

CYANOBACTERIAL EXTRACELLULAR POLYMERIC SUBSTANCES MEDIATED ECO-CORONA FORMATION ON MICRO AND NANOPLASTICS: MECHANISMS, ENVIRONMENTAL FATE, AND IMPLICATIONS FOR HARMFUL ALGAL BLOOMS

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Abstract

One of the most common pollutants of the aquatic ecosystem is Micro and Nanoplastics. They are able to quickly take in the biologically active coats, which are the eco-coronas. The Cyanobacterial extracellular polymeric substances are characterized by polysaccharides, proteins, lipids and other functional groups. The eco-corona formation is driven by the extracellular polymeric substances which aids in aggregation, changes the surface properties and supports biofilm formation. Plastics that are extracellular polymeric substances coated exhibit altered transport characteristics, increased sedimentation and increased bioavailability. This is an increase in their incorporation in food webs and transfer of contaminants. Micro and Nanoplastics hold Cyanobacterial aggregates in the bodies of water where the pools are characterized by blooms and prolong the duration of the harmful algal bloom and the proliferation of the toxins. The composition of extracellular polymeric substances, particle size, environmental stress factors and photochemical reactions affect the formation of the eco-corona, where tight binding of extracellular polymeric substances triggers adhesion and soluble extracellular polymeric substances triggers aggregation. Various methods of analytical techniques like microscopy, vibrational spectroscopy, mass spectrometry and fluorescence techniques are essential in characterizing these dynamic coats. This knowledge of the Cyanobacterial extracellular polymeric substances mediated eco-corona formation illuminates the behavior of plastics, the pollutant cycling process, and Harmful algal blooms dynamics. It focuses on the fact that plastics are not passive contaminants but active agents of ecology.

1. Introduction

Plastic pollution is a very widespread environmental problem, where the Micro (MPs, <5mm) and Nanoplastic (NPs, <1mm) are widely spread in all the aquatic ecosystems of the globe. They are released directly by the primary sources of plastics or formed as a result of the degradation

of the bigger plastic debris. When they enter the freshwater and marine environment they have important interactions with living biological materials and organism. A growing amount of scholarly evidence suggests that plastic particles are not simply passive contaminants; on the contrary, they quickly get covered by biomolecules and

microbial polymers found in the environment, leading to the formation of a biologically active surface layer, which is often called an eco-corona (Zhu et al., 2025). Extracellular polymeric substances (EPS) has a prominent role in determining the microbial communities and interactions of the particles within the eutrophied and cyanobacterium charged aquatic environments. They are high molecular weight, complex organic polymers that comprises of polysaccharides, proteins, and lipids. Cyanobacteria and other microorganisms secrete these polymers, and they play a role in the process of cell adhesion, flocculation, biofilm development, and environmental stress protection (Silva et al., 2020; Rusanowska et al., 2023). There is an abundance of Cyanobacteria in the eutrophic waters and they cause harmful algal blooms. They emit extensive amounts of EPS that impact on the local biogeochemical processes and particle interactions. It has been shown that EPS can be used to neutralize the charges and bridge the plastic particles in the aggregation process since the experiments have shown that Cyanobacterial EPS was effective in clearing the polystyrene Microplastics in aqueous solutions (Zhu et al., 2025). It has been demonstrated that being exposed to Microplastics may change the composition of EPS. Considering *Microcystis aeruginosa*, the polystyrene Microplastic of varying sizes induce serious alterations in the EPS composition based on their size. That implies that the Cyanobacteria physiology and secretion of polymers are altered by the interaction with plastics (Song et al., 2023). The practical characteristics of EPS are also proved by the fact that they attach to plastic particles with adsorption. The studies have shown that various

EPS fractions (soluble, loosely bound and tightly bound) have diverse adsorption capacities on Microplastics using EPS based on activated sludge which is a matrix rich in extracellular polymers. Hydrophobic and π - π interactions are the driving forces of these interactions (Wei et al., 2023). This review has mechanistic information on the potential of EPS interactions to control the environmental outcome and transportation of plastics in the aquatic environment. The Cyanobacterial EPS also affects the ecological processes. The release of EPS as growth phase occurs, which leads to the so called whitening events (carbonate precipitation), is also a major driver in freshwater with blooms, proving its utility in the regulation of both biological and inorganic particle aggregation (Martinho de Brito et al., 2023). These varied functional applications indicate that EPS engages with a great variety of aquatic constituents, such as Microplastics and Nanoplastic. These interactions should determine the environmental fortune and ecological effects of plastic particles. Although we are informed about the fact of interaction between EPS and plastic particles, there are considerable gaps of knowledge in terms of how exactly eco-corona is formed through Cyanobacterial EPS. How these biopolymer coatings modify the environmental route of Micro and Nanoplastic (MPs and NPs) in Cyanobacteria contaminated waters and how these biopolymer coats may influence the dynamics of harmful algal bloom (HAB) remains uncertain. The literature available on specific EPS properties or complex microbial assemblage remains sparse, so the actual contribution made by Cyanobacterial polymers towards the development of the eco-corona and their following effects on the environment remains largely unknown.

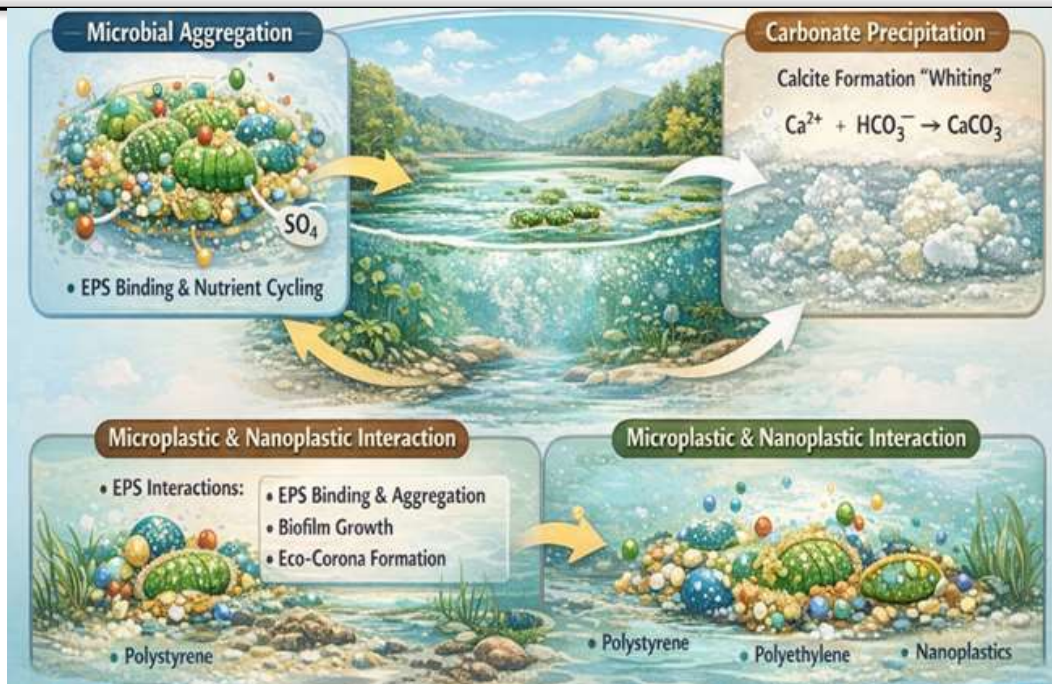


Figure 01. Ecological role of the Cyanobacterial extracellular polymeric substances

2 Composition, Types, and Environmental Regulation of Cyanobacterial EPS

The Cyanobacteria release extracellular polymeric substances (EPS), which are effectively mixtures of proteins, lipids and polysaccharides. The functional groups such as sulphate, amino, hydroxyl and carboxyl groups are present and their presence gives the functional groups active sites which can bind with different particles present in the water. These polymers play essential roles in cell adhesion, aggregation and nutrient recycling especially during environmental pressure such as micro-plastic pollution, limited nutrients or temperature variations of the bacteria. The study of the *Arthrospira platensis* has shown that the synthesis and properties of EPS vary according to environmental conditions (light intensity and the level of nitrate) level. Fourier Transform Infrared (FTIR) analysis revealed that the major functional groups present are carboxylate and sulphate ones. These chemical labelers can be useful as docking sites where favorable particles can be linked by electrostatic forces (Silva et al., 2020). The *Gloeocapsa gelatinosa* EPS is constructed of a wide range of nine monosaccharides such as mannose, xylose, and arabinose. These are the sugars,

together with the uronic acids, which determine the charge and hydrophilic character of the polymer, which ultimately determines the manner in which it attaches itself to the surrounding (Gongi et al., 2022) Soluble EPS (S-EPS) which freely floats in the water column works well to bind with Microplastics and induce bio flocculation. This particular fraction has been demonstrated to accumulate and exclude polystyrene particles in *Cyanocohniella rudolphia* by a mixture of bridging as well as charge neutralization (Zhu et al., 2025). This brings out the importance of the chemical diversity of the EPS matrix being what determines in the end the manner in which particles clump in the environment. *Anabaena variabilis* increases its EPS production when it is stressed by shading as well as by high-density polyethylene. This additional polymer is useful in removing the Microplastics out of the water column and into the sediment (Gopalakrishnan and Kashian, 2023). The same change in EPS chemistry is exhibited in *Microcystis aeruginosa* that is treated with polystyrene. It was also found that the bacteria produce varying amounts of polysaccharides and humic like components with regard to the size of the plastic

particles and ultimately determine the manner in which they will clump together (Song et al., 2023). The variability in the EPS production and its chemical composition is brought about by abiotic stressors such as temperature variations, nutrient availability, and pollutant concentrations. These alterations are paramount in that they determine the way Cyanobacteria will cluster and which way blooms will form. One such example is nutrient limitation, which causes cells to produce more EPS to make their clusters stable and persistent with the course of time (Xu et al., 2014). Microbial EPS is the major framework of biofilms generated on the Microplastics. Hamm et al. (2025) state that such sticky layers change the surface chemistry of the plastic to fundamentally become puncturing sites where the further biological growth and adsorption of pollutants occur. The process implies that Cyanobacterial EPS is an indirect yet extremely important factor in the colonization of Microplastics in water bodies. Cyanobacterial EPS

has a chemical diversity that makes it attach itself to Microplastics and other pollutants. This being a very sensitive matrix to the environment, its composition basically determines its interaction with pollutants in bloom laden systems. This interaction of charged groups with different sugars and the manner in which the bacteria adjust to the stress situation gives the precise biochemical pattern required of eco-coronas to be created on the Micro and Nanoplastic surfaces.

Critical Insight: Chemical diversity of Cyanobacterial EPS and how its changes depending on the environment that enables it to adsorb diverse surfaces. This versatility has basically been the factor which enables such polymers to construct the biological coatings or eco-coronas which develop on particles within the water systems.

Table 1: Interactions of Cyanobacteria, EPS, and Microplastics

Cyanobacterial Species	Characteristics of EPS	Primary Effect	References
<i>Spirulina sp.</i>	Carbohydrate content is High; rich in polysaccharides which is Sulfated.	Under stress increases of EPS yield from 0.32 to 4.59 mg; which help heavy particle binding.	(Lestari et al., 2025)
<i>Microcystis aeruginosa</i>	Extracellular polysaccharides and microcystins rich matrix which is sticky.	On polystyrene form dense biofilm; increased toxin release can trigger by microfibers.	(Lu et al., 2022)
<i>Synechocystis sp.</i>	Very Complex hetero-polysaccharides (made of 7+ monosaccharides).	EPS density changes by light and nutrient, aggregation with plastics alter cell to cell.	(Madsen et al., 2023)
<i>Anabaena variabilis</i>	Total organic carbon is high; under shading increase EPS.	Microplastics shading triggers defense-induced EPS, help particle deposition.	(Gopalakrishnan & Kashian, 2023)
<i>Nostoc muscorum</i>	Degrading enzymes produces like laccase and esterase.	Shows bioremediation potential; able to degrade polystyrene	(Yasmine et al., 2025)
<i>Synechococcus sp.</i>	Having Negatively charged groups (hydroxyl, carboxyl, phosphate).	Acts as a protective barrier by increasing cell wall thickness by 15–20 nm.	(Kokilathasan et al., 2025)
<i>Aphanizomenon flos-aquae</i>	Tightly Bound EPS (TB-EPS) is dominated.	Reduce electrostatic repulsion by plastic result in rapid colony formation and aggregation.	(Jin et al., 2022)

<i>Oscillatoria princeps</i>	Carbohydrate profile is modified contains super oxide dismutase enzymes.	Disrupts photosynthesis and alters toxin distribution in EPS by polyethylene exposure.	(Zhao et al., 2024)
<i>Cyanothece sp.</i>	EPS with extremely high bioflocculant activity is produce.	Aggregates Nano and Microplastics effectively into large flocs for easy removal.	(Barone et al., 2024)
<i>Calothrix sp.</i>	Thick protective sheath that rich in amino acids (MAAs).	Biofilms is stabilize on plastic by produces high biomass EPS.	(Zammit et al., 2026)
<i>Nostoc commune</i>	Glycan and Uronic acid content are very high.	Acts as a natural bio-flocculent and trapping micro-fibers within its sticky sheath.	(Pereira et al., 2019)
<i>Anabaena cylindrica</i>	Abundant Carboxyl and Hydroxyl groups.	For neutralize the surface charge of Nanoplastic it provide anionic binding sites.	(Wu et al., 2025)
<i>Gloeocapsa sp.</i>	High basal levels of gel-like EPS naturally.	Having outstanding removal capacity; plastics incorporate directly into the matrix of EPS.	(Cunha et al., 2019)
<i>Planktothrix agardhii</i>	Non-ribosomal peptides in the matrix are diverse.	To create plastisphere it interacts with micro-plastic which enhancing toxin stability.	(Toporowska, 2026)
<i>Chroococcus sp.</i>	EPS rich in uronic acids and negatively charged groups.	To facilitate hetero-aggregation it neutralizes surface charges of polystyrene.	(Lestari et al., 2025)
<i>Lyngbya majuscula</i>	Lipo-peptides and high content of lipid in EPS.	MP help in adsorption of hydrophobic pollutants into the biofilm of Lyngbya species.	(Sabat et al., 2025)
<i>Phormidium sp.</i>	EPS fibrous structure with high strength.	In marine sediments form filamentous bridges that trap fragments of Microplastics.	(Mourelle et al., 2025)
<i>Trichodesmium erythraeum</i>	Specific nitrogen-fixing EPS and low ratio of carbohydrate to protein.	Microplastics interfere with buoyancy control by adhering to the specialized EPS tufts.	(Wu et al., 2021)
<i>Fischerella sp.</i>	EPS rich in pigments which are sheath specific (e.g., scytonemin).	In EPS high UV protection enable the species to maintain biofilm growth on plastics in shallow water.	(Gao, 2017)
<i>Limnothrix redekei</i>	EPS (SL-EPS) fractions are highly soluble.	Eco-corona on Nanoplastic forms rapidly and significantly reducing their acute toxicity to zooplankton.	(Khattar et al., 2010)

3. Mechanisms of EPS Mediated Eco Corona Formation

An emergent molecular and surface phenomenon, eco-corona formation on micro and Nanoplastic

in aquatic environments involves the adsorption of extracellular polymeric substances (EPS) secreted by microbes (such as Cyanobacteria, microalgae and heterotrophic communities) onto

the plastic surfaces changing their physicochemical identity and ecological behaviour. EPS are high weight polymers that comprise of polysaccharides, proteins, humic materials, and other functional groups that allow various binding activities with plastic particles.

3.1 Functional Group Interactions and Adsorption Chemistry

Extracellular polymeric substances consist of varied functional groups (carboxyl, hydroxyl, amide, and aromatic groups), which stimulate attachment to plastic surfaces through an assemblage of hydrophobic interactions, π - π electron donor acceptor interactions and electrostatic forces. Researchers working in the context of wastewater have proven that tightly bound EPS (TB- EPS) exhibit better adsorption onto polystyrene Microplastics (PSMPs) compared to loosely bound (LB-EPS) or soluble EPS (S-EPS), meaning that the functional chemical properties of EPS polymers relate to plastic affinity (Wei et al., 2023). The sequence of adsorption in these systems is TB-EPS, LB-EPS, S-EPS which indicates the impact of aromaticity and hydrophobicity on eco-corona assembly (Wei et al., 2023). The physicochemical responses in Cyanobacterial systems are activated by EPS generated during exposure to Microplastic. *Rudolphia* (*Cyanocohniella rudolphia*) soluble EPS (S-EPS) was found to increase with exposure to polystyrene micro-plastic (PSMP) and agglomerate particles in contact through neutralization of charges and bridging interactions, highlighting that EPS is a useful plastic binding organic layer (Rodrigues et al., 2025).

Cyanobacterial EPS is a carboxyl-hydroxyl-amide-aromatic-rich binding protein, which is bound to the micro-plastic surfaces via an electrostatic interaction, hydrophobic interaction, and π interaction. The highest adhesion occurs with tightly bound EPS and soluble EPS supports particle bridging and aggregation which helps in the formation of eco-corona.

3.2 Particle Size, Surface Area, and Binding Dynamics

The formation of eco corona is determined by particle properties like size and surface chemistry. Nanoplastic have a bigger surface to volume ratio, so they have more reactive sites to adsorb EPS compared to larger Microplastics. Although there are specific studies of Nanoplastic on Cyanobacteria, other research on Nanoplastic in marine and aerobic sludge systems indicates that Nanoplastic interactions with EPS can alter the protein secondary structures and flocculation processes, indicating that nanoscale plastics may cause more pronounced EPS binding to change microbial aggregation behaviour (Wang et al., 2023). Besides, the generation of EPS by the algae and Cyanobacteria is usually enhanced by the Microplastics, which further increases the chances of particle coating and hetero-aggregation. In *Anabaena variabilis*, high density polyethylene Microplastics enhanced the production of EPS during stress conditions indirectly, which promoted micro-plastic deposition in aquatic systems (Gopalakrishnan & Kashian, 2023).

3.3 Corona Maturation and Dynamic Restructuring

Eco coronas tend to be precursors of biofilm formation organized microbial colonies that are incorporated within EPS. EPS coated plastic surfaces offer microbial colonization sites, which are termed the plastisphere, the underlying mechanisms by which EPS promotes micro-plastic colonization have been detailed in literature on biofilms on plastics as dynamic niches modulating particle associated properties (e.g., enhanced adsorption and microbial activity). Plastic biofilms also modify the roughness of surfaces, chemical activity, and chemistry between them with other environmental pollutants and essentially function as living eco coronas (Jia et al., 2024).

3.4 Influence of Environmental Stressors on Corona Assembly

The production and composition of eco corona are influenced by environmental factors such as nutrient level, temperature and pollutant stressors that in turn affect the production and

composition of EPS. The higher level of exposure to Microplastic and stressful situations are usually associated with higher levels of EPS release, which increases the potential of plastic biopolymer association. The algal species and Cyanobacteria species show a higher level of EPS production during pollutant stress, which may enhance the process of particle aggregation and vertical transport in aquatic environments (Sun et al., 2020; Gopalakrishnan and Kashian, 2023). These EPS mediated stress responses are important since the eco corona composition has a direct impact on plastic fate; it can impact sinking rates, hetero aggregation with organic matter, interactions with higher trophic levels.

3.5 Functional Consequences of Eco Corona Formation

With the development of an eco-corona, plastic particles change their environmental identity, influencing the transportation of these particles, their bioavailability, and environmental impacts. EPS coatings improve hetero aggregation with natural colloids and organisms, which results in improved sedimentation, and may be incorporated into food webs. Particle surface charge and hydrophobicity are also modulated using eco coronas and may determine pollutant adsorption and microbial colonization behaviour and, therefore, the pollutant cycling and ecotoxicological responses.

Critical Insight:

The formation of eco coronas on micro and nano plastics is affected by complicated molecular interactions that include functional EPS groups, particle surface attributes and environmental stress. Not only does this dynamic process redefine the physicochemical identity of the plastics, but also mediates the ecological fate of the plastics, both by aggregation, biofilm formation and altered transport behaviour.

4. Structural and Functional Changes in Plastics Induced by Cyanobacterial EPS-Mediated Eco-Corona

When Micro and Nano plastics are introduced into water, they quickly react with Cyanobacterial

dissolved biomolecules and extracellular polymeric substances (EPS). This process contributes to the development of an eco-corona which essentially changes the physicochemical and biological behavior of plastic particles. Cyanobacterial EPS are multifaceted combinations of polysaccharides, proteins, lipids, nucleic acids and humic like compounds containing reactive functional groups such as hydroxyl, carboxyl, amide and carbonyl functional groups. These functional groups bind to the surface of the plastic through hydrogen bond, electrostatic, and hydrophobic forces, as well as van der Waals force to create fast surface conditioning (Li et al., 2024; Chin et al., 2024). After some primary adsorption, the eco-corona facilitates the second chemical transformations. Components of EPS that act as photosensitizers may participate in the formation of reactive oxygen species in the presence of light and induce oxidation of the surfaces of polymer and allow the creation of new polar functional groups. It enhances corrosivity and reacts with the surface, and in this manner, more EPS can be deposited and the corona layer becomes stable with time (Li et al., 2024). Biochemical aging changes initially passive surfaces on plastics to chemically reactive interfaces with the ability to strongly react with contaminants and natural organic matter around them. EPS (extracellular polymeric substances) activates the generation of reactive oxygen species (ROS) under the influence of light. These ROS oxidize the plastic surfaces to produce polar functional groups such as -OH, -C=O and -COOH. The oxidized surface subsequently attaches additional EPS and establishes a stable eco-corona that is reacting and interacting with the environment more (Table 02). Biofilm and attachment of microbes are also supported by the EPS coating. The colonization on the conditioned surface by Cyanobacterial cells and other microorganisms entraps them into a structure of EPS that enhances the surface roughness, heterogeneity and effective surface area (Gao et al., 2025). This structural change increases the particle-particle contacts and hetero-aggregation with minerals, organic debris and other Microplastics. More binding sites of dissolved

substances are also provided by increased surface complexity, which further changes the

environmental behavior of plastics (Chin et al., 2024; Gao et al., 2025).

Table 02: Photochemical Mechanism of EPS Mediated Eco-Corona Formation on Microplastics

Phase	Chemical Process	Key Intermediates
Activation	$EPS + h\nu \rightarrow EPS^*_{(excited)}$	Excited State EPS*
ROS Flux	$EPS^* + O_2 \rightarrow {}^1O_2$ (Singlet Oxygen) $O_2 + e^- \rightarrow O_2^{\cdot-}$ (Superoxide) $H_2O_2 + h\nu \rightarrow 2OH^{\cdot}$	${}^1O_2, O_2^{\cdot-}, OH^{\cdot}$
Oxidation	$Plastic + ROS \rightarrow Plastic^{\cdot}$ $Plastic^{\cdot} + O_2 \rightarrow Plastic-OO^{\cdot}$ (-OH, -C=O, -COOH)	Carbonyl/Carboxyl Groups
Binding	$Plastic (Oxidized) + EPS \rightarrow Eco-Corona$	Stable Bio-interface

Note: (*) indicates an excited high-energy state;
 (•) denotes highly reactive free radicals;
 $h\nu$ represents light energy;
 -OH/-C=O/-COOH are oxidized binding sites

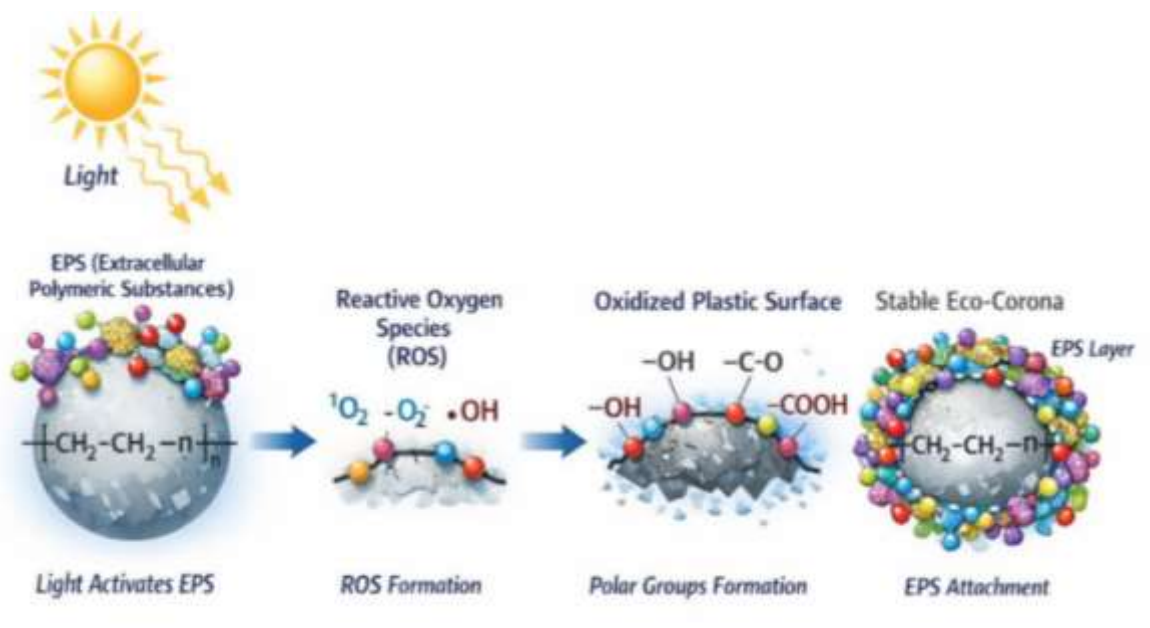


Figure 03: Schematic representation of eco-corona formation on plastic particles

The eco-corona functions in a very powerful way in terms of increasing the adsorption capacity of plastics towards organic pollutants, antibiotics, and heavy metals. The actin of protein rich EPS layers forms a biological readiness of connecting to contaminants by means of electrostatic interaction, hydrogen bonding, and complexation. In the experimental studies, it was demonstrated that biofilm coated Microplastic

adsorb significantly more tetracycline and other organic substances than pristine particles, which means that the formation of the eco-corona enhances the importance of the plastics as the transmitters of contaminants (Fu et al., 2025; Wang et al., 2026). ESP and biofilm also changes the hydrodynamic behavior of plastic particles. The biomass added raises the density of particles and neutralization of charges and bridging among

polymers enhance aggregation. These reactions increase vertical transportation and sedimentation of particles which would be otherwise floating. It has been shown through laboratory experiments that the aggregation and deposition of

Microplastics is substantially enhanced by algal EPS, indicating that the formation of eco-coronas plays a major role in redistributing the plastics of the water column to the sediments (Gopalakrishnan & Kashian 2022).

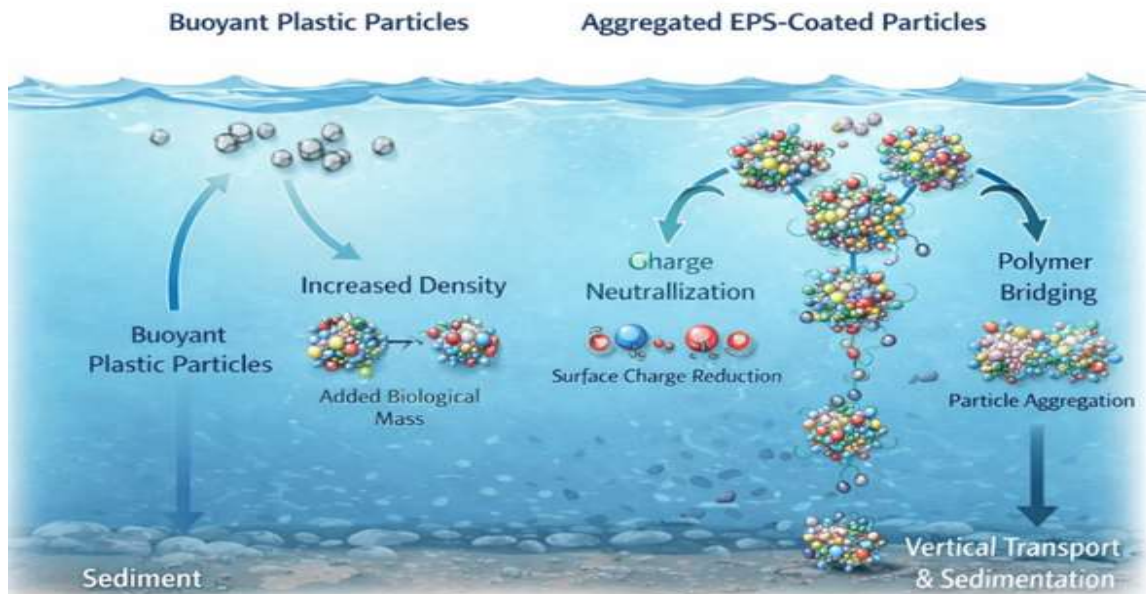


Figure 04: Effect of EPS and biofilm on vertical transport of plastic particles

The eco-corona alters biological interactions besides changes in physical and chemical aspects. There are organic nutrients and signaling compounds in the EPS layer which draw in microbial communities and enhance ecological appeal of the plastics. Alteration of surface roughness, charge and biochemical composition affect ingestion by zooplankton and filter feeders and could result in an amplification of trophic transfer of plastics and their associated contaminants (Chin et al., 2024). These processes are what make the Cyanobacterial EPS alter plastics as mere objects into living and interacting organisms in nature.

Critical insight:

Cyanobacterial EPS mediation of ecological corona formation is a mechanistic engine that also accelerates plastic aging, augments contaminant loading, augments aggregation and sedimentation, and augments ecological interactions, thereby

exacerbating the environmental hazard of Micro and Nanoplastics.

5. Environmental Fate and Transport

5.1 Vertical Distribution and Sediment Accumulation

The interactions between Micro and Nanoplastic (M/NPs) and Cyanobacterial extracellular polymeric substances (EPS) are very strong in water bodies. The EPS adsorbs on the plastic surfaces forming sticky eco coronas that enhances aggregation with other suspended matter in the water, such as particulate organic matter (POM) and natural organic matter (NOM). These heteroaggregates, also known as bio-flocs, enhance the mass of the particles and speed up their sinking, improving the movement of vertical transfers between the surface waters and sediments (Ge and Lu, 2023, Zhu et al., 2025). The eco-corona covered plastics may be buried in sediments and moved to long-term storage, which helps to pollute the environment in the long run.

Metals and organic pollutants also have binding sites on eps coating eco-corona coated plastics,

which makes them reservoirs of related contaminants (Junaid and Wang, 2021).

Table 03: Classification and Chemical Drivers of Cyanobacterial Eco-Corona Formation

Eco-Corona Type	Functional Groups in EPS	Factors	Stress Adaptation	References
Hard Corona have high affinity biopolymer binding to MP surface	Carboxyl (-COOH) essential for surface attachment	Light	Nutrient Limit	(Barone, 2024; Lestari, 2025)
Soft Corona have weak electrostatic interactions.	Amino (-NH ₂) for attraction to negatively charged plastics	Nutrients	Shading as a defensive response induces EPS production.	(Gopalakrishnan, 2023; Madsen, 2023)
Living Corona form metabolically active biofilm layer on the particle	Hydroxyl (-OH) Strong hydrogen bonding	Temperature	Contaminants	(Jin, 2022; Lu, 2022)
Complex Corona is heterogeneous layer with toxins, minerals, and mixed EPS.	Sulfate (-SO ₄) Increase negative charge density of the matrix	MP Type: (PE, PP, PS)	Weathering Provide physical anchor points	(Wu et al., 2021)

5.2 Horizontal Transport and Persistence

Hydrodynamic and turbulence conditions and water chemistry affect the lateral transport of M/NPs. Eco-coronas change the particle surface charge, hydrophobicity and aggregation characteristics, influencing the suspension or sedimentary behavior of plastics (Zhu et al., 2025). Changes in EPS composition and stability of the coating can be caused by environmental stressors as UV exposure or changes in salinity, pH, and further affect particle mobility and persistence in aquatic environments (Ge & Lu, 2023). The processes define the distribution of plastics horizontally and their exposure to the various ecological compartments.

5.3 Role in Biogeochemical Cycling

M/NPs that have been coated with EPS are organic carbon and nutrient carriers that mediate their transport through the water column. The vertical export of carbon and nutrient complexes can be boosted by the association of plastics, which can affect the biogeochemical cycles and

potentially modify the productivity of the ecosystem (Ge & Lu, 2023). As well, EPS facilitates aggregation with particulate organic matter and form complex flocs, which settle faster and cause carbon fluxes in aquatic systems (Junaid and Wang, 2021).

5.4 Food Web and Transfer

M/NPs have eco-coronas, which enhance their chances of ingestion by both the zooplankton and benthic organisms. EPS layer has the ability to replicate natural food particles and increase palatability and uptake. After being ingested, adsorbed contaminants are likely to be transmitted by the plastics, further endangering the biomagnification through trophic levels and bioaccumulation (Rodrigues et al., 2025). This brings to the fore the role of eco-coronas in altering the exposure routes as well as the ecological risk presented by plastic pollution.

Critical Insight:

One of the most important factors of plastic environmental fate is eco-corona formation. Not

only it controls the vertical and horizontal transportation, but also determines the sedimentation, persistence, and biota interactions. Knowledge of such interactions is needed in predicting ecological exposure, dynamics of contaminants, and long-term effect of plastics in water bodies.

6. Implications for Harmful Algal Blooms (HABs)

6.1 Plastics as Physical Scaffolds for Cyanobacteria

Micro and Nanoplastics (M/NPs) in the water bodies give an attachment point to Cyanobacteria, which form aggregates. Cyanobacterial extracellular polymeric substances (EPS) cause adhesion to plastic surfaces forming stable Cyanobacterial plastic aggregates, which positively affect cell clustering and colony formation in their role as physical scaffolds (Gopalakrishnan and Kashian, 2023). All these aggregates may remain in surface waters, which serve as microhabitats and support the growth of Cyanobacterial proliferation.

6.2 Influence on Bloom Formation and Persistence

Contacts between Cyanobacteria and plastics have the ability to alter the dynamics of the bloom. Low levels of plastics can enhance the growth of species like *Anabaena variabilis* as it offers them extra carbon sources but in high concentration, stress responses may develop that cause high EPS production (Gopalakrishnan and Kashian, 2023). Increased EPS leads to aggregation, decreases the rate of sinking of Cyanobacterial colonies and increases the residence time in the photic zone, furthering the persistence of the bloom (Huang et al., 2025).

6.3 Effects on Toxin Dynamics

Cyanobacterial masses generate toxins like microcystins which are hazardous to the environment and human health. Research suggests that the formation of eco-corona around M/NPs is capable of enhancing per cell synthesis and extracellular discharge of microcystins which stabilize toxin containing aggregates in the surface

waters. Moreover, plastics have the ability to adsorb cyanotoxins, which can serve as a carrier of toxins over a longer distance, thereby exposing other organisms to further exposure and leading to bioaccumulation (Pestana et al., 2021).

6.4 Feedback Between Plastic Pollution and HABs

Plastic pollution and HABs could enter into a positive feedback loop. Cyanobacterial blooms cause high amounts of EPS that improves the formation of eco-coronas on plastics. The EPS coated plastics, in their turn, stabilize Cyanobacterial aggregates, leading to a greater bloom persistence or intensity in eutrophic waters. Such a loop can lead to an increase in the rates and intensity of bloom in the nutrient enriched as well as the plastic contaminated areas (Gopalakrishnan and Kashian, 2023; Huang et al., 2025).

Critical Insight:

The eco-coronas that are mediated by EPS on Micro and Nanoplastic stabilize Cyanobacterial aggregates, yielding a positive feedback which maintains harmful algal blooms and increases the transport of toxins (Gopalakrishnan and Kashian, 2023; Huang et al., 2025). This implies that besides being a pollutant, plastics have an active role in promoting the formation of blooms as well as ecological exposure, and their impact in the dynamics of HABs is significantly underestimated.

7. Analytical Techniques Eco Corona Study

The study of eco-coronas on Micro and Nanoplastic demands various analytical methods to demonstrate morphology and chemical composition in addition to molecular characteristics. Other microscopy methods are also typically used to illustrate plastics and any coating stored on them in more detail by using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) as the methods of choice (Huang et al., 2023; Mariano et al., 2021). Both vibrational spectroscopy like Fourier transform infrared (FTIR) spectroscopy and Raman spectroscopy are required to determine the type of polymers and the functional groups; FTIR can be utilized to chemically

fingerprint Microplastic and organic coating and Raman spectroscopy can be used to complete high resolution molecular data (Huang et al., 2023; Mariano et al., 2021; Zea Cobos et al., 2024).

Spectroscopic methods are also sensitive to the changes in spectral characteristics in the presence of eco-coronas in the natural colloids or EPS into which they affect the intensities and patterns of the peaks (Mariano et al., 2021; Athulya and Chandrasekaran, 2023). Polymer identification and determination Mass spectrometry and thermal analysis (e.g., pyrolysis GC/MS) can be used to identifying and quantify polymer products of thermal decomposition that can provide sensitive chemical discovery of polymer compared to vibrational techniques (Huang et al., 2023). Fluorescence based methods like Nile Red staining make it much easier to visualize and count plastics in complicated samples and possibly help differentiate organic coatings and the plastic substrate (Zea Cobos et al., 2024). Collectively, the methods offer complementary information on the formation of the eco-corona, its composition, and its effects on its detectability in an analytical and environmental behaviour.

Critical Insight:

Microscopy, spectroscopy, and molecular technologies must be combined to comprehend formation and composition of eco-corona completely because compared to single methods, none of them can provide the intricacy of the plastic and EPS interactions. This underscores the fact that analytical methods should be multiscale in order to determine ecological effects and environmental behaviour of Micro and Nanoplastic.

8. Knowledge Gaps and Future Directions

Nevertheless, there is still a wide knowledge gap in the area of eco-coronas of Cyanobacteria EPS on Micro and Nanoplastic. Majority of the studies concentrate on the model species, including *Microcystis aeruginosa* and *Anabaena variabilis*, but the composition of EPS differs broadly among Cyanobacteria and impacts the particle aggregation, biofilm formation, and contaminant binding (Song et al., 2023; Zhu et al., 2025). The

field scale studies have not been conducted on a long-term basis and thus, the interactions among the seasons, space, and microbial community are not well understood (Ge & Lu, 2023; Junaid and Wang, 2021). In experiments, the clean plastics are commonly used, whereas natural waters can be characterized by mixed types of plastics that are weathered, which affects EPS adsorption, corona stability, and interactions between the pollutants (Li et al., 2024; Huang et al., 2025). Besides, EPS production and eco-corona formation are subject to environmental stressors like temperature variations, UV radiation, salinity variations, nutrient enrichment, and climate change, although their interaction is manifested in few and little characterized aspects (Gopalakrishnan and Kashian, 2023; Sun et al., 2020). Lastly, there are no predictive models associating EPS characteristics, plastic types, and dynamics of the blooms at the ecosystem scales (Zhu et al., 2025; Huang et al., 2025). The combination of multispecies EPS data, realistic plastic types, environmental stressors, and field observations into predictive frameworks is the key to the assessment of ecological, toxicological effects, the enhancement of risk assessment, and to the management of Micro and Nanoplastic pollution of HAB prone waters.

9. Conclusion

The eco-corona formation caused by Cyanobacterial EPS is the key to a fundamental change in the environmental identity and behavior of Micro and Nanoplastics in aquatic ecosystems. EPS enhances aggregation, sedimentation, biofilm growth and contaminant adsorption and conversion of inert particles into biologically active particles and by coating plastic surfaces effectively. These interactions do not only alter plastic transportation and persistence, but also allow its inclusion within food webs and enhance the severity and spread of harmful algal bloom. In spite of mechanistic progress, the key gaps in the species specific EPS characterization, field dynamics over the long-term, plausible plastic types and interactive processes of multiple environmental stressors persist. A combination of multispecies EPS profiles, plastics that are


environmentally relevant, and ecosystem scale observations will be needed in the future to predictive modeling, risk assessment, and mitigation of future efforts. Generally, Cyanobacterial EPS may be considered a primary driver of the interrelationship between Micro and Nanoplastics pollution and the ecological impact, which is why Micro and Nanoplastics should be reflected on as an active point of the aquatic biogeochemical cycle rather than an inert pollutant.

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