Review

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A mini-review of petroleum and sludge bioremediation using microorganisms

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Abstract. Bioremediation, a process led by microorganisms, is gaining prominence for its effectiveness in transforming environmental pollutants into harmless compounds, particularly in heavily contaminated areas. Microbes in polluted environments showcase impressive genetic and enzymatic adaptability, reducing toxicity. This approach offers a promising avenue for eco-friendly and cost-effective remediation, with intricate mechanisms and metabolic approaches that address various challenges, including petroleum contamination and sludge management, thus presenting sustainable solutions for environmental and waste management issues.

Keywords: Bioremediation, microorganisms, petroleum, sludge

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1. Introduction

Bioremediation, a natural process primarily orchestrated by microorganisms, plays a pivotal role in immobilizing or converting environmental pollutants into harmless substances [1]. This method has garnered increasing attention for remediating severely contaminated soil and water, particularly when harnessed with highly efficient indigenous microorganisms. Microbes residing in polluted soils display an incredible ability to endure by altering their genetic makeup and enzymatic processes, reducing the toxicity of their surroundings [2]. Consequently, these microorganisms emerge as a promising resource for advancing bioremediation applications, boasting advantages such as environmental friendliness, cost-effectiveness, minimal energy requirements, and remarkable efficacy in breaking down or transforming a wide range of hazardous compounds, including hydrocarbons, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAH), pharmaceuticals, radionuclides, and heavy metals (Cr, Cd, As, Hg, etc.) [3]. The process of microbial bioremediation involves intricate mechanisms such as biodegradation, biotransformation, and biosorption/bioaccumulation [3]. From a cellular metabolism perspective, this process can be categorized into two main approaches: metabolism-dependent (active method) and metabolism-non-dependent (passive method), depending on whether pollutants are transformed during microbial cell metabolism or through physicochemical interactions with cell wall ligands [3], [4]. One specific area of bioremediation focuses on petroleum contamination, where numerous microorganisms have demonstrated significant potential for degrading petroleum-derived substances, including various hydrocarbons, with specific genes and enzymes playing crucial roles [5]. Additionally, specialized bacterial strains have shown remarkable proficiency in degrading specific chemical components of petroleum [6]. Another facet of bioremediation pertains to sludge management, encompassing sewage sludge, ash sludge, pond sludge, and petroleum-contaminated sludge [7].

Innovative microbial-driven approaches are emerging as effective means for the bioremediation of these diverse sludge types, offering sustainable solutions for environmental and waste management challenges [2].

2. Bioremediation of petroleum

Sources of hydrocarbons including petroleum, pesticides, and other hazardous organic matter, are one of the main pollutants in soil, surface water, and groundwater [8][9]. Various chemical compounds in crude oil, oil products, and petroleum consist of different weights of hydrocarbons such as saturated and branches alkanes, mono- and poly-cyclic aromatics, homo- and hetero-cyclic aromatic and large aromatic molecules, and these compounds seriously affect the health of soil and purity of water [10][8]. The soil degradation in Mongolia is caused by excessive mining results in contaminating the soil with heavy metals, further causing 77% of soil degradation and desertification nationwide [11]. Petroleum pollution is mainly from gas stations, railway stations, car repair centers, oil fields, mining, and transportation of petroleum-derived products. Hydrocarbons in petroleum are very dangerous to living organisms such as plants, animals, and humans, and it has carcinogenic, mutagenic, and neurotoxic properties [10][9]. Microbial bioremediation degrades complex organic compounds to simple inorganic compounds like CO_2 and H_2O [9]. Several microorganisms have been isolated from petroleum-derived contaminated soils and these organisms showed a high potential for bioremediation application. Common microbial species that can remediate petroleum-derived products are listed in **Table 1**, and some of them could work at less than 25°C [12][3][5]. Some special genes include *alkB* and *nahAC* code for enzymes that can break down alkane and naphthalene [5]. Moreover, other enzymes such as hydrolases, oxygenase, demethylase, dehalogenases, transferases, and oxidoreductases contribute to pollutants' aerobic and anaerobic degradation [12]. Some special microbes produce biosurfactants that contribute to the main role of reduction of bacterial surface tension and degradation of pollutants [6].

Researchers have been paying much attention to investigating new microbial species that have efficient remediation activity [12]. *Mycobacterium austroafricanum* was isolated and identified from a gasoline-contaminated aquifer, and the result of the study revealed that bacteria degraded 86% of gasoline in 28 days [42]. *Rhodococcus* sp. is able to survive and work under low temperatures and high salt conditions, moreover, bacteria degrade 65% of crude oil in 9 days [6]. *Bacillus subtilis*-27 can survive and work under different ranges of temperature and salinity, and degrade 65% of crude oil in 5 days in laboratory conditions [43]. A mixture of bacterial consortiums including *Raoutella ornithinolytuca* strain PS, *Bacillus subtilis* strain BJ11, *Acinetobacter lwoffii* strain BJ10, *Acinetobacter pittii* strain BJ6, and *Serratia marcescens* strain PL degraded more than 94% of crude oil in 10 days in a liquid medium and 65% of crude oil in 40 days in soil [44]. A selected bacterium consortium degraded 80–82% of BTEX (benzene, toluene, ethylbenzene, and xylene) in a liquid medium in 7 days [45]. *Flavobacterium petrolei* sp. nov which was isolated and identified from oil-contaminated Arctic soil degraded 60% of diesel oil in a liquid medium within 14 days [46]. Also, some special bacterial strains have been shown to efficiently degrade of chemical compounds of petroleum. For instance, the *Pseudomonas aeruginosa* L10 strain efficiently degrades some chemical components of diesel oil including C10-C26 n-alkanes, naphthalene, phenanthrene, and pyrene [47]. Both *Delftia* sp. and *Achromobacter* sp. have shown a potential to degrade polyaromatic carbon (naphthalene, phenanthrene, fluoranthene, and pyrene) and aliphatic hydrocarbons (C12, C16, C20, and C32) [48].

3. Bioremediation of sludge

Waste sludges, such as sewage and ash sludge, pond sludge, and petroleum-contaminated sludge, are raising environmental concerns in the context of waste management [3]. These sludges, generated from various sources, require sustainable disposal solutions. Bioleaching, bioremediation, and biodegradation methods play a pivotal role in addressing the ecological impact and promoting environmentally friendly waste management practices [7]. These diverse sludge categories represent critical areas of research in environmental science, encompassing municipal and industrial waste as well as hydrocarbon-related activities.

After industrial and municipal wastewater treatment, massive amounts of primary and secondary sludge are produced. The primary sludge is produced from the mechanical treatment of the wastewater, and the secondary sludge is from the biological treatment [7]. The most common method of removing sludge is burning it until it becomes fly ash [3]. Coal and fuel oil are traditional energy resources in developing countries. In Mongolia, all the thermal power plants, industries, and civilians living in Ger burn coal for energy. Because of these reasons, massive amounts of fly ash and bottom ash are continuously produced. Different inorganic materials and metals like Al, Cd, Cr, Cu, Ni, Pb, and Zn are compromised in the sludge and fly ash [7][48]. Several anthropogenic pollutants including nonylphenol are usually found in sewage sludge [49]. Therefore, environmentally friendly methods such as bioleaching,

Table 1. Common microbial species isolated from contaminated place

Microbial species	Source of isolation	Reference
Arthrobacter spp.	Nuclear waste contaminated sediment Diesel contaminated soil	[13][14]
Achromobacter sp.	Crude oil-contaminated seawater	[15]
Alcaligenes sp.	Petroleum oil-contaminated sites	[16]
Enterobacter sp.	Petroleum oil-contaminated sites	[16]
Brevibacterium sp.	Crude oil-contaminated soil	[17]
Planococcus sp.	Diesel contaminated ocean	[18]
Pseudomonas sp.	Oil contaminated soil, Heavy metals contaminated soil, Hydrocarbon contaminated soil	[18][19][20][21]
Phenylobacterium sp.	PAHs contaminated soil	[22]
Collimonas sp.	Oil contaminated soil	[23]
Corynebacterium sp.	Oil contaminated soil	[24]
Rhodococcus sp.	Oil contaminated soil, Nuclear waste contaminated sediment Diesel contaminated soil and waste canola oil	[23][25][26][14]
Bacillus sp.	Hydrocarbon contaminated soil, PAHs contaminated soil	[27][28]
Nocardioides sp.	Oil contaminated soil	[29]
Nocardia sp.	Nuclear waste contaminated sediment	[30]
Marinobacter sp.	Sediment Oil-producing well	[31][32]
Mycobacterium sp.	PAH contaminated soil	[33]
Micrococcus sp.	Hydrocarbons contaminated soil	[34]
Methylobacterium sp.	Hydrocarbons contaminated soil	[34]
Sphingomonas sp.	PAHs contaminated soil, heavy metals contaminated soil Aromatic fraction of crude oil, jet fuel and diesel contaminated soil	[35][36][37]
Sphingobium sp.	Phenanthrene contaminated soil	[38]
Shewanella sp.	Diesel contaminated ocean	[18]
Streptococcus sp.	Oil contaminated sites	[39]
Stenotrophomonas sp.	Heavy metals contaminated agriculture field	[40]
Flavobacteria sp.	Oil-contaminated arctic soil	[41]

bioremediation, and biodegradation are needed to investigate the disposal of the sludge. There are several studies related to bacterial bioleaching or bioremediation have been published. Among them, *Acidithiobacillus ferrooxidans* is one of the most important species because they get energy from the oxidation of sulfur and from ferric ions (Fe^{3+}) to ferrous ions (Fe^{2+}) oxidation [7]. *A. ferrooxidans* and *A. thiooxidans* successfully degrade sludge by removing 10–100% of heavy metals such as Cu, Cr, Cd, Pb, Mn, Ni, and Zn under anaerobic conditions [3]. Moreover, *A. ferrooxidans* and *A. thiooxidans* reduced 74% and 96.4% of V in fuel oil ash, respectively [50][51]. *A. thiooxidans* removed 25% of Al and 22% of Fe in coal ash [52]. There is another species *Leptospirillum ferroxidans* also uses Fe2+ as an energy source and can tolerate lower pH, and higher concentrations of uranium, molybdenum, and silver than *A. ferrooxidans*, but they have lower tolerance against copper and sulfur [7]. *Bacillus safensis* CN12 is able to degrade extracted nonylphenol solution from sewage sludge after applying cyclodextrin [49]. Interestingly, Mongolian researchers have successfully transformed sewage sludge into the soil by using a mixture of several microorganisms including bacteria, yeast, and fungi, after applying fortified preparation of humin to the sludge [53]. According to this study's result, the treated soil had absence of pathogenic microorganisms, and was odorless.

On the other hand, amounts of surplus organic materials from organic degradation and leftover feed build sludge. Sewage waste from ponds is divided into 4 forms including gases, liquid, semi-solid, and solid or sludge [54]. Furthermore, sludge is categorized into suspended and settled solids [55]. Among them, suspended solids are difficult to remove from water, because of the remaining suspension of small particles in water [56]. By contrast, big particles make settled solids easy to remove [57]. Microbial bioremediation is one of the effective approaches for cleaning pond sludge. Ammonia-oxidizing bacteria and nitrite-oxidizing bacteria from autotrophs contribute to nitrification and denitrification. Microorganisms from heterotrophs convert ammonia nitrogen into harmless substances and they use organic waste as nutrient sources. Nitrite-oxidizing bacteria from genera of *Nitrobacter, Nitrococcus,* and *Nitrospira* convert nitrate to a harmless form of nitrogen. Several genera of denitrifiers including *Bacillus* have been identified [54]. *Bacillus* sp. has shown a potential to decrease the amounts of ammonia, nitrogen, phosphorus, nitrite, nitrate, phosphate ions, and chemical oxygen [58][59][60][61][62]. A mixture of *Bacillus subtilis, Nitrobacter,* and yeast reduced 99.74% of total nitrogen and nitrate [63]. *Marichromatium gracile* YL28 discharged 99.96% of nitrite in pond sludge within 7 days [64]. Bacteria with special enzymes such as phosphatases and phytases can produce phosphorus from organic compounds such as PO_4. Sulfur bacteria from the Chromatiaceae and Chlorobiaceae families consume hydrogen sulfide in anaerobic conditions under sunlight [54].

Furthermore, high-efficiency petroleum degrading microorganisms have been studied and used for the bioremediation of petroleum oily sludge. Indigenous microbial consortium successfully degraded more than 80% of total petroleum hydrocarbon in oil sludge-contaminated soil within 90 days [65]. A mixture of bacterial communities including *Leteimonas huabeiensis, Chelatocossus daeguensis, Pseudomonas aeruginosa, Bacillus subtilis,* and indigenous microorganisms showed high potential to degrade 97% of total petroleum hydrocarbons and to reduce 93% of chemical oxygen demand (COD) from petroleum sludge [66]. The combination of bacterial consortium and wheat bran bulking agent degrades 76% of hydrocarbon in petroleum oily sludge [67].

Summary

In the realm of environmental conservation, bioremediation stands as a powerful natural process led by microorganisms, serving as a beacon of hope in tackling environmental contamination concerns. These microorganisms, particularly when native to the polluted soil, exhibit remarkable resilience by adjusting their genetic composition and enzymatic functions to mitigate the toxicity of their surroundings [2]. Microbial bioremediation showcases its mettle in addressing a wide array of environmental pollutants, ranging from hydrocarbons, polyaromatic hydrocarbons and heavy metals, with the potential to transform these harmful substances into harmless compounds [3]. This process is multifaceted, with metabolic-dependent and metabolic-independent mechanisms, adding layers of complexity to this eco-friendly approach [4].

The bioremediation of petroleum-contaminated soil represents a crucial facet, given the prevalence of hydrocarbon pollutants in various ecosystems [10]. This endeavor has led to the discovery of numerous microorganisms with the capacity to break down petroleum-derived substances efficiently. Specific genes and enzymes are key players in the biodegradation process, contributing to the mitigation of pollutants [5]. Furthermore, researchers are continually exploring novel microbial species with the potential for efficient remediation.

In addition to petroleum-contaminated soil, the management of different types of waste sludge, including sewage and ash sludge, pond sludge, and petroleum-contaminated sludge, presents significant environmental challenges [3]. These waste products result from a variety of industrial and municipal processes and necessitate sustainable disposal solutions [8]. Bioleaching, bioremediation, and biodegradation methods are emerging as pivotal tools to address these challenges, promoting eco-friendly waste management practices and mitigating the environmental impact [7]. These distinct areas of bioremediation research underscore the ongoing efforts to address pollution concerns and promote sustainable environmental stewardship.

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Тойм өгүүлэл

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Нефтийн бүтээгдэхүүн, лагийн бохирдлыг бичил биетэн ашиглан бууруулсан судалгааны тойм өгүүлэл

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Хураангуй. Бичил биетнээр биологийн нөхөн сэргээлт хийх нь хүрээлэн буй орчны бохирдлыг бууруулах, бохирдол ихтэй бүсийг хоргүйжүүлэх давуу талтай. Бохирдолтой орчноос ялган авсан бичил биетний генетикийн болон ферментийн дасан зохицох чадварыг ашиглан, бохирдлыг бууруулдаг. Энэхүү арга нь нефтийн бүтээгдэхүүний бохирдол, лагийг цэвэрлэхэд бичил биетний механизм, бодисын солилцоог ашиглан, байгаль орчинд ээлтэй, зардал багатай нөхөн сэргээх ирээдүйтэй арга замыг бий болгодог. Улмаар байгаль орчин, хог хаягдлын менежментийн асуудлыг шийдвэрлэх ач тустай.

Түлхүүр үгс: Биологийн нөхөн сэргээлт, бичил биетэн, нефтийн бүтээгдэхүүн, лаг

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1. Удиртгал

Биологийн нөхөн сэргээлт нь үндсэндээ бичил биетний тусламжтай явагддаг байгалийн үйл явц бөгөөд хүрээлэн буй орчны хорыг саармагжуулах эсвэл хор хөнөөлгүй бодис болгон хувиргах чухал үүрэг гүйцэтгэдэг [1]. Ялангуяа биологийн идэвх өндөртэй нутгийн бичил биетүүдийг ашиглан бохирдсон хөрс, усыг нөхөн сэргээхэд ихээхэн хувь нэмэртэй арга юм. Бохирдсон хөрсөнд амьдардаг бичил биетнүүд нь хүрээлэн буй орчноос хамааран өөрийн удамшлын бүтэц, ферментийн үйл ажиллагааг өөрчлөн дасан зохицож, орчны хоруу чанарыг бууруулж тэсвэрлэх өвөрмөц чадвартай байдаг [2]. Иймээс эдгээр бичил биетнүүд нь байгаль орчинд ээлтэй, зардал багатай, эрчим хүчний хэмнэлттэй, нүүрсустөрөгч, полихлорт бифенил (PCBs), полиароматик нүүрсустөрөгч (PAH), эм, радионуклид мөн хүнд металл (Cr, Cd, As, Hg гэх мэт) зэрэг олон төрлийн хортой нэгдлүүдийг задлах, хувиргах зэрэг давуу талтай учир биологийн нөхөн сэргээлтэд ашиглах хамгийн тохиромжтой эх үүсвэр юм [3]. Бичил биетнээр нөхөн сэргээх нь био-задрал, биотрансформаци, био-хуримтлал зэрэг нарийн төвөгтэй механизмуудтай [3]. Бичил биетний бодисын солилцооны явцад эсвэл эсийн ханын лигандуудтай физик-химийн харилцан үйлчлэлийн дүнд бохирдуулагч бодисууд өөрчлөгдөхөөс хамааран бодисын солилцооноос хамааралтай (идэвхтэй арга) ба бодисын солилцооноос хамааралгүй (идэвхгүй арга) гэсэн хоёр үндсэн хэсэгт ангилж болно [3][4]. Биологийн нөхөн сэргээлтийн нэг тодорхой чиглэл нь газрын тосны гаралтай бодисыг задлах бөгөөд, үүнд олон тооны бичил биетүүдийн тодорхой ген, ферментүүд ашиглан газрын тосны гаралтай бодисууд, төрөл бүрийн нүүрсустөрөгчидийг задлахад ихээхэн ач холбогдолтой юм. Зарим бактерийн омгууд нь газрын тосны тодорхой бүлэг, химийн нэгдлүүдийг задлах чадвартай [6]. Биологийн нөхөн сэргээлтийн нэг хэсэг нь лагийн менежмент буюу бохир усны лаг, үнсний лаг, цөөрмийн лаг, нефтийн бүтээгдэхүүнээр бохирдсон лагийг боловсруулах юм [7]. Бичил биетнээр биологийн нөхөн сэргээлт хийх нь байгаль орчин, хог хаягдлын менежментийн асуудлыг шийдвэрлэх өндөр үр дүнтэй аргуудын нэг юм [2].

2. Нефтийн бүтээгдэхүүний бохирдлыг бичил биетэн ашиглан бууруулах

Нүүрсустөрөгч агуулсан нефтийн бүтээгдэхүүн, пестицид болон бусад аюултай органик бодис нь хөрс, гадаргын ус, гүний усыг бохирдуулагч гол эх үүсвэр юм [8][9]. Нефт, нефтийн бүтээгдэхүүн нь төрөл бүрийн химийн нэгдлүүд болох ханасан ба салбаралсан алканууд, моно ба полициклик ароматууд, гомо ба гетероциклик аромат болон том аромат зэрэг өөр өөр молекул жинтэй нүүрсустөрөгчөөс бүрддэг бөгөөд эдгээр нэгдлүүд нь хөрс, усны цэвэр байдалд сөрөг нөлөө үзүүлдэг [10][8]. Монгол орны хөрсний доройтол нь хэт их уул уурхайн олборлолтын үр дүнд хөрсийг хүнд металлаар бохирдуулж, улмаар улсын хэмжээнд хөрсний доройтол, цөлжилтийг 77%-д хүргэж байна [11]. Нефтийн бүтээгдэхүүний бохирдол нь шатахуун түгээх станц, галт тэрэгний буудал, авто засварын газар, газрын тосны олборлолт, түүний гаралтай бүтээгдэхүүн тээвэрлэлт зэргээс үүдэлтэй. Нефтийн бүтээгдэхүүн дэх нүүрсустөрөгч нь ургамал, амьтан, хүн зэрэг амьд организмд аюултай бөгөөд хорт хавдар үүсгэх, мутаген, мэдрэлийн системд нөлөөлөх шинж чанартай [10][9]. Бичил биетний биологийн нөхөн сэргээлт нь органик нэгдлүүдийг CO_2, H_2O гэх мэт органик бус нэгдлүүд болгон задалдаг [9]. Нефтийн бүтээгдэхүүний гаралтай бохирдсон хөрсөөс хэд хэдэн бичил биетнийг ялгасан бөгөөд эдгээр нь бохирдол бууруулах идэвх өндөртэй байсан. Нефтийн бүтээгдэхүүний бохирдлыг бууруулах идэвхтэй бичил биетний төрлүүдийг **1-р хүснэгт**эд харуулав. Тэдгээрийн зарим нь 25°C-аас бага температурт идэвх өндөртэй [12][3][5]. Зарим тусгай генүүд нь алкан, нафталиныг задалдаг ферментийн *alkB* болон *nahAC* кодыг агуулдаг [5]. Түүнчлэн гидролаза, оксигеназа, деметилаза, дегалогеназа, трансфераза, оксидоредуктаза зэрэг ферментүүд нь бохирдуулагчийн аэроб ба анаэроб задралыг дэмждэг [12]. Зарим сонгомол бичил биетнүүд нь өөрийн эсийн ханаас орчны бохирдлыг задлагч субстрат нийлэгжүүлдэг [6].

Судлаачид бохирдол бууруулах идэвхтэй шинэ бичил биетний төрлийг судлахад ихээхэн ач холбогдол өгч байна [12]. Шатахуунаар бохирдсон уст давхаргаас *Mycobacterium austroafricanum* ялгасан бөгөөд судалгааны үр дүнд 28 хоногийн дотор шатахууны 86%-ийг задалдаг болохыг тогтоосон [42]. *Rhodococcus* sp. бага температур, давс ихтэй нөхцөлд амьдрах чадвартай үүнээс гадна бактери нь 9 хоногийн дотор түүхий нефтийн 65% -ийг задалдаг байна [6]. *Bacillus subtilis*-27 омог нь температур, давсжилтын олон янзын ялгаатай орчинд амьдрах чадвартай бөгөөд лабораторийн нөхцөлд 5 хоногийн дотор түүхий нефтийн 65%-ийг задалдаг [43]. *Raoutella ornithinolytuca* PS, *Bacillus subtilis* BJ11, *Acinetobacter lwoffii* BJ10, *Acinetobacter pittii* BJ6, *Serratia marcescens* PL зэрэг бактериудын нийлмэл бэлдмэл нь түүхий нефтийг шингэн тэжээлт орчинд 10 хоногийн дотор 94%, хөрсөнд 40 хоногийн дотор 65%-тай задалсан үр дүн үзүүлсэн [44]. Сонгосон бактерийн бэлдмэл нь шингэн тэжээлт орчинд 7 хоногийн дотор BTEX (бензол, толуол, этилбензол, ксилол)-ийн 80-82%-ийг задалсан үр дүн үзүүлсэн [45]. Арктикийн хөрснөөс ялгасан *Flavobacterium petrolei* sp. nov. омог нь шингэн тэжээлт орчинд 14 хоногийн дотор дизелийг 60%-тай задалсан [46]. Мөн зарим сонгомол бактерийн омгууд нь нефтийн бүтээгдэхүүний химийн нэгдлүүдийг үр дүнтэй задалдаг болохыг тогтоосон. Жишээлбэл, *Pseudomonas aeruginosa* L10 омог нь C10-C26 n-алкан, нафталин, фенантрен, пирен зэрэг дизель тосны зарим химийн бүрэлдэхүүн хэсгүүдийг үр дүнтэй задалдаг [47]. *Delftia* sp., *Achromobacter* sp. нь полиароматик нүүрстөрөгч (нафталин, фенантрен, фторантен, пирен) болон алифат нүүрсустөрөгч (C12, C16, C20, C32)-ыг задлах чадвартай болох нь тогтоогдсон [48].

3. Лагийн бохирдлыг бичил биетэн ашиглан бууруулах

Бохир усны лаг, үнсний лаг, цөөрмийн лаг, нефтийн бүтээгдэхүүнээр бохирдсон лаг зэрэг хаягдал нь байгаль орчны хог хаягдлын менежментэд ихээхэн асуудалд үүсгэж байна [3]. Олон төрлийн эх үүсвэрээс үүссэн эдгээр лагийг цэвэрлэх, боловсруулах шийдлийг олох шаардлагатай. Байгаль орчинд ээлтэй хог хаягдлын менежментийг дэмжих, экологид үзүүлэх нөлөөллийг арилгахад бичил биетний оролцоотой био-уусалт, био-нөхөн сэргээлт, био-задралын аргууд нь чухал үүрэг гүйцэтгэдэг [7]. Дээр дурдсан лагуудыг судлах нь хотжилт болон үйлдвэрийн нүүрсустөрөгч агуулсан хог хаягдлыг шийдвэрлэхэд чухал ач холбогдолтой.

Үйлдвэрийн болон хотын бохир усны цэвэрлэгээгээр их хэмжээний анхдагч болон хоёрдогч лаг ялгардаг. Бохир усанд механик боловсруулалт хийснээр анхдагч лаг үүсдэг, анхдагч лагт биологийн боловсруулалт хийснээр хоёрдогч лаг үүснэ [7]. Лагийг зайлуулах хамгийн түгээмэл арга бол

Хүснэгт 1. Бохирдолтой газраас ялгасан бичил биетний зүйлүүд

Бичил биетний төрөл	Дээж авсан эх үүсвэр	Эх сурвалж
Arthrobacter spp.	Цөмийн хаягдалд бохирдсон хөрс Дизель түлшээр бохирдсон хөрс	[13][14]
Achromobacter sp.	Түүхий нефтээр бохирдсон далайн ус	[15]
Alcaligenes sp.	Нефтээр бохирдсон газрууд	[16]
Enterobacter sp.	Нефтээр бохирдсон газрууд	[16]
Brevibacterium sp.	Түүхий нефтээр бохирдсон хөрс	[17]
Planococcus sp.	Дизель түлшээр бохирдсон далай	[18]
Pseudomonas sp.	Нефтээр бохирдсон хөрс, Хүнд металлаар бохирдсон хөрс, Нүүрсустөрөгчөөр бохирдсон хөрс	[18][19][20][21]
Phenylobacterium sp.	PAHs бохирдсон хөрс	[22]
Collimonas sp.	Түүхий нефтээр бохирдсон хөрс	[23]
Corynebacterium sp.	Түүхий нефтээр бохирдсон хөрс	[24]
Rhodococcus sp.	Түүхий нефтээр бохирдсон хөрс, Цөмийн хаягдал бохирдсон хөрс, Дизель түлшээр бохирдсон хөрс, Хаягдал рапс тос	[23][25][26][14]
Bacillus sp.	Нүүрсустөрөгчөөр бохирдсон хөрс, PAHs бохирдсон хөрс	[27][28]
Nocardioides sp.	Түүхий нефтээр бохирдсон хөрс	[29]
Nocardia sp.	Цөмийн хаягдал бохирдсон хөрс	[30]
Marinobacter sp.	Хаягдлын цэг Газрын тос олборлох цооног	[31][32]
Mycobacterium sp.	PAH-ээр бохирдсон хөрс	[33]
Micrococcus sp.	Нүүрсустөрөгчөөр бохирдсон хөрс	[34]
Methylobacterium sp.	Нүүрсустөрөгчөөр бохирдсон хөрс	[34]
Sphingomonas sp.	PAHs бохирдсон хөрс, Хүнд металлаар бохирдсон хөрс Түүхий нефтийн үнэртэй хэсэг, Онгоцны түлш болон дизель түлшээр бохирдсон хөрс	[35][36][37]
Sphingobium sp.	Фенантренээр бохирдсон хөрс	[38]
Shewanella sp.	Дизель түлшээр бохирдсон далай	[18]
Streptococcus sp.	Түүхий нефтээр бохирдсон газрууд	[39]
Stenotrophomonas sp.	Хүнд металлаар бохирдсон газар тариалангийн талбай	[40]
Flavobacteria sp.	Түүхий нефтээр бохирдсон хойд туйлын хөрс	[41]

үнс болтол нь шатаах явдал юм [3]. Нүүрс болон шатахуун нь хөгжиж буй орнуудын эрчим хүчний гол нөөц эх үүсвэр. Монголд бүх дулааны цахилгаан станц, үйлдвэр, гэр хороололд амьдардаг иргэд нүүрс түлж эрчим хүчээ авдаг. Энэ шалтгааны улмаас их хэмжээний үнс болон ёроолын үнс тасралтгүй үүсдэг. Янз бүрийн органик бус материал болон Al, Cd, Cr, Cu, Ni, Pb, Zn гэх мэт металлууд лаг болон агаарт дэгдсэн үнсэнд агуулагддаг[7][48]. Бохир усны лаганд нонилфенол зэрэг хүний үйл ажиллагаанаас үүдэлтэй хэд хэдэн бохирдуулагчид олддог [49]. Иймд лагийг байгаль орчинд ээлтэй бичил биетэн ашигласан био-уусгах, био-нөхөн сэргээх, био-задрал зэрэг аргуудыг ашиглаж зайлуулах хэрэгтэй. Бактерийн био-уусгах, био-нөхөн сэргээлттэй холбоотой хэд хэдэн судалгаа хэвлэгдсэн байна. Тэдгээрийн дотроос хамгийн чухалд тооцогдох *Acidithiobacillus ferrooxidans* омог нь хүхэр ба төмрийн ионы исэлдэлт явуулж энерги гарган авдаг (Fe^{3+} -с Fe^{2+}) [7]. *A. Ferrooxidans, A. thiooxidans* омгууд нь анаэроб нөхцөлд Cu, Cr, Cd, Pb, Mn, Ni, Zn зэрэг хүнд металлыг 10-100% зайлуулж лагийг амжилттай задалдаг [3]. Түүнчлэн, *A. ferrooxidans, A. thiooxidans* омгууд нь шатахууны үнсэн дэх V-ийн 74% ба 96.4% -ийг тус тус бууруулсан байна [50][51]. *A. thiooxidans* нь нүүрсний үнсэн дэх Al-ийн 25%, Fe-ийн 22%-ийг зайлуулжээ [52]. Өөр нэг төрлийн *Leptospirillum ferrooxidans* омог нь Fe^{2+}-ийг эрчим хүчний эх үүсвэр болгон ашигладаг бөгөөд A.ferrooxidans-аас бага pH, уран, молибден, мөнгөний өндөр агууламжийг тэсвэрлэх чадвартай боловч зэс, хүхрийн тэсвэрлэх чадвар багатай байдаг [7]. *Bacillus safensis* CN12 нь циклодекстрин нэмсний дараа бохир усны лагаас гаргаж авсан нонилфенолын уусмалыг задлах чадвартай [49]. Мөн, монгол судлаачид лаганд хүчжүүлсэн гуминий бэлдмэлийг хэрэглэсний дараа бактери, дрожж, мөөгөнцөр агуулсан бичил биетний биобэлдмэл ашиглан бохир усны лагийг амжилттай боловсруулсан [53]. Энэхүү судалгааны үр дүнгээс харахад лаг нь үнэргүй, эмгэг төрүүлэгч бичил биетэн илрээгүй байна.

Нөгөөтээгүүр, хоолны хаягдал болон хоёрдогч органик хаягдал нь лагийг бүтээдэг. Цөөрмийн бохирын хаягдлыг хий, шингэн, хагас хатуу, хатуу буюу лаг гэсэн 4 хэсэгт хуваадаг [54]. Цаашилбал, лагийг суспенз болон тунасан хатуу бодис гэж ангилдаг [55]. Тэдгээрийн дотор жижиг хэсгүүдийн суспенз нь усанд үлддэг тул суспенз бодисыг уснаас ялгахад хэцүү байдаг [56]. Эсрэгээрээ, том хэсгүүд нь биет тунадас үүсгэн арилгахад хялбар болгодог [57]. Цөөрмийн лагийг цэвэрлэх үр дүнтэй аргуудын нэг бол бичил биетний биологийн нөхөн сэргээлт юм. Автотроф аммиак исэлдүүлэгч бактери болон нитрит исэлдүүлэгч бактери нь нитрификаци ба денитрификацийг явуулдаг. Гетеротрофуудын бичил биетүүд аммоны азотыг хоргүй бодис болгон хувиргаж, органик хог хаягдлыг шим тэжээлийнхээ эх үүсвэр болгон ашигладаг. *Nitrobacter, Nitrococcus, Nitrospira* төрлийн нитрит исэлдүүлэгч бактери нь нитратыг хоргүй азот хэлбэрт шилжүүлдэг. Денитрификаци явуулдаг хэд хэдэн төрлийн *Bacillus* тодорхойлсон [54]. *Bacillus* sp. аммиак, азот, фосфор, нитрит, нитрат, фосфатын ион, химийн хэрэгцээт хүчилтөрөгчийн хэмжээг бууруулах чадвартай [58][59][60][61][62]. *Bacillus subtilis, Nitrobacter* болон дрожжийн холимог нь нийт азот, нитратын 99.74%-ийг бууруулдаг [63]. *Marichromatium gracile* YL28 нь 7 хоногийн дотор цөөрмийн лаг дахь нитритийн хэмжээг 99.96%-ийг зайлуулсан байна [64]. Фосфатаза, фитаза зэрэг тусгай ферменттэй бактери нь PO_4 гэх мэт органик нэгдлүүдээс фосфор үүсгэдэг. Chromatiaceae болон Chlorobiaceae омгийн бактери нарны гэрлийн дор агааргүй нөхцөлд хүхэрт устөрөгчийг задалдаг [54].

Цаашилбал, нефтийг задалдаг өндөр үр ашигтай бичил биетүүдийг судалж, нефтийн тосны лагийг био-нөхөн сэргээлтэд ашиглаж байна. Нутгийн омгуудаар хийсэн биобэлдмэл нь 90 хоногийн дотор газрын тосны лагаар бохирдсон хөрсөн дэх нийт нефтийн нүүрсустөрөгчийн 80% гаруйг амжилттай задалсан [65]. *Leteimonas huabeiensis, Chelatocossus daeguensis, Pseudomonas aeruginosa, Bacillus subtilis* болон нутгийн омгуудын биобэлдмэл нь газрын тосны нийт нүүрсустөрөгчийн 97%-ийг задалж, химийн хэрэгцээт хүчилтөрөгчийн (COD) 93%-ийг бууруулах өндөр чадамжтай болохыг харуулсан [66]. Бактерийн биобэлдмэл болон улаан буудайн хивгийг хослуулан хэрэглэх нефтийн лаг дахь нүүрсустөрөгчийн 76%-ийг задалдаг нь нотлогджээ [67].

Дүгнэлт

Бичил биетнийг ашиглан биологийн нөхөн сэргээлт хийх нь хүрээлэн буй орчны бохирдлын асуудлыг шийдвэрлэхэд чухал ач холбогдолтой нь харагдаж байна. Бохирдсон хөрснөөс ялган авсан эдгээр нутгийн омгууд нь хүрээлэн буй орчны хоруу чанарыг бууруулахын тулд генетикийн бүтэц, ферментийн үйл ажиллагаагаа тохируулан тухайн орчинд дасан зохицсон байна [2]. Бичил биетний гаралтай био-нөхөн сэргээлт нь нүүрсустөрөгч, полиаромат нүүрсустөрөгч, хүнд металл зэрэг байгаль орчныг бохирдуулагч бодисуудыг бууруулах идэвхтэй ба эдгээр хортой бодисыг хоргүй нэгдэл болгон хувиргах чадвартай [3]. Энэхүү олон талт процесс нь бодисын солилцооноос хамааралтай ба бодисын солилцооноос хамааралгүй механизмтай бөгөөд байгальд ээлтэй, хэд хэдэн ашигт шинж чанарыг нэмж өгдөг [4].

Нефтийн бүтээгдэхүүнээс гаралтай бодисуудыг задлах чадвартай сонгомол бичил биетнүүдийг нефтийн болон нүүрсустөрөгчөөр бохирдсон экосистемүүдээс илрүүлсэн нь бичил биетнийг ашиглан био-нөхөн сэргээлт хийх нь илүү үр дүнтэй гэдгийг харуулж байна. Өвөрмөц ген ба ферментүүд нь биологийн задралын гол хүчин зүйл бөгөөд бохирдуулагч бодисуудыг бууруулахад хувь нэмэр ихээр оруулдаг [5]. Сүүлийн үед судлаачид нөхөн сэргээх идэвх өндөртэй шинэ бичил биетний төрлийг зогсолтгүй эрж хайн судалж байна.

Газрын тосоор бохирдсон хөрсөөс гадна бохир усны лаг, үнсний лаг, цөөрмийн лаг, нефтээр бохирдсон лаг зэрэг янз бүрийн төрлийн хаягдал лагийг цэвэршүүлэлт нь байгаль орчинд ихээхэн бэрхшээл учруулдаг [3]. Эдгээр хаягдал бүтээгдэхүүн нь үйлдвэрлэлийн болон хотын суурингийн аж ахуйн үр дүнд бий болж, нөхөн сэргээлт, цэвэршүүлэлтийн шийдлийг олох шаардлага гарч ирсэн [8]. Эдгээр асуудлыг шийдвэрлэх, байгаль орчинд ээлтэй хог хаягдлын менежментийг сурталчлах, байгаль орчинд үзүүлэх нөлөөллийг бууруулахад ихээхэн нэмэр оруулах гол хэрэгслүүд нь био-уусгалт, био-нөхөн сэргээлт болон био-задралын аргууд болж байна [7]. Биологийн нөхөн сэргээлтийн судалгааны эдгээр тодорхой чиглэлүүд нь бохирдлын асуудлыг шийдвэрлэх, байгаль орчны тогтвортой менежментийг хангахад чиглэсэн хүчин чармайлтын нэгээхэн хэсэг юм.

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