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REVIEW ARTICLE

# Microplastics removal strategies: A step toward finding the solution

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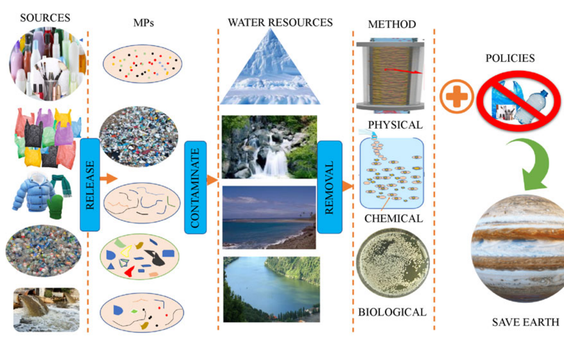
## HIGHLIGHTS

- Physical, chemical and biological methods are explored for MPs removal.
- Physical methods based on adsorption/filtration are mostly used for MPs removal.
- Chemical methods of MPs removal work on coagulation and flocculation mechanism.
- MBR technology has also shown the removal of MPs from water.
- Global policy on plastic control is lacking.

## GRAPHIC ABSTRACT

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## ABSTRACT

Microplastics are an emerging threat and a big challenge for the environment. The presence of microplastics (MPs) in water is life-threatening to diverse organisms of aquatic ecosystems. Hence, the scientific community is exploring deeper to find treatment and removal options of MPs. Various physical, chemical and biological methods are researched for MPs removal, among which few have shown good efficiency in the laboratory. These methods also have a few limitations in environmental conditions. Other than finding a suitable method, the creation of legal restrictions at a governmental level by imposing policies against MPs is still a daunting task in many countries. This review is an effort to place all effectual MP removal methods in one document to compare the mechanisms, efficiency, advantages, and disadvantages and find the best solution. Further, it also discusses the policies and regulations available in different countries to design an effective global policy. Efforts are also made to discuss the research gaps, recent advancements, and insights in the field.



## 1 Introduction

Plastic waste spreading around our planet has become one of the biggest concerns of this century (Barnes et al., 2009). The global production of plastic is more than 335 million tons per year while recycling is much less than the generated plastic waste and accounts for only 9% of the total plastic waste discarded (Geyer et al., 2017; Lv et al., 2019). Dumped plastic waste gets transported throughout the environment by wind, rivers, tides, storm drains, rainwater, floods, industrial runoff, and sewage disposal to the different aquatic ecosystems (Ryan et al., 2009). These then get converted into smaller size plastic particles by various physical, chemical, and biological actions (Arthur et al., 2009; Dudas et al., 2018). Based on their size, plastic particles are labeled into different categories including viz. macro-plastics (>25 mm), meso-plastics (5–15 mm),

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microplastics (< 5 mm), and nano-plastics (< 100 nm) (Arthur et al., 2009; Bergmann et al., 2015). Manufactured MPs, like microbeads, enter directly through the wastewater effluent, and are grouped as primary MPs. On the other hand, plastics that are formed during the process of breakdown from solid plastic waste into smaller particles are considered as secondary MPs (Ballent et al., 2016; Auta et al., 2017). MPs are also released from different activities conducted at point and diffuse sources (Siegfried et al., 2017), such as the washing of clothes, using beauty products like scrubs, household waste, domestic release, agricultural activities, industrial processes, and open dumping (Bhattacharya, 2016; Napper and Thompson, 2016).

Several works have illuminated the presence of MPs in soil (Rillig et al., 2017; Scheurer and Bigalke, 2018; Lehmann et al., 2019; Guo et al., 2020), sediment (Van Cauwenberghe et al., 2013; Karlsson et al., 2017; Peng et al., 2017; Zhao et al., 2018; Mani et al., 2019; Yuan et al., 2019; Chauhan et al., 2021), water (Karlsson et al., 2017; Yuan et al., 2019; Rowley et al., 2020; Chauhan et al., 2021) , and aquatic organism (Karlsson et al., 2017; Yuan et al., 2019). Tons of plastic litter is discarded every year into the different surface water sources. Waste water treatment plants that discharge the effluent mostly to the surface water bodies play a major role in the spread of MPs (Sol et al., 2020). The wastewater that reaches water bodies is either pretreated or untreated and acts as potential source of MPs. In screening systems (pretreatment), macroplastics are removed and generally larger MPs are removed during the wastewater treatment. Additionally, only a small number of larger MPs (commonly microfibers) are detected in effluent. (Carr et al., 2016; Murphy et al., 2016; Sun et al., 2019). Since there are no definite treatment techniques implemented for the MPs removal in a treatment plant, even treated water has some residual MPs (Ali et al., 2021). The treatment stages of wastewater treatment processes significantly decide the fate and journey of MPs in any treatment plant (Blair et al., 2017). The removal efficiency of different treatment stages in treatment plants are approximately 78%–98% at primary stages, 7%–20% at secondary stage and >7% at tertiary treatment. Although treatment plants are showing a high efficiency rate for MPs removal, smaller MPs continue to remain undetected and easily enter the environment (Masiá et al., 2020).

Considering all these facts, there is a need for restricting and filtering out MPs by implementing suitable treatment or removal method. Though several laboratory researchers have developed removal methods for MPs from water and wastewater, still no large-scale treatment exist to remove MPs from the environment. This review discusses all the significant scientific contribution in the field of MPs treatment and removal approaches done to date, so that scientist can extract valuable information and find solutions to improve upon the problem of MPs.

## 2 Microplastics as an emerging threat

Plastic particles have invaded almost every ecosystem of the earth and their significance can be marked by the fact that they are even seen in drinking water (Pivokonsky et al., 2018; Mintenig et al., 2019; Zhang et al., 2020b), rainfall (Xia et al., 2020), air (Gaston et al., 2020; Zhang et al., 2020), polar ice (Kelly et al., 2020), and common salt (Zhang et al., 2020). Most of the used plastics are non-biodegradable and thus can persist and accumulate in great extent under natural spaces or landfills for years or centuries (Barnes et al., 2009). It is estimated that annually more than 8 million tons of plastic is being discarded to the seas and oceans, and at this pace, plastic waste by mass will surpass the amount of fish present in the aquatic systems by 2050 (Macarthur, 2017; Pico et al., 2019). MPs are considered more potent because they can be easily ingested by the aquatic organisms (Dowarah et al., 2020). However, the health consequences and biological effects of MPs and nano-plastics are still poorly understood at mass levels. In an aquatic ecosystem, MPs have been detected at every level of the food chain starting from producers and up to top consumers. The presence of MPs indicates its ability to bioaccumulate and biomagnify (Batel et al., 2016). The bioaccumulation of MPs has shown negative effect in many organisms such as phytoplankton (Mao et al., 2018), zooplanktons (Botterell et al., 2019), fishes (Lusher et al., 2013; Wang et al., 2017), mollusks (Li et al., 2015; Paul-Pont et al., 2016; Su et al., 2018), and even in humans (Liebmann et al., 2018; Wang et al., 2018; Prata et al., 2020). A recent study has marked the presence of MPs in human placenta indicating its potential to reach any part of body (Ragusa et al., 2021). MPs are also known to adsorb and accumulate all sorts of persistent organic pollutants, heavy metals, and hydrocarbons on their surface by different mechanisms, namely hydrophobic interactions, electrostatic interaction, $\pi$-$\pi$ interaction, hydrogen bonding, pore filling and van der walls forces (Torres et al., 2021). The adsorbed substances are further transported throughout the bodies of living organisms and the interactions of the adsorbed substances result in health abnormalities, complexities, and even death (Endo et al., 2005; Rios et al., 2007; Teuten et al., 2009; Wardrop et al., 2016; Hermabessiere et al., 2017; Wang et al., 2018; Li et al., 2019). Research also indicates that MPs have the ability to carry pathogens attached to their surface (Padervand et al., 2020). The common effects of MPs on aquatic organisms include blockage of the intestinal tract, choking, increases exposure to chemicals, and a decline in food consumption (Endo et al., 2005; Clark et al., 2016).

## 3 Microplastics removal from water

Most of the water bodies in the world have been contaminated by the MPs, and due to their omnipresence, it has become increasingly difficult to remove them from water sources by normal processes. To control the level of MPs from the water, we need to restrict the running MP transport chain. Basically, two systematic approaches should be considered for combating MPs pollution. The first approach incorporates stopping or minimizing further MP deposition in bodies of water, and the second approach deals with the removal of MPs already present in the water. In this article we will discuss the available techniques and methods of MP removal from water in detail. These various treatment techniques can be categorized by type and location of the treatment, *in-situ* and *ex-situ* treatments.

Methods where MPs are removed/reduced in the natural water bodies are considered as *in-situ* methods. Examples of *in-situ* methods include auto filtration systems in water bodies (Chen et al., 2020), bioremediation using different organisms that act as an active sink for MPs (Martin et al., 2019), and magnetic micro submarine methods (also can be used *ex-situ*) (Sun et al., 2020b). On the other hand, methods in which water is treated in an artificial setting are considered as *ex-situ* method. *Ex-situ* methods include treatment in the laboratories and water treatment plants. Both, *in-situ* and *ex-situ* methods used for removal of MPs can further be classified into physical, chemical, and biological methods on the basis of mode of treatment (Fig. 1).

Due to the lack of literature on *in-situ* methods, this review majorly focuses on *ex-situ* methods specifically used in waste water treatment plants and in laboratories to cut the supply of MPs to the water bodies. According to the available research to date, we observed that physical methods are explored more followed by chemical and biological methods. The percentage of available research on physical, chemical, and biological methods were 45%, 31%, and 24%, respectively. This review mainly discusses in depth those methods with a high efficiency (approx. or more than 90%) of treatment.

### 3.1 Physical methods of removal

Most of the research that generally follows physical principles like adsorption, filtration, sedimentation etc. are categorized under physical methods (Table 1). Most of these methods were verified in laboratory settings. From the various physical approaches, high efficiency methods used for the removal of MPs were biochar, adsorbent magnetic polyoxometalate-supported Ionic Liquid Phases, magnetic carbon nanotubes, electrocoagulation, rapid sand filter and dissolved air flotation, sponge made of Chitin and graphene oxide, zirconium metal organic framework-based foam, a non-fluorinated superhydrophobic aluminum surface method, and coagulative colloidal gas aphrons (Table 1).

Filtration is a basic mode that is commonly employed for removal of MPs from water and wastewater. Simon et al. 2019 used a disc filter designed with 13 discs of polyester mesh with a pore size of 18 µm that removed 89.7% MPs of size >10 µm. Particles from wastewater are retained by the filter mesh and progressively form a sludge cake on the filters' surfaces. However, the efficiency of this method was reduced by large size plastics that accumulated over the filters and blocked the pores (Simon et al., 2019). Similar study by Talvitie et al.,2017 show a variation in the efficiency of filter ranging between 40%–98.5% (Talvitie et al., 2017). Another type of filter i.e. the rapid sand filter is capable of removing all kinds of MPs by the sand grains and is considered as a good filtration method. Rapid sand filters are made from layers of sand made up of 1 mm of gravel with grain size of 35 mm and 0.5 m of quartz with grain size 0.1e-0.5 mm. This method is effective on MPs of size >20 µm and is low-cost effective technique. Dissolved air flotation is another physical technique for MPs removal from water (Talvitie et al., 2017). In this method air is dissolved at a high pressure in water that results in formation of bubbles. These bubbles attach solid

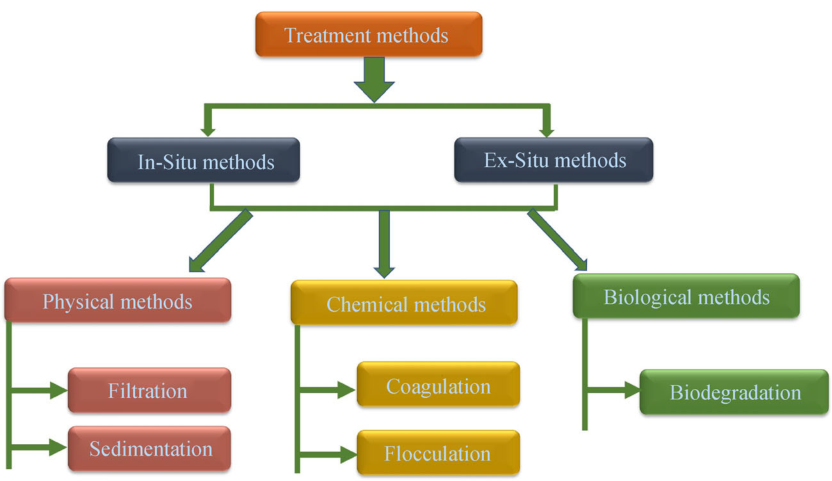


**Fig. 1** Basic classification of MPs removal methods.

**Table 1** Physical methods for removal of MPs.

| Sr. No. | Method | Principle | Target MPs | | Efficiency | Reference |
|---|---|---|---|---|---|---|
| | | | Type | Size (μm) | | |
| 1. | Sponge made of Chitin and Graphene oxide | Adsorption | Polystyrene, carboxylate-modified polystyrene and amine-modified polystyrene | _ | 89.8%, 72.4%, and 88.9% for neat polystyrene, carboxylate-modified polystyrene, and amine-modified polystyrene respectively | Sun et al., 2020a |
| 2. | Zirconium metal-organic frameworks-based foam | Filtration | All MPs | _ | 95.5±1.2% | Chen et al., 2020 |
| 3. | Conventional dissolved air flotation and Positive modification | Hydrophilic/ Hydrophobic interaction and charge attraction | Polyethylene, Polyethylene terephthalate, Nylon 66/PA66 | _ | 32%–38% at 0.4–0.5 | Wang et al., 2021 |
| 4. | Magnetic Polyoxometalate-Supported Ionic Liquid Phases | Adsorption | Polystyrene | 1 and 10 | Over 90% | Misra et al., 2020 |
| 5. | Biochar Adsorbents (pine and spruce bark biochar) | Adsorption | All MPs | _ | 100% (Polyethylene particles) and nearly 100% (fleece fibers) | Siipola et al., 2020 |
| 6. | A non-fluorinated superhydrophobic aluminum surface | Adsorption | Polypropylene | 262±4 | 99% | Rius-Ayra & Llorca-Isern, 2021 |
| 7. | Biochar filters | Adsorption and filteration | Polystyrene MPs spheres (microbeads | 10 | above 95% | Wang et al., 2020b |
| 8. | Biofilter | Gravitational filter | All MPs | >100 | 79%–89% | Liu et al., 2020 |
| 9. | Magnetic micro-submarines | Induced fluid flow field | All MPs | 40 | 70% | Sun et al., 2020b |
| 10. | Magnetic carbon nanotubes | Adsorption | All MPs | _ | 100% | Tang et al., 2021 |
| 11. | Primary Sedimentation | Gravitational settling | All MPs | MPs with high density | 40.7% | Liu et al., 2019 |
| 12. | Disc filter | Retention | All MPs | >10 | 89% | Simon et al., 2019 |
| 13. | Electrocoagulation | Flocculation and settling | Polyethylene microbeads | 300 – 355 | 90% – 100% | Perren et al., 2018 |
| 14. | Rapid sand filter | Filtration | All MPs | >20 | 97% | Talvitie et al., 2017 |
| 15. | Dissolved air flotation | Flotation | All MPs | >20 | 95% | |
| 16. | Disc filter | Retention | All MPs | >20 | 40%–98.5% | Talvitie et al., 2017 |
| 17. | Coagulative colloidal gas aphrons | Adsorption | Carboxyl-modified poly-(methyl methacrylate) and unsurface-coated polystyrene | 5 | 94% | Zhang et al., 2021 |

particles on its surface (including MPs), which are later removed by skimmers (Bui et al., 2020). The use of Polyaluminium Chloride increases the process of flocculation. This method shows an efficiency of 95% and is best for removing low-density particles.

Apart from simple sand filters, another kind of filter that tested positive for MP removal is Biochar. Biochar filters also work on the simple principle of adsorption and filtration. The large size pores of biochar filters are responsible for the retention of MPs. The rough surface of filter supports the physical adsorption of MP between the biochar particles. These experiments were conducted using the activated carbons that showed good efficiency. The non-activated biochar is also considered for the removal of larger MPs. Biochars is a less expensive way of removing MPs from wastewaters but a more detailed knowledge is required about the mechanisms of MP removal (Siipola et al., 2020). Biochar used for removal of MPs in different researches were made from various substances like corn, hardwood, pine, spruce barks etc., alone or in combination by the process of pyrolysis (Siipola et al., 2020; Wang et al., 2020b). The biochar basically worked as filter that separates MPs by adsorbing, trapping, and entangling them on its surface (Wang et al., 2020b) (Fig. 2). Moreover, it has been observed that most of the biochar filters have shown good efficiency in removing MPs under different conditions. Biochar adsorbents made up of pine and spruce bark biochar have proved effective with an efficiency of 100% in removing MPs. Even with low surface area, this method proved to have a high adsorption capacity. But they are only tested for polyethylene particles and fleece fibers. Additionally, this method was effective only for the larger particle size and was not significantly reducing the micrometer-scale MPs particles (Siipola et al., 2020). A comparison study between simple sand filter and biochar filter was conducted to assess their potential for removal of MPs (Wang et al., 2020b). The biochar filter was made from corn straw and hardwood while the sand filter was made from silica sand. Both sand filter and biochar basically trap and entangle MPs in their structure. The biochar showed above 95% removal efficiency for fine (approx. 10 μm) size polystyrene MPs spheres (microbeads) while the sand filter showed an efficiency of 60%–80%. This indicates that biochar filters are a better option for removal of MPs as compared to sand filters (Fig. 2) (Wang et al., 2020b).

Few adsorbents that showed potential in removal of MPs are sponges and foams made from different chemical constituents. A sponge formed by chitin and graphene oxide effectively adsorbed various types of MPs (neat polystyrene, carboxylate modified Polystyrene and amine modified polystyrene) from water (Sun et al., 2020a). The efficiency ranged between 70% and 90%, and the adsorption process was mostly pH dependent. The best performance occurred at pH 6 while lowest performance happened at pH 10. Moreover, reusability, biocompatibility, and biodegradability were the key features of this sponge that enhanced its suitability for treatment of MPs. Recent interesting research implementing Zirconium metal-organic frameworks-based foam (Zr-MOF) has attracted researchers working on MPs (Chen et al., 2020). This method is based on filtration. This method was tested in laboratory and found to be successful in achieving the targets of removing MPs. A series of Zr-MOFs based foam materials made using acetone assisted method in which certain quantity of metal salts and ligands were mixed in acetone and stirred at room temperature to get homogenous solution. It was than autoclaved with a Melamine Foam of approx. 1cm thickness. After this solvothermal process, Zr-MOF was synthesized and loaded onto Melamine foam. This method was extended into various functional Zr-MOF systems with well-tuned MOF loadings. Integrated Zr-MOF based foam materials possess high uniformity, durability, and robustness which can efficiently remove MPs. Further it is suitable for different concentrations of simulated MPs suspension. Among all suspensions, UiO-66-OH@MF-3 was found efficient to remove MPs (up to 95.5%) and can be used efficiently up to 10 cycle sand also for a large quantity filtration. To assess its effectiveness in ambient conditions, it is also tested in the simulated seawater condition. Results show a slight decrease of approximately 1%–2% in removal efficiency of poly(vinylidenefluoride) based MPs when compared with that in water. Based on the success of this method, the author has proposed an automatic filtration system which works on solar power. A platform-based system which includes a filtration unit, pump, and a photovoltaic array were assembled together to form a flotation system for the sea. The energy for the pump will be provided by the photovoltaic cells by capturing solar energy in the sea. The pumped seawater containing MPs will be filtered through the filtration units and the resulted clean seawater will drained back to the sea. This technology is suggested after testing it in simulated conditions in laboratory (Chen et al., 2020).

To make these frameworks, a fluffy and porous melamine foam substrate was used having properties of robustness, stability, and high flexibility. The substrate was

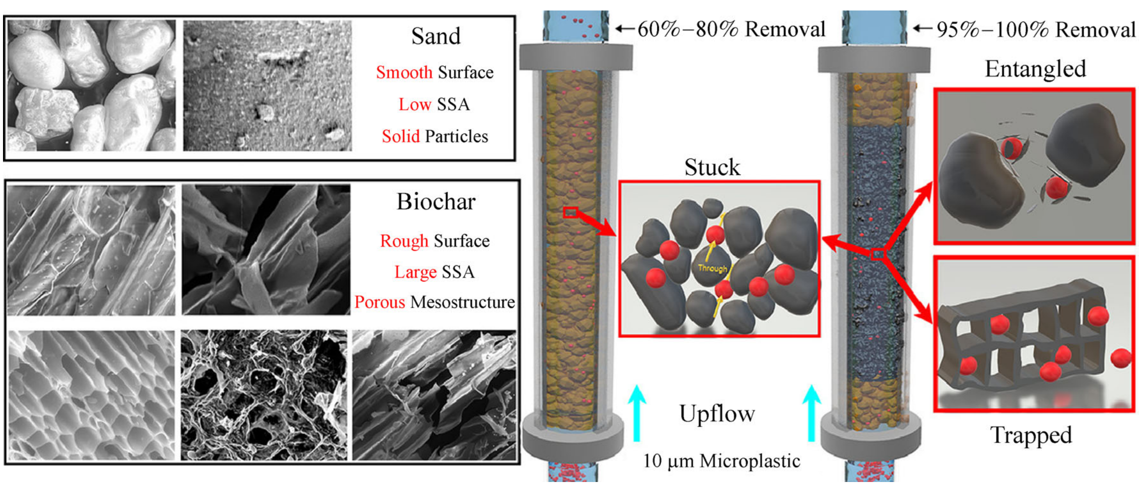


**Fig. 2** Comparison of sand filter and biochar filter. Reproduced with permission from the ref. (Wang et al., 2020b). Copyright 2020 Elsevier.

loaded with stable zirconium metal-organic frameworks. The prepared foam having interpenetrated pores, high metal-organic frameworks uniformity, and wide durability, showed successful MPs removal (95%) in water or seawater conditions (with a slight decrease). This method has shown its capability of removing numerous categories of MPs in suspension with different concentrations. Apart from this, the foam was reusable as it performed up to 10 cycles and can be used to filter large volume of water. This method can serve to remove MPs from bodies of water like rivers, lakes, oceans, etc. (Chen et al., 2020).

Other than adsorption, a charge-based mechanism for coagulation of MPs has also been implemented recently. Electrocoagulation is an electrochemical treatment process used in various wastewater treatment plants (Perren et al., 2018). The process uses electric charge to destabilize and aggregate suspended particles such as heavy metals, MPs, and colloids present in water. An electro-chemical cell with an anode and a cathode, stimulated by a DC power source, is the basic unit of electrocoagulation (Fig. 3). This process separates flocculated materials from water and makes it clean by settling the flocculated material. This method was found effective as it has shown more than 90% removal efficiency for microbeads. This method depends on metal electrode for coagulation. The characteristics of wastewater often disturb the efficacy of this method, but it responded well over a wide range of pH (i.e., pH 3 – 10). Thus, this wide range of pH tolerance supported the efficiency of electrocoagulation method. This method has lots of benefits like low capital cost, low energy efficiency, produces a minimum amount of sludge, and also possesses high efficiency. The presence of high amount of $Cl^-$ ions in wastewater, however, has a slight effect on the removal capacity (Perren et al., 2018).

The adsorption approach is efficient but requires detailed research on size of MPs and also on the adsorbent materials used in the process. A physical separation approach based on adsorption mechanism named as Magnetic polyoxometalate-supported ionic liquid phases is also a good removal technique for MPs (Misra et al., 2020). Other than removing MPs, it also screens organic, inorganic, and microbial pollutants and can be optimized for a large volume of water at an instance. This method successfully removed polystyrene type of MPs of size of 1 and 10μm with a 90% efficiency. Particles from polyoxometalate-supported ionic liquid phases bind with MPs, which can then easily be removed with the help of magnet. Similarly, another advanced method comprising of magnetic carbon nanotubes (M – CNTs) as adsorbates have been designed to remove MPs. The MPs were segregated from water by use of permanent magnets. It effectively adsorbed polyethylene terephthalate, polyethylene, and polyamide type of MPs with 100% efficiency. Furthermore, all the MPs/M – CNTs composites were easily separated from the solutions by magnetic force. The maximum adsorption capacities for polyethylene, polyamide, and polyethylene terephthalate, were 1650, 1100 and 1400 mg-M – CNTs $\cdot$ $g^{-1}$, respectively. Reusability of magnetic carbon nanotubes was also possible, but the efficiency slightly decreased with number of times used. Still, the performance of M – CNTs was impressive with approx. 80% removal of total MPs from the testing solution (Tang et al., 2021). The working mechanism of carbon nanotubes has high removal efficiency and effective ability of recycling.

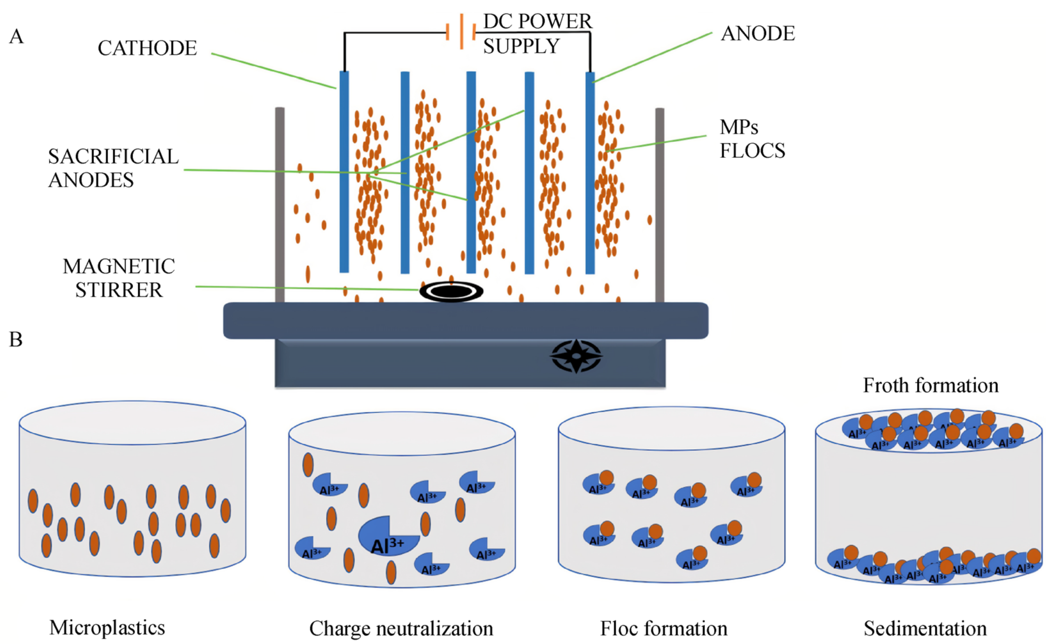


**Fig. 3** (A) Illustration of electrocoagulation reactor setup. (B) Diagrammatic representation of the process of electrocoagulation.

In a recent method a superhydrophobic surface was developed by adding anodization and the liquid-phase deposition of lauric acid for MP removal from saline water. The surface was designed with anticorrosion properties and abrasion resistance to enhance MPs removal efficiency. This method shows a efficiency 99% for MPs removal from the NaCl aqueous solution (Rius-Ayra and Llorca-Isern, 2021). Coagulative colloidal gas aphrons is a unique technique which remove the MP particles of size ~5 μm in diameter with efficiency over 94%. The efficiency of MPs removal was not affected by high salinity like in case of river water or wastewater. So, this study is futuristic method that could be implemented in natural conditions for removing micron size MPs (Zhang et al., 2021).

Various other methods are also explored by the scientists for removal of MPs, but they were found comparatively less efficient. These less effective removal methods included Ultrafiltration (42%), Magnetic micro submarines (70%), Conventional dissolved air flotation and positive modification (32%–38%), and Biofilter (79%–89%) (Table 1). These methods are also beneficial but still more research is required to improve the efficiency and make the methods compatible under different sets of environmental conditions.

Several methods and new approaches are coming into focus in the field of removal of MPs. Among discussed methods, filtration and adsorption-based methods have shown good efficiency for the treatment of MPs-containing wastewater, mainly in combination with other procedures such as biological and sedimentation processes (Padervand et al., 2020). Such methods are easy to implement independently or in any wastewater treatment plant. Biochar filters are easy to make and implement and is a low-cost high efficiency technique. Also, on comparison with sand filters it holds an upper hand in removal of MPs. Sponge made of Chitin and Graphene oxide is also a good option because of their merits like reusability, biocompatibility, and biodegradability. Likewise, Zirconium metal-organic framework-based foam has considerable scope in the field of MPs removal. All these methods are recommendable. But, apart from these methods, some new methods like Superhydrophobic surface, Magnetic Polyoxometalate-Supported Ionic Liquid Phases, A non-fluorinated superhydrophobic aluminum surface, Magnetic carbon nanotubes, and Electrocoagulation are also good options. Few advantages and disadvantages of the physical methods are discussed in Table 2. All of these mentioned methods, however, have some limitations themselves. Thus, more research in real-time scenarios is recommended in all established methods and new approaches.

### 3.2 Chemical methods of removal

Chemical methods involve use of chemicals that either react to transform or breakdown MPs into simpler forms or make floc or show adhesion and thus get removed, by filtration or other techniques from water. Under chemical methods those methods are categorized where chemicals were used in treatment/removal of MPs. The basic principle behind chemical addition involves aggregation, agglomeration, and floc formation that makes MPs suitable for sedimentation or filtration.

Coagulation and flocculation are some of the important mechanisms mostly tested for removal of MPs. Coagulation/flocculation process mainly focuses on segregation of colloidal particles present in the solution by neutralizing their charge, making flocs, and removing them by sedimentation or filtration (Bratby, 1980; Zhou et al., 2021) (Fig. 4). Different types of chemicals or chemical mixtures are used by researchers to enhance the efficiency of coagulation and flocculation process (Table 3). One of the best examples is the mingling of iron, aluminum, and polyamine that were employed for MPs removal (Rajala et al., 2020). This method had a maximum efficiency of 99.4%, and it was reported that ferric chloride and poly aluminum chloride were more efficient than polyamine for removal of MPs. In another research, an alum together with cationic polyamine-coated sand works on the mechanism of coagulation and flocculation and results in 92.7% efficiency for polyethylene of size 10–100 μm (Shahi et al., 2020). Alum, itself is a good coagulating agent but it was observed that the removal was enhanced by 26.8% with the fusion of cationic polyamine-coated sand with alum. The removal of MPs from the water also was found to depend upon the morphology of the particles and follows the separation behavior such as elongated-rough>elongated-smooth>spherical-rough>spherical-smooth. This pattern confirms that elongated-rough particles get removed more efficiently and spherical-smooth show less efficient removal (Shahi et al., 2020). Therefore, it is evident that the above-mentioned method is not efficient for the MPs with small-smooth-spherical characteristic and smaller MPs.

Ma et al. (2019) treated polyethylene MPs by using Al and Fe based salts with the same coagulation and flocculation mechanisms. Al-based salts resulted better in polyethylene removal than Fe-based salts. Moreover, water conditions such as ionic strength, turbidity, and concentration of organic material do not significantly affect the efficacy of polyethylene removal due to its stable chemical nature. This method is only verified for drinking water treatment plants and the results can be different in the case of waste water. Thus, this kind of method needs more research before implementing as a removal method for MPs since pollutant load in the waste water will be much more (Ma et al., 2019). Recently, in a study by Zhou et al. (2021) ( polyaluminum chloride and ferric chloride were used as coagulant in removal of MPs from wastewater. The mechanism involved in this method is that negatively charged particles present in the wastewater are attracted by the positively charged coagulants (polyaluminum chloride and ferric chloride) which finally settle at the bottom by

**Table 2** Comparison of advantages and disadvantages of different methods.

| Methods | Advantages | Disadvantages | References |
|---|---|---|---|
| Physical methods | | | |
| Sponge made of Chitin and Graphene oxide | Reusability, biocompatibility and biodegradability of the sponge enhance its suitability for treatment of MPs | Difficult to scale up. | Sun et al., 2020a |
| Zirconium metal-organic frameworks-based foam | High efficiency in water or seawater conditions (with slight decrease).<br>Capable of removing numerous categories of MPs with different concentration from the MPs suspension.<br>Recyclable Foam.<br>Can be run on solar power. | Only tested in laboratory so, large-quantity filtration tests are essential for the practical applications. | Chen et al., 2020 |
| Dissolved air flotation | High efficiency. | Only remove low-density particles. | Talvitie et al., 2017; Wang et al., 2021 |
| Magnetic Polyoxometalate-Supported Ionic Liquid Phases | It can screen organic, inorganic, and microbial pollutants with MPs<br>Suitable for a large volume of water.<br>High efficiency. | Efficiency specific to polystyrene type of MPs of size of 1 and 10µm. | Misra et al., 2020 |
| A non-fluorinated superhydrophobic aluminum surface | High efficiency.<br>Efficiency higher than 99% for removal from the NaCl aqueous solution<br>Can be implemented in natural conditions. | Efficiency only tested with MPs of size 262µm. | Rius-Ayra & Llorca-Isern, 2021 |
| Biochar filters of different materials | Easy to make filters<br>Good efficiency.<br>High adsorption capacity.<br>Low cost of biochar production.<br>Low maintenance. | Tested only for selected type and shape of MPs<br>Not efficient for reduction of micrometer-scale MPs particles | Siipola et al., 2020; Wang et al., 2020b |
| Magnetic carbon nanotubes | High efficiency.<br>Reusability of magnetic carbon nanotubes. | The efficiency slightly decreased with number of times used. | Tang et al., 2021 |
| Electrocoagulation | Minimum sludge.<br>Energy efficient and cost-effective.<br>Flexibility to automation.<br>Less or no secondary pollution.<br>High efficiency. | Need continuous electricity supply.<br>pH dependent.<br>High amount of $Cl^-$ ions in wastewater effects the removal capacity | Perren et al., 2018 |
| Rapid sand filter | Suitable for all types of MPs.<br>Easy method<br>Low cost. | Only effective on the size of MPs>20µm. | Talvitie et al., 2017 |
| Disc filter | High efficiency. | Large size plastics reduce efficiency by blocking the pores.<br>High maintenance. | Talvitie et al., 2017 |
| Coagulative colloidal gas aphrons | High efficiency<br>Efficiency not affected by salinity. | Size dependent efficiency. | Zhang et al., 2021 |
| Chemical methods | | | |
| Coagulation/ flocculation with different chemicals (Alum, alum combined with cationic polyamine-coated sand, Polyaluminium chloride, ferric chloride, iron, aluminum and polyamine-based chemicals etc.) | High efficiency.<br>Removes other pollutants also.<br>Easy to operate. | Mostly investigated in laboratory.<br>Alkaline conditions and high stirring speed can affect efficiency.<br>Sometimes not efficient for the MPs with small-smooth-spherical surface.<br>Not efficient on smaller MPs. | Ma et al., 2019; Rajala et al., 2020; Shahi et al., 2020; Wang et al., 2020a; Zhou et al., 2021 |
| Influence of linear and branched alkyltrichlorosilanes | Good efficiency | Efficiency in natural settings is still needed to be verified for widespread application<br>Efficient for MPs size in the range between 1 µm- 1mm. | Sturm et al., 2020 |
| Biological methods | | | |
| Membrane bioreactor | High efficiency<br>Easily implemented in waste water treatment plants | Shape dependency of the removal percentage.<br>Membrane fouling | Talvitie et al., 2017; Lares et al., 2018; Lv et al., 2019; Bayo et al., 2020 |

(*Continued*)

| Methods | Advantages | Disadvantages | References |
|---|---|---|---|
| Conventional activated sludge | Robust, cost-effective and flexible. Can treat a wide range of influent concentrations, Applicable for large-scale treatments | Long retention times in the tank, High cost of energy and the processing Problem of sludge disposal. | Lares et al., 2018 |

gravity. After coagulation and sedimentation, the supernatant part was collected and further processed for filtering, drying and weighing. The precipitated MPs flocs were then tested for characterization. They also revealed that alkaline conditions and high stirring speed are important factors in enhancing MPs removal efficiency.

A combination of adsorption, agglomeration, and filtration was also employed by Sturn et al. (2020) to treat MPs. They used linear and branched alkyl trichloro silanes and reported a 98% efficiency for the high-density polyethylene, low-density polyethylene, and polypropylene treatment (Sturm et al., 2020). In the sol-gel method, a highly cross-linked solid that is inorganic-organic macromolecule is formed by successive hydrolysis and condensation of the precursors. This method has shown good efficiency for MPs size in the range between 1 μm to 1 mm. Moreover, it shows the best removal capacity for 3-5 carbon chain atoms. However, its efficiency in natural settings is still needed to be verified for widespread application.

Most chemical methods of MP removal are based on coagulation and flocculation that are also tested for MPs

**Table 3** Chemical methods for removal of MPs.

| Name of method | Principle | Target MPs | | Efficiency | Reference |
|---|---|---|---|---|---|
| | | Type | Size | | |
| Alum coagulant and alum combined with cationic polyamine-coated sand | Coagulation and flocculation | Polyethylene | 10–100 μm | 70.7%–92.7% | Shahi et al., 2020 |
| Granular activated carbon | Filtration | All types | 1–5 μm | 56.8%–60.9% | Wang et al., 2020a |
| Coagulation combined with sedimentation | Coagulation and settling | All types | >10 μm<br>5–10 μm | >99<br>40.5%–54.5% | Wang et al., 2020a |
| Coagulation/flocculation with iron, aluminum and polyamine-based chemicals | Coagulation and flocculation | Polystyrene spheres | 1 and 6.3 μm | 95% for 1 μm MPs and above 76% for 6.3 μm MPs | Rajala et al., 2020 |
| Coagulation, flocculation by Al- and Fe-based salts | Coagulation, flocculation | Polyethylene | _ | _ | Ma et al., 2019 |
| Influence of linear and branched alkyltrichlorosilanes | Adsorption + agglomeration + filtration | Low density polyethylene, High density polyethylene and Polypropylene based MPs | 1 μm–1 mm | 98.3±1.0% | Sturm et al., 2020 |
| Polyaluminum chloride and ferric chloride coagulation | Coagulation | Polystyrene and polyethylene | _ | _ | Zhou et al., 2021 |
| Photocatalysis | Visible light-induced heterogeneous photocatalysis activated by zinc oxide nanorods | Low-density polyethylene | – | 30% | Tofa et al., 2019 |
| Photocatalysis | Degradation: green photocatalysis using a protein-based porous N-$TiO_2$ semiconductor | High density polyethylene | 700 and 1000 μm | _ | Ariza-Tarazona et al., 2019 |
| Ozone | Chemical degradation | All types | _ | 89.9% | Hidayaturrahman and Lee, 2019 |
| Alkoxy-silyl Induced Agglomeration | Agglomeration | Polyethylene, polypropylene | Independent of the type, size, and amount | – | Herbort et al., 2018 |
| Inorganic-organic hybrid silica gels | Host-guest interactions | Polyethylene, polypropylene, Polyethylene terephthalate | _ | _ | Herbort and Schuhen, 2017 |

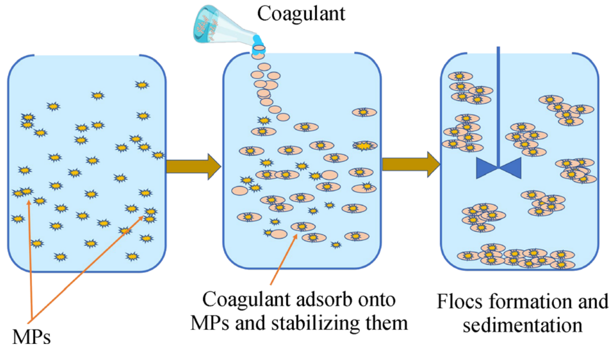


**Fig. 4** Process of coagulation/flocculation for MPs removal.

removal. To make these methods specific to MPs removal, however, researchers are trying to find new coagulants or flocculants which target MPs and help in their separation. Ferric chloride, polyaluminum chloride, alum together with cationic polyamine-coated Aluminum based salts are such efficient examples. But, the efficiency depends on the type of coagulant, pH, the chemical composition of the media and the concentrations (Padervand et al., 2020). New approaches are trying to mix two or more mechanisms to get better efficiency. A combination of adsorption, agglomeration, and filtration by using linear and branched alkyl trichloro silanes reported high efficiency for the high-density polyethylene, low-density polyethylene, and polypropylene treatment. Most of the coagulation and flocculation-based methods could be implemented in treatment plants with more research and testing. Few advantages and disadvantages of the chemical methods are discussed in Table 2. Various other methods listed in Table 3 namely photocatalysis, alkoxy-silyl induced agglomeration and inorganic organic hybrid silica gels are also reported during this study but the efficiency of these methods was found to be low (i.e., under 30%). These methods should have been adopted again with different set of conditions to improve the efficiency. New approaches also need to be tested in natural settings for a real-time-efficient solution to limit MPs pollution.

### 3.3 Biological methods of removal

Biological methods use organisms to tackle the issue of MP pollution by degrading MPs present in the environment. Several organisms have been tested for their potential to degrade MPs present in water and wastewater. Among all biological organisms mostly microorganisms are studied in the context of MPs degradation potential. Microbial activities can affect the MPs degradation and thus can be a very important approach to save aquatic life either in situ or *in-vitro* treatment measure (Harrison et al., 2011). As shown in Fig. 5 microbes can breakdown complex plastic polymers to simpler monomer forms. Aerobic degradation results into $CO_2$ and water as products while anaerobically forms $CO_2$, water, methane, and $H_2S$ (Chandra and Enespa, 2020). Several algae, fungi, and bacteria have been tested successful in this process. A list of such microorganisms is mentioned in Table 4.

Herein, mentioning the role of microorganisms in MPs degradation is important because it is highly possible that microorganisms can breakdown MPs into simpler forms. A study by Paco et al.2017 found that the fungus *Zalerion maritimum* has potential to degrade polyethylene by changing its morphology and chemical structure (Paço et al., 2017). Further, research in this area can bring possible solutions for MPs degradation in the future. Apart from microorganisms some other organisms also proved to act as a sink of MPs in aquatic body. Research works have also been conducted on organisms like Red Sea giant clam (*Tridacnamaxima*)(Arossa et al., 2019), Antarctic krill (*Euphausia superba*) (Dawson et al., 2018) and some Corals (Martin et al., 2019; Corona et al., 2020) for assessing their capacity to adsorb MPs. Although, their reported efficiency was very low for treatment of MPs but we cannot ignore their effect on fate of MPs.

Microalgae are an impressive biological tool for removing fine MPs (Cunha et al., 2020). Similarly, corals are also declared as natural sinks for MPs in oceans as verified in the laboratory (Martin et al., 2019). In a study by Corona et al. (Corona et al., 2020), MPs removal efficiency of mushroom coral collected from reef of island of Magoodhoo, Faafu Atoll, Republic of Maldives showed efficiency of 97% for virgin + Biofouled plastic of size 200–1000 μm in the laboratory setting. This experiment suggested that corals are one of the important sinks for MPs in oceans. However, since corals are sensitive organisms, it cannot be marked as a full-time solution for MPs removal in *ex-situ* conditions. The main reason that MPs sink in these organisms is retention, adhesion, or ingestion as shown in Fig. 6 (Arossa et al., 2019). Although there are great possibilities in MPs removal using living organisms in natural systems, much is required to enhance its capacity and lower down the span of degradation.

Traditionally, plastics were considered as non-biodegradable items but now these are known to be degraded and metabolized by different organisms, especially by microbes. The abundance of microorganisms in the environment and their potential in attacking MPs seems to be one of the most effective solutions to MPs. Moreover, several enzymes that are capable of hydrolyzing the different plastics have been identified (Wei and Zimmermann, 2017). However, the better understanding of depolymerases enzyme contributing in the breakdown of plastics is lacking and also enhancing the efficiency of enzymatic degradation is still a big challenge. Therefore, future efforts are warranted to identify more depolymerases from the plastic-degrading organism and enhancing their efficacy by biotechnology. We thus expect that major research efforts will be needed to find and engineer

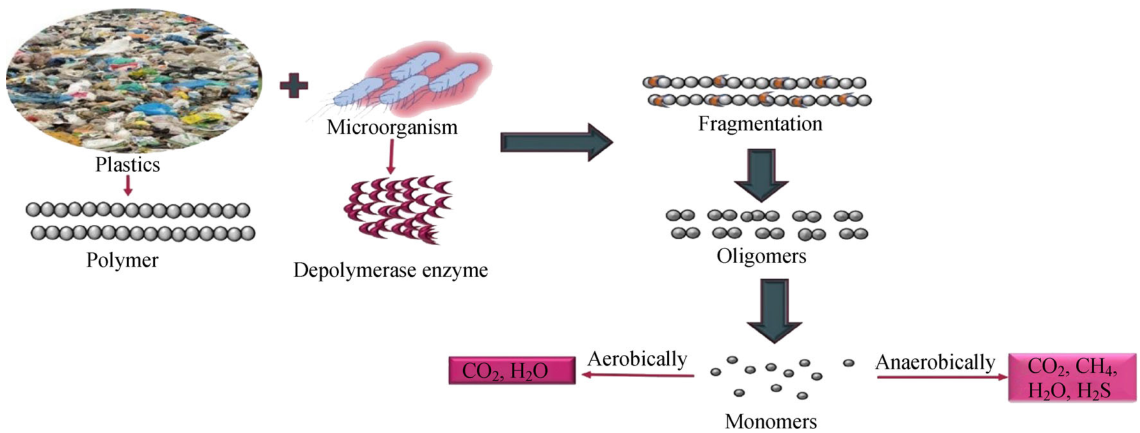


**Fig. 5** Degradation of plastic particle by the action of microbes.

efficient MPs degrading enzymes and its associated processes that can offer a possibility to develop biological treatment technology for MPs. Another recent biological technique which works on the mechanism of microbial 'trap and release', was engineered for MPs removal (Liu et al., 2021). In this method, MPs efficiently get trapped and aggregated in sticky exopolymeric substances produced by engineered bacterium, *Pseudomonas aeruginosa* biofilms and then trapped MPs can be dispersed or released by biofilm dispersal mechanism for downstream resource recovery or recycling. This trap-and-release' bio-aggregation method works for every type and size of plastic material. Further, it does not depend on concentration of MPs. The increased total mass will help simple and easier removal by filtration or sedimentation in tanks. This method was successful in laboratory but its implementation in wastewater is risky as claimed by the authors. Further, the author suggests that the indigenous bacteria from a system could be explored in the future to make an efficient technology under the natural conditions. Although removal techniques started to come in to the light, much more work and research remains. Many groups and organizations are working together to find a good solution to put an end on this problem. With all the effort, a hope exists that in future we will have a MPs specific removal treatment technology.

Biological technologies for removal of MPs are very less in number and these are basically assessed in the waste water treatment plants. Mostly, membrane bioreactor (MBR) technology is tested to evaluate the removal efficacy of MPs from the wastewater. Apart from MBR other efficient methods are Anaerobic-Anoxic-Oxic, Oxidation ditch and Conventional activated sludge (Table 5). A conventional technology of MPs treatment with impressive results is MBR technology. This technology consists of an aerobic tank or membrane filtration tank including a MBR unitin it (Fig. 7) (Talvitie et al., 2017; Lares et al., 2018). MBR has been used in the waste water treatment for a long time, but its implementation for MPs treatment has only been tested recently. MBR is the fusion of membrane filtrations processes and suspended growth biological reactors used to treats primary effluent containing suspended solids as well as dissolved organic matter and nutrients. The suitability of MBR for MPs removal has been highlighted with an efficiency of 99.9% by (Poerio et al., 2019). While implementing MBR for MPs Talvitie et al. (Talvitie et al., 2017) reported 99.9% and Lares et al. (Lares et al., 2018) observed 99.4% efficiency for all types of MPs present in the water. MBR could be a good option for the MPs removal, but it is still not specific for MPs removal of varied sizes. Further, it has been observed that MPs of smaller sizes, are capable of escaping this process particularly fibers, due to the high length-to-width ratio hence cannot be completely removed by MBR (Ngo et al., 2019; Freeman et al., 2020). Conventional activated sludge process method also showed high efficiency i.e., 98.3% (Lares et al., 2018). But this technology needs a large area, and it also produces sludge in high quantities (Bui et al., 2020). Another biological method is oxidation ditch, which is modified activated sludge biological treatment process that is used to remove biodegradable organics with its long solid's retention times. This method also provided a good efficiency of 97% for removal of MPs (Lv et al., 2019).

Biological methods still remain under studied for the MPs removal. Many researchers are searching for possible solutions for the removal of MPs with different biological organisms. Since biological organisms are sensitive to several factors, such methods require more effort and research for efficient implementations on a larger scale. Biological methods like oxidation ditch, activated sludge, and MBR has shown good efficiency for MPs removal. Few advantages and disadvantages of the biological methods are discussed in Table 2. Among these methods, MBR is an advanced technology and is getting more attention in the field of MPs removal. Since, biological methods can be helpful in both in situ and *ex-situ* MPs removal, more research is recommended in this field.

**Table 4** List of Microorganisms employed for MPs removal.

| Microorganism | Type of microorganism | Type of plastics | Efficiency | Reference |
|---|---|---|---|---|
| *Bacillus subtilis* | Bacteria | Polyethylene | 9.26% | Vimala and Mathew, 2016 |
| *Phanerochaete chrysosporium, NCIM 1170 (F1) and Engyodontium album MTP091* | Fungus | Polypropylene, pro-oxidant blended and starch blended polypropylenes | Approx. 18.8 and 9.42% gravimetric weight loss and 79 and 57% TGA weight loss | Jeyakumar et al., 2013 |
| *Serratia marcescens marcescens* | Bacteria | Linear Low-Density Polyethylene | _ | Odusanya et al., 2013 |
| *Rhodococcus ruber* | Bacteria | Polyethylene | 8% | Orr et al., 2004 |
| *Chaetomium globosum* | Fungus | Polyurethane | _ | Oprea and Doroftei, 2011 |
| *Bacillus sphericus Alt; Bacillus cereus BF20* | Bacteria | Low-Density Polyethylene film | Weight loss 2.5%–10% | Sudhakar et al., 2008 |
| *Zalerion maritimum* | Fungus | Polyethylene pellets | _ | Paço et al., 2017 |
| *Alcanivorax borkumensis* | Bacteria | Low-Density Polyethylene film | Weight loss 3.5% | Delacuvellerie et al., 2019 |
| Cyanobacterial species like *Phormidium lucidum* and *Oscillatoria subbrevis* | Bacteria | Low-Density Polyethylene film | _ | Sarmah and Rout, 2019 |
| *Exiguobacterium* sp. YT2 | Bacteria | Polystyrene film | 7.5% | Yang et al., 2015 |
| *Microbacterium* sp. NA23*; Paenibacillus urinalis NA26;* *Bacillus* sp. NB6; *Pseudomonas aeruginosa NB26* | Bacteria | Polystyrene film | _ | Atiq et al., 2010 |
| *Bacillus* sp. Strain 27; *Rhodococcus* sp. Strain 36 | Bacteria | Polypropylene mps | 4–6.4 | Auta et al., 2018 |
| *Aneurinibacillus aneurinilyticus; Brevibacillus agri; Brevibacillus* sp.; *Brevibacillus brevis* | Bacteria | Polypropylene film and pellets | 22.8–27.0 | Skariyachan et al., 2018 |
| *Stenotrophomonas panacihumi* | Bacteria | Polypropylene film | _ | Jeon and Kim, 2016 |
| *Pseudomonas citronellolis* | Bacteria | Plasticized PVC film | 13 | Giacomucci et al., 2019 |
| *Mycobacterium* sp. NK0301 | Bacteria | Plasticized PVC film | _ | Nakamiya et al., 2005 |
| *Poliporus versicolor; Pleurotus sajor caju* | Fungus | PVC film | _ | Kırbaş et al., 1999 |
| *Aspergillus* sp. S45 | Fungus | Polyester PUR film | 15–20 | Osman et al., 2018 |
| *Penicillium* sp. | Fungus | Impranil DLN; polyester/polyether PUR film | 8.9 | Magnin et al., 2019 |
| *Acinetobacter gerneri* | Bacteria | Impranil DLN | _ | Howard et al., 2012 |
| *Bacillus muralis* | Bacteria | Polyethylene terephthalate | _ | Narciso-Ortiz et al., 2020 |
| *Zalerion maritimum* | Fungus | Polyethylene | 43% | Paço et al., 2017 |
| *Rhodococcus ruber* | Bacteria | Polyethylene | 8% | Orr et al., 2004 |

## 4 Policies regarding microplastics pollution

MPs are invading our environment abruptly through both point and non-point sources and thus causing pollution (Kabir et al., 2020). Due to the lack of awareness and absence of the regulations for MPs, these are still used as components in most of the cosmetic and personal care products, which finally ends in the aquatic bodies (Auta

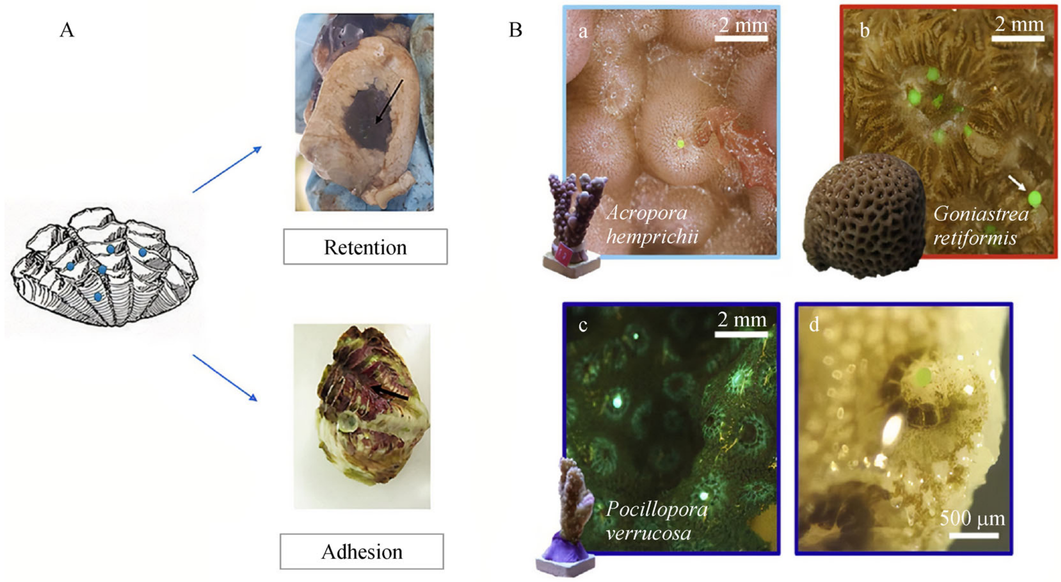


**Fig. 6** (A) Adsorption mechanism in *Tridacna maxima* (B) Different organisms showing presence of MPs (a) *Acropora hemprichii*, (b) *Goniastrea retiformis* and (c) *Pocillopora verrucosa* (d) magnified image of *Pocillopora verrucosa*. Reproduced and modified from the ref. (Arossa et al., 2019) and (Martin et al., 2019). Copyright 2019 Elsevier.

**Table 5** Biological methods for removal of MPs

| Sr. No. | Name of method | Principle | Target MPs | | Efficiency | Reference |
|---|---|---|---|---|---|---|
| | | | Type | Size | | |
| 1 | Microalgal-based biopolymer | Aggregation and flocculation | Polystyrene nano- and MPs | < 300 µm | Potential to removal nano or MPs | Cunha et al., 2020 |
| 2 | Anaerobic-Anoxic-Oxic | Microbial biodegradation | All types | 25–104 µm | 93.7 | Edo et al., 2020 |
| 3 | MBR | Microbial biodegradation | MPs polyvinylchloride | | 99.5% | Lv et al., 2019 |
| 4 | Oxidation ditch | Microbial biodegradation | Polyethylene terephthalate, Polystyrene Polyethylene Polypropylene | >500 mm and between 62.5 and 125 mm | 97 | Lv et al., 2019 |
| 5 | MBR | Microbial biodegradation | All MPs | 0.5–1mm | 99.4% | Lares et al., 2018 |
| 6 | Conventional activated sludge | Microbial biodegradation | All MPs | 0.5–1mm | 98.3% | Lares et al., 2018 |
| 7 | MBR | Microbial biodegradation | All MPs | >20 µm | 99.9% | Talvitie et al., 2017 |
| 8 | MBR | Microbial biodegradation | All MPs | _ | 79.01% | Bayo et al., 2020 |

et al., 2017; Prata, 2018). Today the world is at a stage where it cannot completely prohibit the use of plastic but can join hands to find a sustainable solution to save our earth. The single-use plastics are a major source responsible for production of secondary MPs. Following Germany, 65 more countries restricted plastics by enforcing different laws, policies, bans, fines, and plastic bag taxes, etc.(Lam et al., 2018). Single-use plastic bans proved to be helpful for plastic reduction with a 94% reduction in the United States (LA County, California), 55% in Italy, 94% in Ireland, 85% in England, 80% in Israel, 70% in the Netherlands, and a 40% reduction in use and litter (Schnurr et al., 2018).

Different countries such as Canada, France, and the United States have already enforced regulation against MPs (basically primary MPs) to restrict their level in the environment. Other countries like South Korea, Sweden, Belgium, and Italy are following suit by formulating strict

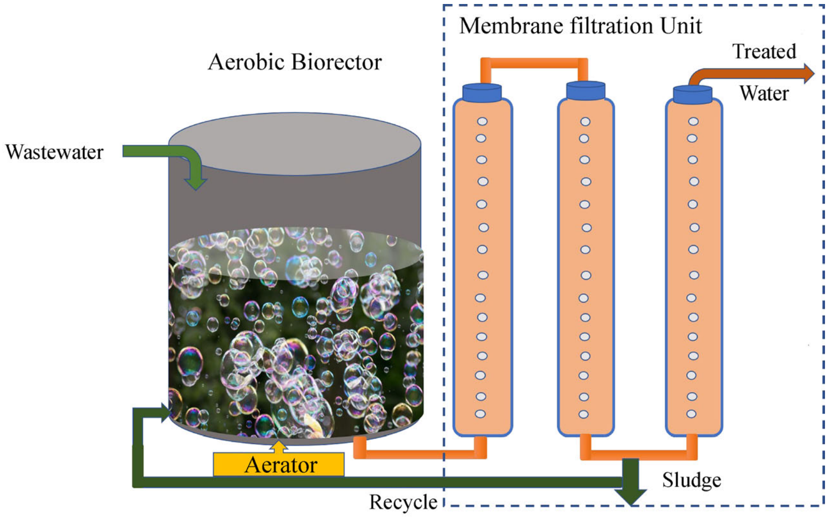


**Fig. 7** General structure of a MBR unit.

drafts and ideas to combat MPs pollution. Countries like Canada, the UK, Ireland and, the United States have started banning the products containing microbeads (Prata, 2018). Seeking this objective a few aware countries have already opted legal regulations and others have started framing new policies and regulations to strictly address this issue.

## 5 Conclusions and suggestions

MPs are a huge problem, and recent research surrounding MPs have proved that the impact of MPs will be more devastating in the future than current predictions. There are several reports about the negative impact of MPs pollution on the environment and living beings including humans. In conclusion, an efficient method for MPs treatment and a policy that can be implemented strictly throughout the globe is urgently warranted to control MPs in the environment. Most research regarding the removal of MPs is conducted *in-vitro* under controlled conditions, and there are high chances of reduction in efficiency under natural conditions. When these methods are performed with real case scenario, such as for treatment of wastewater, which is a mixture of contaminants, efficiency could alter and show different results for different treatment methods. Although wastewater treatment plants have shown good efficiency, there is an urgent need to create and add specific MPs removal unit in water treatment plants. We suggest researchers explore the possibility of an integrated approach in which physical, chemical, and biological methods can be used in combination to get maximum efficiency. Further, considering MPs are serious threat, it should be brought to the global stage and declared as a global issue on a similar magnitude as climate change and ozone layer depletion. A global commission should be constituted by involving all major countries so that efforts could be made worldwide. Government bodies should also start considering MPs pollution while drafting environmental protection policies and try to set a permissible limit for MPs like they have done so with other toxins and pollutants. On the whole, government bodies should encourage and fund researchers in this area to develop cost-effective and efficient methods of MPs testing and control.

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