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Effectiveness of fish scales in the adsorption of heavy metals: a systematic review

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ABSTRACT

Industrial activity has increased the presence of heavy metals in surface waters and effluents, posing an environmental and health threat due to their persistence, toxicity, and bioaccumulation potential. In this context, fish scales are a promising alternative as an adsorbent due to their composition, which is rich in proteins, collagen, calcium salts, hydroxyapatite, and chitosan—components that promote the retention of metal ions. This systematic review evaluated the effectiveness of fish scales in adsorbing heavy metals, with a particular focus on Pb, Cd, Cr, Zn, and Cu. To this end, studies published between 2015 and 2026 were analyzed, and 44 articles were selected based on inclusion criteria, following the PRISMA methodology. The results showed that the most commonly used species were black tilapia (*Oreochromis niloticus*), Mozambique tilapia (*Oreochromis mossambicus*), and Indian carp (*Catla catla*), which highlights their experimental relevance and availability as raw materials. Likewise, removal efficiency was influenced by variables such as pH, adsorbent dose, and contact time, reaching efficiency values between 80.37% and 100% under optimized conditions. It was also found that chemically modifying the scales—through acid treatments and the incorporation of hydroxyapatite or a combination with chitosan to improve porosity—increases the number of active sites and optimizes interaction with the metals. In conclusion, the evidence supports the use of fish scales as a low-cost, technically viable alternative—consistent with the circular economy—for the remediation of water contaminated with heavy metals.

Keywords: adsorption, circular economy, heavy metals, scale-based treatment, water pollution.

Eficácia das escamas de peixe na adsorção de metais pesados: uma revisão sistemática

RESUMO

A atividade industrial tem aumentado a presença de metais pesados em águas superficiais e efluentes, gerando uma ameaça ambiental e à saúde pública, devido à sua persistência, toxicidade e capacidade de bioacumulação. Nesse contexto, as escamas de peixe representam uma alternativa promissora como adsorvente, em razão de sua composição rica em proteínas, colágeno, sais de cálcio, hidroxiapatita e quitosana, componentes que favorecem a retenção de íons metálicos. A presente revisão sistemática teve como objetivo avaliar a eficácia das escamas de peixe na adsorção de metais pesados, com especial atenção ao Pb, Cd, Cr, Zn e Cu. Para isso foram analisados estudos publicados entre 2015 e 2026, sendo selecionados 44 artigos de acordo com os critérios de inclusão, seguindo a metodologia PRISMA. Os resultados mostraram que as espécies mais utilizadas foram a tilápia-preta (*Oreochromis niloticus*), a tilápia-de-Moçambique (*Oreochromis mossambicus*) e a carpa indiana (*Catla catla*), evidenciando sua relevância experimental e disponibilidade como matéria-prima. Além disso, a eficiência de remoção foi condicionada por variáveis como o pH, a dosagem do adsorvente e o tempo de contato, atingindo valores entre 80.37% e 100% em condições otimizadas. De forma complementar, foi identificado que a modificação química das escamas, por meio de tratamentos ácidos e da incorporação de hidroxiapatita ou da combinação com quitosana, para melhorar a porosidade, aumenta os sítios ativos e otimiza a interação com os metais. Conclui-se que as evidências respaldam o uso de escamas de peixe como uma alternativa de baixo custo, tecnicamente viável e alinhada com a economia circular para a remediação de águas contaminadas com metais pesados.

Palavras-chave: adsorção, contaminação da água, economia circular, metais pesados, tratamento com escamas.

1. INTRODUCTION

The growing problem of heavy metal pollution, driven by rapid industrial expansion, poses a significant threat to ecosystems and human health (Bilal *et al.*, 2024). Heavy metals are persistent and non-biodegradable compounds, making them one of the primary causes for environmental concern (Guerra and Espinoza, 2025) due to their toxicity and high density (Londoño *et al.*, 2016). This highlights that conventional treatment methods still have significant limitations when it comes to the efficient removal of metals from complex matrices (Caixeta *et al.*, 2025).

Among heavy metals, cadmium (Cd) is recognized as one of the most toxic and persistent in the environment; therefore, its removal from wastewater is crucial, as it can cause adverse effects even at minimal concentrations (Jaafar *et al.*, 2021). Another hazardous metal is lead (Pb^{2+}), which poses serious health risks, as it affects a wide range of human organs and systems (Bilal *et al.*, 2024). Similarly, chromium, present in both trivalent (Cr^{3+}) and hexavalent (Cr^{6+}) forms, is a common contaminant in industrial and mining effluents. The mining sector also releases mercury (Hg), which is used as an amalgam in artisanal gold mining and is highly toxic and bioaccumulative (Teshale *et al.*, 2020).

In response to this problem, biosorption—or biological adsorption—has emerged as a promising and environmentally friendly technology for removing heavy metals from contaminated water (Bilal *et al.*, 2024). Adsorption has been selected as the preferred method for treating metal-laden wastewater, since many solid materials can concentrate these elements on their surfaces (Guerra and Espinoza, 2025). Adsorption is a physicochemical process in which atoms, ions, or molecules from a gas, liquid, or dissolved solid adhere to the surface of a solid material called an adsorbent (Pourhakkak *et al.*, 2021). In this context, it has been reported that chemical modification with acetic acid ($C_2H_4O_2$) produces a more porous surface and facilitates metal adsorption, with a removal rate of 94% for Cd^{2+} and 83% for Pb^{2+} on modified tilapia scales (Hernández *et al.*, 2025).

Among the various biosorbents studied—such as microbial biomass, agricultural waste, and others—fish scales stand out for their high adsorption potential. According to Pal and Maiti (2020), fish scales—traditionally considered waste—have been successfully used as biosorbents to immobilize heavy metals in sediments, thereby reducing their bioavailability and toxicity. Fish scales, especially those from the species Tilapia sp., can be thermochemically transformed into an effective adsorbent thanks to their mineral component, hydroxyapatite (HAp) (Omar *et al.*, 2020). The adsorption process using HAp involves mechanisms of ion exchange, surface complexation, and precipitation, making it highly effective at adsorbing toxic contaminants such as Pb, Cr, Cd, Cu, Ni, and Co (Liaw *et al.*, 2020). The combination of HAp nanoparticles and collagen fibers, together with the large specific surface area of fish scales, enhances adsorption performance (Sultana *et al.*, 2025). Furthermore, the integration of HAp with chitosan to form porous composites with adjustable channels significantly improves adsorption efficiency (Liaw *et al.*, 2020). In this regard, the mechanism of heavy metal adsorption by fish scales is primarily explained by the interaction of metal ions with the functional groups present in their protein–mineral matrix (collagen and hydroxyapatite) through electrostatic attraction processes (De la Cruz, 2026).

In light of the above, this article aims to evaluate the effectiveness of fish scales in adsorbing heavy metals. To achieve this objective, we will analyze the composition of fish scales, the species from which they are obtained, the types of metals treated, and the benefits of reusing biological waste within the framework of the circular economy. Regarding the last point, Manjudevi *et al.* (2024) emphasize that the recovery of fish scales aligns naturally with these principles, transforming a waste product from the fishing industry into a useful input for environmental remediation.

2. MATERIALS AND METHODS

2.1. Search strategy

To conduct this systematic review, an exhaustive literature search was carried out in accordance with the guidelines of the PRISMA statement (Page *et al.*, 2021). Three scientific databases—Scopus, Web of Science, and ScienceDirect—were used to identify studies published between 2015 and 2026. All searches were performed using the following keywords in both Spanish and English: “fish scales”, “heavy metals”, and “adsorption”. These were combined with the Boolean operator “AND” to make the search more specific and restricted. The final search equation applied was: (“fish scales”) AND (“heavy metals”) AND (“adsorption”). In addition, manual searches were performed through Google Scholar and SciELO.

2.2. Selection criteria

The inclusion criteria established for this review were: a) Original research articles; b) Articles written in English or Spanish; c) Publications within the 2015–2026 period; and d) Studies that directly evaluated the efficacy of fish scales in heavy metal adsorption. On the other side, the exclusion criteria were defined as follows: a) Review papers or secondary sources; b) Articles unrelated to the main objective of the study; and c) Studies published outside the selected period. The article selection process began with the review of titles, keywords, and abstracts (screening), which was carried out independently by two authors. The initial search retrieved a total of 121 studies. After removing duplicates and performing a preliminary review of titles and abstracts, 58 potential articles were selected. Based on the inclusion and exclusion criteria, 44 studies were finally included in the analysis. The process of selecting studies is shown in Figure 1.

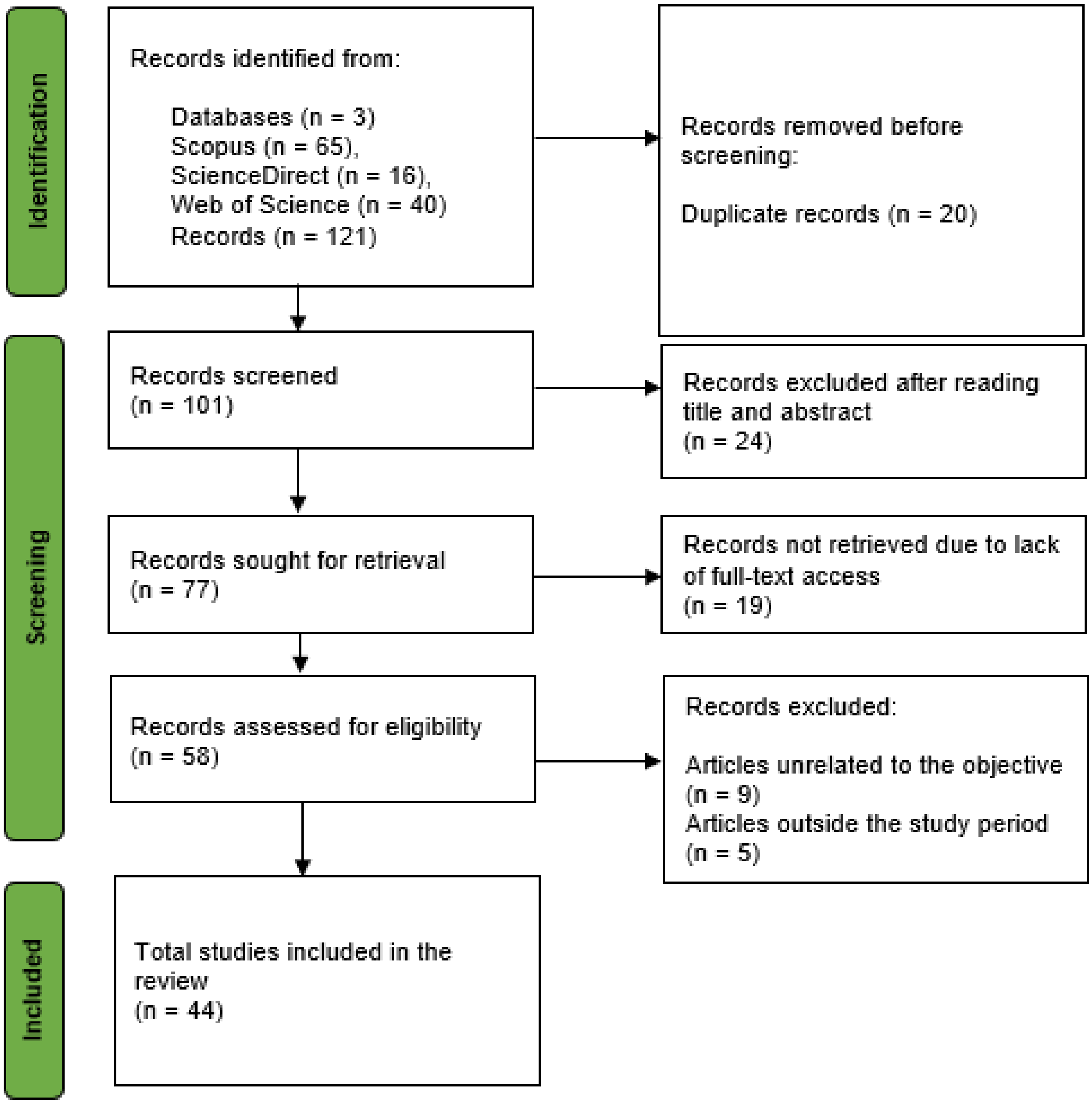

Figure 1. PRISMA Flow Diagram of this systematic review.

3. RESULTS AND DISCUSSION

3.1. Geographical area

To analyze the information by geographical area, the online tool MapChart (https://www.mapchart.net/) was used (Figure 2). Through visual representation with a map, it was identified that the country with the highest number of publications was India, with five, followed by Colombia and Nigeria, each with four. Next came Malaysia, Iran, and Peru, with three publications each; Ghana, Ethiopia, and Pakistan recorded two publications; while Taiwan, Sweden, Romania, Bangladesh, Morocco, Russia, Venezuela, Mexico, Turkey, Iraq, Indonesia, Serbia, Brazil, China, Croatia, and Botswana each accounted for one publication.

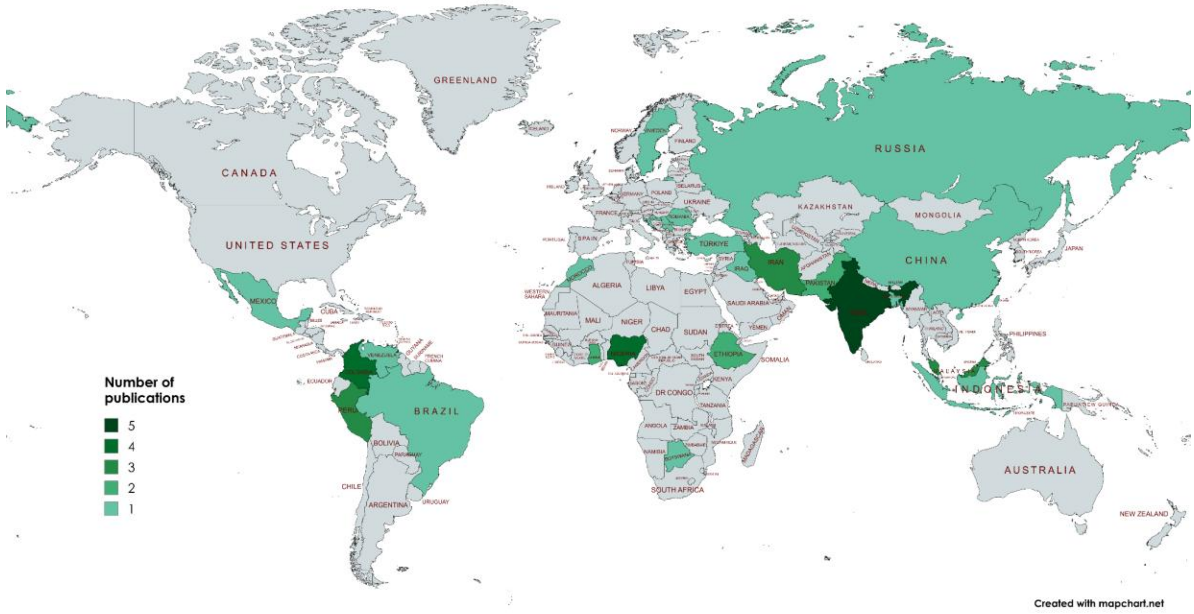

Figure 2. Number of publications identified by country.

3.2. Temporality

The data indicate that according to the Scopus database studies addressing this topic span from 1982 to 2026. The publication trend exhibits a positive and consistent increase over time, with a marked exponential growth in scientific production beginning in 2013. Furthermore, the years 2022, 2023, 2024, and 2025 recorded the highest number of publications, with 247, 318, 412, and 431 documents, respectively. Likewise, it was decided to take into account the progress of publications on the subject up to the current year, 2026. Figure 3 shows a comparison between the year of publication and the number of articles published.

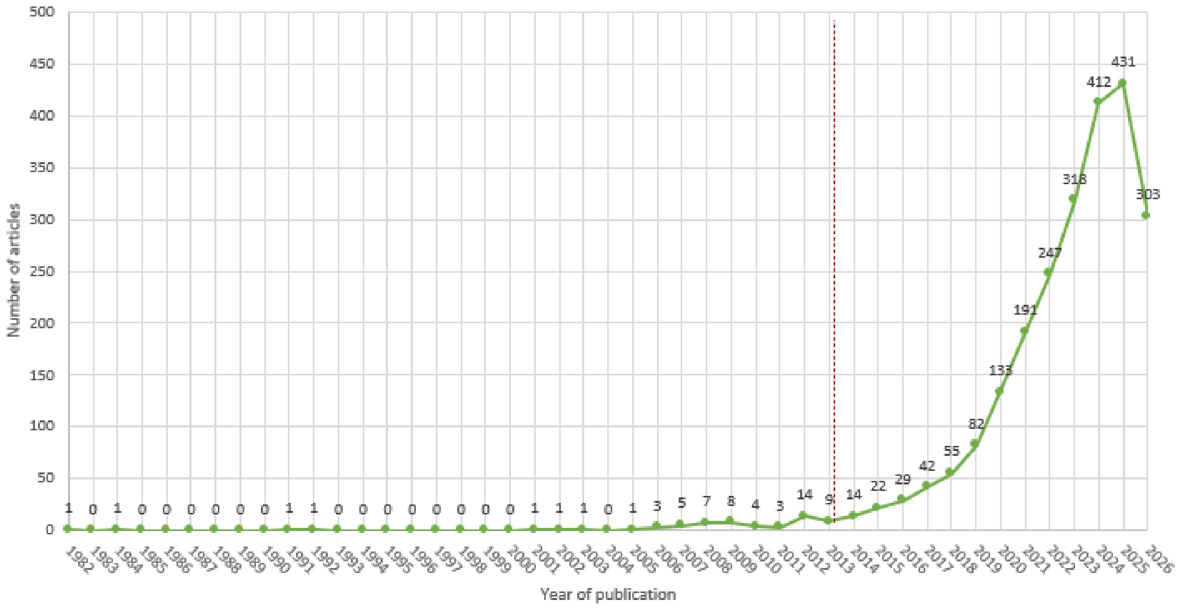

Figure 3. Number of articles by year of publication according to the Scopus database (1982–2026).

3.3. Composition of fish scales

The composition of fish scales—particularly those of carp species—is primarily made up of proteins, collagen, and connective tissues, coated with calcium salts. These scales represent a significant natural source of calcium phosphate in the form of HAp (Khalid *et al.*, 2021). The

HAp extracted from fish scales is considered non-toxic, bioactive, and biocompatible, making it highly suitable for environmental remediation applications (Khalid *et al.*, 2021). Furthermore, when the scales are converted into a magnetic bionanocomposite, they exhibit a spherical morphology with variable average diameters, which increases the specific surface area available for adsorption (Elmi *et al.*, 2018).

On the other hand, chitosan is a natural biopolymer that has been extensively investigated as both a coagulant and an adsorbent of heavy metals (Figure 4). It can be obtained from fish residues through extraction and deacetylation of chitin (Hernández *et al.*, 2025). Thus, the recovery of HAp and chitosan from fish waste not only embodies a circular economy approach—by reducing waste from the fishery industry—but also contributes to the development of new, sustainable, and efficient materials for environmental applications.

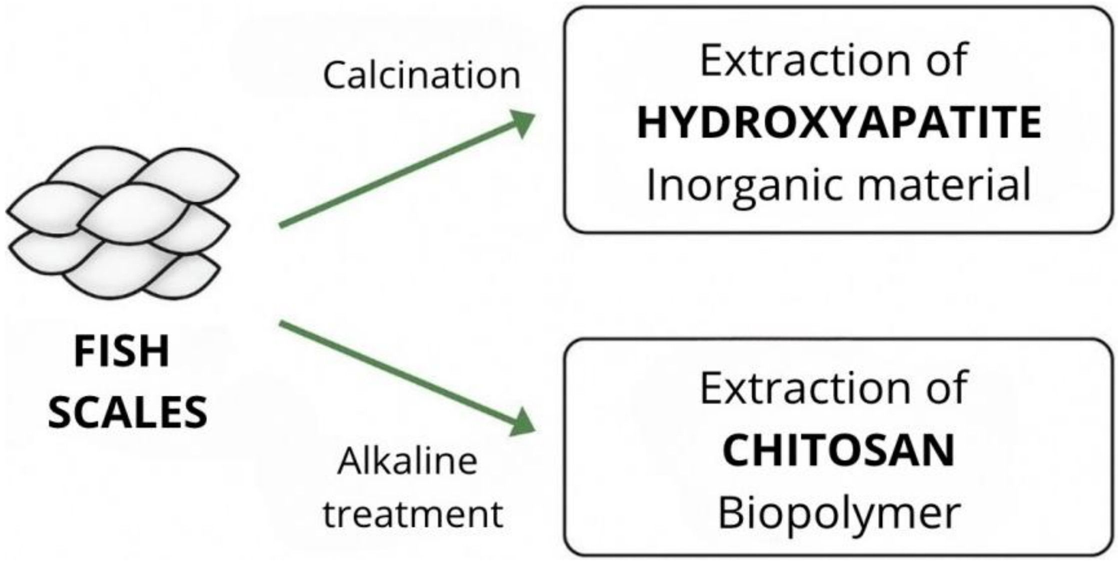

Figure 4. Derivatives obtained from fish scales.

3.4. Evaluation of fish scales from different species used in heavy metal adsorption

The use of fish scales as heavy metal adsorbents has become a topic of interest due to their high efficiency, low cost, and potential for reuse in various environmental applications. Several studies have been conducted on the adsorption capacity of scales from different fish species, emphasizing the importance of parameters such as pH, dosage, and contact time to achieve optimal removal of contaminants from wastewater (Table 1). For instance, Kwaansa-Ansah *et al.* (2019) reported that Nile tilapia *(Oreochromis niloticus)* has been widely studied for its ability to adsorb Cu, Mn, and Fe from polluted river waters, thereby validating its usefulness as a bioindicator of environmental contamination. Similarly, Othman *et al.* (2016) found that Mozambique tilapia *(Oreochromis mossambicus)* scales act as a cost-effective adsorbent for Zn and Fe in wastewater, achieving high removal rates under optimal experimental conditions. In Nigeria, croaker fish *(Micropogonias undulatus)* scales were introduced as a novel biosorbent, demonstrating higher adsorption capacities compared to the commonly used tilapia scales (Ighalo and Eletta, 2021). This broadens the potential use of different fish resources for wastewater treatment.

Additionally, species such as the rainbow trout *(Oncorhynchus mykiss)* have gained relevance, as they have been evaluated not only for the concentration of heavy metals in the water used for aquaculture but also for the presence of these metals in their tissues (De la Cruz, 2024). Another study conducted in Peru also analyzed this species to assess heavy metal levels in surface waters (González and Murga, 2020), reinforcing the importance of monitoring water quality in rivers and aquaculture production centers. Similarly, common carp *(Cyprinus carpio)* scales have shown high adsorption efficiency for Fe, Zn, and Mn from acid mine drainage waters, achieving percentages close to 100%. Even after desorption, these scales retain the ability to remove metal ions, although with lower performance (Damian and Varvara, 2022). Other less studied species, such as the Javelin grunter *(Pomadasys kaakan)* and the Indian carp *(Catla catla)*, have also shown successful adsorption results. The Javelin grunter can adsorb up to 95% of Cu^{2+} ions, while acid-treated Indian carp scales improved their adsorption properties for Cr^{3+} and Co^{2+} due to increased porosity and the presence of hydrophilic functional groups (Javad *et al.*, 2023; Sultana *et al.*, 2025). Likewise, species such as the European sardine (*Sardina pilchardus*) and the seabass *(Dicentrarchus labrax)* have also demonstrated significant adsorption capacity, achieving 88.2% Cd and 95% copper (Cu) removal, respectively (Jaafar *et al.*, 2021; Uzunoğlu and Özer, 2016).

Table 1. Fish species studied for the adsorption capacity of their scales.

Countries	Common name	Scientific name	Family	Authors
Ghana Malaysia Colombia	Nile tilapia (black tilapia)	*Oreochromis niloticus*	Cichlidae	Kwaansa-Ansah *et al.* (2019) Selimin *et al.* (2022) Lugo-Arias *et al.* (2026)
Nigeria	White corvina Striped croaker Shiny nose fish	*Genyonemus lineatus* *Micropogonias undulatus* *Polydactylus quadrifilis*	Sciaenidae Sciaenidae Polynemidae	Onwordi *et al.* (2019) Ighalo and Eletta (2021) Fadeiye *et al.* (2026)
Peru	Rainbow Trout Queen corvina	*Oncorhynchus mykiss* *Cynoscion albus*	Salmonidae Sciaenidae	De la Cruz (2024) De la Cruz (2026)
Turkey	Sea bass or robalo	*Dicentrarchus labrax*	Centropomidae	Uzunoğlu and Özer (2016)
India	Rohu	*Labeo rohita*	Cyprinidae	Pal and Maiti (2020)
Romania Serbia	Common carp	*Cyprinus carpio*	Cyprinidae	Damian and Varvara (2022) Bajić *et al.* (2025)
Morocco	Common sardine	*Sardina pilchardus*	Clupeidae	Jaafar *et al.* (2021)
Iran	Javelin grunter	*Pomadasys kaakan*	Haemulidae	Javad *et al.* (2023)
Iraq	Mesopotamian himri	*Barbus luteus*	Cyprinidae	Maktoof (2023)
Bangladesh Sweden	Indian carp	*Catla catla*	Cyprinidae	Fijol *et al.* (2020) Sultana *et al.* (2025)
Malaysia Taiwan Russia	Mozambique tilapia	*Oreochromis mossambicus*	Cichlidae	Othman *et al.* (2016) Liaw *et al.* (2020) Shaikhiev *et al.* (2020)
Pakistan	Masheer	*Tor putitora*	Cyprinidae	Bilal *et al.* (2024)
China	Pacific cod	*Gadus macrocephalus*	Gadidae	Dong *et al.* (2026)

3.5. Effectiveness of adsorption with fish scales in the removal of heavy metals

Several studies have demonstrated the efficiency of fish scales from different species in the adsorption of heavy metals, considering various control variables such as contact time, dosage, temperature, and pH (Table 2). According to Ighalo and Eletta (2020), maximum adsorption efficiencies of 96.45% for Zn^{2+} (145.5 min, 7.01 g L^{-1}, 30°C, pH 5.4) and 98.76% for Pb^{2+} (179.3 min, 6.61 g L^{-1}, 20°C, pH 3.4) were reported. Meanwhile, Stevens and Batlokwa

(2017) achieved 81.97% efficiency for Zn^{2+} and 80.37% for Pb^{2+}, optimizing the conditions to a pH of 7.52, adsorbent dosage of 76.99 mg, contact time of 62.37 min, and an initial concentration of 24.45 mg L^{-1}. Similarly, Selimin *et al.* (2022) obtained an adsorption efficiency of 61.43% for Cr^{6+} within 60 minutes using 6 g of HAp as the adsorbent.

Regarding adsorption capacity, Fijol *et al.* (2020) reported maximum values of 360.5 mg g^{-1} HAp for Cd^{2+} and 112.6 mg g^{-1} HAp for Pb^{2+}, attributed to mechanisms such as ion exchange, surface complexation, and coprecipitation. Likewise, Sultana *et al.* (2025) showed that acid-treated fish scales achieved removal efficiencies above 85% for Cr^{3+} and Co^{2+} under optimal conditions, highlighting the advantages of chemically modified materials with potential for sustainable and low-cost environmental applications.

Table 2. Efficiency of fish scales in the adsorption of heavy metals.

Heavy metals	Specie used	Adsorption capacity	Treatment system			Authors
			Contact time	Dosage	pH	
Copper (Cu^{2+})	*Dicentrarchus labrax*	95%	48 contact hours	1 g L^{-1}	3	Uzunoğlu and Özer (2016)
Lead (Pb^{2+}) and Zinc (Zn^{2+})	Does not specify	Pb: 80.37% Zn: 81.97%	62.37 min	76.99 mg L^{-1}	7.52	Stevens and Batlokwa (2017)
Lead (Pb^{2+})	*Genyonemus lineatus*	98%	150 min	0.858 mg g^{-1}	6	Onwordi *et al.* (2019)
Lead (Pb^{2+})	Does not specify	99%	120 min	20 g	-	Alli (2020)
Cadmium (Cd^{2+}) and Lead (Pb^{2+})	*Catla catla*	360.5 mg g^{-1} HAp for Cd 112.6 mg g^{-1} HAp for Pb	-	-	-	Fijol *et al.* (2020)
Zinc (Zn^{2+}) and Lead (Pb^{2+})	*Micropogonias undulatus*	Zn: 96.45% Pb: 98.76%	145.5 min 179.3 min	7.01 g L^{-1} 6.61 g L^{-1}	5.4 3.4	Ighalo and Eletta (2020)
Lead (Pb^{2+})	*Tilapia sp.*	100%	10 min	4% HAp	7	Omar *et al.* (2020)
Cadmium (Cd^{2+}) and Lead (Pb^{2+})	*Labeo rohita*	Cd: 87.90% Pb: 97.20%	120 min	1 g L^{-1}	$<$ 6.9	Pal and Maiti (2020)
Chromium (Cr^{3+})	Does not specify	99.75%	90 min	0.8 g	5	Teshale *et al.* (2020)
Cadmium (Cd^{2+})	*Sardina pilchardus*	88.20%	60 min	50 a 300 mg L^{-1}	3	Jaafar *et al.* (2021)
Chromium (Cr^{6+})	*Oreochromis niloticus*	61.43%	60 min	6 g HAp	5	Selimin *et al.* (2022)
Nickel (Ni^{2+}) and Copper (Cu^{2+})	*Pomadasys kaakan*	Ni: 82% Cu: 95%	120 min	20 g L^{-1} HAp	10 8	Javad *et al.* (2023)

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Lead (Pb^{2+})	*Tor putitora*	7.50%	30 min	-	9	Bilal *et al.* (2024)
Iron (Fe^{2+})	*Tilapia sp.*	99.82%	60 min	2 g	4	Ramadhini *et al.* (2024)
Arsenic (As^{5+}) and Chromium (Cr^{6+})	*Cyprinus carpio*	As: 92.61 mg g^{-1} Cr: 65.5 mg g^{-1}	90 min	1 mg	5.38	Bajić *et al.* (2025)
Lead (Pb^{2+}) and Cadmium (Cd^{2+})	*Tilapia sp.*	Pb: 83% Cd: 94%	90 min 120 min	0.4 g 1 g	4	Hernández *et al.* (2025)
Chromium (Cr^{3+}) and Cobalt (Co^{2+})	*Catla catla*	13.5 mg g^{-1} of Cr 11.8 mg g^{-1} of Co	-	-	-	Sultana *et al.* (2025)
Lead (Pb^{2+})	*Cynoscion albus*	21.88 mg g^{-1}	30 min	0.30 g	2	De la Cruz (2026)
Nickel (Ni^{2+}), Zinc (Zn^{2+}) and Copper (Cu^{2+})	*Polydactylus quadrifilis*	Ni: 87.0% Zn: 91.5% Cu: 98.2%	100 min 100 min 120 min	10 g	6 7 6	Fadeiye *et al.* (2026)

Figure 5 shows the different heavy metals analyzed using fish scales, with the adsorption of lead (Pb) being the most frequently investigated. The predominance of this metal in various studies is due to its persistence in the environment and its presence as a priority pollutant in water bodies (Bilal *et al.*, 2024). On the other hand, Cu has also been widely studied due to its industrial and agricultural use, since, in high concentrations, it can negatively affect aquatic life (Kwaansa-Ansah *et al.*, 2019; Jaafar *et al.*, 2021). There are few studies on Ni, Cd, Zn, Pb, Cr, Mn, and Co. Although studies with fish scales are still in their infancy, highly toxic metals such as Hg, which is present in mining effluents and capable of bioaccumulation, could be treated with this adsorption procedure using scales and be the subject of future research (Teshale *et al.*, 2020).

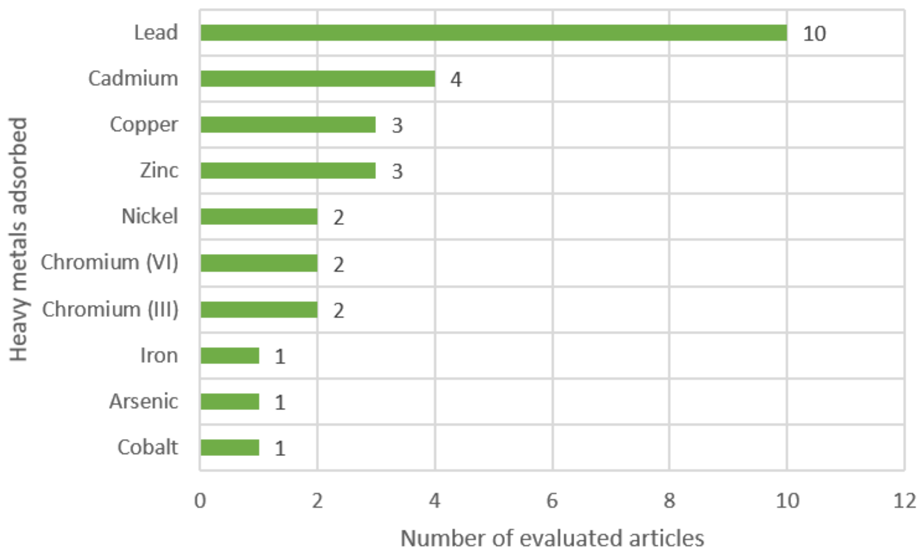

Figure 5. Number of articles evaluating the adsorption of different heavy metals using fish scales.

Once fish scales have adsorbed heavy metals, they become hazardous waste requiring proper disposal because of their high concentrations of these contaminants (Teshale *et al.*, 2020). The management of this waste can be complex, as it cannot be disposed of in the conventional manner due to the toxicity of the metals adsorbed (Duwiejuah *et al.*, 2024). Although using fish scales helps to reduce the amount of organic waste, they also have limitations and disadvantages that must be considered when choosing this adsorbent. Nevertheless, the best way to manage this waste would be, if feasible, to promote its recovery or, otherwise, its safe final disposal.

3.6. Benefits of using waste within the circular economy

Fish scale waste, when recycled within a circular economy framework, offers significant environmental and economic benefits. In this regard, transforming it into valuable products not only reduces resource waste but also generates greater value per unit weight of processed byproduct (Hublin *et al.*, 2024). In addition, this waste can be used to manufacture bioplastics from eco-friendly, economical, and natural materials, offering a viable alternative to highly polluting synthetic plastics (Surya *et al.*, 2023). For their part, Dong *et al.* (2026) highlight that the hierarchical structure and main components of fish scales—such as hydroxyapatite and collagen—possess excellent multifunctionality, which fosters the development of new materials and opens up broad prospects in environmental remediation, food, and agriculture. In summary, by converting waste that severely pollutes the ecosystem into useful materials, an environmentally beneficial effect is achieved, thereby consolidating a sustainable and circular model (Manjudevi *et al.*, 2024).

The use of fish scales combined with Neem leaves (*Azadirachta indica*) follows the principle of waste valorization and waste reduction through their reuse in new processes, such as adsorption, which is directly aligned with the core principles of the circular economy (Preetham and Vengala, 2021). Along these lines, several studies have highlighted the effectiveness of various natural residues—including fruit peels, agricultural by-products, fungi, dairy manure, and fish scales—as low-cost adsorbents (Shaikh, 2020). Fish scales, in particular, stand out for their high adsorption efficiency for heavy metals, thereby expanding the range of treatment alternatives for contaminants in different environmental contexts and promoting innovation in environmental technologies.

Moreover, recent research has confirmed the feasibility of biomass waste-based techniques, such as those using aloe vera (*Aloe vera*) or fish scales, to produce materials with adsorptive capacities suitable for heavy metal fixation (Guerra and Espinoza, 2025). Likewise, other studies have demonstrated that fish scales achieve faster adsorption of heavy metals compared to other biomass residues, reflecting greater efficiency and productivity in competitive environmental processes characterized by shorter processing times and lower treatment costs (Onwordi *et al.*, 2019). Additionally, it has been shown that fish scales transformed into biochar act as an effective, economical, and sustainable adsorbent for the removal of pollutants such as fluoride from wastewater, reaching removal efficiencies of up to 97.4% under optimal control parameters (Khandare and Mukherjee, 2019). This reinforces the idea that waste reuse is feasible and can significantly contribute to solving environmental problems, particularly in water decontamination.

Similarly, in Colombia, tilapia scales were identified as a source of chitosan, which has structural properties and crystallinity percentages superior to those of commercial chitosan, validating its potential as a biopolymer for industrial and environmental processes (Garcia *et al.*, 2016). Although adsorption based on other materials of biological origin, more specifically agro-industrial waste and/or residual biomass, remains an efficient alternative for the removal of heavy metals in wastewater (Tejada-Tovar *et al.*, 2015), the use of fish waste as part of adsorption processes that contribute to the circular economy is noteworthy.

Figure 6 shows the steps of a circular economy model using fish scales according to Selimin *et al.* (2022): (1) waste collection and selection, (2) waste pretreatment, (3) deproteinization, (4) alkaline treatment, (5) neutralization and pH adjustment, (6) drying and product recovery, (7) product application in water treatment, (8) evaluation and optimization, and (9) cycle closure and recovery. These steps demonstrate the potential of using fish scales in a circular economy approach to convert waste into valuable inputs for the treatment of contaminants such as heavy metals.

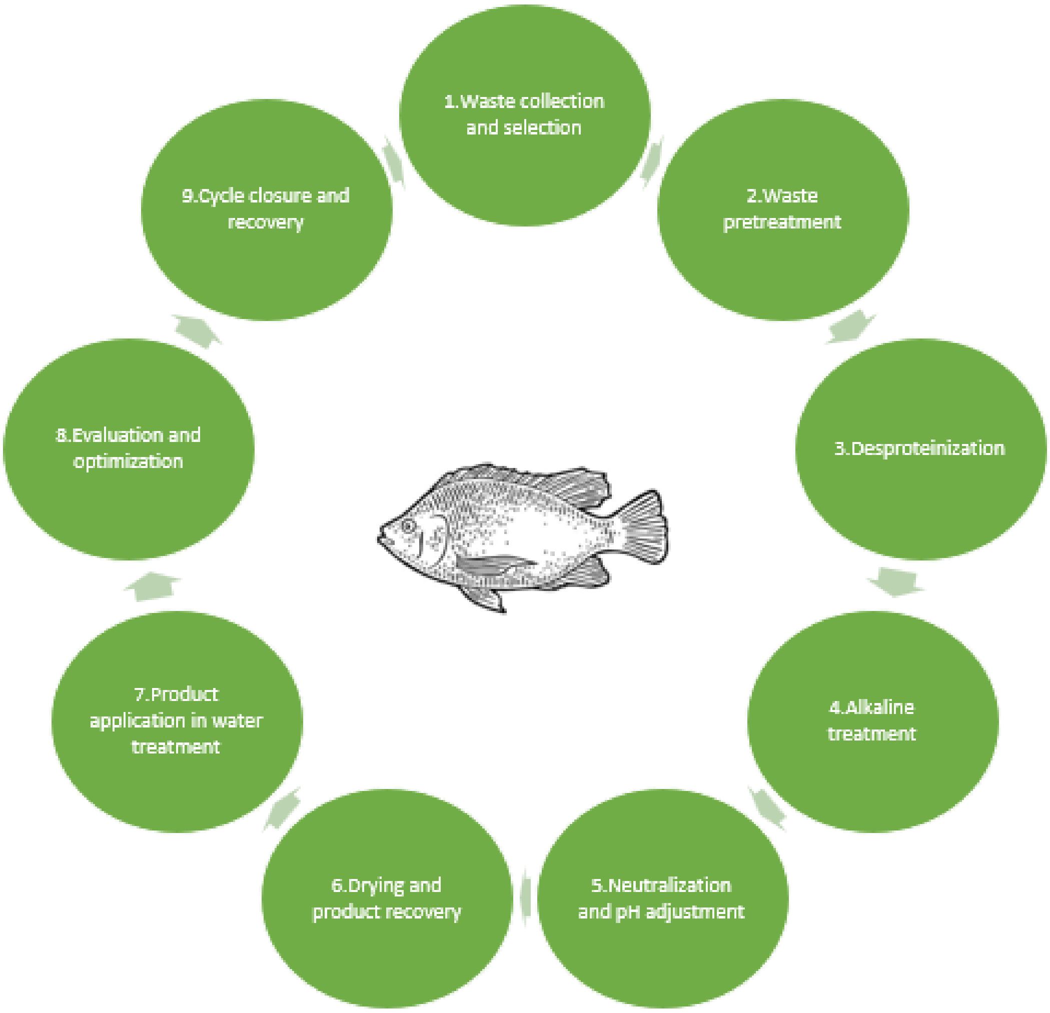

Figure 6. Steps of a circular economy model using fish scales.

4. CONCLUSIONS

Fish scales are rich in protein, collagen, and calcium salts, with hydroxyapatite being the main active component in heavy metal adsorption. This material is non-toxic, biocompatible, and has physicochemical properties that favor the capture of metal contaminants. In addition, the transformation of scales into magnetic bionanocomposites or their combination with other biopolymers, such as chitosan, significantly increases their effectiveness.

Various fish species have been evaluated as sources of scales for heavy metal adsorption, with tilapia (*Oreochromis niloticus and Oreochromis mossambicus*), common carp (*Cyprinus carpio*), corvina (*Micropogonias undulatus*), rainbow trout (*Oncorhynchus mykiss*), sardine (*Sardina pilchardus*), and sea bass (*Dicentrarchus labrax*) being the most commonly reported in the literature. The choice of species influences the effectiveness of the process, as the morphological and chemical characteristics of the scales vary between species.

With regard to adsorption capacity, high efficiency has been demonstrated in the removal of heavy metals such as lead, cadmium, chromium, zinc, and copper, achieving adsorption percentages of over 90% under optimal conditions of pH, dosage, and contact time. Chemical modification of the scales, such as acid treatment or the incorporation of hydroxyapatite, further improves their adsorption capacity, making them a viable alternative to conventional methods.

The use of fish scales as a heavy metal adsorbent is a clear example of waste recovery under the principles of the circular economy, as it transforms waste from the fishing industry into a useful resource for environmental remediation. This approach promotes sustainability by reincorporating materials into the production cycle, minimizing environmental impact, and promoting innovation in treatment technologies for wastewater management.

To corroborate these findings, it is recommended that research be conducted to evaluate the performance of fish scales under real-world wastewater treatment conditions resulting from various human activities. It would also be important to analyze their economic viability, their regeneration, and their safe final disposal once the scales are saturated with heavy metals.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

6. ACKNOWLEDGEMENTS

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