Abstract: As concerns about the substantial effect of various hazardous toxic pollutants on the environment and public health are increasing, the development of effective and sustainable treatment methods is urgently needed. In particular, the remediation of toxic components such as radioactive waste, toxic heavy metals, and other harmful substances under extreme conditions is quite difficult due to their restricted accessibility. Thus, novel treatment methods for the removal of toxic pollutants using extremophilic microorganisms that can thrive under extreme conditions have been investigated during the past several decades. In this review, recent trends in bioremediation using extremophilic microorganisms and related approaches to develop them are reviewed, with relevant examples and perspectives.

Keywords: bioremediation; toxic pollutants; extreme conditions; extremophilic microorganism

1. Introduction

Due to the rapid industrial growth, the environment and public health are threatened by the huge amount of toxic pollutants that have accumulated in the environment. Therefore, maintaining and protecting the environment from toxic pollutants has become a great challenge for mankind over the past few decades. Recently, various strategies have been intensively exploited to protect the environment by preventing the dispersion of toxic pollutants into it. For example, physicochemical methods such as electrochemical treatments, excavation, ion exchange, precipitation, reverse osmosis, evaporation, and sorption have been developed for the removal of toxic substances [1–4]. However, many of these techniques are not yet commonly applied to the actual treatment of contamination due to critical drawbacks such as high cost and secondary contamination possibly associated with them [5–7]. As an alternative, microbial bioremediation has attracted much attention as a promising technology that can overcome the shortcomings of the currently used physicochemical methods (Figure 1) [8–10]. Specifically, extremophilic microorganisms offer the most suitable approach for the treatment of toxic pollutants [11–14] because not only can they detoxify toxic pollutants through microbial cellular metabolism but also they can withstand extremely harsh conditions [11,13–15]. Herein, we focus on recent trends in bioremediation processes for the treatment of toxic pollutants such as inorganic heavy metals, harmful organic substances, and radioactive elements using extremophilic microorganisms and on the perspectives of this approach in public health.
Thus, many studies have been attempted to develop sustainable bioremediation processes using the process of pollutants by using physicochemical methods is not always successful due to limited pH, and desiccation observed in environments such as deep sea, volcanoes, and deserts. However, tetraether lipids having a diverse array of polar head groups and a bulky isoprenoid core [20–23].

Extremophilic microorganisms have evolved not only to convert unstable toxic pollutants into sufficiently stable conditions through unique biological mechanisms. During the process of adaptation, extremophilic microorganisms have adapted and evolved in various ways to thrive under extreme conditions through unique biological mechanisms. During the process of adaptation, extremophilic microorganisms have evolved not only to convert unstable toxic pollutants into sufficiently stable beneficial resources for their cellular metabolism but also to become highly tolerant to toxic matter. Thus, many studies have been attempted to develop sustainable bioremediation processes using the survival strategies of extremophilic microorganisms. Here, we briefly describe the adaptation and survival mechanisms that can be used for bioremediation.

2. Survival Strategies of Extremophilic Microorganisms under Extreme Conditions

Extreme environments are defined as habitats that make the prospect of survival difficult for most organisms on earth. These are mostly natural conditions such as extreme temperatures, salinity, pH, and desiccation observed in environments such as deep sea, volcanoes, and deserts. However, these extreme conditions can also appear in polluted areas containing harmful organic substances [16], heavy metals [17], and/or radioactive waste [18]. Under extremely polluted conditions, the clean-up process of pollutants by using physicochemical methods is not always successful due to limited accessibility to the pollutants and secondary contamination. Thus, there is a need to combine microbial biotechnology and chemistry to advance the remediation processes. Over the past century, extremophilic microorganisms have adapted and evolved in various ways to thrive under extreme conditions through unique biological mechanisms. During the process of adaptation, extremophilic microorganisms have evolved not only to convert unstable toxic pollutants into sufficiently stable beneficial resources for their cellular metabolism but also to become highly tolerant to toxic matter. Thus, many studies have been attempted to develop sustainable bioremediation processes using the survival strategies of extremophilic microorganisms. Here, we briefly describe the adaptation and survival mechanisms that can be used for bioremediation.

2.1. Acidophilic and Alkaliphilic Microorganisms

Acidophilic microorganisms can survive under extremely low pH (less than pH 3) conditions, maintaining pH homeostasis by controlling proton permeation [19]. For example, microorganisms from the genera Thermoplasmata, Ferroplasma, and Sulfolobus can regulate proton permeation under extremely low pH conditions due to a highly impermeable cell membrane mainly composed of tetraether lipids having a diverse array of polar head groups and a bulky isoprenoid core [20–23].
The modulation of the influx of protons through the proton pump system is important to survive at low pH, and putative proton pump proteins such as H^+\text{-}ATPase, symporters, and antiporters from *Ferroplasma* type II and *Leptospirillium* group II are involved in maintaining pH homeostasis [21,24,25]. Moreover, F_0F_1-type adenosine triphosphate synthase in *Bacillus* *acidocaldarius*, *Thermoplasma acidophilum*, and *Leptospirillium ferriphilum* is known to play a critical role in regulating proton permeation [25]. In addition to these mechanisms, several other auxiliary mechanisms, involving for example, chaperone proteins and cytoplasmic buffering capacity contribute to survival strategies under extremely low pH conditions by protecting intracellular molecules such as DNA, RNA, and proteins [25].

Contrary to acidophilic microorganisms, alkaliphilic microorganisms can resistant high pH. To date, three key biological mechanisms have been identified as survival strategies in these microorganisms. First, under extremely high pH conditions, some alkaliphilic *Bacillus* spp. can increase the generation of proton motive force through synthesizing a secondary acidic cell membrane consisting primarily of peptidoglycan, teichuronic acid, and teichuronopeptide [26,27]. Increasing the proton motive force contributes to not only energy generation but also pH balance [28–30]. Second, sodium motive force can also promote pH balance under extremely high pH conditions [31,32]. Under high Na^+ ion conditions, Na^+/H^+ antiporters extrude Na^+ ions and absorb a greater amount of extracellular H^+ ions than that of extruded Na^+ ions, thereby activating a bioenergetic process and regulating the internal pH [33]. Finally, the production of organic acids that can be used for pH calibration is known to be an important biological process in maintaining pH balance [34,35].

### 2.2. Halophilic Microorganisms

Halophilic microorganisms can thrive in a high-salt environment which hinders organisms’ survival due to osmolar imbalance and metabolic problems [36,37]. Previous studies on halophilic microorganisms reported two fundamental adaptation strategies to survive under extremely high salt conditions. The first is to use a “salt-in” strategy that refers to the accumulation of inorganic osmoprotectants such as KCl inside the cell to maintain the osmotic balance both inside and outside the cell [37]. It has been demonstrated that *Halobacterium salinarum* can accumulate 3.97 M and 4.57 M of K^+ and Cl^− ions, respectively, inside the cell using the ATP-dependent K^+ transport system (the KdpFABC complex and cationic amino acid transporter-3 (Cat3) and Na^+ efflux antiporters (NhaC) to balance the osmotic gradient under high-salt conditions [38–41]. Moreover, halophilic microorganisms have evolved an abundance of negatively charged aspartate and glutamate residues on protein surfaces that can interact with water molecules to form a water cage that prevents protein precipitation and dehydration [41–44].

As another adaptation strategy, some halophilic and halotolerant bacteria use the ‘compatible solutes adaptation’ strategy to maintain osmotic balance by using compatible organic solutes such as polyols, glucosylglycerol, sucrose, trehalose, ectoine, and betaine [45,46]. For example, the halophilic bacterium *Spiribacter salinus* M19-40 produces enhanced levels of compatible solutes such as ectoine and trehalose when they are exposed to a high NaCl concentration [45]. These organic solutes have a critical role in reducing the thermodynamic activity of water to compensate for the external osmotic pressure [47].

### 2.3. Psychrophilic and Thermophilic Microorganisms

Psychrophilic microorganisms usually have a preferred temperature range of 1–4 °C. Unlike mesophilic microorganisms, whose preferred temperature range is 30–37 °C, psychrophilic microorganisms can fully maintain cellular metabolism even at temperatures below 0 °C. To adapt to these harsh conditions, they have evolved several physiological adaptation mechanisms, including membrane fluidity control, molecular chaperones’ action, and antifreeze molecules’ synthesis [48,49]. For example, they can modulate membrane fluidity by altering its lipid composition, increasing the amount of polyunsaturated fatty acids and polar/non-polar carotenoids and decreasing the size of the lipid head groups [19,49]. A variety of temperature-induced enzymes such as cold-shock proteins...
(Csps) and heat-shock proteins (Hsps) are also involved in cold-shock resistance by regulating signaling cascades that protect damaged proteins and cofactors [50]. Moreover, various antifreeze proteins and polysaccharides such as trehalose, mannitol, and exopolysaccharides, which are constituents of biofilm, can act as cryoprotectants [51].

Thermophilic microorganisms with a preferred temperature above 60 °C activate similar survival mechanisms to psychrophilic microorganisms. For example, *B. acidocaldarius*, a thermophilic spore-forming bacterium, modulates membrane lipid fluidity by increasing hopanoids (a subclass of triterpenoids) to resist high temperatures [52]. The thermophilic archaeon *Metanocococcus jannaschii* can resist high temperatures by regulating membrane lipid composition. When these microorganisms were exposed to high temperature, the diether lipids decreased from 80% to 20%, while the caldarchaeol-based and cyclic archaeol-based lipids increased from 10% to 40% [53,54]. In addition, thermophilic microorganisms have evolved various biomolecules to induce thermal stability, e.g., by increasing the guanine/cytosine content of DNA or developing a positive supercoiled DNA structure [55]. Moreover, they not only possess very rich ribosomal proteins but also have a well-developed heat-shock response to allow normal protein synthesis even at high temperatures [56,57].

2.4. Radiophilic Microorganisms

Radiophilic (radio-tolerant) microorganisms can thrive in environments with high levels of radiation, including ultraviolet light and gamma rays. Previous studies on how they can adapt and survive under high-dose radiation and oxidative stress conditions have revealed that they possess robust DNA repair systems and antioxidation mechanisms to withstand intensive irradiation stress [58–63]. For example, RecA proteins from *Deinococcus radiodurans* R1, which is a representative radiophilic microorganism, plays a crucial role in repairing damaged DNA under gamma ray irradiation [63,64]. When it is exposed to a high dose of irradiation, the expression levels of several novel proteins (PprA, PprM, PprI, and DdrABCDO) and of DNA damage response regulons are dramatically increased and contribute to DNA repair and damaged genome reconstruction [65–68].

Radiophilic microorganisms also have efficient antioxidant enzymes, such as catalase (CAT), superoxide dismutase (SOD), and peroxidase, which are responsible for the scavenging of reactive oxygen species (ROS) [63,69]. For example, CATs and SODs from *D. radiodurans* exhibit a 30-fold higher ROS scavenging activity than radiation-sensitive bacteria such as *Escherichia coli* and *Saccharomyces cerevisiae* [63]. Moreover, non-enzymatic factors such as relatively high intracellular manganese concentrations, polyphosphate granules, carotenoids, and pyrroloquinoline quinone are also involved in the efficient scavenging of various ROSs as well as in the protection against protein damage [70–73]. Other non-enzymatic factors protecting biomolecules from ionizing radiation are a high intracellular Mn/Fe concentration ratio, orthophosphates, large amounts of free amino acids, and small peptides that have been found in the polyextremophilic microorganism *H. salinarum* [74].

3. Bioremediation Using Extremophiles

3.1. Treatment of Heavy Metal Pollutants

Concerns about the toxicity of heavy metals have been drastically increasing because even a tiny amount can be dangerous for public health and the environment. Moreover, currently used chemical treatments of toxic heavy metals under extreme conditions is often hampered by their poor accessibility. Thus, the development of sustainable bioremediation methods using extremophilic microorganisms for the treatment of heavy metals has been investigated during the past several decades (Table 1). In the case of extremely acidic conditions, acidophilic microorganisms that can thrive under low pH conditions have been used as host strains for the detoxification of heavy metals through biomining processes such as bioleaching and bio-oxidation [75–78]. There have been several reports on the development of bioremediation processes using *Acidithiobacillus* strains, which are the most common acidophilic and chemolithotrophic microorganisms. For example, industrial-scale bioleaching has
been performed using *Acidithiobacillus ferrooxidans* [79–81]. Romero-González et al. [82] reported the bioremediation of 100 mg/L of U(IV) ex situ from polluted mine water using *At. ferrooxidans* NCIMB 8455, while Jameson et al. [83] demonstrated the utility of *At. ferrooxidans* and *Acidithiobacillus ferrivorans* strains for hydrogen sulfide (H₂S)-assisted copper precipitation (>99%) under acidic conditions (pH 2.5–2.6). In other studies, the efficient reduction of vanadium ions [vanadate; V(V)] to V(IV) and the biosorption of cadmium cations were successfully achieved by *Acidocella aromatica* PFBC and *Acidiphilium symbioticum* H8, respectively, under highly acidic conditions [84,85].

More efficient decontamination of toxic heavy metals can be obtained using a microbial consortium, a major advantage of which is to synergize different enzymatic systems and metabolic pathways of individual microorganisms. Recently, the bioaugmentation of heavy metals using an acid mine drainage (AMD)-isolated acidophilic microorganism consortium was performed on polluted port sediment. The extraction of more than 90% Cu²⁺, Cd²⁺, Hg²⁺, and Zn²⁺ was successfully achieved using an acidophilic microbial consortium consisting of *Acidithiobacillus thiooxidans*, *At. ferrooxidans*, *Acidiphilium cryptum*, and *Leptospirillum ferrooxidans* [86]. Another study also reported the in situ bioremediation of AMD soil defined as highly acidic (pH 3.21), sulfate (6285 mg/L), and heavy metals. The introduction of an enriched microbial consortium composed of acidophilic microorganisms and metal-resistant strains of *Chloroflexi* (29%), *Acidobacteria* (21%), *Proteobacteria* (16%), and *Firmicutes* (2%) into AMD soil enabled 97% reduction of dissolved sulfate and increased the pH to 7.5 [87].

Halophilic microorganisms offer great advantages in the treatment of toxic pollutants in high-salt environments. For example, bioremediation using marine bacteria is a promising solution for the decontamination of seawater from toxic heavy metals, as these bacteria can survive at high salt concentrations. There have been a few reports on the removal of toxic heavy metals using several marine bacteria. For instance, *Vibrio harveyi* showed a good capability to accumulate cadmium cations inside the cell with a high adsorption capacity (up to 23.3 mg Cd²⁺/g of dry cells) [88]. Another marine bacterium, *Enterobacter cloacae*, can chelate Cd, Cu, and Co by up to 65%, 20%, and 8%, respectively, from mixed-salts solutions [89]. In addition to marine bacteria, some thermophilic microorganisms such as *Geobacillus thermantarcticus* and *Anoxybacillus amylolyticus* have considerable biosorption capacity for heavy metals, which suggests their applicability for the removal of heavy metals in polluted environments [90].

As the development of biotechnology progresses, more advanced bioremediation methods that are superior to traditional methods have been reported. Unlike conventional bioremediation methods whose principle is based on the microorganism itself, new methods present improved efficiency and specificity thanks to the use of biomolecular engineering approaches. For instance, S-layer proteins, which have high stability and activity toward various heavy metals, are produced by lactic acid bacteria and are promising biomolecules for toxic heavy metal decontamination under very low pH (pH 2) conditions [91]. The S-layer proteins from *Lactobacillus plantarum* YW11 showed 99.9% Pb adsorption capacity [92]; scanning electron microscopy–energy dispersive X-ray analysis demonstrated that the Pb²⁺ ions were efficiently adsorbed and accumulated on the cell surface of *L. plantarum* YW11 in a process mediated via S-layer proteins. The interaction of S-layer proteins from two *Lactobacillus kefiri* strains (CIDCA 8348 and JCM 5818) has also been investigated for the adsorption of various metal ions such as Cd²⁺, Zn²⁺, Pb²⁺, and Ni²⁺ [93].
Furthermore, bioaugmentation through introduction of various extremophilic microorganisms has shown excellent performance in the removal of organic hydrocarbon pollutants. Low-temperature-adapted *Pseudoalteromonas* sp. P29 and *Oleispira antarctica* RB-8T exhibited high efficiencies in the degradation of hydrocarbon mixtures composed of diesel, military jet fuel, and crude oil.
oil [102,103], while the halotolerant microorganisms *Marinobacter sedimentalis*, *Marinobacter falvimaris*, and *Marinobacter nanhaiticus* D15-8W were able to transform biphenyl, phenanthrene, anthracene, and naphthalene into useful carbon sources in hypersaline environments (e.g., salt lakes, salt marshes, and highly saline soils) [104,105]. In particular, extracellular polymeric substances (EPSs), which are cellular components of halophilic microorganisms, play a critical role in the remediation of organic pollutants from hypersaline environments. Exopolysaccharides secreted by halophiles can act as biosurfactants that contribute toward aggregating oils and emulsifying hydrocarbons, as well as offer cellular resistance toward toxic heavy metals. Halophilic microorganism *Halobacillus* sp. EG1HP4QL develops the ability to utilize crude oil as the sole carbon source within 12 days and to degrade paraffin (34.5%), naphthalene (49.6%), mono- and bicyclic aromatic hydrocarbons (51.2%), polycyclic aromatic hydrocarbon (43.5%), and alcohol–benzene resins (25.5%) [106]. EPS-producing *Halomonas* strain TG39 was also used for bioremediation of a hydrocarbon-contaminated Deepwater Horizon spill site [107]; the extracted EPS was effective not only in increasing the solubilization of aromatic hydrocarbons but also in enhancing the degradation rate of phenanthrene. Hence, bioremediation using extremophilic microorganisms is a promising method for the treatment of organic contaminant-polluted areas under extreme conditions because the organic pollutants can be metabolized by the microorganisms.

### 3.3. Microbial Treatment of Radioactive Waste

Recent advances in synthetic chemistry and separation methods have led to the design of various adsorbent systems including surface-modified nanomaterials and/or hybrid composites for the treatment of radionuclides in soil or aqueous media. For example, surface-modified iron oxide (Fe₃O₄) nanoparticles have been applied to selectively adsorb toxic heavy metals such as Cr(III), Co(II), Ni(II), Cd(II), Pb(II), and As³⁺ from aqueous media [108]. Furthermore, engineered Au nanomaterials have been developed that are excellent adsorbents for the desalination of non-radioactive and radioactive iodine anions [109–111]. However, there are still several problems in the practical application of these methods. First, a large volume of secondary radioelement-contaminated solid adsorbents is generated during the desalination procedure, and so the removal of unsettled adsorbents after the treatment requires an additional expensive step. Second, small- (nano- or micro-) sized adsorbents tend to lose their stability and properties under particularly harsh conditions such as high salt concentration and high radiation. Therefore, employing extremophilic microorganisms that can be used as a live cleaning agent offer a useful alternative for the treatment of radioactive waste (Table 3).

The microbial treatment of radioactive waste can be accomplished through the interactions between microorganisms and radioisotopes, such as biomineralization, biotransformation, and biosorption [112–115]. Among these, mineralization of the target element inside bacterial cells has been proposed as the main strategy for the removal of radionuclides from a contaminated area [116,117]. As an example, *Shewanella* and *Geobacter* strains can reduce some alpha nuclides such as U(VI), Pu(IV), Am(V), and Th(IV) to make them harmless [15,114,116,118,119]. Anderson et al. reported the removal of uranium from aqueous media by using acetate-stimulating *Geobacter* species, while enhanced removal efficiency was demonstrated by supplementation with glucose, ethanol, and acetate as an electron donor [120]. Since the 1990s, a variety of extremophilic microorganisms that can thrive under high levels of ionizing radiation conditions (>15 kGy) have been identified [121–123]. Among these, *D. radiodurans*, which is one of the most radio-resistant microorganisms, has received much attention as a biological material for on-site treatment of radionuclide-contaminated environments [124,125] (Table 3). Moreover, a variety of studies investigating the development of the bioremediation processes using *D. radiodurans* for the removal of radionuclides pollutants have been reported [123,126–129]. A genetically engineered *D. radiodurans* strain expressing a non-specific acid phosphatase from *Salmonella enterica* serovar Typhi [127–129] or bacterial Ni/Co transporter (NiCoT) [130] can precipitate the oxidized form of uranium pollutants and radioactive cobalt (⁶⁰Co), respectively.

In recent years, the combination of extremophilic microorganisms with nanotechnology has emerged as a central strategy in efforts to treat polluted environments. A few case studies...
including the biosynthesis of various nanomaterials using extremophilic microorganisms have been reported [131–135]. With the advent of nano-biotechnology, the combination of extremophilic microorganisms with nanomaterials (nano-adsorbents and reductants) will be a promising technology for useful bioremediation applications. For example, a highly efficient and stable method for the removal of radioactive iodine (125I) using *D. radiodurans* with biogenic Au nanoparticles has been reported [131], in which more than 3.7 MBq of 125I was efficiently removed (>99%) within 30 min. More recently, the thermo-acidophilic archeon *S. tokodaii* 7T (NBRC 100140) capable of synthesizing biogenic Pd(0) nanoparticles (mean diameter: 8.7 nm) showed four-fold increased Cr(IV) reduction with 2.0 mg Cr(VI)/L/h/Pd(0) compared to a commercial Pd/C catalyst ([0.5 mg Cr(VI)/L/h/Pd(0)]) [136]. Another study also demonstrated efficient Cr(IV) reduction using Pd(0) nanoparticles synthesized by the acidophilic Fe3+-reducing bacteria *Ac. aromatica* PFBCT and *Ap. cryptum* SJH via a one-step microbiological reaction [137].

**Table 3.** Extremophilic microorganisms used in radioactive waste bioremediation.

| Radionuclide | Extremophile | Resistance | Removal Efficiency | Reference |
|--------------|--------------|------------|--------------------|-----------|
| U(VI), Cr(VI), Tc(VII) | Deinococcus geothermalis | Radiation (12 kGy), high temperature (55 °C) | >99% | [123] |
| D. radiodurans | ND | Radiation (6 kGy) | 95–100% | [126] |
| Cr-60 | *D. radiodurans* expressing PhoN | Radiation (6.4 kGy) | >60% | [130] |
| I-125 | *D. radiodurans* expressing NiCoT | Radiation (8 kGy) | >99% | [131] |

4. The Future Direction

Pollution, which has emerged as a side effect of the rapid growth of industrialization and urbanization, is a worldwide threat to the environment and public health. Thus, the development of highly efficient and stable methods for cleaning up polluted environments has become a major challenge. Although a variety of conventional methods to remove toxic pollutants have been developed over the past several decades, there are still many hurdles that need to be overcome to realize practical applications [138]. Hence, extremophilic microorganisms, which can thrive under harsh conditions, have been receiving particular interest as bioagents for the removal of toxic pollutants.

Although conventional microbial bioremediation processes have succeeded in the removal of various toxic pollutants, current methods still require much effort to overcome their limitations in terms of cost-effectiveness, removal efficiency, and practicality. *E. coli* and *Bacillus* spp. are commonly considered host strains for microbial bioremediation processes, being well known due to their broad use with well-established genetic engineering tools [139,140]. However, despite intensive genetic engineering, the practical use of these microorganisms for on-site remediation is extremely limited, owing to their relatively weak resistance to harsh conditions and low removal efficiency. Thus, to overcome these limitations, subsequent strategies based on the combination of extremophilic microorganisms with advanced biotechnology from fields such as systems metabolic engineering, synthetic biology, and nanotechnology have enhanced the performance of bioremediation through reprogramming the nature of wild-type microorganisms [141,142]. Several approaches based on biotechnology and nanotechnology are (1) screening and identification of microorganisms that have a strong tolerance for harsh conditions, (2) making microorganisms capable of degrading a variety of environmental toxic pollutants, (3) increasing the removal capacity and specificity of microorganisms toward target pollutants, and (4) expanding the removal spectrum of microorganisms using biogenic nanoparticles. Moreover, a variety of advanced tools in bioengineering, such as in silico flux analysis, biostatistics, and multi-omics analysis, will allow us to access the possibly infinite potential of extremophilic microorganisms for the treatment of environmental toxic pollutants.
5. Conclusions

When considering all the aspects presented in this review, extremophilic microorganisms appear as attractive bioagents for the clean-up of toxic pollutants contaminating the environment, due to their unique characteristics such as toughness, adaptability, and strong resistance to extreme conditions. Although many challenges still need to be addressed, the adoption of extremophilic microorganisms for the development of bioremediation processes is an environmental imperative for us to meet the needs of global public health. Indeed, combining extremophilic microorganisms with biotechnology and nanotechnology will open new avenues toward developing highly efficient and eco-friendly methods for the treatment of toxic pollutants (Figure 2).

Figure 2. A schematic diagram of advanced bioremediation using extremophilic microorganisms combined with biotechnology and nanotechnology. Representative candidates that can be used as a host strain for the treatment of pollutants in the environment are shown.

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