The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES
20(3): S.I(3). 1429-1454, 2025 www.thebioscan.com

AN OVERVIEW OF NANOMATERIALS FROM MARINE ENVIRONMENTS

Vijay Krishanan*[1], Devasena, B [2], Nafisa Farheen [3], Rajeswari, R [4] and Geetha, C[5]

[*1&2]Peri college of physiotherapy, Chennai -48, TN, India
[3]Peri college of Pharmacy, Chennai -48, TN, India
[4]Peri Institute of Technology, Chennai - 48, TN, India
[5]Peri college of Nursing, Chennai -48, TN, India

DOI: 10.63001/tbs.2025.v20.i03.S.I(3).pp1429-1454

KEYWORDS:

Marine environment, nanomaterial's, nano/micromachines, carbon nanotubes, nanobots, robotic fish, marine debris and marine habitat.

Received on:

01-09-2025

Accepted on:

03-10-2025

Published on:

11-11-2025

ABSTRACT

Sea water is a harsh environment with high ionic concentration, which allows nanomaterial's (NMs) to change their behaviour dramatically. Rapid agglomeration, destabilization, and deposition may cause the NMs to disappear from surrounding water. Organic substances contacts with metal-bearing NMs may alter their dispersion, physical and chemical properties, and durability in the water columns. To assess human and ecological hazards and develop regulatory standards for modified NMs release, accurate and sophisticated detection of engineered nanostructures in marine environments is essential. Still, due to the inadequacy of NMs characterization techniques, comprehending their destiny and behaviour in marine habitats are still limited. Sulfur species, organic compounds, trace element cycling, distribution, and interaction between colloidal and dissolved phases have all been found to be crucial candidates for analysing the different ecological processes courses in marine habitats using electrochemistry strategies coupled with advanced spectroscopy and microscopy techniques.

Introduction

Nanotechnology (NT) has provided unique solutions in a variety of industries, including consumer goods, high-tech industries, and infrastructure. While nano-enabled products are becoming more prevalent in daily life, there are presently over 3,000 nano-enabled consumer items on the industry [1] as well as countless industrial manufacturing devices and parts in use [2]. The use and disposal of nano-enabled products, as well as the unintentional synthesis of NMs, will almost certainly result in their discharge into the environment, posing a hazard to public health and the ecosystem [3]. The degree of exposure of an organism to a substance and its hazard evaluation determine risk. The former is a tangible property, whereas the latter is heavily influenced by its surroundings. When photo catalytic titanium dioxide nanoparticles (TiO_2) are exposed to sunlight, they create reactive oxygen species (ROS), which can be harmful.

However, the amount of ROS produced depends on the parameters controlling photo excitation efficiency [4]. Adsorption of organics and aggregation in natural aquatic systems, such as ocean waters, can significantly reduce ROS generation [5]. Furthermore, aggregation containing suspended particle matter will generate bigger size aggregations that descend to the seafloor, minimizing solar exposure [6]. The fate of NMs in the marine environment must thus be determined in order to estimate their danger. When NMs interact with marine environment, the following factors are present:

Increased Mortality of Marine Crustaceans (MC)

Anastasia Georgantzopoulou *et al.* from SINTEF and NIVA investigated how TiO_2 and silver nanoparticles function in wastewater treatment facilities and how they affect freshwater and marine organisms in a study conducted at the Norwegian Institute for Water Research. The scientists built a laboratory-scale waste water treatment plant using sludge from a waste water treatment facility in Norway, then added ecologically adequate amount of TiO_2 and silver nanoparticles over a five-week period. They tested the effects of the converted nanoparticles on marine and freshwater organisms, as well as rainbow trout gill cells, using the treated waste water. Both crustacean species had different effects as a result of the experiment. While mortality in the marine copepod rose by 20% to 45 percent, exposure to the treated waste water had no effect on the freshwater crustacean [7].

Effects on Algal Species

Furthermore, whereas the treated waste water containing nanoparticles had an effect on algal growth, the two algal species did not respond in the same way: while the marine algae (*Skeletonema pseudocostatum*) responded with a growth inhibition of 20%-40%, the growth of the freshwater algae (*Raphidocelis subcapitata*) was triggered by a 40% increase, followed by an increase in cell aggregation. Perhaps the latter is a defensive mechanism designed to decrease the amount of surface area exposed to hazardous particles [7].

Effects on marine organisms

NPs can attach to a cell's surface and obstruct vital pore and membrane processes. Endocytosis, diffusion through pores, or ion transport systems is other ways it might enter the cell. The nanoparticles can possibly interfere with electron transport pathways or enhance ROS formation by interfering with organelle functions once it has entered the cell. ROS generation can cause nucleic acid damage, protein oxidation, and cell membrane rupture [8, 9].

Fish

Ingestion from water or sediment for demersal species (Bluespotted ribbontail ray, *Rhinogobius flumineus* and Pacific hagfish), gill or gut epithelial cells, or diffusion through the chorion pore channel for embryos are all potential absorption routes for ZnONPs in fish [10]. There are few studies on the effects of ZnONPs on marine fish. After 96 hours of exposure to ZnONPs of 4 and 40 mg l^{-1} ZnO-NPs, the marine medaka fish *Oryzias melastigma* larvae showed only an elevation of HSP70. The protein expression of both HSP70 and SOD was significantly increased in *Oryzias melastigma* larvae treated to $ZnSO_4$ at the same zinc ion concentrations. The findings suggested that the test medaka larvae exposed to ZnONPs were not under oxidative stress, and that the harmful impact of ZnONPs was attributable primarily to ionic zinc released from the NPs [11].

Salinity

Salinity variations are prevalent in estuaries, and marine pollution is mainly found in coastal locations, where organisms would be exposed to both salinity fluctuations and chemical contaminants. Because salinity impacts both the physiological processes of animals and the physicochemical features of nanoparticles, this connection is difficult. Due to the presence of chloride, sulphate, and organic matter in natural saltwater, a rise in salinity typically increases the degree of metal complexation. Increased SAL can limit ion dissolution from metal-oxide-based NPs, lowering the NPs' toxicity due to the release of free metal ions [12].

Sea animals

Researchers from China and California have published a new study that raises the possibility that NPs in sunscreens are harmful to aquatic organisms. Their research focuses on embryos of sea urchins and indicates that NMs in sunscreens and boat-bottom paints render these sea animals more sensitive to poisons. This is the latest in a series of studies conducted by academics from across the world that demonstrate nano-sunscreens may be damaging to sea animals [13]. Nano zinc oxide is a common constituent in sunscreens, toothpastes, and other beauty products. Nano copper oxide is utilized in a variety of applications, including electronics and technology, as well as antifouling coatings that keep barnacles and mussels from clinging to vessels [13].

Sea turtle

CuNPs and copper ions reduce sperm motility, viability, and enzymatic activity in the Chinese soft-shelled turtle's cauda epididymis. Furthermore, sperm motility is strongly linked to mitochondrial function, as mitochondria are the cell's energy producer and, at the same time, the primary source of intracellular ROS, causing electron transport disruption [14-16].

Coral Reefs

Due to consumer desire for creams and sprays that penetrate into the skin without leaving a white residue, sunscreen with nanoparticles has gained popularity. However, research reveals that the chemical compounds are more unstable than traditional sunblock, a characteristic of the technology that might cause difficulties for individuals and the environment. Nanoparticles from sunscreen have been observed to accumulate in coral reefs environments, according to a previous study published in April. The study indicated that chemical accumulation might damage the coral reefs [17].

Engineered nanoparticles from nano-enabled consumer and industrial devices may infiltrate coastal waters and oceans *via* direct and indirect pathways following use and disposal, as indicated in Figure 1 and 2. Engineered nanoparticles are expected to be extensively modified before entering the aquatic environment in this situation [18]. Direct routes, such as shipping emissions, water-based recreational activities, the release of untreated waste water, and other human activities, are more likely to release engineered nanoparticles in their designed form [18]. When engineered nanoparticles reach the environment, their destiny determines their potential toxicity, a factor that many toxicological investigations have overlooked [19]. As a result, a thorough knowledge of the processes that control engineered nanoparticles destiny in the environment is required [20]. Several investigations on the destiny and impact of engineered nanoparticles in natural waterways have been done, including rivers [21], lakes [22], and estuaries [23]. Because engineered nanoparticles are projected to swiftly agglomerate and settle on the sediments, less research has focused on marine waters.

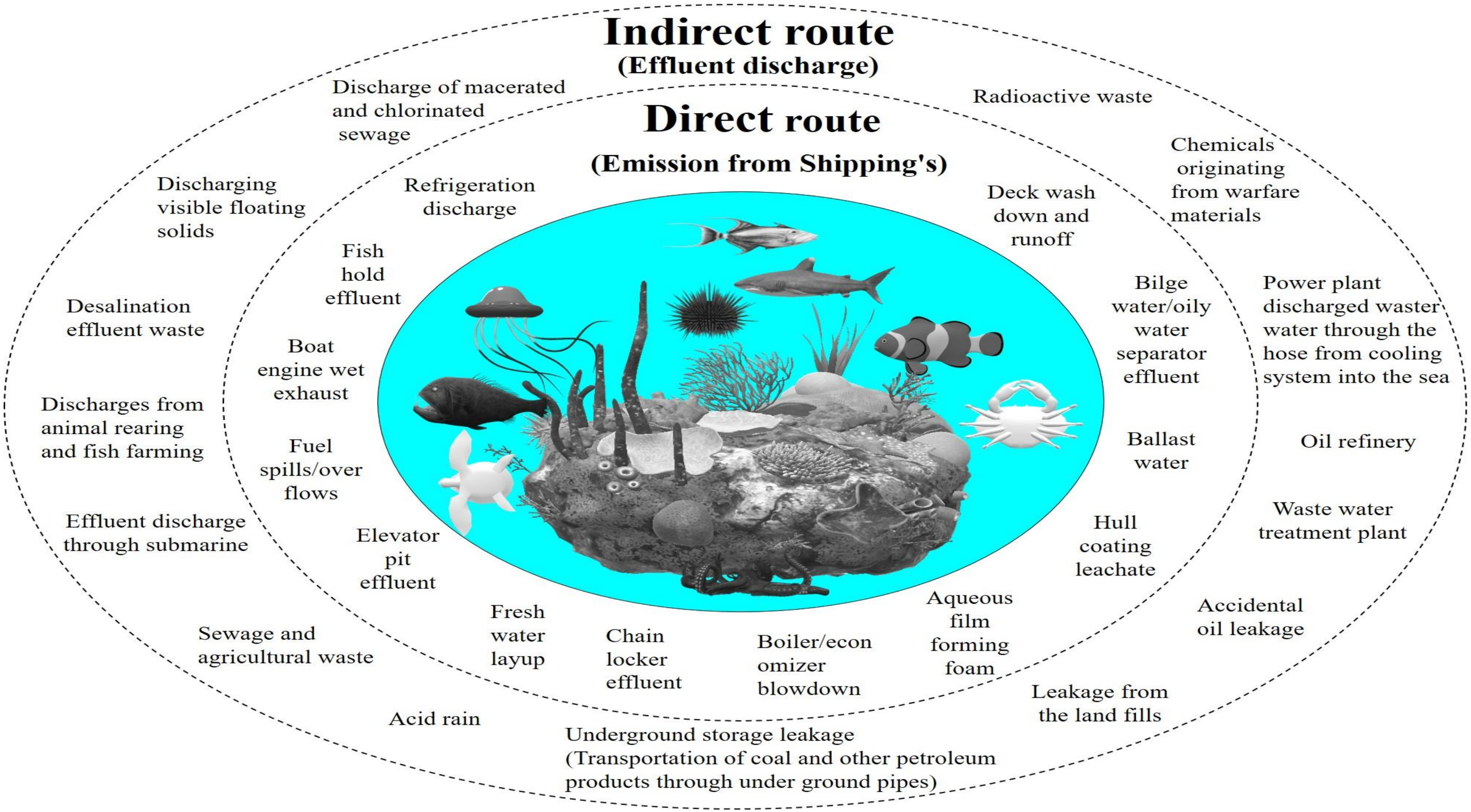

Fig. 1: Engineered nanoparticles impact on the maritime environment [25-30].

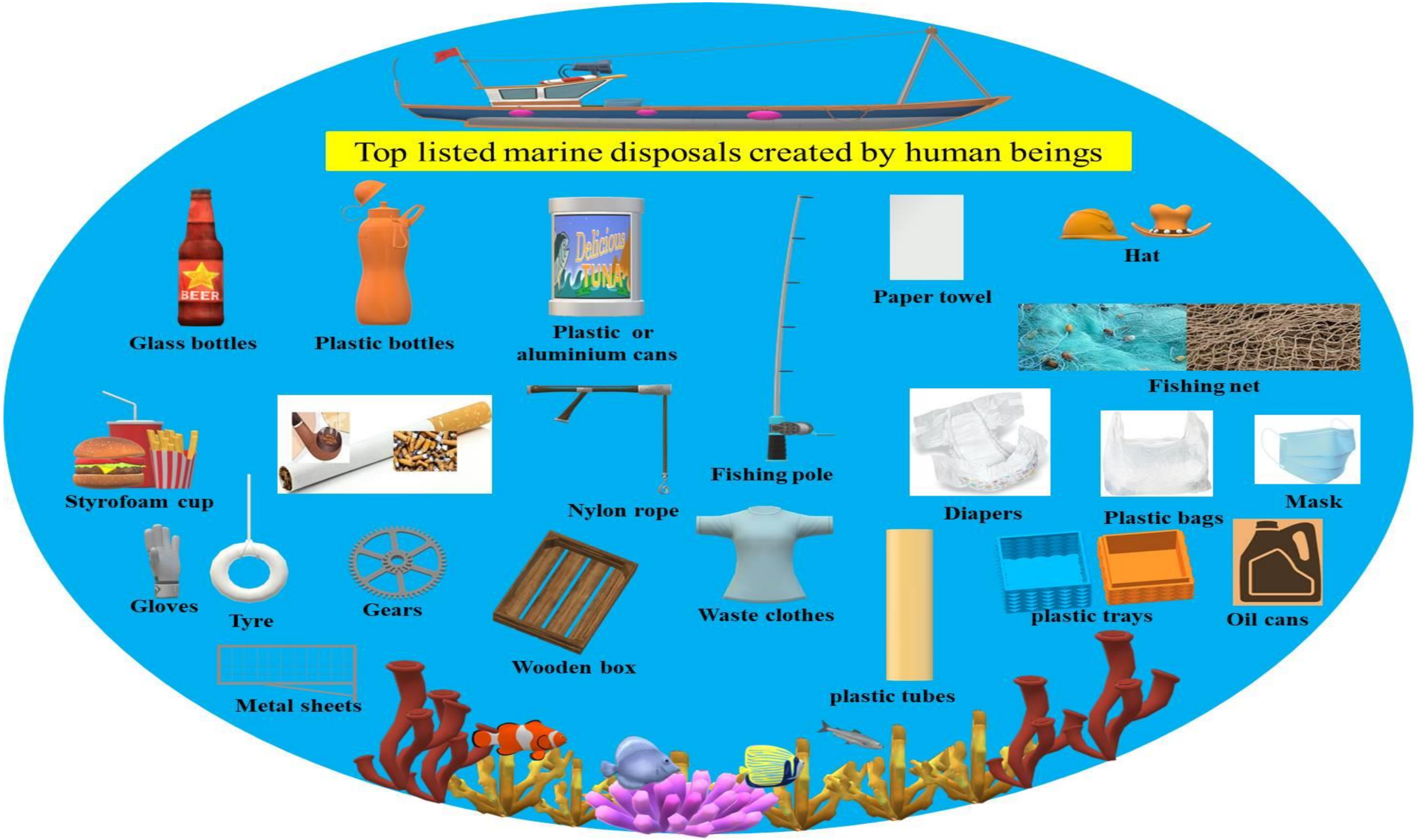

Fig. 2: Top listed marine debris [29,30]

Characterization of NMs present in the marine resources

Physical and chemical procedures for nanoparticles synthesis are extremely expensive. The scientific community targeted living entities in order to lower the unavoidable costs of downstream processing of produced NMs and to expand the use of nanoparticles.

As indicated in table 1, nature has evolved numerous procedures for the synthesis of nano and micro length scaled inorganic materials, which have contributed to the establishment of a relatively new and mostly unexplored area of research based on the synthesis of NMs [31].

Table 1: Synthesis and characterization of NPs using MRs

Name of the organisms	Type of biosynthesis	Particle size and shape	Techniques used	Biological activity	Reference
Padina species	Silver nanoparticles (AgNPs)	~25-60nm Spherical	Uv-vis, FT-IR, FESEM-EDX and SEM	Antibacterial activity using *S. aureus*, *B. subtilis*, *P. aeruginosa*, *E. coli* and *S. typhii*	31
Ulva rigida, *Gracilaria foloofera* and *Cystoseira myrica*)	AgNPs	12, 17 and 24 nm Spherical	Uv-vis, FT-IR and TEM	Anticancer activity using HFb-4 cells Antimicrobial activity using *B. cerus*, *E. coli*, *S. aureus*, *C. neoforrmans*, *C. albicans*, *T. cataneum* and *T. mantigrophytes*	32
U. fasciata, *Grateloupia species*, *P. capillacea* and *C. mediterranae*	AgNPs	4-80nm Spherical	UV-vis, XRD, HR-TEM and SEM-EDX	Antibacterial activity using *E. coli*, *S. aureus*, *S. faecalis*, *P. aureogenosa* and *V. damselsa*	33
MA (*Ulva lactuca*)	AgNPs	20-56nm Spherical	UV-vis, SEM-EDX, TEM, XRD and FT-IR	Anticancer activity using Hep-2, MF7, HT29 and Vero cells	34
Amphora species	AgNPs	42-46 nm Rod	UV-vis, FESEM-EDX, FT-IR and XRD	Antibacterial activity using *E. coli*, *P. vulgaris*, *E. faecalis* and *B. subtilis*	35

Halymenia porphyroides	AgNPs	34.3 and 80 nm Spherical	UV-vis, FT-IR, XRD, TGA, SEM and TEM	No activity (NA)	36
Padina pavonica	AuNPs	30-100 nm Spherical	UV-vis, FT-IR, XRD, SEM and TEM	Antibacterial activity using *E. coli* and *B. subtilis*	37
Laminaria ochroleuca	AgNPs	10-20 nm Spherical	UV-vis, SEM with EDX, HR-TEM with SAED, FT-IR and TGA	Antibacterial activity using *E. coli*, *S. aureus*, *K.pneumonia*, *P. aeruginosa*, *B. cereus* and *M. luteus*	38
Isochrysis galbana	AgNPs	10 nm Spherical	UV-vis and TEM with EDX	Antibacterial activity using *E. coli* and *P. vulgaris*	39
Chnoospara minima	AgNPs	84 nm Spherical	UV-vis, DLS, Zeta potential and SEM with EDX	Anticancer activity using MCF-7 cells	40
P. pavonica and *S. acinarium*	Fe_3O_4NPs	10-19.5nm Spherical	UV-vis, SEM with EDX, HR-TEM with SAED and FT-IR	Bioremediation (Bioremoval of Pb)	41
Phormidium formosum	AgNPs	1.83-26.15 nm Spherical	UV-vis, TEM and FT-IR	Antimicrobial activity using *Vibrio species*, *P. aeruginosa*, *S. marcescens*, *Aermonas hydrophilic*, *S. aureus*, *Proteus species*, *E. coli* and *C. albicans*	42
(*Rhizophora stylosa*)	AgNPs	5-87 nm Spherical	UV-vis, XRD, DLS and TEM	Antimicrobial activity using *E. coli* and *S. aureus*	43
Cystoseria myrica, *Sargassum latifolium* and *Padina australis*	Cu_2ONPs	12-26 nm Spindle	UV-vis, XRD, FT-IR, TEM, FE-SEM	Antimicrobial activity using *E. coli*, *S. aureus* and *P. aeruginosa*	44

Polychaete	AgNPs	40-90 nm Spherical	UV-vis, AFM, SEM with EDX, XRD and FT-IR	Antibacterial activity using *E. coli*, *S. aureus*, *P. aeruginosa* and *S. typhii*	45
Nocardiopsis dassonvillei	AgNPs	29.28 nm Spherical	UV-vis, FT-IR, TEM and DLS	Antimicrobial activity using *S. aureus*, *P.aureogenosa*, *K. pneumonia*, *P. mirabilis*, *A. niger* and *C. albicans*, Insecticidal activity using *Macrosiphum rosae*. Antioxidant activity by DPPH assay ANCA using $CaCo_2$ cell line	46
Sea urchin	AuNPs	~150 and ~25 nm Spike	UV-vis, FESEM, XRD and TEM	NA	47
Sea urchin	TiO_2NPs	10-65 nm Spherical	TEM and DLS	TLR/p38 MAPK mediated signaling pathway	48
Sardine fish scale	AgNPs	25-80 nm S	UV-vis, FT-IR, XRD and SEM with EDX	Larvicidal activity using *Anopheles stephensi*	49
Carcinus maenas and *Ocypode quadrata*	AgNPs	40-50 nm Spherical	UV-vis and SEM	Antimicrobial activity using *E. coli*, *S. aureus*, *Pseudomonas species*, *Klebsiella species*, *Candida species* and *A. niger*	50
Chitosan	AgNPs	10-60 nm Spherical	UV-vis, FT-IR, XRD, AFM, TEM and DLS	Antimicrobial activity using *S. aureus*, *Bacillus species*, *E. coli*, *Pseudomonas species*, *Proteus species*, *Serratia species*, *Klebsiella species*, *A. niger*, *A. flavus*, *A. fumigatus* and *C. albicans*	51
Vibrio alginolyticus	AgNPs	50-100 nm Spherical	UV-vis and SEM-EDX,	NA	52
Citricoccus	AuNPs	25-65 nm Spherical	UV-vis, SEM-EDX and TEM	NA	53

Saccharophagus degradans and *Saccharomyces cerevisiae*	MnO_2NPs	34.4 nm Hexagonal and Spherical	UV-vis, TEM, SEM, FR-IR and XRD	NA	54
Paracoccus haeundaensis	AuNPs	20.93±3.46 nm Spherical	UV-vis, SEM, FT-IR and DLS	Antioxidant using DPPH assay Anticancer activity using HaCaT and HEK293 cells	55
Oscillatoria willei	AgNPs	100-200 nm Spherical	UV-vis, FT-IR and SEM	NA	56
Pseudomonas fluorescens	AgNPs	1-10 nm S	UV-vis, FT-IR, SEM and TEM	Antimicrobial activity using *S. aureus*, *E. coli*, *C. albicans*, *A. niger* and *F. proliferatum*	57
Streptomyces albidoflavus	AgNPs	10-30 nm Spherical	Zeta potential, TEM and FT-IR	Antibacterial activity using *E. coli*, *B. subtilis*, *K. pneumonia* and *Micrococcus luteus*	58
Penicillium fellutanum	AgNPs	5-25 nm Spherical	UV-vis and TEM	NA	59
Aspergillus sydowii	AuNPs	8.7-15.6 nm Spherical	UV-vis, TEM, SADE and EDAX	NA	60
Sargassum wightii	AuNPs	8-12 nm Spherical	UV-vis, TEM and XRD	NA	61
Trichodesmium ertthraeum	AgNPs	26.5 nm Cubical	UV-vis, XRD, FT-IR, FESEM, AFM and DLS	Antibacterial activity using *P. mirabilis* and *S. aureus*	62
Cladosporium cladosporioides	AgNPs	100 nm Spherical	UV-vis, XRD, FT-IR, FESEM, AFM and DLS	Antioxidant activity using DPPH assay	63
B.subtilis	AgNPs	60 nm Spherical	UV-vis, XRD, FT-IR and TEM	NA	64
Pseudomonas species	AgNPs	156 and 265 nm Spherical	UV-vis	Antibacterial using *S. aureus*, *B. subtilis*, *S. typhii* and *V. cholera*,	65

Tracking of nanostructured materials emissions in the maritime environment using ecotoxicological instruments

The development of novel environmental nanostructured materials, such as those able to remove pollutants and lowering their bioavailability in aqueous media, presently lacks a testing framework for their environmental safety in terms of impact on aquatic biota [66]. Effect concentrations can be produced and integrated with the nanostructured materials effectiveness concentrations to reduce/limit any danger connected with its field deployment by incorporating ecotoxicity in the testing framework. Whether analytical chemistry is required to identify pollutants in seawater and assess the effectiveness of the proposed environmental nanostructured materials in terms of remediation, it is insufficient to define its possible environmental side effects [67]. Instead, as indicated in table 2, ecotoxicological instruments aimed at assessing the danger to marine species might meet these objectives and should be included into the marine ecosystem.

Table 2: Ecotoxicological tools

Name of the tools	Application	Reference
Graphene Oxide USTC-6	Recovery of oil spills from the water	[68]
Hydrophobic SiO_2NPs/polydimethylsiloxane (Dip coating method)	Oil spills remediation	[69]
fluorous metal organic framework 1 and 2	Oil spills cleanup and hydrocarbon storage Removes organic pollutants from oil spills	[70]
Magnetic nano carbon tubes Magnetic nanocomposite Super-paramagnetic iron oxide nanoparticles (FeONPs)	Removal of oil spills	[71]
Magnetic nanoparticles	Removal of oil spills caused by crude oil	[72]
Cellulose nanocrystals	Removal of oil spills caused by crude oil	[73]
Joule-heated graphene wrapped sponges		[74]
Carbon nanotube based aerogels and sponges	Removes the oil spills	[75]
Carbon nanotube based aerogels and sponges	Remediation of petroleum impurities from water	[76]
Graphene Oxide Quantum Dot (coupled with *Bacillus cereus*	Removes oil spills and also removes organic pollutants	[77]

Magnetite nanomaterials	Removes oil spills	[78]
Magnetic nanoparticles	Removes oil spills	[79]
Plant extract (*Anthemis pseudocotula*) based synthesized nagnetite nanomaterials	Petroleum oil spill collectors	[80]
Gr aphine	Oil spill clean up	[81]
Polyurethane foam coated with Carbon Nanofibers	Selective absorption in oil/water mixtures	[82]
Graphene Oxide melamine nanocomposite	Removes crude oil spills	[83]
3D magnetic graphene ball	Removes oil spills from water	[84]
Ceramic nanomaterials	Separation of oil/water mixtures	[85]
Polyvinylpyrrolidone coated MNPs	Oil remediation	[86]
3D Graphine	Cleans oil spills and removes dyes and organic pollutants in water	[87]
Yeast magnetic bionanocomposite	Oil spills clean up	[88]
Robotic vehicle with nanoparticles	Oil spills cleaning	[89]
Magnetic nanoparticles	Collection of petroleum crude oil spill pollutants from salt water	[90]
Polydimethylsiloxane	Selectively removes oil/water mixtures	[91]
Carbon sponges	Oil remediation	[92]
Iron nanoparticles	Removes oil spills	[93]
Iron oxide nanosheets	Removes oil spills	[94]
Alumina nanoparticles	Removal of oil spills from oil/water mixtures	[95]
Magnetic nanoparticles	Removes oil spills	[96]
Magnetic nanoparticles	OR from water	[97]
Magnetic nanoparticles	OR from water	[98]
White Graphene	Clean up the oil spills	[99]
Polystyrene fibers	Clean up the oil spills	[100]
Melamine sponge	OS clean-up and recovery	[101]
Peptide-based gel	Clean up the oil spills Removes lead and cadmium metals from oil spills recovery	[102]
Graphine/polyester sponge	Oil spills cleanup	[103]
TiO_2NPs	Remediate crude oil exposure	[104]
Eichhorina crassipes magnetic nanoparticles	Remediation of water polluted with petroleum crude oil	[105]
Montmorillonite clay	Partial treatment of SW	[106]
Magnetic detergent	Removal of diesel spills removal from saltwater	[107]
Carbon nanotubes	Absorbent for marine oil spills	[108]
Ionophore-based electrode	absorbent for marine oil spills	[109]
	Electrochemical sensing of lead	[109]
Graphine nanoparticles	Electrochemical detection of heavy metal ions	[110]
Cellulose	Removal zinc ions from salt water	[111]
Iron oxide nanoparticles	Removal of heavy metals	[112]

In reality, studies examining the toxicity of each individual NM are limited when compared to the number of various NMs synthesized for salt water decontamination (Table 2). Similarly, there are few multidisciplinary studies on the ability of novel synthetized NMs to remediate and their ecotoxicological impact on marine creatures in the existing literature. This encourages better collaboration across diverse study domains, such as chemistry, physics, engineering, and ecotoxicology, as well as increased research efforts on engineered nanoparticles ecotoxicological evaluation [113]. Ecotoxicity tests should mimic real-world conditions before and after the nanoremediation process, taking into account the unique characteristics of NMs, such as their various sizes, structures, and shapes, which contribute to their interactions with the remediation media, influencing their behavior and toxicity [113].

Applications of nonorobotics in controlling marine pollution

To reduce undersea pollution, efforts are being done. A robotic fish that monitors the levels of underwater pollution and aquatic life may soon be a new species of paraphyletic aquatic life in the world's seas (Fig. 3).

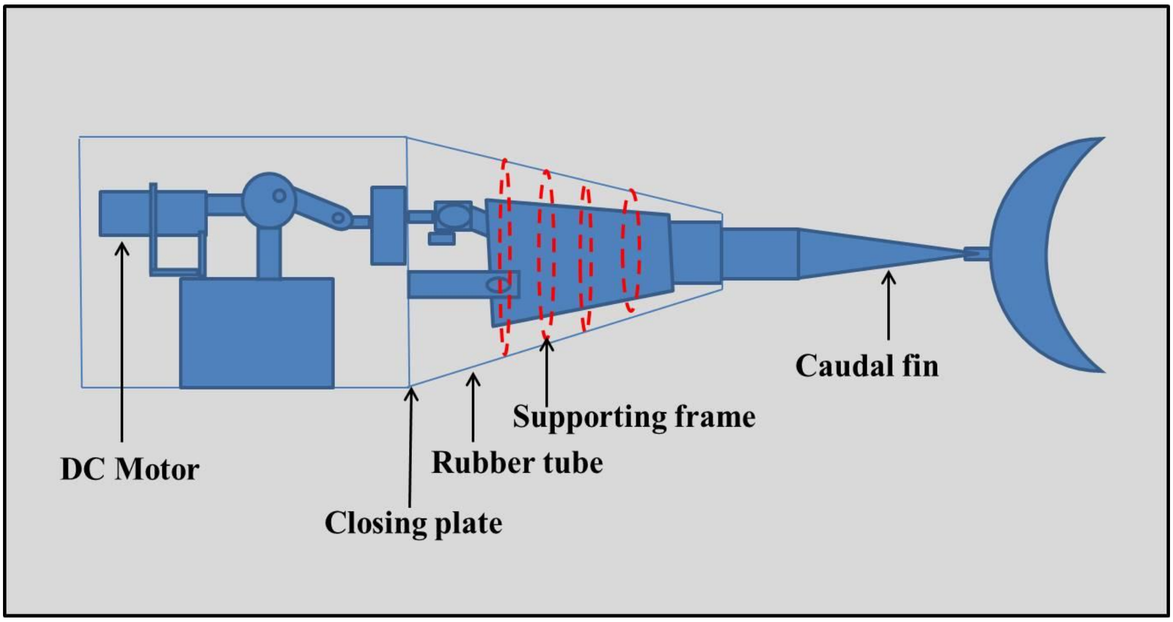

Fig. 3: Structure of robotic fish [114]

There are several underwater vehicles employed today to monitor undersea activity and clean up rivers, but they don't quite resemble aquatic life in terms of size and shape [114]. Additionally, the mobility and quantity of noise produced by these tracking technologies restrict autonomous underwater vehicles. The ability of little fish to move efficiently in watery environments, make greater use of the water, and create less noise can be attributed to their small size [115]. Small fish will also use the absence of noise in a big aquatic habitat as a survival strategy to keep larger predators from locating them. Robotic fish technology is significant for a number of reasons, including pollution monitoring, but also because it enables researchers to examine eating patterns and behavioural patterns that may be used to better understand a particular species and aid in environmental conservation [116].

The small robots, which have platinum inside coating and a graphene oxide exterior covering, can perform a lot more than you may expect. The polluting metals are absorbed by graphene oxide, while magnetic control is made possible by the nickel core. The platinum covering serves as the chemical "engine" for the nanobots, which are driven forward by a reaction with hydrogen peroxide. Each robot is roughly the width of a human hair, which is astounding to consider. The graphene bots are also reusable, and they can even make many passes over the same contaminated region. In the future, employing some sort of internal influence, experts now see the potential for autonomous control. Although the focus of this study was on the removal of lead, future research will modify the nanobots to remove a variety of heavy metals from varied settings [117].

Tiny fish shaped robot

Chinese researchers have created a robotic fish that can filter water of microplastics. The bionic fish is barely 13 millimetres in length and is made of the synthetic material polyurethane. It is capable of swimming as quickly as plankton. Microplastics adhere to the fish because of the substance used to make it. Additionally, even when injured, the robot may rebuild its robustness and usefulness by steadily absorbing pollutants. With this study, quick locomotions and functional execution are no longer mutually exclusive, and we predict that additional integrated robots that need multifunction integration will benefit from our nanostructural design's effective extended route [118, 119].

Role of Nano/Micromachines in marine environment

By using micromotors based on magnesium Janus particles magnesium particles coated in nanometric layers of titanium, nickel, and gold and further functionalized with a hydrophobic coating of octadecanethiol to scavenge oil droplets in water, nanotechnology can enhance oil remediation [120]. These micromotors, in contrast to the preceding illustration, propel themselves using hydrogen bubbles that are produced as a result of a process involving water reduction at the magnesium surface. The magnesium surface rapidly becomes coated, or passivated, by an oxide layer and is unable to generate the reaction with water that creates the bubbles, which is one possible problem with this motor. Because it interacts with the chloride ions in saltwater to aid in the removal of the oxide passivation layer through a mix of macrogalvanic corrosion and pitting corrosion processes, the gold coating on the motor provides assistance with this issue. These tiny motors, like the one in the first illustration, adhere to oil droplets and aid in their capture and transportation in water. These micromotors have the potential to be useful in the removal of oil droplets from saltwater since they can independently propel in seawater [120].

These nano- and micromotors could offer an effective and eco-friendly option for cleaning up oil spills. The nature of the motor and the usage of saltwater as the only fuel source in the case of the magnesium Janus micromotors make them exceptionally biocompatible and environmentally benign [121]. The nano/micromotors have the capacity to catch, transfer, and remove oil droplets from water, in contrast to dispersants, which break up the oil slick and carry the oil down the water column [122]. These nano/micromachines, in addition to having corrosion problems, also tend to slow down after gathering oil droplets. The issues with durability and speed of these nano/micromotors are still being researched [123]. Unfortunately, no instances of these nano/micromotors being employed for oil spill management have been reported, and it is unclear what happens to the nomachines once they connect to the oil. The usage of nano/micromotors for oil spill cleanup is in its early stages. However, based on the few instances we have, it is clear that they might have significant uses in water treatment and oil spill mitigation, possibly revolutionising the area of environmental remediation [124].

Conclusion

The majority of nanoparticles environmental impact research is now focused on nanotoxicity. The indirect impact of manufactured nanoparticles can represent bigger ecological hazards than direct toxicity, according to this paper. Abiotic + biotic and organic material change at the nano and microscale are at the heart of macroscopic experiences in the sea, according to extensive examinations of surface active chemicals in marine ecosystems. The use of spectroscopy and microscopy techniques has allowed researchers to investigate the environmental impact of manufactured nanoparticles that govern the destiny of organic molecules and their interactions with metal-bearing nanoparticles in the marine environment.

Indeed, environmental nanomaterials are very dynamic in seawater, and a thorough physical-chemical characterization of their acquired characteristics is essential for a fair evaluation of exposure scenarios and associated dangers to the environment and people. Nanosized objects interact with living things in a fundamentally different way than conventional contaminants due to their eco-interactions with the environment's nanomaterials and biomolecules, including existing chemical pollutants. These new exposure scenarios must be considered when approaching the ecotoxicity study of nanosized objects. In order to fully understand environmental nano-bio interactions from an ecotoxicological perspective, the eco-corona concept must be included. In order to simulate actual exposure situations, protracted exposure circumstances and additional sublethal end-points that bridge the impact from a single organism to populations and communities should be considered in terms of biological impacts. In order to quantify actual exposure to commercial items incorporating environmental nanomaterials and to foresee risks for marine biota, a better examination of nano-enabled products is also strategically necessary. In order to improve our understanding of the effects of environmental nanoparticles on benthic populations, our advice for future research is to move beyond the use of conventional model species. Thus, it is suggested to use an ecologically based safer by design strategy (eco-design), in which an ecotoxicological testing strategy will enable the selection of the best eco-friendly and ecologically sustainable environment nanomaterials, significantly reducing any potential future side effects in terms of toxicological risk for natural ecosystems, including the marine environment.

References

1. Aiken, G. R., Hsu-Kim, H., & Ryan, J. N. (2011). Influence of dissolved organic matter on the environmental

fate of metals, nanoparticles, and colloids.
2. Alldredge, A. L., Passow, U., & Logan, B. E. (1993). The abundance and significance of a class of large, transparent organic particles in the ocean. Deep Sea Research Part I: Oceanographic Research Papers, 40(6), 1131-1140.
3. Andow, D. A., & Hilbeck, A. (2004). Science-based risk assessment for nontarget effects of transgenic crops. BioScience, 54(7), 637-649.
4. Sharma, V. K. (2009). Aggregation and toxicity of titanium dioxide nanoparticles in aquatic environment—a review. Journal of Environmental Science and Health Part A, 44(14), 1485-1495.
5. Manzano, M., & Vallet-Regí, M.A.R.I.A. (2012). Revisiting bioceramics: bone regenerative and local drug delivery systems. Progress in Solid State Chemistry, 40(3), 17-30.
6. Praetorius, A., Badetti, E., Brunelli, A., Clavier, A., Gallego-Urrea, J. A., Gondikas, A., ... & von der Kammer, F. (2020). Strategies for determining heteroaggregation attachment efficiencies of engineered nanoparticles in aquatic environments. Environmental Science: Nano, 7(2), 351-367.
7. Georgantzopoulou, A., Farkas, J., Ndungu, K., Coutris, C., Carvalho, P. A., Booth, A. M., & Macken, A. (2020). Wastewater-aged silver nanoparticles in single and combined exposures with titanium dioxide affect the early development of the marine copepod Tisbe battagliai. Environmental Science & Technology, 54(19), 12316-12325.
8. Bhatt, I., & Tripathi, B. N. (2011). Interaction of engineered nanoparticles with various components of the environment and possible strategies for their risk assessment. Chemosphere, 82(3), 308-317.
9. Baker, T. J., Tyler, C. R., & Galloway, T. S. (2014). Impacts of metal and metal oxide nanoparticles on marine organisms. Environmental pollution, 186, 257-271.
10. Handy, R. D., Von der Kammer, F., Lead, J. R., Hassellöv, M., Owen, R., & Crane, M. (2008). The ecotoxicology and chemistry of manufactured nanoparticles. Ecotoxicology, 17(4), 287-314.
11. Wong, S. W., Leung, P. T., Djurišić, A. B., & Leung, K. M. (2010). Toxicities of nano zinc oxide to five marine organisms: influences of aggregate size and ion solubility. Analytical and bioanalytical chemistry, 396(2), 609-618.
12. Nugegoda, D., & Rainbow, P. S. (1989). Palaemon elegans and Palaemonetes varians. Mar Ecol. Prog. Ser, 51, 57-75.
13. Wu, B., Torres-Duarte, C., Cole, B. J., & Cherr, G. N. (2015). Copper oxide and zinc oxide nanomaterials act as inhibitors of multidrug resistance transport in sea urchin embryos: their role as chemosensitizers. Environmental Science & Technology, 49(9), 5760-5770.
14. Varfolomeev, E. E., & Ashkenazi, A. (2004). Tumor necrosis factor: an apoptosis JuNKie?. cell, 116(4), 491-497.

15. Mostek, A., Słowińska, M., Judycka, S., Karol, H., Ciereszko, A., & Dietrich, M. A. (2018). Identification of oxidatively modified proteins due to cryopreservation of carp semen. Journal of animal science, 96(4), 1453-1465.

16. Yang, L., Wei, Y., Gao, S., Wang, Q., Chen, J., Tang, B., & Bian, X. (2022). Effect of Copper Nanoparticles and Ions on Epididymis and Spermatozoa Viability of Chinese Soft-Shelled Turtles Pelodiscus sinensis. Coatings, 12(2), 110.

17. https://www.theatlantic.com/politics/archive/2014/08/how-your-sunscreen-hurts-coral-reefs/445035/

18. Kaegi, R., Englert, A., Gondikas, A., Sinnet, B., von der Kammer, F., & Burkhardt, M. (2017). Release of TiO2–(Nano) particles from construction and demolition landfills. NanoImpact, 8, 73-79.

19. Baalousha, M., & Lead, J. R. (2013). Nanoparticle dispersity in toxicology. Nature nanotechnology, 8(5), 308-309.

20. Von Der Kammer, F., & Flemming, H. C. (2007). Colloidal transport in porous media. F. H. Frimmel (Ed.). New York: Springer.

21. Reed, R. B., Martin, D. P., Bednar, A. J., Montaño, M. D., Westerhoff, P., & Ranville, J. F. (2017). Multi-day diurnal measurements of Ti-containing nanoparticle and organic sunscreen chemical release during recreational use of a natural surface water. Environmental Science: Nano, 4(1), 69-77.

22. Gondikas, A. P., Kammer, F. V. D., Reed, R. B., Wagner, S., Ranville, J. F., & Hofmann, T. (2014). Release of TiO2 nanoparticles from sunscreens into surface waters: a one-year survey at the old Danube recreational Lake. Environmental science & technology, 48(10), 5415-5422.

23. Hassellöv, M. (2007). Changes in size distribution of fresh water nanoscale colloidal matter and associated elements on mixing with se... Geochimica et Cosmochimica Acta, 71, 3292-3301.

24. Gondikas, A., Gallego-Urrea, J., Halbach, M., Derrien, N., & Hassellöv, M. (2020). Nanomaterial fate in seawater: A rapid sink or intermittent stabilization?. Frontiers in Environmental Science, 151.

25. https://www.worldscientific.com/worldscibooks/10.1142/1649

26. Al Muzaini, M., Mendonca, V., Al Sariri, T., & Al Jabri, M. (2004). Waste water discharge into the marine environment in the Sultanate of Oman: sources and standards—an overview of the current situation. Proceedings of the 3rd Marine Waste Water Discharges (MWWD), Catania, Italy, 27.

27. http://www.waterencyclopedia.com/Po-Re/Pollution-of-the-Ocean-by-Sewage-Nutrients-and-Chemicals.html

28. https://www.maritime-executive.com/editorials/stop-discharging-visible-floating-solids -from-sewage-in-high-seas

29. https://www.water.ie/help/wastewater/treatment/from-drain-to-sea/

30. https://seos-project.eu/marinepollution/marinepollution-c02-s10-p01.html

31. Bhuyar, P., Rahim, M. H., Sundararaju, S., Maniam, G. P., &

Govindan, N. (2020). Antioxidant and antibacterial activity of red seaweed Kappaphycus alvarezii against pathogenic bacteria. Global Journal of Environmental Science and Management, 6(1), 47-58.

32. Algotiml, R., Gab-Alla, A., Seoudi, R., Abulreesh, H. H., El-Readi, M. Z., & Elbanna, K. (2022). Anticancer and antimicrobial activity of biosynthesized Red Sea marine algal silver nanoparticles. Scientific reports, 12(1), 1-18.
33. Kathiraven, T., Sundaramanickam, A., Shanmugam, N., & Balasubramanian, T. (2015). Green synthesis of silver nanoparticles using marine algae Caulerpa racemosa and their antibacterial activity against some human pathogens. Applied Nanoscience, 5(4), 499-504.
34. Devi, J. S., Bhimba, B. V., & Ratnam, K. (2012). Anticancer activity of silver nanoparticles synthesized by the seaweed Ulva lactuca in vitro. Sci Rep, 1(4), 242.
35. Tevan, R., Govindaraju, M., Jayakumar, S., Govindan, N., Rahim, M. H. A., Maniam, G. P., & Ichwan, S. J. (2017). Antimicrobial activities of silver nanoparticles bio-synthesized from diatom Amphora sp. J. Eng. Sci. Res, 2, 176-184.
36. Manam, D., & Kiran, V. (2020). Biosynthesis and Characterization of Silver Nanoparticles From Marine Macroscopic Red Seaweed Halymenia Porphyroides Boergesen (Crypton) and Its Antifungal Efficacy Against Dermatophytic and Non-Dermatophytic Fungi. Asian Journal of Pharmaceutical and Clinical Research, 13(8).
37. Isaac, G., & Renitta, R. E. (2015). Brown Algae mediated synthesis, characterization of gold nano particles using Padina pavonica and their antibacterial activity against human pathogens. Int J Pharm Tech Res, 8(9), 31.
38. Kaidi, S., Belattmania, Z., Bentiss, F., Jama, C., Reani, A., & Sabour, B. (2021). Synthesis and Characterization of Silver Nanoparticles Using Alginate from the Brown Seaweed Laminaria ochroleuca: Structural Features and Antibacterial Activity.
39. Mohy El-Din, S. M., & El Said, H. S. (2017). Biosynthesis of silver nanoparticles from the marine microalga Isochrysis galbana and their antibacterial activity against pathogenic bacteria. Egyptian Journal of Botany, 56(2), 371-379.
40. Keerthirathna, L.R., Peiris, D.; Samarakoon, K., Samarakoon, S., Rathnayaka, R., Sirimuthu, N. (2021). Green synthesis, characterization, and bioactivity of silver-nanoparticles from algal polysaccharide of Chnoospara minima, in Proceedings of the 1st International Electronic Conference on Biomedicine, 1–26 June.
41. El-Kassas, H. Y., Aly-Eldeen, M. A., & Gharib, S. M. (2016). Green synthesis of iron oxide (Fe3O4) nanoparticles using two selected brown seaweeds: characterization and application for lead bioremediation. Acta Oceanologica Sinica, 35(8), 89-98.
42. Elkomy, R. G. (2020). Antimicrobial screening of silver nanoparticles synthesized by marine cyanobacterium Phormidium

formosum. Iranian Journal of Microbiology, 12(3), 242.

43. Willian, N., Syukri, S., Zulhadjri, Z., & Arief, S. (2021). Marine plant mediated green synthesis of silver nanoparticles using mangrove Rhizophora stylosa: Effect of variable process and their antibacterial activity. F1000Research, 10(768), 768.

44. Soureshjani, P. T., Shadi, A., & Mohammadsaleh, F. (2021). Algae-mediated route to biogenic cuprous oxide nanoparticles and spindle-like CaCO 3: a comparative study, facile synthesis, and biological properties. RSC Advances, 11(18), 10599-10609.

45. Singh, R., Sahu, S. K., & Thangaraj, M. (2014). Biosynthesis of silver nanoparticles by marine invertebrate (polychaete) and assessment of its efficacy against human pathogens. Journal of Nanoparticles, 2014.

46. Khalil, M. A., El-Shanshoury, A. E. R. R., Alghamdi, M.A., Alsalmi, F.A., Mohamed, S.F., Sun, J., & Ali, S.S. (2021). Biosynthesis of Silver Nanoparticles by Marine Actinobacterium Nocardiopsis dassonvillei and Exploring Their

51. Kalaivani, R., Maruthupandy, M., Muneeswaran, T., Beevi, A. H., Anand, M., Ramakritinan, C. M., & Kumaraguru, A. K. (2018). Synthesis of chitosan mediated silver nanoparticles (Ag NPs) for potential antimicrobial applications. Frontiers in Laboratory Medicine, 2(1), 30-35.

52. Rajeshkumar, S., Malarkodi, C., Paulkumar, K., Vanaja, M., Gnanajobitha, G., & Annadurai, G. (2013). Intracellular and extracellular biosynthesis of silver nanoparticles by using marine

Therapeutic Potentials. Frontiers in Microbiology, 12.

47. Li, Y., Zhai, M., & Xu, H. (2019). Controllable synthesis of sea urchin-like gold nanoparticles and their optical characteristics. Applied Surface Science, 498, 143864.

48. Ma, J., Hui, A., Liu, J., & Bao, Y. (2015). Controllable synthesis of highly efficient antimicrobial agent-Fe doped sea urchin-like ZnO nanoparticles. Materials Letters, 158, 420-423.

49. Murugan, K., Subramaniam, J., Rajaganesh, R., Panneerselvam, C., Amuthavalli, P., Vasanthakumaran, M., ... & Aziz, A. T. (2021). Efficacy and side effects of bio-fabricated sardine fish scale silver nanoparticles against malarial vector Anopheles stephensi. Scientific Reports, 11(1), 1-12.

50. Packia Lekshmi, N. C. J., Shini, A. B., Jeeva, S., Rajabrindha, J., & Bharath, M. S. (2015). Synthesis of silver nanoparticles using haemolymph of marine crabs (Carcinus maenas and Ocypode quadrata) and its influence on clinical pathogens. J Chem Pharm, 7, 598-606.

bacteria Vibrio alginolyticus. Nanosci Nanotechnol, 3(1), 21-25.

53. Camas, M., Celik, F., Sazak Camas, A., & Ozalp, H. B. (2019). Biosynthesis of gold nanoparticles using marine bacteria and Box–Behnken design optimization. Particulate Science and Technology, 37(1), 31-38.

54. Salunke, B. K., Sawant, S. S., Lee, S. I., & Kim, B. S. (2015). Comparative study of MnO2 nanoparticle synthesis by marine bacterium Saccharophagus

degradans and yeast Saccharomyces cerevisiae. Applied microbiology and biotechnology, 99(13), 5419-5427.

55. Patil, M. P., Kang, M. J., Niyonizigiye, I., Singh, A., Kim, J. O., Seo, Y. B., & Kim, G. D. (2019). Extracellular synthesis of gold nanoparticles using the marine bacterium Paracoccus haeundaensis BC74171T and evaluation of their antioxidant activity and antiproliferative effect on normal and cancer cell lines. Colloids and Surfaces B: Biointerfaces, 183, 110455.
56. Ali, D. M., Sasikala, M., Gunasekaran, M., & Thajuddin, N. (2011). Biosynthesis and characterization of silver nanoparticles using marine cyanobacterium, Oscillatoria willei NTDM01. Dig J Nanomater Biostruct, 6(2), 385-390.
57. Prabhawathi, V., Sivakumar, P. M., & Doble, M. (2012). Green synthesis of protein stabilized silver nanoparticles using Pseudomonas fluorescens, a marine bacterium, and its biomedical applications when coated on polycaprolactam. Industrial & engineering chemistry research, 51(14), 5230-5239.
58. Prakasham, R. S., Kumar, B. S., Kumar, Y. S., & Shankar, G. G. (2012). Characterization of silver nanoparticles synthesized by using marine isolate Streptomyces albidoflavus. Journal of Microbiology and Biotechnology, 22(5), 614-621.
59. Kathiresan, K., Manivannan, S., Nabeel, M. A., & Dhivya, B. (2009). Studies on silver nanoparticles synthesized by a marine fungus, Penicillium fellutanum isolated from coastal mangrove sediment. Colloids and surfaces B: Biointerfaces, 71(1), 133-137.
60. Vala, A. K. (2015). Exploration on green synthesis of gold nanoparticles by a marine-derived fungus Aspergillus sydowii. Environmental Progress & Sustainable Energy, 34(1), 194-197.
61. Singaravelu, G., Arockiamary, J. S., Kumar, V. G., & Govindaraju, K. (2007). A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, Sargassum wightii Greville. Colloids and surfaces B: Biointerfaces, 57(1), 97-101.
62. Sathishkumar, R. S., Sundaramanickam, A., Srinath, R., Ramesh, T., Saranya, K., Meena, M., & Surya, P. (2019). Green synthesis of silver nanoparticles by bloom forming marine microalgae Trichodesmium erythraeum and its applications in antioxidant, drug-resistant bacteria, and cytotoxicity activity. Journal of Saudi Chemical Society, 23(8), 1180-1191.
63. Hulikere, M. M., & Joshi, C. G. (2019). Characterization, antioxidant and antimicrobial activity of silver nanoparticles synthesized using marine endophytic fungus- Cladosporium cladosporioides. Process biochemistry, 82, 199-204.
64. Sathiyanarayanan, G., Kiran, G. S., & Selvin, J. (2013). Synthesis of silver nanoparticles by polysaccharide bioflocculant produced from marine Bacillus subtilis MSBN17. Colloids and Surfaces B: Biointerfaces, 102, 13-20.

65. Thomas, R., Viswan, A., Mathew, J., & Radhakrishnan, E. K. (2012). Evaluation of antibacterial activity of silver nanoparticles synthesized by a novel strain of marine Pseudomonas sp, Nano Biomed. Eng, 4(3), 139-143.
66. Corsi, I., Fiorati, A., Grassi, G., Bartolozzi, I., Daddi, T., Melone, L., & Punta, C. (2018). Environmentally sustainable and ecosafe polysaccharide-based materials for water nano-treatment: An eco-design study. Materials, 11(7), 1228.
67. Esposito, M. C., Corsi, I., Russo, G. L., Punta, C., Tosti, E., & Gallo, A. (2021). The era of nanomaterials: a safe solution or a risk for marine environmental pollution?. Biomolecules, 11(3), 441.
68. Jiang, Z. R., Ge, J., Zhou, Y. X., Wang, Z. U., Chen, D., Yu, S. H., & Jiang, H. L. (2016). Coating sponge with a hydrophobic porous coordination polymer containing a low-energy CF3-decorated surface for continuous pumping recovery of an oil spill from water. NPG Asia Materials, 8(3), e253-e253.
69. Ge, J., Ye, Y. D., Yao, H. B., Zhu, X., Wang, X., Wu, L., ... & Yu, S. H. (2014). Pumping through porous hydrophobic/oleophilic materials: an alternative technology for oil spill remediation. Angewandte Chemie, 126(14), 3686-3690.
70. Yang, C., Kaipa, U., Mather, Q. Z., Wang, X., Nesterov, V., Venero, A. F., & Omary, M. A. (2011). Fluorous metal–organic frameworks with superior adsorption and hydrophobic properties toward oil spill cleanup and hydrocarbon storage. Journal of the American Chemical Society, 133(45), 18094-18097.
71. Singh, H., Bhardwaj, N., Arya, S. K., & Khatri, M. (2020). Environmental impacts of oil spills and their remediation by magnetic nanomaterials. Environmental Nanotechnology, Monitoring & Management, 14, 100305.
72. Cardona, D. S., Debs, K. B., Lemos, S. G., Vitale, G., Nassar, N. N., Carrilho, E. N. V. M., ... & Labuto, G. (2019). A comparison study of cleanup techniques for oil spill treatment using magnetic nanomaterials. Journal of environmental management, 242, 362-371.
73. Wu, M. B., Zhang, C., Pi, J. K., Liu, C., Yang, J., & Xu, Z. K. (2019). Cellulose nanocrystals as anti-oil nanomaterials for separating crude oil from aqueous emulsions and mixtures. Journal of Materials Chemistry A, 7(12), 7033-7041.
74. Ge, J., Shi, L. A., Wang, Y. C., Zhao, H. Y., Yao, H. B., Zhu, Y. B., ... & Yu, S. H. (2017). Joule-heated graphene-wrapped sponge enables fast clean-up of viscous crude-oil spill. Nature nanotechnology, 12(5), 434-440.
75. Kukkar, D., Rani, A., Kumar, V., Younis, S. A., Zhang, M., Lee, S. S., ... & Kim, K. H. (2020). Recent advances in carbon nanotube sponge–based sorption technologies for mitigation of marine oil spills. Journal of colloid and interface science, 570, 411-422.
76. Kharisov, B. I., Dias, H. R., & Kharissova, O. V. (2014). Nanotechnology-based remediation of petroleum impurities from water. Journal of Petroleum Science and Engineering, 122, 705-718.

77. Mu, L., Zhou, Q., Zhao, Y., Liu, X., & Hu, X. (2019). Graphene oxide quantum dots stimulate indigenous bacteria to remove oil contamination. Journal of hazardous materials, 366, 694-702.
78. Abdullah, M. M., Faqihi, N. A., Al-Lohedan, H. A., Almarhoon, Z. M., & Mohammad, F. (2022). Fabrication of magnetite nanomaterials employing novel ionic liquids for efficient oil spill cleanup. Journal of Environmental Management, 316, 115194.
79. Abdullah, M. M., Al-Lohedan, H. A., & Atta, A. M. (2016). Novel magnetic iron oxide nanoparticles coated with sulfonated asphaltene as crude oil spill collectors. RSC advances, 6(64), 59242-59249.
80. Abdullah, M., Atta, A. M., Allohedan, H. A., Alkhathlan, H. Z., Khan, M., & Ezzat, A. O. (2018). Green synthesis of hydrophobic magnetite nanoparticles coated with plant extract and their application as petroleum oil spill collectors. Nanomaterials, 8(10), 855.
81. Elhenawy, S., Khraisheh, M., AlMomani, F., Hassan, M. K., Al-Ghouti, M. A., & Selvaraj, R. (2021). Recent Developments and Advancements in Graphene-Based Technologies for Oil Spill Cleanup and Oil–Water Separation Processes. Nanomaterials, 12(1), 87.
82. Visco, A., Quattrocchi, A., Nocita, D., Montanini, R., & Pistone, A. (2021). Polyurethane foams loaded with carbon nanofibers for oil spill recovery: mechanical properties under fatigue conditions and selective absorption in oil/water mixtures. Nanomaterials, 11(3), 735.
83. Xu, G., Zhang, L., Yu, W., Sun, Z., Guan, J., Zhang, J., ... & Guo, Z. (2020). Low optical dosage heating-reduced viscosity for fast and large-scale cleanup of spilled crude oil by reduced graphene oxide melamine nanocomposite adsorbents. Nanotechnology, 31(22), 225402.
84. Tao, T., Li, G., He, Y., & Yang, X. (2019). 3-D magnetic graphene balls as sorbents for cleaning oil spills. Nanomaterials and Nanotechnology, 9, 1847980419857373.
85. Zulfiqar, U., Thomas, A. G., Matthews, A., & Lewis, D. J. (2020). Surface engineering of ceramic nanomaterials for separation of oil/water mixtures. Frontiers in chemistry, 8, 578.
86. Mirshahghassemi, S., Ebner, A. D., Cai, B., & Lead, J. R. (2017). Application of high gradient magnetic separation for oil remediation using polymer-coated magnetic nanoparticles. Separation and Purification Technology, 179, 328-334.
87. Riaz, M. A., McKay, G., & Saleem, J. (2017). 3D graphene-based nanostructured materials as sorbents for cleaning oil spills and for the removal of dyes and miscellaneous pollutants present in water. Environmental Science and Pollution Research, 24(36), 27731-27745.
88. Debs, K. B., Cardona, D. S., da Silva, H. D., Nassar, N. N., Carrilho, E. N., Haddad, P. S., & Labuto, G. (2019). Oil spill cleanup employing magnetite nanoparticles and yeast-based magnetic bionanocomposite. Journal of Environmental Management, 230, 405-412.
89. Shah, M., Shah, S. K., & Shah, M. (2018, July). Autonomous robotic

vehicle for oil spills cleaning with nano particles. In 2018 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS) (pp. 1-6). IEEE.

90. Atta, A., Al-Lohedan, H., & Al-Hussain, S. (2016). Collection of petroleum crude oil spill pollutants from sea water using high magnetization antimicrobial biocompatible magnetite nanoparticles. Dig. J. Nanomater. Bios, 11, 185-197.
91. Nguyen, D. C., Bui, T. T., Cho, Y. B., & Kim, Y. S. (2021). Highly Hydrophobic Polydimethylsiloxane-Coated Expanded Vermiculite Sorbents for Selective Oil Removal from Water. Nanomaterials 2021, 11, 367.
92. Piperopoulos, E., Calabrese, L., Mastronardo, E., Milone, C., & Proverbio, E. (2020). Carbon-based sponges for oil spill recovery. In Carbon Nanomaterials for Agri-Food and Environmental Applications (pp. 155-175). Elsevier.
93. Bagga, P. S., Patwardhan, S. D., & Sharma, S. (2018, March). A mathematical model for oil spill clean up using ferromagnetic nanoparticles. In Offshore Technology Conference Asia. OnePetro.
94. Saber, O., Mohamed, N. H., & Arafat, S. A. (2015). Conversion of iron oxide nanosheets to advanced magnetic nanocomposites for oil spill removal. RSC advances, 5(89), 72863-72871.
95. Franco, C. A., Cortés, F. B., & Nassar, N. N. (2014). Adsorptive removal of oil spill from oil-in-fresh water emulsions by hydrophobic alumina nanoparticles functionalized with petroleum vacuum residue. Journal of colloid and interface science, 425, 168-177.
96. Kudaibergenova, R., Ualibek, O., Sugurbekov, E., Demeuova, G., Frochot, C., Acherar, S., & Sugurbekova, G. (2021). Reduced graphene oxide-based superhydrophobic magnetic nanomaterial as high selective and recyclable sorbent for oil/organic solvent wastewater treatment. International Journal of Environmental Science and Technology, 1-16.
97. Mirshahghassemi, S., & Lead, J. R. (2015). Oil recovery from water under environmentally relevant conditions using magnetic nanoparticles. Environmental science & technology, 49(19), 11729-11736.
98. Malhas, R., Al-Ibrahim, Y., Al-Meraj, A., Abdullah, H., & Alshatti, A. (2021). Application of magnetic separation for oil spill remediation and recovery in Kuwait sea water. DESALINATION AND WATER TREATMENT, 209, 114-120.
99. Ramirez Leyva, J. H. (2018). White Graphene Nanostructured Magnetic Sorbents for Oil-spill Cleanup: Synthesis and Performance Evaluation (Master's thesis, Graduate Studies).
100. Lin, J., Shang, Y., Ding, B., Yang, J., Yu, J., & Al-Deyab, S. S. (2012). Nanoporous polystyrene fibers for oil spill cleanup. Marine pollution bulletin, 64(2), 347-352.
101. Feng, Y., Wang, Y., Wang, Y., & Yao, J. (2017). Furfuryl alcohol modified melamine sponge for highly efficient oil spill clean-up and recovery. Journal of Materials Chemistry A, 5(41), 21893-21897.

102. Mondal, B., Bairagi, D., Nandi, N., Hansda, B., Das, K. S., Edwards-Gayle, C. J., ... & Banerjee, A. (2020). Peptide-based gel in environmental remediation: removal of toxic organic dyes and hazardous Pb2+ and Cd2+ ions from wastewater and oil spill recovery. Langmuir, 36(43), 12942-12953.
103. Wu, R., Bai, Y., Ming, Z., Chen, L., Yang, H., Yang, S. T., & Luo, J. (2017). Hydrothermal reduction of graphene oxide by glucose for the preparation of graphene/polyester staple sponge and its applications in oil spill cleanup. Journal of Bioresources and Bioproducts, 2(2), 61-66.
104. Guidi, P., Bernardeschi, M., Scarcelli, V., Lucchesi, P., Palumbo, M., Corsi, I., & Frenzilli, G. (2022). Nanoparticled Titanium Dioxide to Remediate Crude Oil Exposure. An In Vivo Approach in Dicentrarchus labrax. Toxics, 10(3), 111.
105. Atta, A. M., Mohamed, N. H., Hegazy, A. K., Moustafa, Y. M., Mohamed, R. R., Safwat, G., & Diab, A. A. (2020). Green technology for remediation of water polluted with petroleum crude oil: Using of Eichhornia crassipes (Mart.) Solms combined with magnetic nanoparticles capped with myrrh resources of Saudi Arabia. Nanomaterials, 10(2), 262.
106. Baskaran, V., & Saravanane, R. (2020). Effect of montmorillonite Clay in partial treatment of Sea water. Environmental Nanotechnology, Monitoring & Management, 14, 100326.
107. López, Y. C., Ortega, G. A., & Reguera, E. (2019). Magnetic detergent with potential application for diesel spills removal from seawater. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 561, 120-127.
108. Arum, L. A. S., Pawestri, Y. E., Zaki, M., Mahendratha, M. H. W., Awaliya, N., & Pratama, M. M. A. (2021, September). An overview on carbon nanotubes as innovative absorbent for marine oil spill. In IOP Conference Series: Earth and Environmental Science (Vol. 847, No. 1, p. 012034). IOP Publishing.
109. Pan, D., Wang, Y., Chen, Z., Lou, T., & Qin, W. (2009). Nanomaterial/ionophore-based electrode for anodic stripping voltammetric determination of lead: an electrochemical sensing platform toward heavy metals. Analytical chemistry, 81(12), 5088-5094.
110. Zuo, Y., Xu, J., Zhu, X., Duan, X., Lu, L., & Yu, Y. (2019). Graphene-derived nanomaterials as recognition elements for electrochemical determination of heavy metal ions: a review. Microchimica Acta, 186(3), 1-17.
111. Liberatori, G., Grassi, G., Guidi, P., Bernardeschi, M., Fiorati, A., Scarcelli, V., ... & Corsi, I. (2020). Effect-based approach to assess nanostructured cellulose sponge removal efficacy of zinc ions from seawater to prevent ecological risks. Nanomaterials, 10(7), 1283.
112. Usefi, F. (2016). Application of Iron Oxide Nanomaterials for the Removal of Heavy Metal. Journal of Materials Science & Surface Engineering, 4(2), 347-350.
113. Esposito, M. C., Corsi, I., Russo, G. L., Punta, C., Tosti, E., & Gallo, A. (2021). The era of nanomaterials: a safe solution or a risk for marine

environmental pollution?. Biomolecules, 11(3), 441.

114. Kato, N., & Kamimura, S. (Eds.). (2008). Bio-mechanisms of swimming and flying: fluid dynamics, biomimetic robots, and sports science. Springer Science & Business Media.
115. Mazumder, S. K. (Ed.). (2011). Wireless networking based control (pp. 85-102). Cham, Switzerland: Springer.
116. https://interestingengineering.com/science/graphene-nanobots-clean-pollutants-ocean
117. Vilela, D., Parmar, J., Zeng, Y., Zhao, Y., & Sánchez, S. (2016). Graphene-based microbots for toxic heavy metal removal and recovery from water. Nano letters, 16(4), 2860-2866.
118. https://www.moneycontrol.com/news/trends/current-affairs-trends/this-robot-fish-can-suck-up-microplastics-from-water-8825701.html
119. Wang, Y., Su, G., Li, J., Guo, Q., Miao, Y., & Zhang, X. (2022). Robust, healable, self-locomotive integrated robots enabled by noncovalent assembled gradient nanostructure. Nano Letters, 22(13), 5409-5419.
120. Zukunft, P. F. (2010). Summary Report for SubSea and SubSurface Oil and Dispersant Detection: Sampling and Monitoring. DIANE Publishing.
121. Rico-Martínez, R., Snell, T. W., & Shearer, T. L. (2013). Synergistic toxicity of Macondo crude oil and dispersant Corexit 9500A® to the Brachionus plicatilis species complex (Rotifera). Environmental Pollution, 173, 5-10.
122. Gulec, I., & Holdway, D. A. (2000). Toxicity of crude oil and dispersed crude oil to ghost shrimp Palaemon serenus and larvae of Australian bass Macquaria novemaculeata. Environmental Toxicology: An International Journal, 15(2), 91-98.
123. Guix, M., Orozco, J., Garcia, M., Gao, W., Sattayasamitsathit, S., Merkoçi, A., ... & Wang, J. (2012). Superhydrophobic alkanethiol-coated microsubmarines for effective removal of oil. Acs Nano, 6(5), 4445-4451.
124. Gao, W., Feng, X., Pei, A., Gu, Y., Li, J., & Wang, J. (2013). Seawater-driven magnesium based Janus micromotors for environmental remediation. Nanoscale, 5(11), 4696-4700.