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Full Length Research Article

BIOMIMETICS OF FISH SCALES: VALUE AND PROSPECTS

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ABSTRACT
The body of an ideal fish is covered by scales which are either thin or thick. These scales arise as external growths from the epidermis of the skin. Fish scales are known to contain pigmentation that gives colour to the scales for example, the Minytrema melanops is greyish brown in colour because of the grey colour from the scales while its close relative the small mouth buffalo Ictiobus bubalus is Olive-bronze in colour. Fish scales in general contain a variety of pigments that give the fish a variety of colors. Fish scales constitute about 2% of the total body weight, but said to be rich in nutritive components just as the flesh of the fish. The scale of fish is similar to the structure of a typical bone. Fish scales comprise of 40% - 55%collagen type 1, hydroxyapatite and calcium carbonate fat, lecithin and scleroprotein. The mechanical testing of fish scales was reported to show that the unique design of the strength of scales is significant for mechanical characteristics. Again, the mechanical strength and toughness displayed by fish scale composition (external ganoine layer and internal layer) with enforced mineral properties enable the protective nature of the scales. Fish skin can be used like any other leather for various wear-resistant items such as shoes bags and purses. With the use of various tanning processes and chemicals, fish skin is successfully used for shoes and clothing.

Keywords: Application, Biomaterials, Biomimetic, Calcium, Fish scale, Mechanical properties, Industrial application.

INTRODUCTION
Fish scales are the small, plastic-like rigid plates covering on the body of fish. They grow out of the fish to cover the skin.
Scales can be referred to as exoskeleton covering the fish skin. The scales of fish are of different types. Scales are either small, thin calcareous, bony, cornified, large plates which fit closely firmly or loosely to overlap and cover the skin of fish. The arrangement of these scales is usually in margins and patterns directed towards the tail.

The body of an ideal fish is covered by scales which are either thin or thick. These scales arise as external growths from the epidermis of the skin. The epidermis contains numerous mucus cells that produce and secrete mucus or slime which protect the fish from pathogens such as bacteria, fungus and parasites from easily penetrating the skin of the fish (Agbugui and Oniye 2019) All bony fishes of the Class Osteichthyes and some Order in the Class Chondrichthyes (Cartilagenous fishes) have scales of varying size, shape, colour and thickness (Fish and Fisheries). Fishes with scales belong to the class Osteichthyes. In as much as most fish bear scales, the catfish do not have scales, the Agnathans do not also bear scales.

Fish scales are known to contain pigmentation that gives colour to the scales for example, the *Minytrema melanops* is greyish brown in colour because of the grey colour from the scales while its close relative the small mouth buffalo *Ictiobus bubalus* is Olive-bronze in colour (Agbugui *et al*., 2021). Fish scales in general contain a variety of pigments that give the fish a variety of colors.
The pigments deposit growth rings that assist in aging fish, these rings are annuli markings formed from marked seasonal changes from the wet and dry periods of the year, (Pandy and Shukla 2005). The deposits form a lateral line along the body of the fish usually from below the opercula region to the caudal peduncle, this lateral line acts as a sensory receptor for the fish in water and assist in detecting vibrations in water (Pandy and Shukla 2005).
The information about fish, fish scales, the fundamental and functional properties, the composition of fish scales and use to fish life cannot be over emphasized. The abundant information about fish scales usually from exotic species. The reference to local species especially in Nigeria is limited. The information concerning the prospects of fish scale industry could be easily accepted if species easily harvested by fisher folks in Nigeria can be generated.

This paper aims at making available information of scales of fish species found in Nigerian water bodies. The paper intends to add to knowledge of the functional properties of fish scales, its imports to fish, relevance to fish life, prospects of fish skin and fish scale industry.
This paper reviews the biomimetic of fish scale, use to fish life and its effect in fish industry and prospects to existence of man.

Formation of Scales
Scales are found in vertebrates. Scales emerge from the epidermal and dermal layers of vertebrates and serve as external coverings. The Malpighian layer of the epidermis secrete cornified scale derivatives. These cornified scales are found in reptiles, birds and mammals. Fish scales are developed from the mesenchymal layer of the dermis (Bhavya, 2022).

Fish scales could be smooth, rough, small, large, thin, thick, hard, cornified, bony plates, fused, or overlap. Fish scales could cover the whole body of the fish such as *Protopterus annectens* or a portion of the fish as seen in Acipenser. Different species of fish have scales of different sizes, shapes and colour. Some species are however scale-less such as cat fish *Chrysicthys nigrodigitatus*.

Characterisation of Fish Scales
Fish scales are called dermal scales which are mesenchymal in origin (Bhavya, 2022). These scales vary in size, arrangement and shape for different species. All fishes have scales except for the catfishes of the family Siluridae. For the ones that have, the scales cover the whole fish from the snout to the caudal peduncle e.g., *Pomadasys jubelini*, *Minytrema melanops and Hydrocynus vittatus*.

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Some fish have scales just on localized areas of the body for example the Chimaeras, Acipenser and Polyodon (Froese and Pauly, 2022).
Anatomically, scales are classified as ctenoid, placoid, rhomboid cosmoid and cycloid (Pandy and Shukla 2005). Placoid scales arise from the secretion of the epidermal and dermal layers of fish such as the elasmobranchs. The other types of scales are often found in teleost fishes (Bond 1979).

***Cosmoid Scales*:**
Cosmoid scales are found in the lungfishes. In Australia, the Australian lungfish *Neoceratodus forester* is the extant species of fish that possess cosmoid scales (Clement and Bray 2022). In Nigeria, the West African lungfish *Protopterus annectens* is a typical example of a fish with cosmoid scales. (Plate 1). Another fish with the cosmoid scales is the tiger fish *Hyrocynus vittatus.* The scales consist of a double bone layer, comprising lamellar and vascular bone; the outer layer is considered as a dentin-like cosmine. The external layer of the scale is thin with enamel- like layer called vitrodentine, flexible (Agbugui and Oniye 2022) though closely attached and embedded in (Plate 2 and Plate 3).
Clement and Bray (2022), has described the cosmoid scale to have a hard, enamel-like outer layer, an inner layer of cosmine (a form of dentine), then a layer of vascular bone (isopedine) as shown in the scales of *Hydrocynus vittatus* (Plate 2 and Plate 3).

Plate. 1. Cosmoid scale *of Protopterus annectens Agbugui and Oniye 2019*

Plate. 2. Cosmoid scale *of Protopterus annectens*

Plate. 3. Cosmoid scale *of Hydrocynus vittatus*
Inner layer without vitrodentine

Clement and Bray (2022), has described the cosmoid scale to have a hard, enamel-like outer layer, an inner layer of cosmine (a form of dentine), then a layer of vascular bone (isopedine) as shown in the scales of *Hydrocynus vittatus* (Plate 2 and Plate 3).

Ganoid Scales:
Ganoid scales are also called Rhumboid scale. Ganoid scales are obtained in various forms and structure (Bond 1979), the scales have an enamel-like material (ganoine) in them making them look like teeth and feel like bones fused into socket, the scales are heavy with a hard inorganic outer surface. The Placoid scales are found in fishes such as the *Polypterus bichir* (Agbugui and Oniye 2022) as shown below in Plate 4a.
Froese (2022) has reported that the middle layer of the ganoid scale is cosmine containing numerous branching tubules, while, the innermost layer is thickest and is made up of lamellar bone, isopedine (Yang *et al*., 2013).

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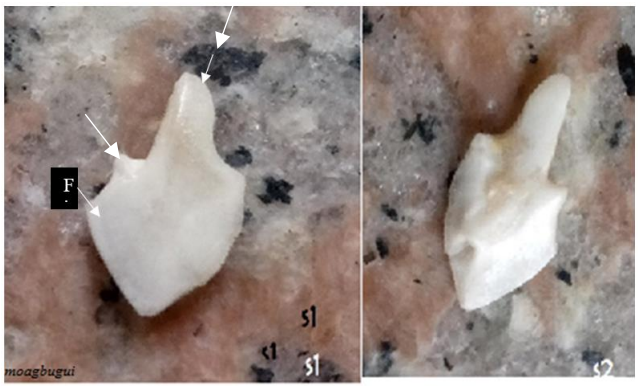

Plate 4a the Rhumboid scale of P. bichir
S1; outer side of the scale, s2; inner side of the scale
Source; Agbugui and Oniye 2022

a: median spine, b: basal spine

As shown above, the scales of *P. bichir* which is ganoid lack surface or visible growth rings but is covered on the outside with a hard glittering layer of ganoine. The scales do not grow like scales of other bony fishes. These scales grow by the addition of new layers to lower as well as upper surface. Plate.4b.

Plate.4b. Rows of Ganoid scales on *P. bichir*
Source: Agbugui and Oniye 2022

Fishes with ganoid scales are commonly called ganoid fishes. Other fish bearing ganoid scales are the Acipenser (Chondrostean) and Lepidosteus (holostean) (Freose and Pauly 2022). The scales in *P. bichir* as shown above are hard rhombic plates, looking polished, tightly and firmly fitting from edge to edge to the skin. This gives the complete armour nature covering to the fish. The Alligator gar common to the waters of the North America is another fish with ganoid scales. The scales are not overlapping like other fish scales but have thick hard and bony interlocking scales. The scales are covered with ganoine (crystalline material coating) (Yang *et al*., 2013). However, Bazerra *et al*. (2020) has reported that the scales of the Arapaina are reduced in their thickness and rigidity. The scales are thinner than those of the bichir and gars, do not possess the ganoine layer and resemble typical cycloid scales.

Cycloid scales:
Cycloid scales are found in teleost fishes. These scales are composed of concentric rings called annuli from yearly markings and depositions of vitrodentine (Yang et al., 2013), the scales are rigid, yet flexible, light and do not have the enamel-like nature of ganoid and cosmoid scales. The scales are however firm and tough enough to provide protection from predators. Cycloid scales lack cteni (spinous teeth), the focus is not distinctly visible.
In Nigeria, fishes with cycloid scales include *Pomadasys jubelini, Hydrocynus vittatus, Minytrema melanops, Lates niloticus, Heterotis niloticus, and Gymnarchus niloticus.* Fig 5 shows scales of *Pomadasys jubelini* (Agbugui and Oniye 20014, Agbugui and Oniye 2022, Agbgui *et al*.,2021, Agbugui and Adeniyi 2021)
The first part of the scale to be developed is the focus which turns out to be the central part of the scale. As the fish grows older, the radii develop round the focus to the edge of the scale. The radii are not necessarily a perfect circle but a round ridge that is quiet observable. This is evident in Plate. 5

Plate. 5. Cosmoid scale *of Hydrocynus vittatus* External layer with vitrodentine
F, focus; R, radii

***Placoid Scales*:**
Placoid scales are seen in elasmobranchs otherwise known as cartilagenous fishes such as sharks. The scales are embedded in the dermis with each scale in the form of a plate with a sharp projection (Esmeali et al., 2014) The placoid scale resembles the ganoid scale but with a sharper pointed tooth-like edge. The tooth-like edge is also known as the spine, the hard external layer is covered with enamel-like substance called vitrodentine (Esmeali *et al*., 2014). The placoid scales are closely set in skin but do not overlap each other and giving a sand paper-like quality to the skin.

Ctenoid Scales:
Ctenoid scales look like cycloid scales. The ctenoid scales are either elongated or circular but have a serrated outer edge and the internal layer. The internal section is embedded in the skin and has a comb-like edge. The scales are firmly attached to the skin and the free hind section do not overlap (Naqvi *et al*., 2014) as in other fish scales.
Fishes that bear ctenoid scales are tilapia, Sole fish. The external layer is bony, stiff and hard while the internal layer is said to be collagen-filled. The external surface offers protection to the fish while the inner layer soft but soft to give flexibility, and aid movement (Bond 1979).

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The external layer bears the cteni, tubercles and a large base that is not conical (Plate 7). The radii are seen to form circular rings called circuli. These are the yearly markings forms on the scales. As earlier said and as seen on cycloid and ctenoid scales, yearly marks are quiet observable and as such possible for the use of age determination. The circuli are arrange to fit the shape of the scale. Fishes with ctenoid scale have a conspicuous focus which is located at the posterior end and is the first part of the scale to be formed during ontogenesis.

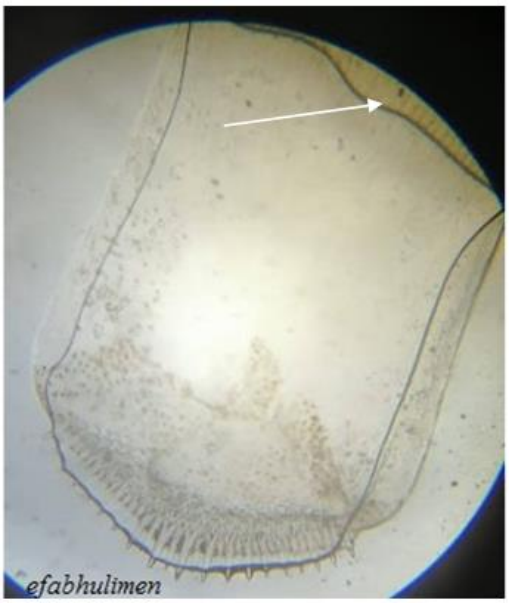

Plate 6. Ctenoid scale of Solea solea
Inset arrow is the anterior comb-like edge also called grooves

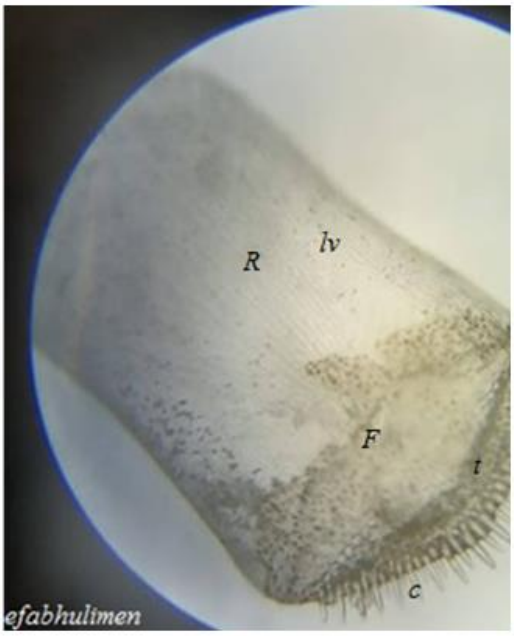

Plate 7. Ctenoid scale of Solea solea
R, radii; lv, lateral view; f, focus; t, tubercules; c, cteni

Composition of Fish Scale

Fish scales constitute about 2% of the total body weight, but said to be rich in nutritive components just as the flesh of the fish, it is similar to the structure of a typical bone and comprise of 40% - 55%collagen type 1, hydroxyapatite and calcium carbonate fat, lecithin and scleroprotein (Bhavya, 2022). The collagen from fish scales is often used in its hydrolyzate form which is a combination of protein hydrolysate and collagen peptide (Bhavya, 2022). These components are reported to be higher in fresh water species (Yaseen, 2021). Other constituents include protein, carbohydrate, lipid, ash, and moisture (Yaseen, 2021). In addition, elements such as calcium, iron, sodium, magnesium, phosphorus are present in minute concentrations (Suo-Lian *et al*., 2017; Nkansah *et al*., 2022). naqvi *et al*. (2014), reported that the scales of farmed and locally purchased *Ctenopharyngodon idella* have protein contents of 21.80% and very low lipid content of 0.74%. Since the scales of fishes are not edible parts to humans it is therefore necessary production and formulation of food and feed for livestock, and poultry due to rich protein content and low-fat contents as well as low-cost alternatives. Other elements found in fish scales include calcium, sulphur, sodium, phosphorus and magnesium, but these elements are found in trace amounts (Pati *et al*., 2010).

Fish protein hydrolysate (FPH) is a form of fish protein broken down to simpler protein peptides, this hydrolysate can be obtained from all species of fishes at various amounts and at varying degrees of hydrolysis (Yaseen, 2021). It is reported that all parts of fish and fish waste can be used to obtain FPH (Gil-Duran *et al*., 2016). In a study of the production and characterization of protein hydrolysate from parrot (*Chlorurus sordidus),* it was reported that the hydrolysate was obtained under varying temperature and was optimized with time, this by product is an essential material for pharmaceutical, agricultural and organic fertilizer producing industries (Prihanto *et al*., 2019).

It is reported by Omar *et al.* (2019) and Nkansah *et al*. (2022), that Calcium hydroxyapatite is a useful component in an absorption process, it serves as an organic adsorbent that can remove pollutants from water, furthermore, the cost-effective use of fish scales in the removal of Pb and Fluoride from water. The removal of the pollutants is credited to the hydroxyl groups of the hydroxyapatite in fish scale.

Mechanical Properties of Fish Scales

The scale of fish consists of three characteristic layers.
The innermost layer consisting of a compact bone- isopedine, the intermediate or middle layer of spongy vascular bone and the outer layer is of dentine (Yaseen *et al*., 2021).
The mechanical testing of fish scales was reported by Ikoma *et al*., (2003) that the unique design of the strength of scales is significant for mechanical characteristics, and the mechanical strength and toughness displayed by fish scale composition (external ganoine layer and internal layer) with enforced mineral properties enable the protective nature of the scales.

Fish scale and aging

The circuli formation is due to the excess calcium salts secreted by the skin and their subsequent deposition on the scale. So, the distance between circuli indicates a fast or slow growth period (Begum 2021). This is especially useful in temperate waters where pronounced retardation of growth of body and scales occurs in fall

and winter, causing the spacing between the circuli to decrease and thus leaving a band on the scales called an annulus or periodic zone. The stress of spawning, movement from fresh to salt water, parasitism, injury, pollution, and sharp and prolonged change in temperature may all leave marks on the scales similar to annuli which may be false annuli (Bagum 2021). Scales grow in a direct relationship with body growth, making it possible to measure the distance between annuli and back calculate the age at different body sizes (Yaseen *et al*., 2021). Cycloid and ctenoid scales are of considerable help in calculating the age of and growth rate of fishes. Many species undergo seasonal growth which is apparent from the lines of growth on the scale. In some species like Salmo, spawning marks can be seen on the scales, so that it is possible to find how many times a fish has spawned.

Scales grow throughout life in size with the fish. Growth results in concentric lines which make age determination possible in salmon, trout, bass and several other species. For every species, its scale pattern is rather constant. Thus, arrangement, number, form and structure of scales play an important role in identification and classification of fish species.

Effects of the Properties of Scales

The function of scales of fish is numerous and vary for various reasons.

Protective covering and self-defense: Many organisms are covered with body armour for protection. The scales of fish act as a protective shield over the skin of the fish. Fish scales could protect the fish from direct injury such as punctures, abrasion and force from unsuitable rough environment. The thickness of the armour could vary from fish to fish. This use is seen in the bichir with tough and hard ganoid scales as against Tilapia with more flexible scales. Scales protect fish from parasites that can easily penetrate the skin and flesh (Agbugui and Oniye 2019). Fish spines and thorn ward off predators and larger fish. Again, offering protection through camouflage from the use of reflection and color of scales to provide optimal survival.

Fishes with scales capable of demonstrating mechanical strength of great magnitude to resist punctures, abrasion, unsuitable rough environment, and resist penetration is the teleost fish is also considered to demonstrate great mechanical properties in similar conditions where penetration resistance is favored (Rawat *et al*., 2021). The invention and usage of body amour to protect the chest and other sensitive and delicate parts of the body are necessary to improve or replace the Kelvar product. The biomimetic inspiration where scales can be used for the production of body has been put to test by Stopfort and Adadi (2018) and Yaseen *et al*., (2021) where scales can serve as body covering to mimic the Kevlar bullet proof is rapidly advancing. Different fish species were used in the study. The most promising fish with high amour protective properties was the *Arapaima gigas* (Yang 2013), its dermal layers have two regions; a bony layer for protection and the second surface thick layer made of soft flexible collagen. The mechanical speed shows that the scales provide favorable reduced penetration to low-speed projectiles (Bond 1979). Other scales from fish species like the Teleost may not have the same mechanical strength but the studies have reported that the scales were efficient in the reduction of damage to skin and propagation. The study had some challenges proving that scales could fracture and lose their structure due to excess load (Yaseen *et al*., 2021). This therefore provides some opportunity for progress and further development. Fishes like the *Protopterus annectens, Polypterus bichir* and *Heterotis niloticus* found in the West African, Nigeria have tough scales with high mechanical strength. However, data on such scales are lacking (Agbugui and Oniye 2022)

Locomotion: Large scales offer paramount protection but restricts movements as seen in *Heterotis niloticus*, the bichir and the Alligator gar, while light small scales offer lesser protection but increases agility and movement of fish as seen in *Minytrema melanops* and *Gymnarchus niloticus* (Agbugui and Adeniyi 2021; Agbugui *et al.,* 2021), hence the electric eel, *Anguilla Anguilla* have microscopic scales with a tremendous swift movement. In general, the arrangement of scales in rows overlapping and the flexibly packed orientation aids motion in fishes (Agbugui and Oniye 2022).

Classification: Fish scales are used in taxonomy and nomenclature. This is to identify and group fish species into taxa. Scales are often used to distinguish between primitive and modern day fish, cyprinoid and siluroid fishes which are scales-less. Hence, the fish are grouped into fishes with ganoid, cycloid, placoid and ctenoid scales. Furthermore, these scales represent and reveal characteristics of either teleost fishes which are bony, cartilagenous fishes such as Chondrichthyes and lung fishes or even completely scale-less (Pandy and Shukla 2005), such as the siluroid fish. Other ways of fish identification using scales include the number of fish scales along the lateral line, above or below the lateral line as described by (Agbugui and Oniye, 2022).

Age and growth of fish: The scales of fish show yearly markings around them which is representation of increase in size is. Hence fish is said to grow throughout life. Not all fishes have markings on their scale (Bond 1970), this is not to conclude that fish scales without annuli rings and marks have not reached a full year or not mature.

***Adornment*:** scales of various fish show different colours ranging from white, silver, brown, green, pink and reddish depending on the type of fish, location and natural habitat.

***Scales are used for making tip points of arrows*:** The scales are sometimes dipped into poison for potency (Anon 2022).

Prospects for fish scale industry:

Production of environmentally friendly fertilizer:

Fish scales are reported to produce organic fertilizer from the fermentation of fish scales using bacteria. A study was carried out on fish scales as potential substrate for production of alkaline protease and amino acid rich aqua hydrolyzate by *Bacillus altitudinis* GVC11. The result was an alkaline protease which contained non-essential amino acids that could be used as nutritional supplements by farmers (Harikrishna *et al*., 2017). This form of fertilizer is cost effective and environmentally friendly, a valuable way of restoring the habitat, environment and reducing waste.

Leather industry

The fish leather industry is dependent on the amount of scale fish harvested. Fish skin and scales is recently becoming an important fishery by product perhaps because of the increasing demand for fish, it is more environmentally friendly as compared to other endangered and protected animal products such as alligator and

zebras. Although the fish skin/scales are not solely bio-degradable, it is said to be durable. It is reported that fish skin is just as durable as other skin types, the leather is approximately nine times as strong as the leather obtained from cows because the fibers in the skin of fish crisscross rather than the vertical and horizontal pattern (Annon, 2005). In Kenya, fish skin can be used like any other leather for various wear-resistant items such as shoes bags and purses. With the use of various tanning processes and chemicals, fish skin is successfully used for shoes and clothing (William 2022). Furthermore, the skin types of sturgeon, carp, and conger were analyzed and possessed by Zengin *et al*., (2015) to show that all three fish leathers had adequate physical strength to be used in the manufacture of leather goods. In the waters of Nigeria, some fish have scales firmly fitted into the skin hence descaling becomes difficult. Some fish species are dried and smoked with the skin perhaps again because most of the scales do not general go off. Such fish can be looked in to as sources for fish leather. This industry is virgin and might possibly promote the diversity and prospects of fish industry in Nigeria.

Comprehensive Extraction from Fish Scales

This process will facilitate the production of functional and nutritive components from fish scales. The by- products of fish scale extraction include collagen, again, hydroxyapatite or soluble scleroprotein. The waste liquid also contains calcium hydrogen phosphate after decalcification, the waste liquid can be made into feed additives. Such study has been reported by Wang (2014), and Suo-Lian *et al*., (2017) to promote the extraction of calcium hydrogen phosphate, NaOH to be mixed with waste acid. The results were products that could effectively save resources, protect the environment and improve the economic value of fish scales thereby promoting the fish industry.

Removal of heavy metals from energy produced waste (option for bioremediation)

Heavy metals can be released into the environment from petroleum industry, industrial waste, agricultural waste (Agbugui and Abe, 2022). The release of heavy metals into the environment can cause environmental pollution, environmental degradation and the cause deleterious effect to animals, plants and humans thereby disrupting the food chain and other living organisms hence the need for an environmentally friendly option away from the chemical and physical removal of heavy metals from the environment was adopted. This leads research to a need for bio inspired material such as fish scales. Mustapha (2003), reported the use of fish scales to absorb Chromium, lead and arsenic from a petroleum polluted environment where the microbial action from the fish scales led to a great reduction in the level of chromium**.**

Highlights:

The highlights of this manuscript include;

1. The beauty of fish scales as a covering to different fish species
2. The value (toughness, strength, durability) of fish scales to fish life
3. The prospects and possible use of fish scale to man and his environment

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