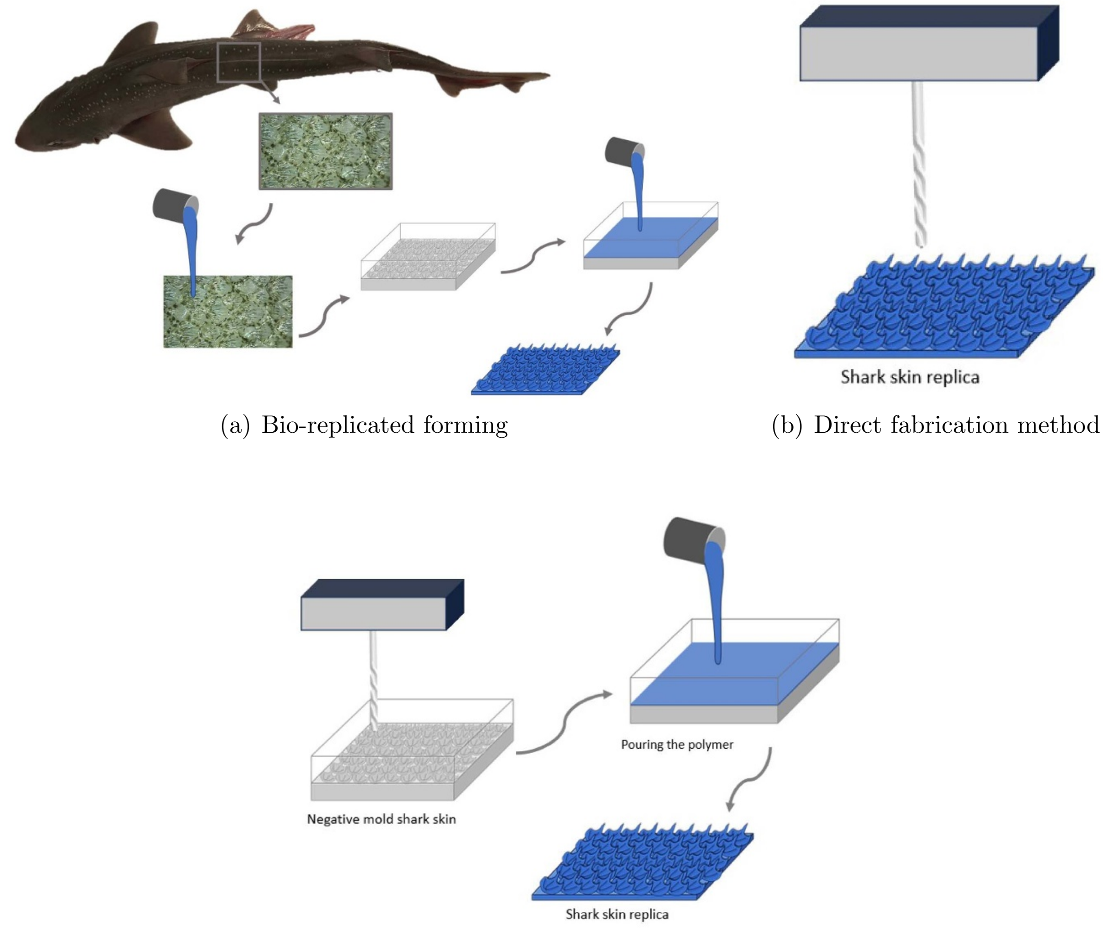
Imitating shark skin offers many advantages across diverse industrial sectors, including applications in vessels, aircraft, and the interior of water pipes for friction reduction (Bixler and Bhushan 2013, Ibrahim *et al* 2018, Domel *et al* 2018b). Different methods are available for manufacturing these replicas. This section explores various fabrication techniques and considers potential applications. Additionally, the performance of different bio-inspired surfaces will be explored and analyzed.

The majority of the existing studies on shark skin-inspired low-drag surfaces fall into the following categories: (1) simplified structures with rectangular or triangular line patterns such as riblets, (2) direct replication or 3D printing of biological shark skin (Jo *et al* 2021).

Different techniques for manufacturing biomimetic shark skin are discussed by Pu *et al* (2016). Three primary approaches are examined: (1) the bio-replicated forming method, (2) the direct fabrication of surface microstructures, and (3) the indirect fabrication of surface microstructures.

The bio-replicated forming method replicates surface microstructures using real biological surfaces as templates, as shown schematically in figure 5(a). The negative mold is made by pouring a polymer over real shark skin. Subsequently, a polymer is poured over the negative mold to create a realistic shark skin replica (Han and Zhang 2008, Pu *et al* 2016). Although this method is effective for high fidelity to biological templates, it is constrained by limited resources and cost, making it unsuitable for large-scale applications.

The direct fabrication method constructs microstructures without a negative template and instead uses techniques such as surface machining to create the biomimetic samples as shown in figure 5(b). Although this method offers competent designs, it



(a) Bio-replicated forming (b) Direct fabrication method

(c) Indirect fabrication method

Figure 5. Basic principle of techniques for manufacturing biomimetic shark skin.

is generally limited to small-area applications due to cost and efficiency limitations.

The indirect manufacturing method is applied with techniques such as grinding. This indirect manufacturing method also makes use of a negative mold, which captures a shape or form of the object in a reversed or negative way, as shown in figure 5(c). In contrast to the bio-replicated forming method, this technique directly fabricates the negative mold itself instead of casting a polymer over an existing biological template.

Both (Wen *et al* 2014, Pu *et al* 2016) highlight the advantages of 3D printing for making skin models of sharks, compared to traditional manufacturing methods such as computer-controlled CNC milling or casting. The speed of 3D printing allows for fast and efficient creation of large synthetic membranes. Additionally, 3D printing enables the combination of materials with different mechanical properties, such as embedding rigid bio-mimetic denticles in flexible membranes. Unlike techniques such as casting, 3D printing offers control over specific denticle parameters, including size, morphology, spacing, distribution pattern, and mechanical properties (Wen *et al* 2014). Literature addresses the significant challenge of using 3D printing to replicate the overlapping and overhanging structural features of real shark skin denticles, which is not possible with casting or simple mechanical fabrication procedures (Wen *et al* 2014). However, performing 3D printing on the actual scale of the shark denticles while maintaining the full surface complexity of natural denticles is still limited.

To overcome the limitations of conventional fabrication approaches, as well as 3D-printing, the photoreconfiguration was developed and first mentioned by Jo *et al* (2021). This technique provides a way to create complex and biomimetic structures at the micrometer scale. The process consists of two steps: (1) forming an array of tiny pillars using a mold, and (2) photo reconfiguration of the micropillars, which changes the shape of these pillars. Initially, a soft mold is produced to shape the azopolymer, which results in the formation of an array of micropillars that serves as the basis for the subsequent structure. The micropillars created in the first step are then modified through a photoconfiguration process. This involves exposing the azopolymer to slant irradiation using the interference light produced by two circularly polarized lights. This specific type of illumination causes the micropillars to undergo a transformation, creating an asymmetric riblet geometry on top of the structure (Jo *et al* 2021). The overall goal of this fabrication technique is to replicate the unique surface features found in shark skin that contribute to reduced drag.

Wen *et al* (2023) investigated the mechanical properties of shark skin fabrics with different denticle sizes, focusing on (a) tensile strength, (b) Young's modulus, and (c) breaking elongation. They produced the fabric with the help of a Form3 3D printer. The printer employed a photopolymerization method to create the intricate microstructure of shark skin fabric. The Form3 printer has a high resolution of 25 microns on the X and Y axes, ensuring detailed replication of shark denticles. The printing involved simultaneous fabrication of the fabric and denticles using Flexible 80A resin, an acrylate-based material compatible with most photopolymerization 3D printers. In the horizontal direction, the fabric with small denticles exhibited the highest tensile strength, measuring 8.73 MPa. Increasing denticle size by 50% led to a 29.67% decrease in tensile strength (6.14 MPa). A 20% increase in denticle size resulted in an 18.35% decrease (7.52 MPa to 6.14 MPa) (Wen *et al* 2023). Conversely, in the lengthwise direction, fabric with medium denticles had the highest tensile strength and breaking elongation. The medium denticle fabric showed a 7.17% increase in elongation at break compared to small denticles, while the large denticle fabric exhibited a 19.07% decrease. In the horizontal direction, the fabric with small denticles had the highest elongation at break, indicating their potential to enhance breaking elongation in this orientation. These findings highlight the influence of denticle size on the mechanical characteristics of shark skin fabrics, providing valuable insights for applications in material engineering and biomimetic design.

4.2. Applications of biomimetic shark skin

Current engineering applications often use simplified riblet structures inspired by the shark skin. The application of riblet structures shows promise in diverse fields, ranging from maritime to aerodynamics or fluid dynamics in pipes, offering potential improvements in efficiency and performance.

Researchers aim to simplify denticle morphology to create cost-effective and feasible riblet structures for mass applications. For instance, in the aircraft industry, a reduction in fuel consumption of up to 3% has been achieved by applying a riblet structure on 70% of the surface area (Pu *et al* 2016). For pipe flow engineering, riblet-structured surfaces have been employed for drag reduction in pipe flow and have proven at least a 5% resistance reduction (Pu *et al* 2016). While all riblets share similar functionality, their drag-reduction effectiveness varies based on geometry. For instance, a review of Bechert *et al* (1997) revealed that blade-type riblets exhibit the highest drag reduction, reaching up to 9.9%, compared to scalloped and sawtooth riblet types.

Despite efforts to create 3D riblets with features resembling actual shark skin, experiments of Dean and Bhushan (2010) with staggered segmented-blade riblets failed to achieve greater drag reduction than optimum continuous blade riblets. The conclusion drawn is that three-dimensional riblets composed of segmented two-dimensional riblets are unlikely to significantly outperform continuous two-dimensional riblets.

The research of Domel *et al* (2018b) explored other variations inspired by shark denticles. The experimentation involved testing these variations on an airfoil, considering three distinct shapes. The first shape closely replicated the shark denticle, the second resembled more of a 2D bump that slopes up and then gradually smoothens back down, and the third combined elements from both the shark denticle and the 2D bump, a continuous shark-inspired profile (Domel *et al* 2018b). The experiments involved passing air over the airfoil and measuring the outcomes at various angles of attack. Additionally, the lift-to-drag ratio was calculated to assess performance.

The continuous shark-inspired profile outperformed the 2D bump profile and shark denticle in terms of lift-to-drag ratio across various angles of attack (Domel *et al* 2018b).The continuous shark-inspired profile showed the lift benefits at low angles and maintained these advantages at higher angles, unlike the 2D bump. Additionally, it significantly reduced drag at higher angles, similar to the shark denticle. The continuous shark-inspired profile exhibited the greatest improvement at the angle of maximum lift-to-drag ratio. Unlike other foils, it overcame the obstacle of structural complexity associated with replicating shark denticles, making it easily adaptable for large-scale production. This advancement enhances the potential adoption of the technology in aquatic and aerospace applications. The study emphasizes that the flow regime examined (Reynolds $\approx 4 \times 10^4$) is applicable to various systems, such as interior sections of wind turbine blades, helicopter blades, drones, and autonomous underwater vehicles. Additionally, the mechanisms identified in this study could be relevant for higher flow regimes, offering potential enhancements for movement through air and water (Domel *et al* 2018b).

The study of Dean and Bhushan (2010) found that vortices above riblets mostly interact with the tips, causing localized high-shear stresses. The valleys between riblets have lower shear stresses across most of the surface. Because the vortices are located above the ends of the riblets, the shear stress decreases, reducing the effect of a larger surface area. Although some secondary vortices enter the riblet valleys, their flow results in a small rise in shear stress (Bechert *et al* 1986, Dean and Bhushan 2010). This phenomenon was further demonstrated by Miyazaki *et al* (2018), indicating that non-uniform grooves enhance secondary flows better than the commonly used uniform grooves.

Ibrahim *et al* (2018) performed a numerical analysis of design modifications with biomimetic shark skin to show potential improvements for both rectangular and container ship models. The modifications result in a reduction in wall shear stress, a 3.75% reduction in resistance coefficient, and a 3.89% reduction in resistance force for the container ship model. Encouraged by these findings, the study suggests further validation through experimental procedures to increase the impact of this research on the global shipping and maritime industry.

4.3. Hydrodynamic function of biomimetic shark skin

In the study of Oeffner and Lauder (2012), a robotic flapping foil device was employed to assess the impact of shark skin surface features and two biomimetic surfaces on self-propelled swimming speed. The device, designed for studying fish-like propulsion, enabled accurate measurement of swimming speeds, controlled motion programs, and flow quantification using digital PIV. Rigid and flexible foils were created from fresh shark skin and two manufactured biomimetic shark skins. The study aimed to test the hypothesis that denticles enhance swimming speed by comparing against a control condition with reduced or absent denticles.

In this context, the study used self-propelling foils that swam under a specific motion program that imitated their natural movement. The study compared the measured surface curvatures of flexible shark skin foils with those observed in live sharks swimming in a laboratory flow tank. The results showed that the foils' curvature values (0.17–0.25 cm^{-1}) aligned well with measured maximal mid-body values from live spiny dogfish (Oeffner and Lauder 2012). This indicates that when self-propelling, the shark skin membranes bend to a similar extent as the skin of a live shark during unrestrained locomotion.

The study suggests that the effect of skin denticles on shark skin goes beyond drag reduction and plays a crucial role in enhancing thrust. While existing literature has predominantly focused on drag reduction, the denticles are found to alter vortex location. This effect, especially on the tail surface where flow separation and vortex formation occur, could potentially increase thrust rather than solely reducing drag. The findings propose that similar effects of denticles could enhance lift and maneuvering forces on pectoral fins, where vortices are generated during maneuvering (Oeffner and Lauder 2012).

The study of Wen *et al* (2014) used a robotic system to evaluate how biomimetic shark skin affects swimming performance. The three main findings of this study were: (1) Biomimetic shark skin showed a maximum reduction of 8.7% in static drag at lower current speeds but showed increased drag at higher speeds. (2) During swimming, biomimetic shark skin provided a speed increase of up to 6.6% and a reduction in energy consumption of up to 5.9% under most kinematic conditions. (3) In particular, compared to a smooth film, the 3D printed shark skin film generated an improved leading edge vortex (LEV). The study highlights the nuanced influence of shark-skin characteristics on swimming performance and highlights the need to consider specific exercise programs to understand the benefits of biomimetic shark skin.

Wen *et al* (2015) performed a study that aimed to evaluate the effect of denticle arrangement on the swimming performance of biomimetic shark skin using three different denticle patterns: (1) the staggered-overlapped, (2) the linear-overlapped and (3) the linear-non-overlapped array. The researchers used multi-material additive manufacturing to print rigid denticles on flexible panels, assembling them into two-layer membranes for testing. Static drag and dynamic swimming tests were conducted to understand the functional significance of denticle arrangements. The study analyzed the effects of changing denticle arrangement and spacing on swimming performance. The results showed that the linearly-non-overlapped pattern exhibited the slowest swimming speeds, while the staggered-overlapped pattern outperformed others, showing nearly 20% faster speeds on average despite having a larger total surface area (Wen *et al* 2015). This suggests that denticle arrangement plays a crucial role in enhancing swimming performance.

Domel *et al* (2018a) investigated the influence of denticle size on the performance of biomimetic shark skin. Using 3D printing, model membranes with varying denticle sizes were created, and static tests were conducted to assess drag forces at different flow speeds. Dynamic tests were performed to examine the relationship between denticle size and power consumption during self-propulsion. Results indicate that smaller denticles, particularly at higher self-propelled speeds, lead to improved swimming performance with lower power consumption. Despite the increased surface area of foils with denticles, certain motion parameters, including pitch and frequency, and denticle size combinations contribute to enhanced swimming (Domel *et al* 2018a). However, limitations include constraints on accurately 3D printing small shark denticles and flexible membranes. Due to the impracticality of printing shark denticles at their actual size, this study effectively produced a synthetic skin with a surface roughness (Sq) 10 times that of the Shortfin Mako shark.

Bechert *et al* (2000) investigated the bristling effect observed in the skin of Mako sharks. They tested the biomimetic skin in an oil channel, which allowed them to magnify the microscopic features of biological shark skin by a factor of 100 due to the viscosity of the oil. This method allowed for the precise reproduction of the intricate shape of shark scales, their flexible attachment, and the variable angle at which the scales are positioned. The experiments revealed interesting results, showing that closely spaced scales with minimal gaps modestly reduced shear stress. However, the synthetic sharkskin replica did not exceed the effectiveness of optimized two-dimensional ribbed surfaces in reducing shear stress (Bechert *et al* 2000).

4.4. Future research and innovations

While significant research has already been conducted on shark skin, continuing research will enhance our understanding and potentially provide new insights. Bio-inspired shark skins are currently being implemented, and they are already showing progress despite the fact that they do not replicate the full complexity of a denticle. There are still research gaps that need to be addressed to expand these developments. The researchers who analyze real shark skin rely solely on samples collected from deceased sharks. Although the skin of a dead shark undoubtedly still possesses several distinctive characteristics, in a live shark, other components may play a role, such as muscle stiffness, that may contribute to overall dynamics. Measuring the tension that the skin experiences while swimming is a challenging task with real sharks, but it is a fascinating way to gain valuable insights.

Future research could include a broader range of shark species in the studies that examine the locomotion of sharks and thereby test the influence of distance, pattern, or size of denticles on the drag and dynamic motion of the shark. Different species exhibit variations in denticle patterns, sizes, and arrangements, influencing their hydrodynamic performance differently. Understanding how these factors interact can provide a more nuanced understanding of their combined impact on drag reduction and dynamic motion.

Although there has been research focusing on the bristling effect of the Shortfin Mako shark, still a variety of questions remain. Currently, while efforts have been made to mimic the bristling effect, further research is still required to fully replicate this phenomenon and its effect on thrust generation. A biomimetic skin that can effectively mimic the bristling effect may illustrate many hydrodynamic benefits.

With 3D printing constantly undergoing new developments, achieving an increasingly refined replica of shark skin is within reach. The potential for multi-material 3D printing further enhances the feasibility of creating a biomimetic skin with the characteristics described above. The application of advanced printing techniques will ultimately facilitate the replication of the intricate structure, especially the scale of denticles, to successfully mimic their complexity. Furthermore, recent advances in deep machine learning are poised to revolutionize CFD (Runchal and Rao 2020). This innovation is expected to improve the speed, accuracy, and user-friendliness of CFD software. Runchal and Rao (2020) discusses that deep machine learning will play an important role in creating digital twin and reduced order models, changing the way CFD is applied.

5. Discussion

The microscopic examination of shark skin reveals dermal denticles, tooth-like structures coated with enamel and dentine arranged in rows along the skin. These denticles vary in size, shape, and density depending on their location on the shark's body. The evolutionary significance lies in their ability to disrupt the boundary layer of water next to the skin, reducing turbulence during swimming. Different species and regions of sharks exhibit variations in denticle morphology, with differences in the length, width, and density of denticles contributing to their unique hydrodynamic properties. The arrangement and structure of denticles, as seen in the microscopic examination, play a crucial role in disrupting flow patterns and reducing drag. Studies employing CFD shed light on the disruption of longitudinal vortices by multi-ridged non-uniform grooves, contributing to passive turbulent flow control. The research emphasizes the significance of flexible scales in regulating flow separation, particularly in regions prone to unfavorable pressure gradients. This bristling effect observed in Mako sharks demonstrates the adaptability of the shark's skin to different flow conditions and its ability to erect denticles passively in response to flow reversal, without requiring movement of the body.

The review extends to the material properties of shark skin, including stiffness, strength, and toughness. Research suggests that denticle density did not significantly correlate with ultimate tensile strength. However, an increase in denticle density was associated with higher stiffness and reduced toughness. Understanding the stress–strain characteristics and tensile mechanical properties provides insights into the design of biomimetic shark skin.

The exploration of biomimetic shark skin for various industrial applications, including vessels, aircraft, and water pipes, holds significant promise. The diverse fabrication methods include bio-replicated forming, direct fabrication of surface microstructures, and indirect fabrication of surface microstructures. Each approach has its advantages and limitations, influencing factors such as cost, efficiency, and scalability for large-scale applications. The ability of 3D printing to create intricate structures with specific denticle parameters is highlighted, allowing for control of the size, morphology, spacing, and mechanical properties. Efforts to simplify denticle morphology for cost-effective and feasible mass applications are evident in various studies exploring different riblet structures. Blade-type riblets, in particular, have been identified as exhibiting the highest drag reduction. The continuous shark-inspired profile, combining elements from both the shark denticle and a 2D bump, outperforms traditional profiles in terms of lift-to-drag ratio improvements across various angles of attack. Notably, this profile overcomes structural complexity issues associated with replicating shark denticles, making it adaptable for large-scale production. The impact of shark skin features on swimming performance is discussed, and these studies investigate the influence of shark skin on self-propelled swimming speed, drag reduction, and energy consumption. The findings suggest that shark skin not only reduces drag but also plays a crucial role in enhancing thrust during swimming.

6. Conclusion

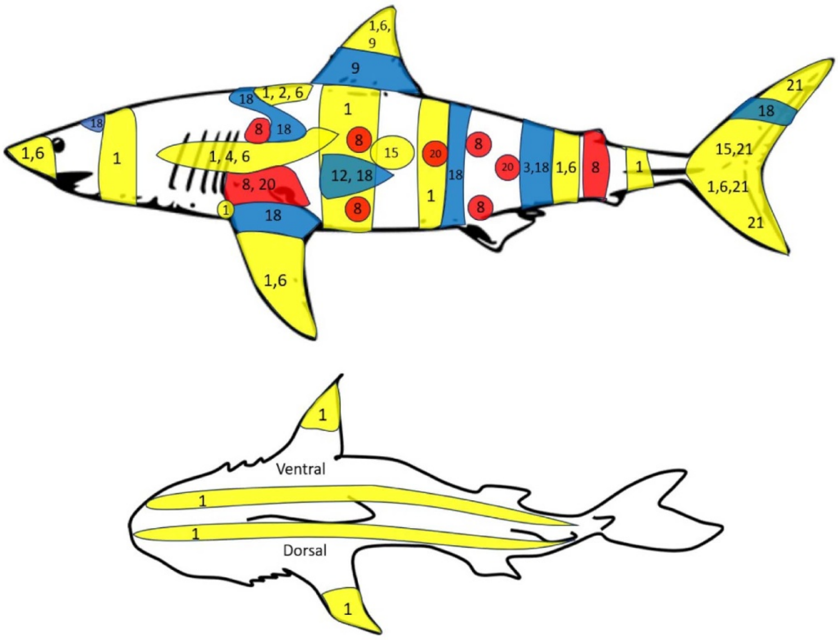
The comprehensive review of shark skin properties reveals a fascinating interplay of morphology, hydrodynamics, and material properties. The evolutionary adaptations of shark skin, particularly the role of dermal denticles, provide insights into nature's solutions for drag reduction and efficient swimming. The diverse morphological variations in denticles, coupled with their impact on hydrodynamics, present a rich field for interdisciplinary research. The current state of scientific knowledge highlights the intricate details of shark skin, from microscopic structures to macroscopic adaptations, contributing to breakthroughs in technology and materials science.

Biomimetic shark skin presents a promising avenue for reducing drag and enhancing performance in various applications. The choice of fabrication methods, particularly the utilization of 3D printing, showcases advantages in terms of efficiency, flexibility, and control over denticle parameters. However, challenges remain, such as the need for technological advancements to replicate the intricate morphology of shark skin at biological scales. The implementation of the simple riblet structures, inspired by shark skin, already shows significant potential for resistance reduction and improved efficiency. In locomotion studies, the impact of shark skin on swimming speed and thrust enhancement is evident. Beyond drag reduction, shark skin denticles alter vortex location, potentially increasing thrust and playing a crucial role in lift and maneuvering forces. To summarize, biomimetic shark skin, with its various applications and ongoing advancements in fabrication and understanding its impact on performance, holds great promise for revolutionizing various industries and contributing to more efficient and sustainable technologies.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Appendix



A: Image of locations shark skin samples

Skin properties	Morphology	Hydrodynamics
8,19,20	1,2,4,6,15,16,21	3,5,7,9,10,11,12,13,14,17,18

B: Number of study that conducted research in that section

1	(Díez et al., 2015)	12	(Du Clos et al., 2018)
2	(A. W. Lang et al., 2008)	13	(Luo et al., 2015)
3	(Du et al., 2022)	14	(C. Zhang et al., 2022)
4	(M. Gabler-Smith et al., 2021)	15	(M. K. Gabler-Smith & Lauder, 2022)
5	(Feld et al., 2019)	16	(Motta et al., 2012)
6	(Ankhelyi et al., 2018)	17	(A. Lang et al., 2015)
7	(Afroz et al., 2017)	18	(A. Lang et al., 2011)
8	(Naresh et al., 1997)	19	(Wainwright et al., 1978)
9	(Patricia et al., 2019)	20	(Creager & Porter, 2018)
10	(A. W. Lang et al., 2014)	21	(Popp et al., 2020)
11	(D.-y. Zhang et al., 2011)	-	-

C: Table of various studies

Figure 6. (A) Locations where samples were taken for the various studies that investigated skin properties, morphology or hydrodynamics. (B) Number of study that conducted research in that section. (C) Various studies that investigated skin properties, morphology or hydrodynamics.

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