Holistic approach to understand how teleost fish scales fulfill their biological function - from nano to macro structure organization

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Abstract:
The United Nation's Food and Agriculture Organization (FAO) 2022 report on "The State of World Fisheries and Aquaculture" estimates that processed fish generate up to 70% of waste [1]. Among those, fish scales represent a large portion of the waste that is not yet valorized. A better understanding of the structure from nano- to macroscale, including the composition of fish scales is then very important for the upcycling of this by-product. To this end, we chose to focus on 3 species from different environments: tilapia (*Oreochromis niloticus*) which is raised in freshwater, and salmon (*Salmo salar*) and sardine (*Sardina pilchardus*) that spend most of their life in marine water. Teleost fish scales have already been identified as composites made of Type I collagen fibers organized in layers and mineralized with hydroxyapatite [2]. We discovered these fiber orientations change within the entire surface of the fish scale. A complete mapping, using Small Angle X-ray Scattering (SAXS) analysis from synchrotron setup at SOLEIL, has been successfully performed on the 3 species revealing a higher number of orientations in the focus area in comparison with the edges of the scales (Figure 1). In addition, X-ray micro computed tomography (micro-CT) has shown congruent information, with a thinning of the scales thickness on the edges, suggesting a decreasing number of collagen layers when the distance to the focus area increases. Furthermore, highly mineralized spots have been sighted for the first time in the internal collagen layers of the focus area of tilapia's scales. The composition of fish scales was evaluated using thermogravimetric analysis (TGA), Fourier transform infrared spectroscopy with attenuated total reflectance mode (FTIR-ATR), scanning electron microscopy coupled with energy dispersive X-ray analysis (SEM-EDX), elemental analysis CHNS and amino acids analysis. Variations of collagen/mineral ratio and collagen content have been highlighted and correlated to environmental constraints as seawater and freshwater species display some differences. This study also investigated the mechanical properties of teleost fish scales with tensile tests. These results offer perspectives for valorizing teleost fish scales as source of native collagen and for mimicking the scales' 3D structure for novel material development.

Keywords: fish scale, collagen, hydroxyapatite, 3D structure, composition, teleost, upcycling.

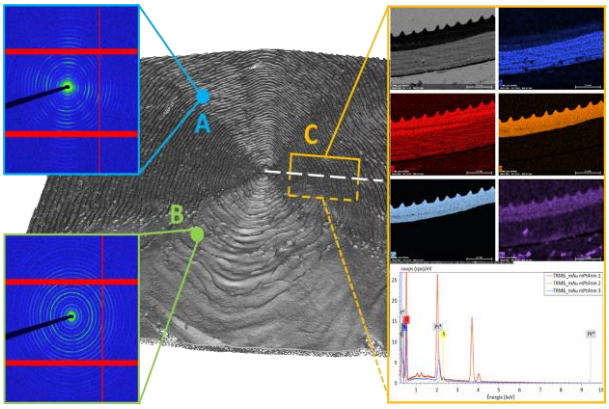

Figure 1: Combination of techniques, e.g. micro-CT, SAXS and SEM-EDX, for the structural and composition analysis of a teleost fish scale - *Salmo salar*: 3D image is from micro-CT ; (A) and (B) locate two spots in the anterior and posterior areas of the scale, respectively, where the X-ray beam hit for SAXS analysis ; (C) is a cross section of the anterior area observed with SEM-EDX, where the bi-layer structure collagen/mineral is visible.

References:

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[2] Quan, H.; Yang, W.; Lapeyriere, M.; Schaible, E.; Ritchie, R.O.; Meyers, M.A. Structure and Mechanical Adaptability of a Modern Elasmoid Fish Scale from the Common Carp. *Matter* **2020**, *3*, 842–863.