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Title:

"Green and Blue Nanotechnologies (Part I): Ecotoxicological Profile and Purifying Power in Experimental Aquaculture"

عنوان المشروع1275:مشروع مبتكر لإنتاج الأسماك والطحالب الدقيقة:مركز بحث و محطة تجريبية في جامعة سكيكدة لدعم الأمن الغذائي والاقتصاد الأزرق"

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Dedication

Note : the following dedication is written in Arabic as an expression of heartfelt gratitude in my native language.

بسم الله الرحمن الرحيم

قال تعالى:

"وَإِذْ تَأَذَّنَ رَبُّكُمْ لَئِن شَكَرْتُمْ لَأَزِيدَنَّكُمْ"

﴿إبراهيم: ٧﴾

وفي ختام هذه الرحلة العلمية التي تعاقبت .ويسّر لي طريقي، وأوصلني إلى ما أنا عليه اليوم بفضله ومنّه وعظيم عطائه فيها لحظات الكد والتعب، وتخللتها دروب الإصرار والعزيمة، أُهدي هذا العمل المتواضع إلى من كانوا لي خير معين، ونبع حنين، ورفاق يقين في كل حين

إلى أمي الحبيبة وأبي العزيز، نبض القلب، ونور الدرب، وعطر الحياة، على حبكما ودعمكما الذي لا يخبو له جود، وتشجيعكما الذي كان لي وقودًا في كل صعود

إلى صديقتَيَّ آية . إلى عائلتي الكريمة، التي كانت ولا تزال لي ظلًا وضياء، وسندًا في كل ابتلاء، وأمانًا في كل رجاء وإيمان، ومن ساندني ورافقني في مساري المهني او الدراسي، من الزملاء والزميلات، وعلى رأسهم فؤاد، صاحب الفضل والدعم الكريم، لكم مني جزيل الشكر ووافر التقدير. لقد كانت كلماتكم ومواقفكم النور الذي رافقني في أصعب اللحظات

أنا أقف هنا اليوم بفضلٍ من الله، ثم بفضل من آمن بي، وكذلك بفضل التحديات التي اعترضت طريقي، فهذّبتني، وقوّتني، ودفعتني لإتمام المسيرة بثباتٍ أشد، وأملٍ أبعد، وهدفٍ أوضح أُهدي هذا العمل المتواضع إلى كل من آمن بي، حتى في اللحظات التي شككتُ فيها بنفسي

Abstracts

Abstracts : French, English and Arabic

Intitulée : **" Nanotechnologies vertes et bleues (Partie I) : profil écotoxicologique et pouvoir épuratoire en aquaculture expérimentale".**

عنوان المشروع1275:مشروع مبتكر لإنتاج الأسماك والطحالب الدقيقة:مركز بحث و محطة تجريبية في جامعة سكيكدة لدعم الأمن الغذائي والاقتصاد الأزرق".

Spécialité : Ecotoxicologie Animale

Auteurs : **RAHMANI ASSIL**

Année : 2024-2025

Résumé

Ce travail s'inscrit au croisement de l'**écotoxicologie animale**, de la **biotechnologie verte** et de la **biotechnologie bleue**, avec pour ambition de créer une **station expérimentale et startup universitaire** dédiée à l'innovation durable en aquaculture. Deux formulations ont été testées chez le tilapia (*Oreochromis sp.*) : les **nanoparticules de zinc issues de *Moringa oleifera* (ZnO-NPs MOR)** et les **nanoparticules mixtes fer/zinc biosynthétisées à partir d'*Olea europaea* (Fe/Zn-NPs OLE)**.

L'expérimentation a été menée in vivo sur 120 individus de *Oreochromis* sp., répartis en trois régimes alimentaires pendant 8 semaines. Le groupe **ZnO-NPs (MOR)** a présenté la **meilleure performance de croissance**, avec un gain pondéral moyen de **38,9 ± 3,8 g** et un **SGR de 1,62 ± 0,11 % j^{-1}**. De son côté, le régime enrichi en **Fe/Zn-NPs (OLE)** a également montré des résultats remarquables, avec un gain pondéral moyen de **35,2 ± 3,9 g** et un **SGR de 1,52 ± 0,14 % j^{-1}**, surpassant nettement les valeurs obtenues chez les témoins (**27,4 ± 2,9 g**). **Les taux de survie ont été élevés chez les deux régimes enrichis par rapport aux témoins**, traduisant une bonne tolérance et confirmant le potentiel de ces formulations innovantes en aquaculture.

Nos résultats révèlent un **profil écotoxicologique sécurisant** confirmé par des **indices de risque (THQ et THQs)** inférieurs à 1 : *pour le fer*, chez l'adulte, **THQ Fe ≈ 0,02–0,03** et chez l'enfant **THQs Fe ≈ 0,005–0,02** ; *pour le zinc*, chez l'adulte **THQ Zn ≈ 0,03–0,05** et chez l'enfant **THQs Zn ≈ 0,004–0,03**, garantissant une consommation sans danger même pour les groupes sensibles. Côté **bioaccumulation**, les **facteurs de bioconcentration (FBC)** traduisent une absorption maîtrisée : *pour le fer*, **FBC Fe ≈ 6–33** contre plus de **200–400** chez le témoin ; *pour le zinc*, **FBC Zn ≈ 6–13**, bien régulés par ZnO-NPs (MOR).

Parallèlement, les deux traitements ont démontré un **pouvoir épuratoire remarquable** de l'eau d'élevage , les **ZnO-NPs (MOR)** régulent efficacement l'absorption du zinc tout en stabilisant la charge métallique de l'eau, alors que le régime à base de **Fe/Zn-NPs (OLE)** valorise surtout le **pouvoir épuratoire** : diminution spectaculaire des nitrates (**1,11 mg/l → 0,03–0,05 mg/l**) et des nitrites (**0,58 mg/l → 0,017–0,027 mg/l**), stabilisation du **pH ≈ 7–7,43**, baisse des **matières en suspension (MES)** et des **solides dissous totaux (TDS)**, et légère hausse de l'**oxygène dissous** (**+0,2–0,3 mg/l**), essentielle au bien-être des poissons.

Cette étude souligne l'importance cruciale de la **dose**, cœur de la démarche en écotoxicologie, pour maximiser l'efficacité tout en préservant la sécurité. **En somme, ces résultats mettent en évidence le *double pouvoir* des nanoparticules vertes : d'une part, elles optimisent le profil écotoxicologique – illustré par des indicateurs tels que les THQ, THQs et FBC – garantissant ainsi une consommation sans risque, y compris chez les enfants ; d'autre part, elles améliorent significativement la qualité de l'eau d'élevage grâce à un effet clarifiant et purificateur durable.**

Dans la continuité, nous projetons de développer un **système intégré** associant **biofloc, photocatalyse et recyclage** au sein d'une station expérimentale pour soutenir l'**économie bleue et circulaire** et renforcer la sécurité alimentaire nationale.

Mots clés : Biotechnologie vertes, ZnO-NPs (MOR), Fe/Zn-NPs (OLE), Seuils écotoxicologie, FBC, THQ, FBC, biotechnologie bleue, Projet innovant et sécurité alimentaire.

Titled: **" Green and Blue Nanotechnologies (Part I): Ecotoxicological Profile and Purifying Power in Experimental Aquaculture"**

عنوان المشروع1275:مشروع مبتكر لإنتاج الأسماك والطحالب الدقيقة:مركز بحث و محطة تجريبية في جامعة سكيكدة لدعم الأمن الغذائي والاقتصاد الأزرق".

Speciality : Animal Ecotoxicology

Authors: **RAHMANI ASSIL**

Year: 2024-2025

Summary

This work lies at the intersection of animal ecotoxicology, green biotechnology and blue biotechnology, aiming to launch an **experimental station and university startup dedicated to sustainable aquaculture innovation**. Two nanoparticle formulations were evaluated on tilapia (*Oreochromis* sp.): zinc oxide nanoparticles synthesized from *Moringa oleifera* (ZnO-NPs MOR) and mixed iron/zinc nanoparticles biosynthesized from *Olea europaea* (Fe/Zn-NPs OLE).

The in vivo trial involved 120 fish divided into three diets over 8 weeks. The ZnO-NPs (MOR) group achieved the highest growth performance (**38.9 ± 3.8 g**, SGR **1.62 ± 0.11 % day^{-1}**), while the Fe/Zn-NPs (OLE) group also performed strongly (**35.2 ± 3.9 g**, SGR **1.52 ± 0.14 % day^{-1}**), both surpassing the control (**27.4 ± 2.9 g**). Survival rates were high in both enriched diets, confirming good tolerance and potential for sustainable use.

Ecotoxicological safety was confirmed by risk indices well below critical thresholds: **THQ Fe ≈ 0.02–0.03 (adults); THQs Fe ≈ 0.005–0.02 (children); THQ Zn ≈ 0.03–0.05 (adults); THQs Zn ≈ 0.004–0.03 (children)** — ensuring safe consumption even for sensitive populations. Bioaccumulation data supported these findings, with controlled bioconcentration factors (**FBC Fe ≈ 6–33** vs. > 200–400 in controls; **FBC Zn ≈ 6–13**) thanks to the regulating effect of ZnO-NPs (MOR).

Beyond ecotoxicology, both treatments demonstrated a **remarkable water purifying power**: ZnO-NPs (MOR) efficiently regulated zinc levels and stabilized overall metal load in water, while Fe/Zn-NPs (OLE) showed greater purification effects, reducing nitrates (**1.11 mg/l → 0.03–0.05 mg/l**), nitrites (**0.58 mg/l → 0.017–0.027 mg/l**), lowering suspended solids (**MES**) and total dissolved solids (**TDS**), stabilizing pH (**≈ 7–7.43**) and slightly increasing dissolved oxygen (**+0.2–0.3 mg/l**), which is crucial for fish health.

Overall, these results highlight the **dual effect** of green nanoparticles: (1) optimizing the ecotoxicological profile (THQ, THQs, FBC) for safer consumption even by children; and (2) significantly improving water quality through clarifying and purifying action. Importantly, this study also emphasizes **the critical role of dosage** in balancing efficacy and safety — a core principle in ecotoxicology.

Looking ahead, the project plans to integrate **biofloc systems, photocatalysis and recycling technologies** into an experimental station to reinforce the **blue and circular economy** and enhance national food security.

Keywords: Green nanoparticles; ZnO-NPs (MOR); Fe/Zn-NPs (OLE); Ecotoxicological thresholds; FBC; THQ; Bioaccumulation; Blue biotechnology; Circular economy; Food safety.

العنوان:" التقنيات النانوية الخضراء والزرقاء (الجزء الأول): الملف الإيكوتوكسيكولوجي والقدرة التنقية في تربية الأحياء المائية التجريبية ".
عنوان المشروع 1275 :مشروع مبتكر لإنتاج الأسماك والطحالب الدقيقة:مركز بحث و محطة تجريبية في جامعة سكيكدة لدعم الأمن الغذائي والاقتصاد الأزرق".
تخصص : علم السموم البيئية الحيوانية
المؤلف :رحماني أسيل
السنة الجامعية :2024–2025

ملخص

يندرج هذا العمل في تقاطع الإيكوتوكسيكولوجيا الحيوانية والتكنولوجيا الحيوية الخضراء والتكنولوجيا الحيوية الزرقاء، بهدف إنشاء محطة تجريبية وشركة ناشئة جامعية مخصّصة للابتكار المستدام في مجال تربية الأحياء المائية. تم تقييم تركيبتين نانويتين على أسماك البلطي (*Oreochromis* sp.): جسيمات نانوية من أكسيد الزنك مشتقة من *Moringa oleifera* (ZnO-NPs MOR)، وجسيمات نانوية مختلطة من الحديد/الزنك مصنعة بيولوجيًا من *Olea europaea* (Fe/Zn-NPs OLE).

أُجريت التجربة الحية على 120 سمكة موزّعة على ثلاثة أنظمة غذائية لمدة 8 أسابيع. أظهر نظام ZnO-NPs (MOR) أفضل أداء للنمو **3.8 ± 38.9**) غ، **/% 0.11 ± 1.62 SGRيوم**(، بينما سجّل نظام Fe/Zn-NPs (OLE) نتائج قوية أيضًا **3.9 ± 35.2**) غ، **/% 0.14 ± 1.52 SGRيوم**(، متفوقَين بشكل ملحوظ على المجموعة الشاهدة (**2.9 ± 27.4**) غ . كما سجّلت معدلات بقاء عالية في المجموعتين المعززتين، مما يؤكد تحمّلاً جيدًا وإمكانية استخدام مستدامة.

تُظهر مؤشرات الخطر نتائج دون العتبات الحرجة، بما يعكس سلامة إيكوتوكسيكولوجية مؤكَّدة: **THQ Fe ≈ 0.02–0.03(للبالغين)؛ THQs Fe ≈ 0.005–0.02 (للأطفال)؛ THQ Zn ≈ 0.03–0.05 (للبالغين)؛ THQs Zn ≈ 0.004–0.03)للأطفال**، مما يضمن الاستهلاك الآمن حتى للفئات الحسّاسة. كما دعمت بيانات التراكم الحيوي هذه النتائج بفضل عوامل التركيز الحيوي (FBC) المضبوطة **FBC Fe ≈ 6–33** :مقابل 200–400< في الشاهد، و **FBC Zn ≈ 6–13**بفضل دور ZnO-NPs (MOR) التنظيمي.

وعلى صعيد جودة المياه، أظهرت التركيبتان قدرة ملحوظة على التنقية: نظّم نظام ZnO-NPs (MOR) تركيزات الزنك واستقرّت الحمل المعدني الكلي للمياه، بينما امتاز نظام Fe/Zn-NPs (OLE) بتأثير تطهيري أكبر، حيث خفّض بشكل ملحوظ تركيزات النترات (**1.11 ملغ/ل → 0.03–0.05 ملغ/ل**) والنتريت (**0.58 ملغ/ل → 0.017–0.027 ملغ/ل**، وقلّل من المواد العالقة الكلية (**MES**) والمواد الصلبة الذائبة الكلية(**TDS**) ، مع تثبيت قيمة **pH ≈ 7–7.43** وزيادة طفيفة في الأكسجين الذائب (**+0.2–0.3) ملغ/ل** وهو ما يُعدّ بالغ الأهمية لصحة الأسماك.

تسلّط هذه النتائج الضوء على **الدور المزدوج** للجسيمات النانوية الخضراء: (1) تحسين الملف الإيكوتوكسيكولوجي (THQ، THQs، FBC)لضمان استهلاك آمن حتى للأطفال؛ و(2) تحسين كبير في جودة مياه التربية بفضل تأثيرها المُنقّي والمُصفّي. كما تؤكد الدراسة على أهمية تحديد **الجرعة** بدقة لتحقيق التوازن بين الفعالية والسلامة، وهو جوهر تخصص الإيكوتوكسيكولوجيا.

وفي المستقبل، يخطط المشروع لإدماج أنظمة **البيوفلوك** والتقنيات الحديثة مثل **التحفيز الضوئي وإعادة التدوير** ضمن محطة تجريبية لدعم الاقتصاد الأزرق والدائري وتعزيز الأمن الغذائي الوطني.

الكلمات المفتاحية :التقنيات النانوية الخضراء؛ZnO-NPs (MOR)؛ Fe/Zn-NPs (OLE) ؛ حدود الإيكوتوكسيكولوجيا؛FBC ؛THQ ؛ التكنولوجيا الزرقاء؛ الاقتصاد الدائري؛ الأمن الغذائي.

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Général Introduction

1. General context: aquaculture, animal health and water pollution

In recent years, aquaculture has garnered increasing interest across numerous disciplines due to its essential role in providing access to healthy and nutritious food, especially in developing countries, and its potential to ensure food security amidst a continuously increasing global population (Igwegbe et al., 2021).

Fish serves as an excellent source of high-quality protein, as well as vitamins and minerals, elements that are often deficient in carbohydrate-based diets, which are predominant in many parts of the world. Its regular consumption therefore represents a major asset for human health (de Oliveira Sartori & Amancio, 2012).

To illustrate the growing importance of the aquaculture industry, the Food and Agriculture Organization of the United Nations (FAO) reported in 2020 that global aquaculture production increased by 527% between 1990 and 2018, reaching a record high of 114.5 million tonnes (Pauly & Zeller, 2017). In addition to its nutritional benefits, aquaculture also serves as a major economic lever, generating considerable export revenue for many countries. According to the FAO (2020) report, direct revenue from aquaculture farm sales reached USD 263.6 billion (Pauly & Zeller, 2017).

China, the world's largest producer of fish and fishery products since 2002, generated USD 21.7 billion in export revenues from aquaculture production in 2018 (Guggisberg, 2021). Brazil, ranked 14th in the world with an annual production of around 563,000 tonnes, generated USD 1.6 billion in export revenues in 2018 (Pauly & Zeller, 2017; Coldebella et al., 2018).

These data highlight the strategic importance of aquaculture, both for human health and for the economic development of nations.

However, this high productivity is accompanied by growing concerns about the environmental impact of aquaculture, particularly through the generation of effluents in aquatic environments and the discharge of wastewater from farming systems. **(Fig. 1)** (Ighalo et al., 2020).

These discharges are generally characterized by a high organic load, originating from uneaten food, pesticide residues, as well as human waste, which leads to an alteration of the physicochemical parameters of the water and contamination by substances of anthropogenic origin (Coldebella et al., 2018; Iwuozor & Gold, 2018; Zhul-quarnain et al., 2018; Iwuozor, 2019).

The physicochemical characteristics of fish farm waters play a decisive role in the growth, health, and productivity of fish. Beyond these impacts, these discharges can also contain trace metals, persistent organic matter such as polychlorinated biphenyls (PCBs), herbicides, and polycyclic aromatic hydrocarbons (PAHs), which contribute to the chronic pollution of aquatic environments and pose a significant ecological and health risk.

Polycyclic aromatic hydrocarbons (PAHs), derived from multiple anthropogenic sources, are introduced into aquatic ecosystems where they can be bioaccumulated by aquatic organisms (Abbassy, 2018). These compounds have a cumulative effect in trophic chains and can ultimately reach human consumers through the consumption of contaminated fish.

It is therefore essential to maintain water quality at optimal levels, as defined by the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO), in order to reduce the risks associated with hazardous substances in aquatic ecosystems and, at the same time, optimize aquaculture productivity (AG et al., 2013).

In a context of rapid population growth, scarcity of freshwater resources and climate change, it is becoming increasingly difficult to increase the supply of freshwater required for inland aquaculture (Amin et al., 2014). This makes it essential to treat polluted aquatic environments in order to eliminate anthropogenic substances and restore physicochemical conditions that meet standards, ensuring the health of aquatic organisms and human food safety.

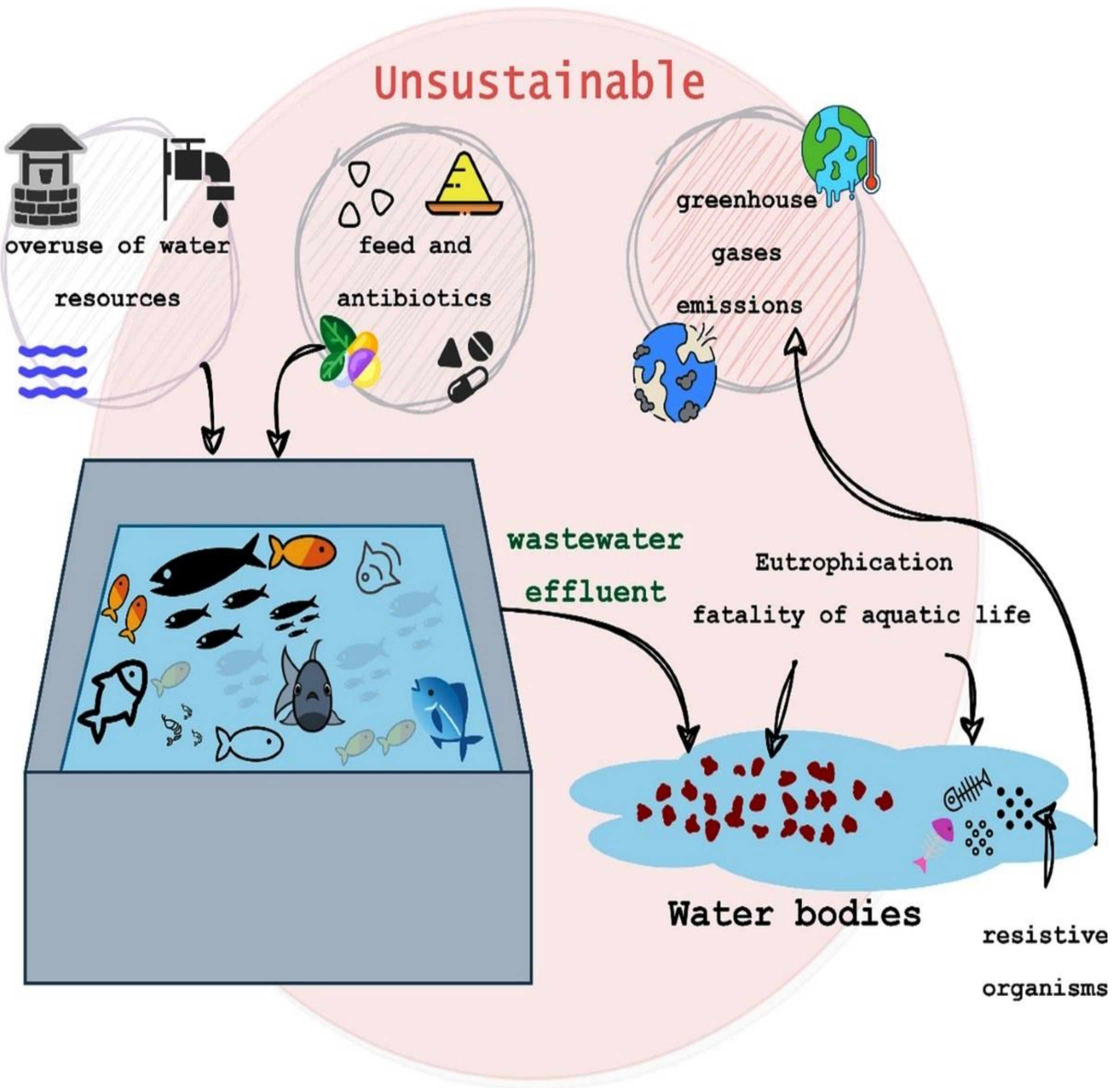

Figure 1. Impact of aquaculture effluents on the aquatic environment (after Jegatheesan et al., 2011).

Traditional methods of treating aquaculture effluents (activated carbon, activated sludge, reverse osmosis, etc.) often prove ineffective in the face of the emergence of organic and anthropogenic micro-contaminants. In addition, increasingly stringent health requirements and the shortage of quality water require the development of innovative, more efficient and sustainable solutions (Amin et al., 2014).

In this context, nanomaterials have demonstrated strong potential as cost-effective and efficient water treatment technologies for new applications in aquaculture (Bolong et al., 2009; Bottero et al., 2006). Thanks to their unique physicochemical properties (high specific surface area, increased reactivity, sorption capacities), nanoparticles offer promising prospects to address the complexity of pollution encountered in aquaculture systems.

Thus, in this study, we review the scientific literature published over the last decade regarding the most promising nanoparticles for the effective treatment of aquaculture effluents. We also address the toxicity issues associated with some of these nanoparticles and the strategies proposed in the literature to control their risks and promote their safe and sustainable application in aquaculture.

2. Towards a green synthesis: sustainability and innovations

Nanotechnologies now occupy a central position in contemporary scientific research, due to their potential for innovation in various fields such as electronics, medicine, catalysis, cosmetics, water purification and environmental protection (Sharma et al., 2019). At the heart of this revolution are nanoparticles (NPs), materials whose physicochemical properties are radically modified at the nanometric scale. Their small size (<100 nm), large specific surface area and increased reactivity give them unique characteristics, which closely depend on their size, morphology, crystallinity and composition.

Among the most studied nanomaterials, zinc oxide nanoparticles (ZnO-NPs) and silver nanoparticles (AgNPs) occupy a prominent place.

ZnO-NPs, wide bandgap (3.37 eV) and high excitation energy (60 meV) semiconductors, exhibit high thermal and chemical stability, as well as remarkable optical and photocatalytic properties, which make them prime candidates for applications ranging from sensors to antimicrobial materials (El-Rafie et al., 2012; Bhuyar & Ganeshan, 2017).

AgNPs, on the other hand, are distinguished by their potent antimicrobial properties, high electrical conductivity, plasmonic activity, and ability to interact effectively with a wide range of microorganisms, even at very low concentrations.

Their effectiveness against antibiotic-resistant bacteria makes AgNPs promising agents in the medical, pharmaceutical, and environmental fields (Rai et al., 2009).

In the interest of sustainability and reducing environmental impacts, the green synthesis of nanoparticles, using plant extracts, is emerging as an innovative alternative to conventional chemical methods, which are often costly and polluting. These processes, carried out at room temperature and without toxic solvents, make it possible to obtain stable, functional NPs compatible with biomedical or environmental uses (Sathishkumar et al., 2009; Vijayakumar et al., 2015).

Plant extracts are now widely used in aquaculture as natural feed supplements to stimulate growth, enhance immunity, and mitigate the toxic effects of nanoparticles (NPs) (Sathishkumar et al., 2009). In particular, nanoparticles biosynthesized from plant extracts are distinguished by their porosity, stability, and ability to effectively penetrate target cells, thus contributing to enhancing the antioxidant and immune status of fish (Rai et al., 2009).

Green synthesis of nanoparticles (NPs) is an emerging research trend in the field of sustainable nanotechnology, due to its numerous advantages: it is non-toxic or low-toxic, environmentally friendly, efficient, and economically advantageous compared to conventional physicochemical methods (Bhatia et al., 2023; Hossain et al., 2021). This approach is based on the use of biological agents such as plants, bacteria, algae, or fungi. Among these agents, plants currently occupy a prominent place in research on green synthesis of NPs, attracting increasing attention from scientists around the world (Tshikhudo et al., 2022).

A wide variety of biosynthesized nanoparticles are currently used in wastewater treatment, due to their high efficiency, biocompatibility, and ability to degrade organic pollutants while maintaining good physicochemical stability (Mohamed et al., 2024). These green NPs are particularly effective for recycling and removing heavy metals from effluents, thus enabling water purification for reuse—a key issue in the sustainable management of water resources on a global scale (Nasrollahzadeh et al., 2021; Roy et al., 2022).

However, the regeneration and reusability of these nanoparticles remain major challenges, particularly for the technological transfer from laboratory scale to industrial applications (Bano et al., 2023). This project is part of this dynamic, exploring the potential of nanoparticles from local plants such as *Moringa oleifera* (ZnO-NPs) and olive leaves (Fe/Zn NPs) both as immunostimulatory feed additives and as bioactive agents for the treatment of aquaculture water.

3. Important parameters of aquatic ecosystems

Water contamination in aquaculture ponds comes mainly from two sources: natural activities and anthropogenic activities. Natural sources mainly include fish metabolism and uneaten food leftovers. On the other hand, the use of agricultural chemicals such as fertilizers and pesticidesrepresentsthe main anthropogenic source of pollution in aquatic environments (Perera et al., 2016).

Pollutants introduced into water bodies include heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and various pesticides (Abbassy, 2018). In addition to these contaminants, several physicochemical parameters of fish pond water are considered in water quality assessment procedures, including: pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), turbidity, water hardness, total organic matter (TOM), extractable organic matter, as well as nitrate and phosphate content (Ighalo and Adeniyi, 2020).

These factors play a determining role in pond productivity and fish growth (Olaifa et al., 2004). In addition, concentrations of microbiological pollutants, such as Escherichia coli, Salmonellae, Staphylococcus aureus, are also significant, especially in ponds located near sewage systems. Indeed, these bacteria can cause infections (diarrhea, wound infections, etc.) following the consumption of contaminated fish, as reported by Kebus et al. (1992).

In the following subsections, these parameters will be addressed categorically, emphasizing their importance for aquatic biocenosis as well as the recommended standardized limits.

The ‘One Health‘ approach applied to aquatic ecosystems highlights the close interconnection among human health, the health of aquatic organisms, and the environmental health (Destoumieux-Garzón et al., 2018; Atlas & Maloy, 2014). In this context, the growing demand for quality water, combined with organic pollution of aquatic environments, represents a major challenge for sustainable development. According to the perspectives of One Health and the United Nations Sustainable Development Goals (SDGs), the preservation of aquatic ecosystems constitutes a fundamental pillar of environmental sustainability (FAO, 2022; United Nations, 2015).

Aquaculture, considered one of the fastest growing and most traded food sectors globally, is expected to become the main source of aquatic protein for humanity by 2050 (Béné et al., 2015). However, this rapid expansion raises environmental concerns related to aquaculture effluents discharged into receiving ecosystems (Boyd et al., 2020).

Despite these concerns, the undeniable benefits of aquaculture , particularly in terms of massive food production and economic benefits,have prompted the scientific community to develop innovative and sustainable strategies aimed at mitigating the negative effects of this activity, rather than limiting its development (Avnimelech, 2006; Tilley et al., 2014).

Unsustainable practices in aquaculture include the excessive use of commercial feeds, the intensive use of chemicals, drugs, and antibiotics, as well as the excessive use of organic and inorganic fertilizers. This is compounded by the accumulation of fish metabolic waste, the decomposition of dead fish, and uneaten feed, leading to significant pollution of aquatic ecosystems (El-Sayed et al., 2021; Mungkung et al., 2022).

Aquaculture effluents are currently considered a major source of pollution. They introduce high concentrations of nitrogen, phosphorus, and suspended solids, along with emerging contaminants such as heavy metals and antibiotic resistance genes into aquatic environments (Ahmad et al., 2024). Without adequate treatment, these effluents pose a serious threat to biodiversity, human health, and the sustainability of aquatic ecosystems (Gupta et al., 2023).

Aquaculture effluents represent a major point source of pollution, particularly due to their high content of nitrogenous wastes (total ammonia nitrogen, nitrites and nitrates), total phosphorus, chemical oxygen demand (COD) and pathogens, which has significant negative effects on water quality and, consequently, endangers the survival of aquatic organisms in natural environments (Gupta et al., 2023; Mungkung et al., 2022).

Dissolved wastes originate from fish metabolic processes or from the decomposition of uneaten feed. The two main compounds of concern in these dissolved wastes are nitrogen (N) and phosphorus (P) (El-Sayed et al., 2021). Among them, ammonia represents a critical pollutant in fish culture waters, particularly in its un-ionized form (NH_3), which is highly toxic to fish, both in the culture system and in the receiving environments if not treated before discharge (Ahmad et al., 2024).

Phosphorus, another metabolite or breakdown product of aquaculture feed, is poorly utilized by fish. Although non-toxic to farmed species, its release into the environment can enrich natural aquatic environments with nutrients and promote eutrophication, depending on the concentration, frequency of release, and size of the receiving water body (Mungkung et al., 2022; Gupta et al., 2023).

Aquaculture effluents are generally discharged into natural aquatic environments; thus, their disposal by environmentally friendly and efficient methods has become essential. In this context, nanomaterials are increasingly used to address major water and wastewater challenges. The term “nanomaterial” refers to materials at the nanoscale, with one nanometer being equivalent to one billionth of a meter (Zhang et al., 2021; Khan et al., 2022).

The use of nanoparticles (NPs) for pollutant reduction has experienced remarkable growth in recent decades. Due to their extremely small size, high reactivity, and catalytic properties, nanoparticles are considered particularly effective agents for the remediation of contaminated water (Li et al., 2023).

Nanoremediation is an innovative remediation technique based on the use of nanomaterials to remove or neutralize pollutants in the environment. These nanoremediation approaches can provide sustainable solutions to environmental pollution problems and significantly reduce the economic costs associated with the remediation of contaminated sites (Ahmed et al., 2022; Li et al., 2023).

3.1. Physicochemical parameters

As mentioned earlier, pH is one of the main classes of water quality parameters. It is a measure of the concentration of hydrogen ions ($[H^+]$) in an aquatic environment. Problems with water pH are generally not due to the water source, but rather to processes occurring during aquaculture (Zweig et al., 1999).

It is essential to control this variable, as it influences many biological and chemical processes within the aquatic environment (Amankwaah et al., 2014). In the case of inland aquaculture, regulatory agencies recommend a pH range between 6.5 and 8.5, which is considered optimal for the health and growth of aquatic organisms (Svobodová, 1993).

The dissolved oxygen (DO) content of an aquatic ecosystem is indicative of the water temperature and the amount of oxygen available to aquatic organisms. Indeed, the solubility of oxygen decreases with increasing temperature and salinity, and vice versa (Chapman, 1996). Therefore, this parameter also reflects the physical and biological processes taking place in the biocenosis. The recommended value for dissolved oxygen is greater than or equal to 5 mg/L (Abbassy, 2018).

Biological oxygen demand (BOD) measures the total amount of dissolved oxygen consumed by microorganisms for the biodegradation of organic matter (such as food particles or wastewater) (Bhatnagar and Devi, 2013). This reflects both the organic and microbial load of the environment. For freshwater aquaculture systems, optimal BOD values are between 2 and 4 mg/L (Chapman, 1996).

Chemical oxygen demand (COD) is a measure of the total oxygen equivalent of organic matter present in the aquatic biotope that can be chemically oxidized by a strong oxidant such as dichromate (Chapman, 1996). According to the World Health Organization (WHO) recommendations for aquaculture, COD should be maintained in a range of 20 to 100 mg/L.

Electrical conductivity (EC) reflects the ability of water to conduct electricity, which is highly dependent on its dissolved salt content. The optimal range for aquaculture is 100–2000 µS/cm (Stone and Thomforde, 2004).

Total dissolved solids (TDS) is the concentration of inorganic salts, organic compounds, and other substances dissolved in water (Weber-Scannell and Duffy, 2007). Traditional water purification methods, such as filtration, are generally effective in reducing TDS. According to Saleh, cited by Abbassy (2018), the desirable range for TDS in freshwater aquaculture is between 500 and 1000 mg/L.

3.2. Heavy metals

Living organisms require certain essential metals for metabolism and the proper functioning of enzymatic processes, and aquatic organisms are no exception to this rule.**(Tab.1)**. For example, copper (Cu), iron (Fe), and zinc (Zn) are essential elements for fish metabolism. In contrast, other metals such as mercury (Hg), cadmium (Cd), arsenic (As), and lead (Pb) have no known biological function (Has-Schön et al., 2008).

These metals, even essential ones, are only required in minute (trace) amounts, and excess can be toxic to the aquatic ecosystem, affecting both fish and other aquatic life (Kingsley Ogemdi, 2019; Iwuozor, 2018; Iwuozor et al., 2021; Ogunlalu et al., 2021; Paul et al., 2019). The toxic effects of heavy metals can include growth retardation, physiological disorders, increased mortality, and reproductive problems in fish (Ebrahimi and Taherianfard, 2011).

For example, Paul et al. (2019) reported that exposure of fish to lead nitrate causes overt genotoxicity as well as histopathological alterations, including gill swelling, lamellae degeneration, liver lesions (damaged hepatocytes), and enlargement of the Bowman's capsule space.

It is therefore essential to maintain the concentration of these metals within the permissible limits for inland water aquaculture systems. Thanks to their small size, large specific surface area and high adsorption properties, nanoparticles (NPs) and nanocomposites are particularly suitable for heavy metal remediation.

Table 1. *Maximum permissible limit values of metals (WHO / US EPA / FAO).*

Metal	***Maximum concentration (µg/L)***	***Remarks***
Arsenic (As)	100	Very toxic, no biological role
Cadmium (Cd)	<1.1	Highly toxic even at low doses
Chromium (Cr)	100	Toxicity by form (Cr(III) vs Cr(VI))
Copper (Cu)	2000	Essential in traces, toxic in excess
Iron (Fe)	300	Essential, but precipitates at pH >7
Nickel (Ni)	<100	May interfere with cellular enzymes
Lead (Pb)	<3.2	Genotoxic, bioaccumulative
Zinc (Zn)	5000	Essential in traces, but irritating in excess

Note: The value of 300 µg/L for iron (Fe) is based on WHO (2011) recommendations for drinking water and freshwater aquaculture practices. Excess iron can affect turbidity and oxygenation, although less toxic than Cd or Pb.

3.3.Biological contaminants

Continental aquatic ecosystems naturally harbor indigenous microflora and microfauna, essential for maintaining ecological balance and the proper functioning of biogeochemical cycles. However, some of these microbial species can produce toxins or act as pathogens, thus altering the health of aquatic organisms. Of even greater concern are exogenous microorganisms, generally introduced through anthropogenic activities such as domestic wastewater, animal waste, or insufficiently treated effluents (Zweig et al., 1999).

These biological contaminants include pathogenic bacteria such as Salmonella spp., Shigella spp., enterotoxigenic Escherichia coli, Campylobacter spp., and Vibrio spp. Once introduced into aquaculture systems, these pathogens can infect fish and invertebrates, leading to disease, reduced growth performance, increased mortality, and even severe epidemics. From a public health perspective, consumption of contaminated aquatic organisms or direct contact with infected waters represent major transmission routes for zoonotic diseases such as diarrhea, typhoid fever, dysentery, and cholera.

Monitoring and controlling biological contaminants in aquaculture environments is therefore essential, both to preserve the health of farmed species and to ensure the safety of fishery products. Recent research has highlighted the potential of certain nanomaterials, including silver nanoparticles (AgNPs) and zinc oxide nanoparticles (ZnO-NPs), for their antimicrobial and antifouling properties, thus offering innovative solutions to limit microbial proliferation in aquaculture systems.

These micro-organizationsPathogens are often associated with water-contaminated diets and can cause illnesses ranging from mild gastroenteritis to more serious and even fatal conditions such as dysentery, cholera, or typhoid fever (Chapman, 1996). Although these microorganisms are ubiquitous in aquatic ecosystems, they do not generally cause disease in fish. However, fish can act as vectors, facilitating the transmission of these pathogens to humans through consumption or handling of contaminated fish products (Zweig et al., 1999).

Thus, to improve both the productivity of continental aquaculture and the health safety of its products, it is imperative to control the microbial load of the aquatic ecosystem. To this end, nanoparticles (NPs), and in particularthosebased on silver (AgNPs) and copper (CuNPs), have been widely studied for their antimicrobial efficacy in aquaculture water treatment. The results of several researches are promising, demonstrating significant potential of these NPs in reducing microbial contamination and preventing waterborne diseases (Van Khanh and Van Cu, 2019; Nezhadheydari et al., 2019).