




FEATURE

There's more to Fish than Just Food: Exploring the Diverse Ways that Fish Contribute to Human Society

Julian D. Olden  | University of Washington, School of Aquatic and Fishery Sciences, WA. E-mail: olden@uw.edu

Jean R. S. Vitule | Universidade Federal do Paraná, Laboratório de Ecologia e Conservação, Departamento de Engenharia Ambiental, Setor de Tecnologia, Curitiba, Brazil

Julien Cucherousset  | Université de Toulouse, Laboratoire Evolution et Diversité Biologique, Toulouse, France

Mark J. Kennard  | Griffith University, Australian Rivers Institute, QLD, Australia

The nest of a River Chub *Nocomis micropogon* with associated stonerollers and shiners from the Tennessee River system. Credit: David Herasimtschuk / Freshwaters Illustrated

Fish are among the most biodiverse vertebrate groups on the planet, playing vital ecosystem roles, supporting considerable commercial, recreational, and artisanal fisheries, and delivering critical ecosystem goods and services for the world's human population. These intrinsic, ecological, and socioeconomic values of fish are well recognized. Much less widely appreciated are the diverse additional ways that fish have contributed to human societies. Here, we explore the assorted uses of freshwater and marine fishes, both presently and in the past, by focusing on their contributions to manufacturing and industry, technology, health care, tools and weapons, apparel and jewelry, and musical instruments, and as curios, souvenirs, and attractions. The material ways by which people depend on fish have continued to grow and evolve over time, resulting in a much more intricate web of human–fish relationships than is often recognized. By demonstrating the importance of fish across all facets of life, we hope that this exploration leads to greater conservation, sustainable management, and ethical treatment of fish now and into the future.

INTRODUCTION

Marine and inland fisheries make vital contributions to food security—both as a direct source of protein, essential fatty acids, and micronutrients, and indirectly via employment and income (FAO 2018). Fisheries also have tremendous cultural and educational importance in human societies. These include longstanding representation in many religious ceremonies and archaeological artifacts, and recreational fisheries providing a significant source of leisure, supplementary nutrition, connection to nature, and influxes to local economies (Arlinghaus et al. 2016; Hunt and McManus 2016; Cooke et al. 2018). Indeed, most people rarely think about fish other than as a source of protein, a pet, a recreational prize, or as a basis for inspiration or worship. Much less widely recognized is the diversity of other ways that fish have contributed to human societies, both presently and in the past.

In this spirit, here we explore the varied uses of freshwater and marine fishes, focusing on their contributions to manufacturing and industry, technology, health care, tools and

weapons, apparel and jewelry, and musical instruments, and as curios, souvenirs, and attractions (Figure 1). We exclude from our review reference to other uses of fish, because they have been treated extensively elsewhere; for example, fish for food or source of recreation, fish, oils as a dietary supplement, the use of fish as a biological control agent, the sociocultural significance of fish for society, or reference to fish in folklore, mythology, religion, spirituality, art, literature, film, and popular culture (e.g., Moyle and Moyle 1991; Flanagan 2001; Abbott 2004; Sommer et al. 2007; Gupta et al. 2016). By increasing awareness of the diverse ways in which fish have and continue to be used by human societies, we hope this our review will promote broader conservation, sustainable management, and ethical treatment of fish into the future.

MANUFACTURING AND INDUSTRY

Fish Glue

Fish glue is an adhesive created by prolonged boiling of fish connective tissue, specifically formed through hydrolysis

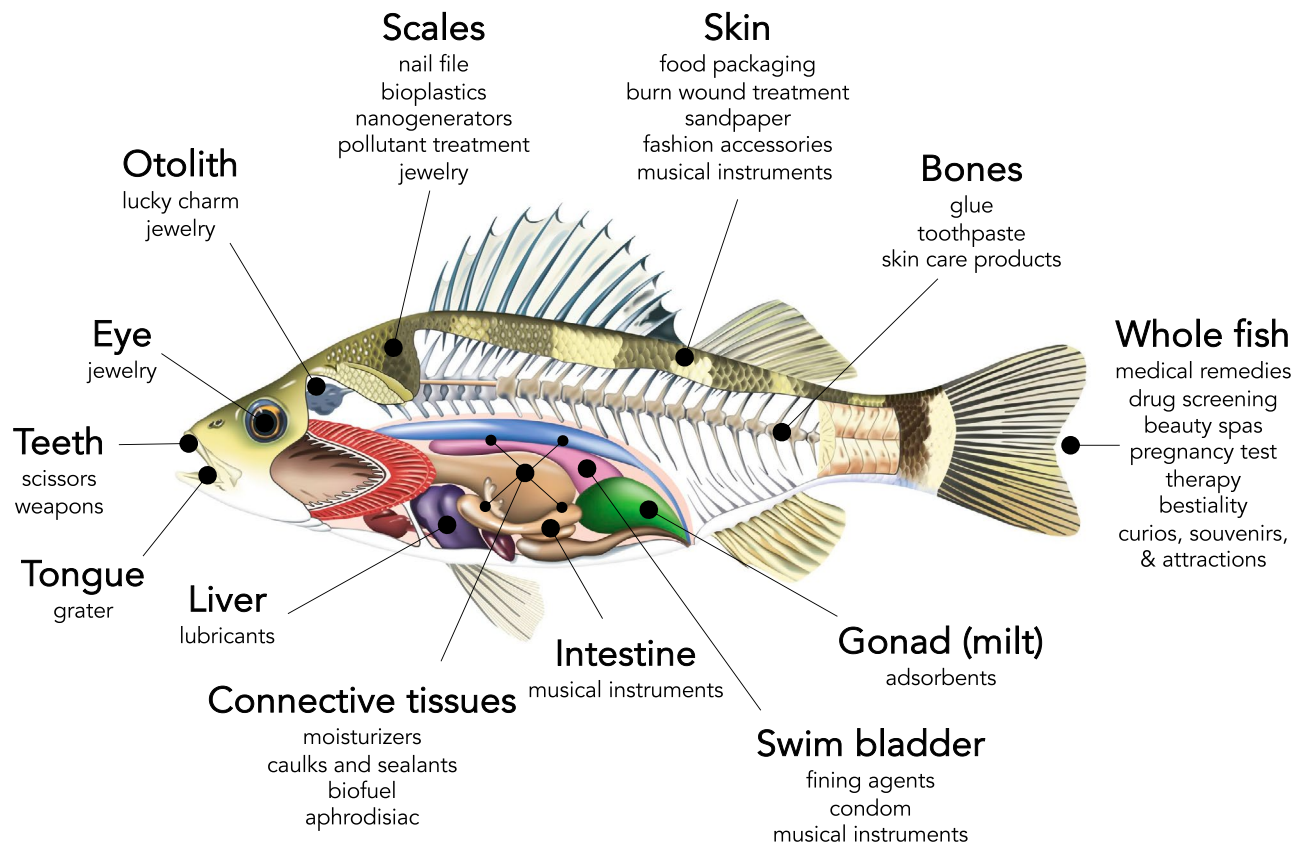


Figure 1. Contributions of fish (whole and in part) to manufacturing and industry, technology, health care, tools and weapons, apparel and jewelry, and musical instruments, and as curios, souvenirs, and attractions.

of the collagen from skins, bones, tendons, and other tissues, similar to gelatin (Figure 2A). Fish glue is transparent, colorless, and water soluble, and comes in many types, ranging from higher quality derived from swim bladders (Isinglass; see below) to lower quality made from the skins, bones, and cartilage. Fish glue was commonly available in the third century, where Hippolytus notes its use by magicians and diviners on the streets of Rome, in about 220 C.E. According to Hippolytus, fish glue had asbestos-like properties, since the trickster “anoints his feet with fish glue” so that he can walk over hot coals without being burned (Scarborough 2015). Later, fish glue was used by the Greeks and Romans to develop veneering, specifically wood bonding, and during the medieval ages, fish glues were used as a source for painting and illuminating manuscripts (Laurie 1910). Fish glue was also used by the Chinese for medicinal purposes. Today, the application of fish glues are rarer in industry (see Akter et al.

2016), but notably are still utilized for making and restoring artifacts (Petukhova 2000).

Fish Oil

Industrial uses of fish oils rendered from a number of different organs are used for: protective coatings on wood, metal, fiber, and concrete; lubricants; medicinal products (see below); and soaps. For example, the large livers of ratfish (Family: Chimaeridae) constitute approximately 60% of their total body weight (Figure 2B) and contain an exceedingly high proportion of oil (as high as 80% of the wet liver weight; Hayashi and Takagi 1980). The large oily liver plays an important role in maintaining neutral buoyancy at the extreme depths in which many species of this family occupy in the world’s oceans. Stories exist of people using ratfish liver oil to lubricate guns, pocket watches, and other fine delicate instruments, and even

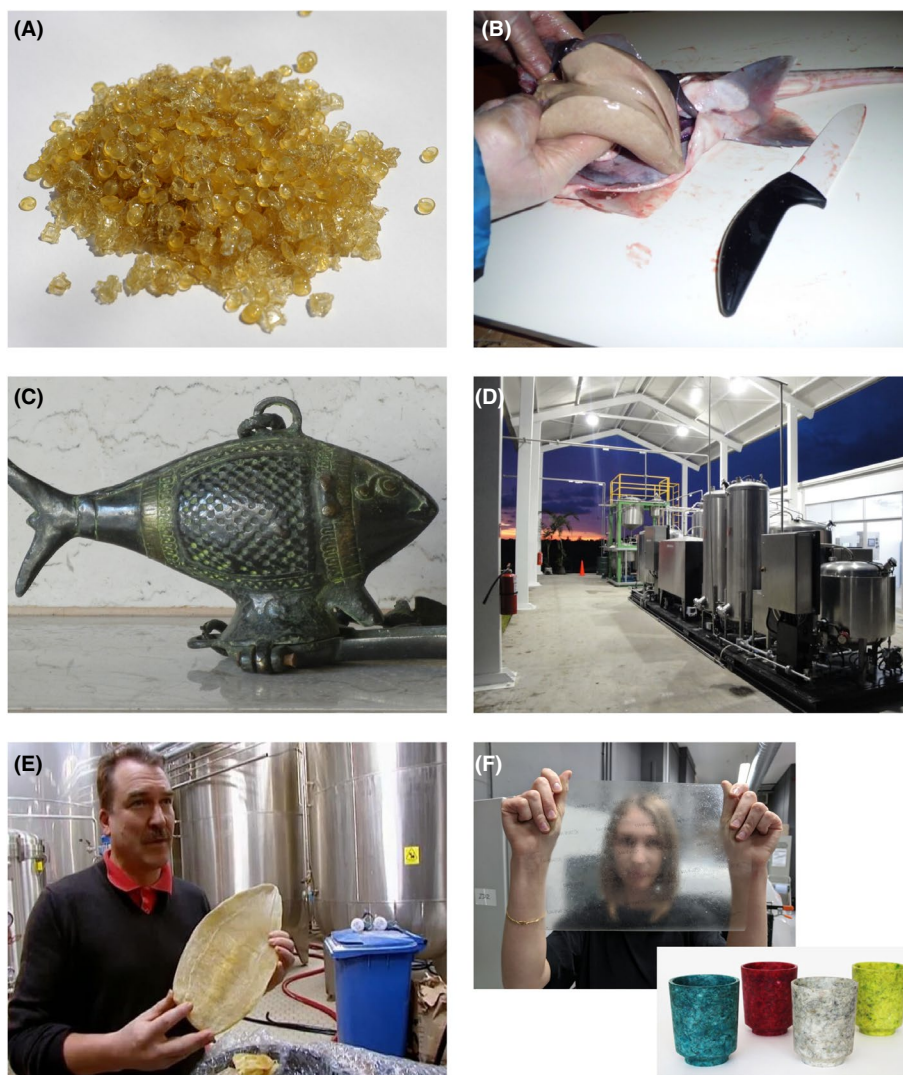


Figure 2. Fish use in manufacturing and industry. (A) Animal (fish) glue in granular form; (B) ratfish liver used to create fish oil; (C) antique fish oil lamp; (D) production facility for biofuel derived from fish waste in Mexico; (E) a beer maker holding a dried swim bladder, aka isinglass; and (F) British product designer Lucy Hughes invented a biodegradable plastic made from fish scales and skin and artist Erik de Laurens has made bioplastic cups from fish scales. Photo credits: (A) Simon Eugster, distributed under a CC-BY-SA 3.0 license; (B) <https://bit.ly/3dYATsD>; (C) <https://bit.ly/2X8X8pQ>; (D) <https://bit.ly/2JH11wj>; (E) <https://bbc.in/2JKWpmW>; (F) REUTERS Stuart McDill and <https://bit.ly/2ULKhlr>.

fishermen applying this oil to fishing reels to prevent rust. Apparently, NASA even considered ratfish liver oil as a good substitute for sperm whale oil to use as a lubricant in their space program.

Fish oils from connective tissues have been shown to be especially beneficial as polymerization agents in alkyds, varnishes, and paints, as a softening agent for the process of tanning leather, and as a farm animal moisturizer to treat dry and brittle horse hooves. Fish oils have occasionally been used in caulks and sealants to achieve prolonged elasticity and binding properties (Fineberg and Johnson 1967). Animal repellents also containing fish meals and oils are marketed as a biodegradable solution to protecting plants and property from nuisance animals such as deer, rabbits, squirrels, and rats. These repellents produce an unpleasant scent/taste that causes a mild irritation to an animal's nasal passage.

Sources of biofuel include a wide variety of plants, as well as animal fats, including those derived from fish (Arvanitoyannis and Kassaveti 2008; Figure 2C). For example, lambari oil (lambari is the common name given to dozens of species of small freshwater fish species from the family Characidae) is widely used in the Brazilian Pantanal to light small lanterns. Similarly, in Russia near the Caspian Sea, lamprey oil has been used for illumination, and *Eulachon Thaleichthys pacificus*—also called candlefish—were dried and then burned as candles because of their high fat content during spawning. Crude fish oil, characterized as a dark brown viscous fatty oil, is also a source of biofuel (Yuvaraj et al. 2016). This process involves heating fish waste to release the oil from fat deposits, and then separating the liquids from the solids via physical pressing and centrifuging. The oil is cleaned and purified, and with the addition of a catalyst, biofuel is produced. For example, Kato et al. (2004) demonstrated the use of ozone-treated fish waste oil as a transportation diesel fuel. Interest in partnering with the fishing industry and producing biofuels is growing, although thus far has been largely limited to small-scale operations (e.g., Lanari and Franci 1998; Figure 2D).

Isinglass

Isinglass, a term derived from the Dutch word *huizenblas* or German *hausenblase* (meaning sturgeon bladder) is a transparent, almost pure gelatin, prepared from the swim bladder of the sturgeon (Family: Acipenseridae; Figure 2E) and certain other fishes with relatively large swim bladders that are easily detachable from the body cavity (Talbot 1905). Isinglass can also be derived from the skin, stomach, intestines, and gills, but this is much less common. The bladders are dried and then cut into thin translucent strips; these strips, which are nearly 80% collagen, are dissolved in hot water, then diluted and cooled into flat disks or converted into a powder to be used as fining agents during alcohol processing (Koochekian et al. 2006). Specifically, isinglass is used commercially to clarify primarily wines and beers by aggregating the yeast and other insoluble particles (Leach 1967). The use of isinglass has decreased with modern brewing methods, although as recent as 2017, trace amounts were still found in every pint of Guinness stout. Isinglass can also be cooked into a paste for specialized adhesive purposes, such as for envelopes and stamps, and to preserve parchments and repair broken porcelain (see Fish Glue), and was also used as a food preservative in Britain before and during World War II, when it was dissolved into water to act as an effective preservative for fresh eggs (Atwell and Crawford 1867).

Mineral/Element Extraction

Recent research has demonstrated the potential of salmon milt (semen) as an adsorbent to recycle rare earth elements (REE) used in various advanced materials, including catalysts, alloys, magnets, optics, and lasers (Takahashi et al. 2014). Solvent extraction has long been an effective method to recover REEs from ore waste, but this expensive process involves the use of toxic and sometimes radioactive chemicals that often are released into the environment. Research has shown that phosphate on the surface of some types of bacteria were much more efficient in attracting REEs, yet growing cultures for use on an industrial scale is not feasible. To address this problem, a team of Japanese scientists demonstrated that dried salmon semen, which could be sourced from a vast fishing industry, was a viable replacement and was very effective in extracting expensive elements (Takahashi et al. 2014). Fish scales have also been used as a natural adsorbent for treatment of organic pollution, such as to remove carotenoid pigment from wastewater in the seafood industry (Stepnowski et al. 2004) and as biofilm colonization media in moving bed bioreactors to treat effluent from dairy farms (Jaafari et al. 2017).

Bioplastics

Scientists continue to explore the potential of using microbial fermentation (i.e., breakdown of carbohydrates by the use of microorganisms) as a process to produce bioplastics from melted scales of fish. Fermented scales undergo cell disruption, washing, centrifugation, and drying to purify the biopolymer, resulting in complete sterilization and no residual odor. Bioplastics from fish scales have been used to manufacture a range of household goods (Figure 2F), apparel (see below), and produce biodegradable plastic sheeting (Figure 2F). Fish scale waste has also been explored as a filler for polymer composites to produce packaging foam material (Chiarathanakrit et al. 2018).

Biodegradability of gelatin-based biopolymer films has led to a growing interest in their use as edible food packaging. Fish skin collagen (and gelatin prepared from it) has low risk of transmitting pathogens when compared to animal gelatin, and it is suitable for consumers who follow Kosher and Halal dietary standards (Krishna et al. 2012). In addition, increasing interest in seafood industries to make use of waste from fish processing is another factor contributing to growth in production of fish gelatin in recent years (Etxabide et al. 2017; de la Caba et al. 2019). Fish viscera, byproducts from processing industries, are also a source of lipases, which can potentially be applied in the detergent processing industry (Patchimpet et al. 2019).

Biotechnology

Fish have inspired new technology, for example, in the field of material sciences. Recently, skin from Electric Eels *Electrophorus electricus* motivated the development of super-stretchable nanogenerators that produce electricity by touch or tapping. This device can be used as deformable and wearable power source, as well as fully autonomous and self-sufficient adaptive electronic skin system (Lai et al. 2016). The unique skin of the Electric Eel has stimulated the development of a new family of high output electrochemical capacitors that are flexible, stretchable, and weavable, and seen as particularly promising for portable and wearable electronics (Sun et al. 2016). Similarly, recent research points to the use of fish scales and swim bladders in creating bio-piezoelectric

nanogenerators (Ghosh and Mandal 2016a, 2016b). For instance, fish scales contain collagen fibers that generate an electric charge in response to several types of ambient mechanical energies, including body movements, machine and sound vibrations, and even wind flow. In the future, the hope is to implant a bio-piezoelectric nanogenerator into a heart for pacemaker devices, where it will continuously generate power from heartbeats for the device's operation.

HEALTH CARE AND SEXUALITY

Cosmetics

Toothpaste containing ground fish bones was originally used by the early Chinese as an abrasive to help remove dental plaque and food from teeth. More recently, fish scales have been used after they are melted, filtered, and separated into collagen and hydroxyapatite. Toothpaste

made from hydroxyapatite looks and tastes like regular toothpaste, but some studies have found it more effective in making teeth white and strong, and in facilitating repair in areas suffering from tooth decay (Prihartini Devitasari et al. 2019).

Crystalline guanine is extracted from ground-up scales of some fish species, including herring (Family: Clupeidae), and is commonly used in cosmetics (Figure 3A). For example, crystalline guanine is added to nail polish, lipstick, mascara, shampoo, and other skin and hair care products, where it provides a shimmering or pearlescent effect (Kim 2012). Crystalline guanine is also used in metallic paints, simulated pearls, and plastics as a colorant. Lamprey (Order: Petromyzontiformes) have a special significance in several Indigenous cultures, including Native American tribes, who use fish oil as hair grease (NPCC 2015).



Figure 3. Fish use in health care and sexuality. (A) Crystalline guanine labeled as “Fish Silver Powder;” (B) doctors wrap a child’s burnt skin with sterilized tilapia fish skin in Fortaleza, Brazil; (C) hagfish slime; (D) *Garra Rufa* fish (kangal fish, doctor fish, nibble fish) is used in health and beauty spas in many parts of the world; (E) condoms (>110 years old) made from the swim bladders of fish (note that these condoms were meant to be reusable, as suggested by the former owner’s careful tally scribed on inside of box of how many times each condom had been used); and (F) specimen jar containing three female Japanese Bitterlings used as a pregnancy test. Photo credits: (A) <https://bit.ly/3aIP3fo>; (B) Paulo Whitaker, Reuters; (C) <https://bit.ly/3aOydMJ>; (D) iStock.com/Jonathan Austin Daniels; (E) <https://bit.ly/2UK4Rjo>; (F) The Board of Trustees of the Science Museum, Creative Commons.

Biomedicine

Collagens derived from fish skins and other protein-rich fish processing byproducts like scales and bones (colloquially known as aqua-collagens) are increasingly explored as an alternative to mammalian-derived collagen for use in a variety of pharmaceutical and biomedical applications (Benjakul et al. 2012). Collagen is the main structural protein in the extracellular space of various connective tissues in animal bodies and has widespread use because of its excellent biocompatibility and biodegradability, and weak antigenicity (Li et al. 2018). Aqua-collagen derived from salmonids, cyprinids, cichlids, and a range of other cartilaginous and non-cartilaginous fishes has been promoted as scaffolds for engineering of bone and other issues, surgical dressings, drug delivery, and skin care products (e.g., Nagai et al. 2004; Pati et al. 2012; Li et al. 2018). Recently, skin from tilapia (Family: Cichlidae) has been suggested as a possible biological cover (dressing) for burn wounds in humans and animals, and as a biological graft in gynecology (Bezerra et al. 2018; Figure 3B). Tilapia skin is an inexpensive and effective option to treat patients with second- and third-degree burns, because it contains large amounts of moisture and type I collagen proteins at levels comparable to human skin. This prevents scarring, while promoting the healing of wounds (Alves et al. 2018). In 2019, a woman became the first transgender person in the world to undergo successful vaginal reconstructive surgery using the skin of tilapia fish (Anonymous 2019).

The first bioelectric phenomenon acknowledged by humans was undoubtedly the electric discharge of certain types of fish (Kellaway 1946). Several fish species have an electric organ discharge that is powerful enough to stun prey or be used for defense. Examples include the South American Electric Eel, electric catfishes (Family: Malapteruridae), stargazers (Family: Uranoscopidae), and electric rays (Order: Torpediniformes). The electrical discharges produced by such fishes were highly appreciated among ancient physicians and were prescribed as an analgesic for the relief of headache, gout, and prolapsed anus (Tsoucalas et al. 2014). During and after the renaissance period, study of the anatomy and mechanics of electric fishes by physicians and scientists paved the way for the discovery of electricity and the evolution of electrotherapy to relieve a range of symptoms and ailments (e.g. headaches, wounds, paralyzed muscles, post-traumatic pain), though with debatable effectiveness (Tsoucalas et al. 2014).

Many chemical compounds have been extracted from fish and are increasingly employed as medical remedies. Some compounds have demonstrated utility in biochemical research or have led to the development of anticancer and antiviral drugs (Costa-Neto 2005). For example, Pacific Hagfish *Eptatretus stoutii* and Atlantic Stingray *Dasyatis sabina* can be sources of cardiac stimulants and antitumors, respectively. The discovery that a chemical compound in Dogfish Sharks *Squalus acanthias* can help prevent infections has led some to believe that this compound may someday also kill parasites, fungi, and bacteria in humans (Wang et al. 2018). Slime from the Atlantic Hagfish *Myxine glutinosa* is also used as a defense mechanism against predators and is a “hydrogel” consisting of ultra-absorbent polymers that hold and retain large amounts of water (Böni et al. 2016; Figure 3C). These hydrogel properties make it potentially useful for drug delivery, tissue engineering and regeneration, and absorbable sutures. Hagfish slime may also have future industrial applications as fibers produced from the slime are exceptionally strong (Fudge et al. 2010).

Fish (most commonly Zebrafish *Danio rerio* [Family: Cyprinidae]) are frequently used as model organisms for drug screening and discovery. Compared to traditional mammalian models, fish provide numerous experimental advantages, including genetic and molecular tractability, amenability to high-throughput screening methods, and reduced experimental costs (Strange 2016). For example, the swim bladder of the Zebrafish, which is similar to the mammalian lung, has provided a real-time, *in vivo* model for examining pulmonary neutrophil infiltration during acute lung injury (Zhang et al. 2016). These examples underscore that medical research continues to explore the utility for fish to provide greater molecular and genetic understanding of human disease, thus significantly enhancing the discovery and application of new therapies.

Fish are widely used in traditional medicines, defined as “the ancient and culture-bound medical practice which existed in human societies before the application of modern science to health” (WHO 1999). Modes of preparation and delivery to treat ailments include: dried and powdered body parts administered as tea or ingested with food, ointments to be rubbed on affected areas (bile, oil, fat, mucous), ear drops (fat), ingestion of the cooked part (live, flesh), taken as a drink (fish oil) or mixed with an alcoholic beverage (whole animal; Alves and Alves 2011). For example, many species of seahorses and pipefishes (Family: Signathidae) are dried and used in traditional medicines in many countries around the world. Although evidence for their health benefits is scant, seahorses have been used in traditional medicine to treat infertility, baldness, asthma, arthritis, and erectile dysfunction. Additionally, recent research indicates seahorses exhibit antitumor, antiaging, and antifatigue properties (Kumaravel et al. 2012).

Fish have also been suggested to be important in animal-assisted therapy. Watching fish in an aquarium can, for example, reduce stress (Costa-Neto 2005) and anxiety (Buttelmann and Römpke 2014), improve physical mobility and reduce blood pressure in patients with cardiac disease (Kongable et al. 1989), and confer physical benefits such as weight gain to older persons with dementia (Edwards and Beck 2002).

Since the early 21st century, *Garra rufa* (also called kargal fish, doctor fish, nibble fish) has been used in health and beauty spas across the world (Figure 3D). The fish nibble on dead skin cells and supposedly release dithranol (a component of dermatological creams) and an enzymatic secretion that enhances the skin condition by normalizing its pH level and helping new skin cells regenerate faster. Although the “doctor fish” treatment has been found to alleviate the symptoms of psoriasis (e.g. Grassberger and Hoch 2006), the treatment is not curative, and its validity as a spa treatment is still widely debated.

Sexuality

Some early condoms were made from the swim bladders of fish (Huxley 1957) with the multi-use of these sheaths dating to about 1640 (Figure 3E). During the English Civil War (circa 1642–1647), condoms made from fish were deployed to the army to reduce transmission of syphilis (Khan et al. 2013). The use of female European Bitterling *Rhodeus amarus* as a pregnancy test was investigated in the 1930's (Gottlieb 1936; Figure 3F). This fish possesses an ovipositor, which was reported to become elongated when the animal was exposed to urine from a pregnant woman. It was presumed that female sex hormones in the urine caused this response in the bitterling. However, the test was considered highly unreliable as

experiments revealed that secretions from the adrenal glands of male and female humans also caused the same effect (Weisman 1938).

In the Middle Ages, the oil of lamprey was believed to increase potency, libido, and contribute to sperm formation. Similarly, the flesh of African electric catfishes (Family: Malapteruridae) is reported as being considered an aphrodisiac and is reported to act as a marital love charm (Kellaway 1946). Several other species, including the swimbladder of Acoupa Weakfish *Cynoscion acoupa* are used in traditional medicine in several Asiatic countries and considered as an aphrodisiac (Martins et al. 2019). In addition, Striped Snakehead *Channa striata* is consumed by women postpartum to promote wound healing and reduce postoperative pain (Ab Wahab et al. 2015). It is also used in southeast Asia as a traditional remedy for a range of other ailments (Mohd Shafri and Abdul Manan 2012).

Fish have been documented to feature in bestiality (human sexual relations with animals) and zoophilia (sexual disorder involving an erotic attraction to animals). For example, there are reports of penile penetration of dead Thornback Rays *Raja clavata* (Beetz and Podberscek 2005), sex with stingrays by professional fishermen in Brazil (anecdotal reports by professional fishermen interviewed by JRSV), and insertion of fish into the vaginas of women (Beirne 1997).

TOOLS AND WEAPONS

The Pirarucu *Arapaima gigas* is a fish belonging to a primitive group of carnivorous bony-tongued fishes (Family: Arapaimidae) that crush their prey with a large tongue studded with teeth. Many small villages in the Amazon use dried Pirarucu tongues as a grater to break down the mandioca root

to produce cassava flour; a major staple food in the developing world (Figure 4A). Pirarucu tongues are also used to scrape dried guaraná plant, to produce guaranine (better known as caffeine) that is used in soft drinks around Brazil. Many people also use the Pirarucu's scales as nail files. Piranhas (Family: Characidae) are notorious for their sharp teeth that can strip prey to bones in a few minutes. Native peoples along the Amazon River use piranha jaws as a cutting device or scissors (Schleser 1997). Skin from sharks and stingrays, which are covered with minuscule dermal denticles (Figure 4B), have a long history of use as sandpaper for the construction of boats and furniture, and crafting utensils (also see description of shagreen below).

Fish parts have been used in many different ways to construct weapons; here we provide just a few examples. The *leiomano* is a shark-toothed club used by various Polynesian cultures, but primarily by the native Hawaiians (Figure 4C). The weapon resembles a thick ping pong paddle inset with shark teeth (preferred species is the Tiger Shark *Galeocerdo cuvier*) that are placed into grooves in the club and sewn into place. The long, bony, spear-shaped bill or rostrum of sailfish and marlins have been fashioned into numerous styles of daggers (Figure 4D). Stingray barbs were also attached to spears and used in initiation ceremonies, fighting and punishment, and for fishing throughout the Australian aboriginal culture. For example, the *kaiya* was composed of an acacia shaft mounted with a cluster of stingray barbs. The shaft was smeared with blood and the butt was painted with bands of pigment. *Kaiya* were used in initiation ceremonies, for fighting and punishment, such as spearing the leg of those who disobeyed tribal laws (McConnel 1953).

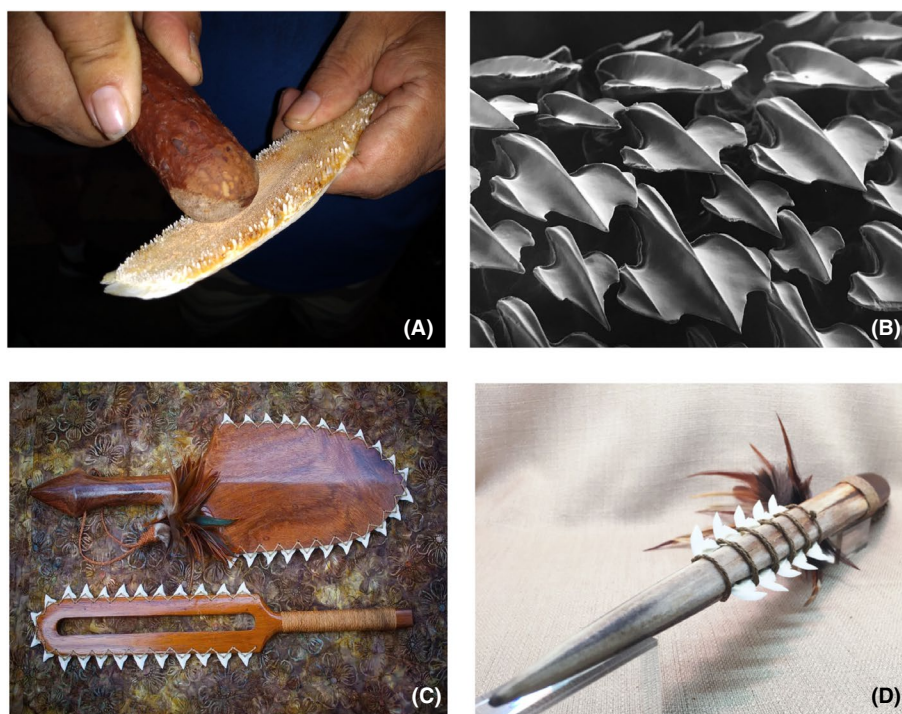


Figure 4. Fish use in tools and weapons. (A) Bony-tongue of Pirarucu used as grater to produce cassava flour from mandioca root; (B) dermal denticles in shark skin, visible under the electron microscope at 135X magnification; (C) shark-toothed club called a *leiomano*; and (D) Hawaiian Koa dagger constructed of a marlin bill flanked with Tiger Shark teeth secured by a strong string fiber and decorated with brown chicken feathers. Photo credits: (A) Jean Vitule; (B) reddit.com; (C) <https://bit.ly/3bZNOsj>; (D) <https://bit.ly/2XbNbI3>.

APPAREL AND JEWELRY

Shagreen is a type of rawhide consisting of rough untanned skin, historically derived from a horse. In the 17th and early 18th centuries, the term “shagreen” began to be applied to leather made from skin of a shark or stingray, and now is produced from the skins of commercially farmed Asian stingrays (Order: Myliobatiformes). In modern times, shagreen is used as a fancy leather for book bindings, pocketbooks, and small cases, because of its reputation for withstanding rough handling and its water-resistant qualities. Shagreen was fashionable in the 1970s for furniture such as small tables, partly due to the renewed interest in the Art-deco period. Shagreen was also used for the hilts and scabbards of swords and daggers to enhance grip.

Fish skin has been used to create a number of consumer products including wallets, belts, gloves (Figure 5A), and even jackets (Figure 5B). For example, apparel such as trousers, jackets, wallets, shoes, and calendars are made with leather

from the skin of Pirarucu in South America. In the northern hemisphere, salmonids are also widely used to produce clothing and associated products from wild specimens or now as a byproduct of the salmon aquaculture industry (Hatt and Kirsten 1969). Historically, Nivkh people in Russia have used fish skin coats for protection against harsh weather conditions (Gall and Hobby 2009).

Fish otoliths (calcium carbonate structure of the inner ear) have been termed lucky stones as they are believed to provide good fortune and charms to ward off illness in some cultures (Figure 5C). Once thought to be mere pebbles, otoliths of Freshwater Drum *Aplodinotus grunniens* were found washed up on beaches along the Great Lakes. According to Hudson (2020), there is a tradition among Great Lakes fishermen and sailors of keeping these otoliths as lucky charms “... to keep them safe from storms, to give them an edge in a card game, or for better luck with the ladies.” After polishing, otoliths are used in jewelry or amulets. Fish eyes, in particular



Figure 5. Fish use in apparel and jewelry. (A) Various fish skin consumer products include wallets, book covers, and shoes; (B) salmon skin coats used in the Amur region of Siberia in the 1800s; (C) polished fish otoliths called lucky stones; (D) eyes from Black Snapper fish crafted into earrings; (E) earrings made of the fins and spines of the Indo-Pacific Lionfish; and (F) bioplastics from fish scales used to make eye spectacles and swimming goggles. Photo credits: (A) Jean Vitule; (B) Collection Nationaal Museum van Wereldculturen. Coll.no. RV-434-1; (C) pinterest.com; (D) <http://www.manyhandsgallery.net>; (E) www.etsy.com; (F) <https://bit.ly/2ULKhlr>.

the crystalline, are also used in pieces of jewelry. For example, the eyes from Black Snapper *Apsilius dentatus* caught by local fishermen can be boiled, cured, and dyed to create sterling silver pieces of jewelry (Figure 5D). Fin spines of the invasive Lionfish *Pterois volitans* in Colombia and Cuba are fashioned into earrings and necklaces (Figure 5E). Also, many cultures make fish bone necklaces, using the vertebrae bones from dried fish. Jewelry such as necklaces and earrings are also produced using the large scales of tarpons (Family: Megalopidae). Finally, bioplastics made from fish scales have been used to create eye spectacles and swimming goggles (Figure 5F).

MUSICAL INSTRUMENTS

On virtually all continents there are musical instruments made, in part, from glue and skin derived from fish. For instance, traditional *Derbakkes* (also known as *darbuka*) comprise burnt clay or light wood coated with fish skin (Standifer 1988). This goblet-shaped hand drum is primarily used in Arabic music, but is also a popular instrument in Balkan, Persian, and Turkish music (Figure 6A). The *riqq* (or *riq*)—a type of tambourine made of a wooden frame with a head made of fish skin—is a traditional musical instrument in Egypt (Figure 6B). Many types of Chinese drums (*ku*) are made from long pieces of bamboo or wood with dried fish skin stretched over one end (Blades 2005).

In addition to percussion instruments, fish parts have also been used to make stringed instruments. In one example, the *viola-de-cocho* is a traditional plucked-string instrument in the Pantanal region of Brazil, specifically in the states of Mato Grosso and Mato Grosso do Sul (Figure 6C). It is made and embellished with fish products such as swim bladder glue and strings derived from various fish parts. It receives this name because it is made of solid wood and carved in the shape of a viola. This instrument is popular among fishermen and local communities (Taborda 2002).

CURIOS, SOUVENIRS, AND ATTRACTIONS

Many fish species are traded and sold as curiosities (curios) and souvenirs around the world, either dried or preserved, whole or in part (Grey et al. 2005). Popular species include sharks, pufferfishes, seahorses, and piranhas (Figure 7A, B). Taxidermied fish are also used as attractions in a variety of businesses. For instance, in places like Peru, Brazil, and Bolivia, traders use whole large fish to decorate shops and charge tourists to pose for photos with the fish (Figure 7C). Taxidermied large fish of many species are extremely common on the walls of restaurants and bars, for example, the taxidermied heads of very large Murray Cod *Maccullochella peelii* in many pubs in southeastern Australia (Figure 7D) and numerous sportfishes are on display on walls of businesses across North America and elsewhere.

CONCLUSION

Human societies across the globe have long recognized the vital role of marine and freshwater fishes in supporting considerable commercial, recreational, and artisanal fisheries. Here, we demonstrate that there's more to fish than just food by reviewing the vast ways by which human society garners a multitude of other benefits from fish. These include contributions to manufacturing and industry, technology, and health care, and comprising elements of tools and weapons, apparel and jewelry, musical instruments, and curios and souvenirs. Diverse values of fish are not merely stories from the past, but



Figure 6. Fish use in musical instruments. (A) Arabic *darbuka*; (B) Egyptian *riqq*; and (C) Brazilian *viola-de-cocho*. Photo credits: (A) <http://www.yalcinkayapercussion.com>, (B) Unknown, distributed under a CC-BY-SA 3.0 license; (C) Jean Vitule.

continue today as new and innovative uses are being actively explored.

Looking to the future, understanding the variety of ways that fish are used by humans is necessary to promote their conservation, sustainable management, and ethical treatment. But a glance into the past shows that with increased value of

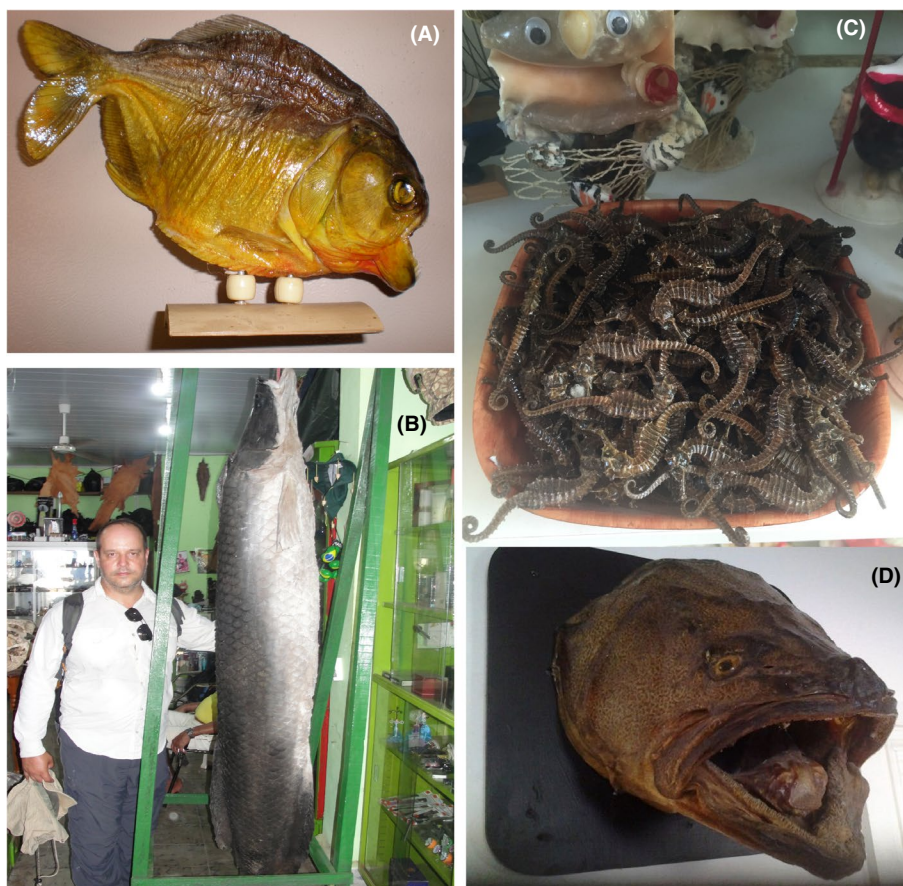


Figure 7. Fish use as curios, souvenirs, and tourist attractions. (A) Dried piranhas; (B) taxidermied Pirarucu pictured with co-author Vitule; (C) dried seahorses; and (D) taxidermied Murray Cod. Photo credits: (A) Jean Vitule; (B) Jean Vitule; (C) <https://bit.ly/2V1Tmvl>; (D) <https://ab.co/2JOpqhf>.

fish often comes decreased consideration for their conservation. In United States, for instance, countless species considered threatened or near threatened by the World Conservation Union are currently exploited for the curios trade (Grey et al. 2005). Similarly, nearly 725,000 fish leather products, worth multiple millions of dollars, are imported annually to the United States. About 93% of these products are obtained from wild fish and one-third of the exploited fish species are considered globally threatened or near threatened (Grey et al. 2006). Such rampant and unsustainable exploitation are crucial issues that must be solved. Yet with these stories also comes rising commitments to sustainable fisheries and the emergence of new opportunities to reduce waste and maximize the use of by-products in the aquaculture industry. We remain hopeful that the material ways by which people depend on fish will continued to grow, resulting in greater appreciate and care for the unwavering bond between humans, fishes, and their ecosystems.




ACKNOWLEDGMENTS

We thank all of our friends and colleagues for always willing to talk, often at significant length, about the immense value of fishes. The goal of this article was to be representative and not comprehensive of the less widely appreciated uses of fish, so we encourage this conversation to continue. Comments from three anonymous reviewers improved the final manuscript.

AUTHOR CONTRIBUTIONS

J.D.O. conceived the original idea of the study and served as overall lead author with important conceptual and writing contributions from all the authors.

ORCID

Julian D. Olden  <https://orcid.org/0000-0003-2143-1187>
 Julien Cucherousset  <https://orcid.org/0000-0003-0533-9479>
 Mark J. Kennard  <https://orcid.org/0000-0003-4383-4999>

REFERENCES

- Ab Wahab, S. Z., A. Abdul Kadir, N. H. Nik Hussain, J. Omar, R. Yunus, S. Baie, N. Mohd Noor, I. I. Hassan, W. H. Wan Mahmood, A. Abd Razak, and W. Z. Wan Yusoff. 2015. The effect of *Channa striatus* (Haruan) extract on pain and wound healing of post-lower segment caesarean section women. Evidence-based Complementary and Alternative Medicine. Available: <https://bit.ly/2ULCNoP>.
- Abbott, A. 2004. The fabulous fish guy. *Nature* 427:672–673.
- Akter, S., B. Sheikh, M. Rahman, S. Bhowmik, N. Alam, M. A. Rahman, and A. N. Alam. 2016. Assessment of fishery wastes and suitability of its utilization in the manufacture of fish glue. *American Journal of Food and Nutrition* 6:77–81.
- Alves, A. P. N. N., E. M. Lima Júnior, N. S. Piccolo, M. J. B. de Miranda, M. E. Q. Lima Verde, A. E. C. Ferreira Júnior, P. G. de Barros Silva, V. P. Feitosa, T. J. P. G. de Bandeira, M. B. Mathor, and M. O. de Moraes. 2018. Study of tensiometric properties, microbiological and collagen content in Nile Tilapia skin submitted to different sterilization methods. *Cell and Tissue Banking* 19:373–382.
- Alves, R. R. N., and H. N. Alves. 2011. The faunal drugstore: animal-based remedies used in traditional medicines in Latin America. *Journal of Ethnobiology and Ethnomedicine* 7:1–43.

- Anonymous. 2019. Trans woman, 35, 'first in world' to get vagina made out of fish skin. Pattaya Today. Available: <https://bit.ly/2RfYew> (January 2020).
- Arlinghaus, R., S. J. Cooke, S. G. Sutton, A. J. Danylchuk, W. Potts, K. M. F. de Freire, J. Alós, E. T. da Silva, I. G. Cowx, and R. van Anrooy. 2016. Recommendations for the future of recreational fisheries to prepare the social-ecological system to cope with change. *Fisheries Management and Ecology* 23:177–186.
- Arvanitoyannis, I. S., and A. Kassaveti. 2008. Fish industry waste: treatments, environmental impacts, current and potential uses. *International Journal of Food Science and Technology* 43:726–745.
- Atwell, B. D., and G. H. Crawford. 1867. Improved mode of keeping eggs. United States Patent Office, patent 65,988. June 25, 1867.
- Beetz, A. M., and A. L. Podberscek. 2005. *Bestiality and zoophilia: sexual relations with animals*. Purdue University Press, West Lafayette, Indiana.
- Beirne, P. 1997. Rethinking bestiality: towards a concept of interspecies sexual assault. *Theoretical Criminology* 1:317–340.
- Benjakul, S., S. Nalinanon, and F. Shahidi. 2012. Fish collagen. Pages 365–387 in B. K. Simpson, editor. *Food biochemistry and food processing*. John Wiley & Sons, Ames, Iowa.
- Bezerra, L. R. P. S., M. O. de Moraes Filho, Z. V. Bruno, E. M. Lima Júnior, A. P. N. N. Alves, A. P. M. Bilhar, M. T. P. M. Dias, and L. C. Rios. 2018. Tilapia fish skin: a new biological graft in gynecology. *Revista de Medicina da UFC* 58:6–8.
- Blades, J. 2005. Percussion instruments and their history. The Bold Strummer, Westport, Connecticut.
- Böni, L., P. Fischer, L. Böcker, S. Kuster, and P. A. Rühs. 2016. Hagfish slime and mucin flow properties and their implications for defense. *Scientific Reports* 6:1–8.
- Buttelmann, D., and A. K. Römpke. 2014. Anxiety-reducing effect: dog, fish and plant in direct comparison. *Anthrozoos* 27:267–277.
- de la Caba, K., P. Guerrero, T. S. Trung, M. Cruz-Romero, J. P. Kerry, J. Fluhr, M. Maurer, F. Kruijssen, A. Albalat, S. Burt, D. Little, and R. Newton. 2019. From seafood waste to active seafood packaging: an emerging opportunity of the circular economy. *Journal of Cleaner Production* 208:86–98.
- Chiarathanakrit, C., S. A. Riyajan, and K. Kaewtatip. 2018. Transforming fish scale waste into an efficient filler for starch foam. *Carbohydrate Polymers* 188:48–53.
- Cooke, S. J., W. M. Twardek, R. J. Lennox, A. J. Zolderdo, S. D. Bower, L. F. G. Gutowsky, A. J. Danylchuk, R. Arlinghaus, and D. Beard. 2018. The nexus of fun and nutrition: recreational fishing is also about food. *Fish and Fisheries* 19:201–224.
- Costa-Neto, E. M. 2005. Animal-based medicines: biological prospection and the sustainable use of zootherapeutic resources. *Anais da Academia Brasileira de Ciencias* 77:33–43.
- Edwards, N. E., and A. M. Beck. 2002. Animal-assisted therapy and nutrition in Alzheimer's Disease 24:697–712.
- Etخابide, A., J. Uranga, P. Guerrero, and K. de la Caba. 2017. Development of active gelatin films by means of valorisation of food processing waste: a review. *Food Hydrocolloids* 68:192–198.
- FAO (Food and Agriculture Organization of the United Nations). 2018. *FAO yearbook. Fishery and aquaculture statistics 2016*. Rome.
- Fineberg, H., and A. G. Johnson. 1967. *Industrial use of fish oils*. U.S. Department of Interior Circular 278. Avi Publishing, Westport, Connecticut.
- Flanagan, R. 2001. *Gould's book of fish: a novel in twelve fish*. Pan Macmillan, Sydney, Australia.
- Fudge, D. S., S. Hillis, N. Levy, and J. M. Gosline. 2010. Hagfish slime threads as a biomimetic model for high performance protein fibres. *Bioinspiration and Biomimetics* 5:035002.
- Gall, T., and J. Hobby. 2009. *Worldmark encyclopedia of cultures and daily life: Europe*. Gale, Farmington Hills, Michigan.
- Ghosh, S.K., and D. Mandal. 2016a. Bio-piezoelectric nanogenerator made with fish scale. *Applied Physics Letters* 109:103701. Available: <https://bit.ly/3aNUeBe>.
- Ghosh, S. K., and D. Mandal. 2016b. Efficient natural piezoelectric nanogenerator: electricity generation from fish swim bladder. *Nano Energy* 28:356–365.
- Gottlieb, R. 1936. The bitterling test for pregnancy. *Canadian Medical Association Journal* 34:431–432.
- Grassberger, M., and W. Hoch. 2006. Ichthyotherapy as alternative treatment for patients with psoriasis: a pilot study. *Evidence-based Complementary and Alternative Medicine* 3:483–488.
- Grey, M., A. Blais, B. Hunt, and A. Vincent. 2006. The USA's international trade in fish leather, from a conservation perspective. *Environmental Conservation* 33:100–108.
- Grey, M., M. A. Blais, and A. C. J. Vincent. 2005. Magnitude and trends of marine fish curio imports to the USA. *Oryx* 39:413–420.
- Gupta, N., A. Kanagavel, P. Dandekar, N. Dahanukar, K. Sivakumar, V. B. Mathur, and R. Raghavan. 2016. God's fishes: religion, culture and freshwater fish conservation in India. *Oryx* 50:244–249.
- Hatt, G., and T. Kirsten. 1969. Arctic skin clothing in Eurasia and America: an ethnographic study. *Arctic Anthropology* 5:3–132.
- Hayashi, K., and T. Takagi. 1980. Composition of diacyl glyceryl ethers in the liver lipids of Ratfish, *Hydrolagus novaezealandiae*. *Nippon Suisan Gakkaishi* 46:855–861.
- Hudson, W. 2020. Lucky stones. Neo-Naturalist.com. Available: <https://bit.ly/3aPci7s> (January 2020).
- Hunt, W., and A. McManus. 2016. Recreational fishing supports health and wellbeing in Western Australia. *Australian and New Zealand Journal of Public Health* 40:292–292.
- Huxley, J. 1957. Material of early contraceptive sheaths. *British Medical Journal* 1:581–582.
- Jaafari, A., N. El, B. Boutaleb, A. Bahlouan, T. Aitcheikh, A. Taieq, S. Lazar Jada, and S. El Antri. 2017. Biodegradation of dairy wastewater by the use of fish scales as packing in moving bed bioreactors. *Journal of Colloid Science and Biotechnology* 5:218–222.
- Kato, S., K. Kunisawa, T. Kojima, and S. Murakami. 2004. Evaluation of ozone treated fish waste oil as a fuel for transportation. *Journal of Chemical Engineering of Japan* 37:863–870.
- Kellaway, P. 1946. The part played by electric fish in the early history of bioelectricity and electrotherapy. *Bulletin of the History of Medicine* 20:112–137.
- Khan, F., S. Mukhtar, I. K. Dickinson, and S. Sriprasad. 2013. The story of the condom. *Indian Journal of Urology* 29:12–15.
- Kim, S., Se-Kwon, K. 2012. *Marine cosmeceuticals: trends and prospects*. CRC Press, Boca Raton, Florida.
- Kongable, L. G., K. C. Buckwalter, and J. M. Stolley. 1989. The effects of pet therapy on the social behavior of institutionalized Alzheimer's clients. *Archives of Psychiatric Nursing* 3:191–198.
- Koochekian, A., Z. Ghorban, and A. Yousefi. 2006. Production of Isin glass from the swim bladder of sturgeons. *Journal of Applied Ichthyology* 22(Supplement 1):419–421.
- Krishna, M., C. I. Nindo, and S. C. Min. 2012. Development of fish gelatin edible films using extrusion and compression molding. *Journal of Food Engineering* 108:337–344.
- Kumaravel, K., S. Ravichandran, T. Balasubramanian, and L. Sonneschein. 2012. Seahorses – a source of traditional medicine. *Natural Product Research* 26:2330–2334.
- Lai, Y. C., J. Deng, S. Niu, W. Peng, C. Wu, R. Liu, Z. Wen, and Z. L. Wang. 2016. Electric Eel-skin-inspired mechanically durable and super-stretchable nanogenerator for deformable power source and fully autonomous conformable electronic-skin applications. *Advanced Materials* 28:10024–10032.
- Lanari, D., and C. Franci. 1998. Biogas production from solid wastes removed from fish farm effluents. *Aquatic Living Resources* 11:289–295.
- Laurie, A. P. 1910. *The materials of the painter's craft in Europe and Egypt from earliest times to the end of the XVII century, with some account on their preparation and use*. JB Lippincott, London.
- Leach, A. A. 1967. Collagen chemistry in relation to isinglass and isinglass finings: a review. *Journal of the Institute of Brewing* 73:8–16.
- Li, J., M. Wang, Y. Qiao, Y. Tian, J. Liu, S. Qin, and W. Wu. 2018. Extraction and characterization of type I collagen from skin of Tilapia (*Oreochromis niloticus*) and its potential application in biomedical scaffold material for tissue engineering. *Process Biochemistry* 74:156–163.
- Martins, R. S., J. G. Alvares, B. L. Mourato, A. O. Ávila Da Silva, and G. C. Cyrino Bastos. 2019. The fishery exploitation of Acoupa Weakfish off Sao Paulo coast, southeastern Brazil. *Boletim do Instituto de Pesca* 45(3). Available: <https://bit.ly/2JH1RH8>.
- McConnel, U. H. 1953. Native arts and industries on the Archer, Kendall and Holroyd rivers, Cape York Peninsula, north Queensland. *Records of the South Australian Museum* 11:1–42.
- Mohd Shafri, M. A., and M. J. Abdul Manan. 2012. Therapeutic potential of the Haruan (*Channa striatus*): From food to medicinal uses. *Malaysian Journal of Nutrition* 18:125–136.

- Moyle, P. B., and M. A. Moyle. 1991. Introduction to fish imagery in art. *Environmental Biology of Fishes* 31:5–23.
- Nagai, N., S. Yunoki, T. Suzuki, M. Sakata, K. Tajima, and M. Muneakata. 2004. Application of cross-linked salmon atelocollagen to the scaffold of human periodontal ligament cells. *Journal of Bioscience and Bioengineering* 97:389–394.
- NPCC (Northwest Power and Conservation Council). 2015. 2014 Columbia River basin fish and wildlife program costs report. Available: <https://bit.ly/2RhPs0y>.
- Patchimpet, J., K. Sangkharak, and S. Klomkiao. 2019. Lipolytic activity of viscera extract from three freshwater fish species in Phatthalung, Thailand: comparative studies and potential use as dishwashing detergent additive. *Biocatalysis and Agricultural Biotechnology* 19:101143.
- Pati, F., P. Datta, B. Adhikari, S. Dhara, K. Ghosh, and P. K. Das Mohapatra. 2012. Collagen scaffolds derived from fresh water fish origin and their biocompatibility. *Journal of Biomedical Materials Research* 100A:1068–1079.
- Petukhova, T. 2000. A history of fish glue as an artist's material: applications in paper and parchment artifacts. *Book and Paper Group Annual* 19:111–114.
- Prihartini Devitasari, S., M. Hudiayati, and D. Anastasia. 2019. Effect of hydroxyapatite from waste of tilapia bone (*Oreochromis niloticus*) on the surface hardness of enamel. *Journal of Physics: Conference Series* 1246. Available: <https://bit.ly/3dWMUOk>
- Scarborough, J. 2015. Fish glue (Gr. IXΘYOKO/MA) in Hellenistic and Roman medicine and pharmacology. *Classic Philology* 110:54–65.
- Schleser, D. M. 1997. Piranhas—everything about selection, care, nutrition, diseases, breeding and behavior. *Barrons's Educational Series*, New York.
- Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. *Fisheries* 32:270–277.
- Standifer, J. A. 1988. The Tuareg: their music and dance. *The Black Perspective in Music* 16:45–62.
- Stepnowski, P., G. Ólafsson, H. Helgason, and B. Jastorff. 2004. Recovery of astaxanthin from seafood wastewater utilizing fish scales waste. *Chemosphere* 54:413–417.
- Strange, K. 2016. Drug discovery in fish, flies, and worms. *ILAR Journal* 57:133–143.
- Sun, H., X. Fu, S. Xie, Y. Jiang, and H. Peng. 2016. Electrochemical capacitors with high output voltages that mimic Electric Eels. *Advanced Materials* 28:2070–2076.
- Taborda, M. 2002. A viola de arame: origem e introdução no Brasil. *Capa* 13:133–152.
- Takahashi, Y., K. Kondo, A. Miyaji, Y. Watanabe, Q. Fan, T. Honma, and K. Tanaka. 2014. Recovery and separation of rare earth elements using salmon milt. *PLoS ONE* 9:1–15.
- Talbot, F. L. 1905. The natural history of isinglass. *Journal of the Institute of Brewing* 11:508–531.
- Tsoucalas, G., M. Karamanou, M. Lymperi, V. Gennimata, and G. Androutsos. 2014. The “torpedo” effect in medicine. *International Maritime Health* 65:65–67.
- Wang, L., J. Sun, S. Ding, and B. Qi. 2018. Isolation and identification of novel antioxidant and antimicrobial oligopeptides from enzymatically hydrolyzed anchovy fish meal. *Process Biochemistry* 74:148–155.
- Weisman, A. I. 1938. Recent laboratory tests for the early diagnosis of pregnancy. *American Journal of Obstetrics and Gynecology* 35:354–364.
- WHO (World Health Organization). 1999. Traditional and modern medicine: harmonizing the two approaches. A report of the consultation meeting on traditional and modern medicine: harmonizing the two approaches, 22–26 November 1999, Beijing, China. WHO Regional Office for the Western Pacific, Manila.
- Yuvaraj, D., B. Bharathiraja, J. Rithika, S. Dhanasree, V. Ezhilarasi, A. Lavanya, and R. Praveenkumar. 2016. Production of biofuels from fish wastes: an overview. *Biofuels* 7:269:1–7.
- Zhang, Y., H. Liu, J. Yao, Y. Huang, S. Qin, Z. Sun, Y. Xu, S. Wan, H. Cheng, C. Li, X. Zhang, and Y. Ke. 2016. Manipulating the air-filled Zebrafish swim bladder as a neutrophilic inflammation model for acute lung injury. *Cell Death and Disease* 7:1–12. **AFS**