



Hydrocarbon Degradation Potentials of Fungi: A Review

Tasiu Mahmud^{1*}, Ibrahim Alhaji Sabo², Zakari Nuhu Lambu¹, Dauda Danlami³ and Adamu Abdullahi Shehu¹

¹Department of Microbiology, Faculty of Sciences, Kano university of Science and Technology, Wudil. P.M.B. 3244, Kano State, Nigeria.

²Department of Microbiology, Faculty of Pure and Applied Sciences, Federal University Wukari, P.M.B. 1020 Wukari, Taraba State, Nigeria.

³Department of Biotechnology, Federal University Lokoja, P.M.B 1154. Kogi State, Nigeria

*Corresponding author:

Tasiu Mahmud

Department of Microbiology,

Faculty of Sciences,

Kano university of Science and Technology,

Wudil. P.M.B. 3244,

Kano State,

Nigeria.

Email: tasiu.microlabs@gmail.com

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ABSTRACT

One of the serious problems affecting the environment nowadays is petroleum hydrocarbon contaminations resulting from the activities in the oil and gas sector, these include: oil-spill, tank leakage, lubrication, petroleum exploitation, transportation, and services. Various techniques including mechanical and chemical methods have been employed for the bioremediation and degradation of hydrocarbons pollutants from the environments, however, some of these methods are generally expensive and may have detrimental effects on the environment, hence bioremediation is the alternative solution to hydrocarbon pollutants. Among microorganisms used in bioremediation technology nowadays, fungi are efficient, reliable, cost-effective, and environmentally friendly that can be used to clean-up and detoxify hydrocarbons contaminants from the environment viz; soil, water, and sediments. Bioremediation using fungi ensures the complete degradation and mineralization of petroleum hydrocarbon contaminants into carbon dioxide, water, inorganic compounds, and cell biomass. This review focuses on the potentials of fungi in the bioremediation of total petroleum hydrocarbons including the polycyclic aromatic hydrocarbons (PAHs). We reviewed and discussed current approaches in the bioremediation of hydrocarbon including the mechanisms of fungal bioremediation of hydrocarbon, which involves biosurfactants production and the use of fungal enzymes in the degradation of hydrocarbon pollutants. In general, fungi are more efficient and effective in the removal of hydrocarbon contaminants from the environments viz., water, soil, and sediments. However, the potentiality of fungi has not been exploited fully, hence further studies are recommended especially in the current genomic and proteomic era.

INTRODUCTION

Various Physical and chemical techniques have been employed in the past for the remediation of hydrocarbon contaminated environments, however, some of these techniques are very expensive and may have detrimental effects on the environments [1]. Water and soil pollutions caused by hydrocarbon contamination have become one of the biggest problems in developing countries [2]. Human activities in the area of oil and gas have been responsible for causing environmental hydrocarbon- pollutions, these activities include oil spills, tank leakage, lubrication, petroleum transportation, exploitation, and services [2,3]. Bioremediation is the alternative technique that can be use in solving hydrocarbon pollutions. Bioremediation

has been described as a process that uses microorganisms or their enzymes to return the natural environments altered by contaminants to its original stages [4,15]. Fungal biodegradation of petroleum hydrocarbon is nowadays, a cost-effective and environmentally friendly process that can be used to clean-up and detoxify hydrocarbon pollutants [5,9].

Fungi is one of the microorganisms previously discovered from sediments, water, and soil that have been polluted by hydrocarbons. In recent years various fungi have been isolated from petroleum hydrocarbon contaminated sites [5,6,7]. Previous studies have shown that fungi are potential biological candidates for hydrocarbon remediation technologies [8,9]. Furthermore, according to some recent investigation, various fungi can be able

to degrade petroleum mixtures, including the polycyclic aromatic hydrocarbons (PAHs), transform hydrocarbon into energy and biomass as well as biological waste products, these activities result in detoxification and elimination of hydrocarbon pollutants from the environment, including soil, water, sediments and industrial waste, presence of hydrocarbons pollutants in these aforementioned environments are serious threat to public health [11,10].

According to existing literature, various approaches has been employed to achieve bioremediation of total petroleum hydrocarbon mixtures using various microorganisms including bacteria, fungi, algae, plants etc. [12]. However, fungi are the most potential microorganisms in terms of biodegradation of petroleum hydrocarbon and other recalcitrant compounds, these abilities are due to their unique characteristics such as diversity (ubiquitous), morphology, versatility, and metabolic capabilities, hence fungi became suitable for bioremediation of hydrocarbons pollutants including the PAHs [13,14]. Furthermore, a previous study on hydrocarbon contaminated soil showed that fungi are more effective than bacteria in the degradation HM-WH, because the reported biodegradation efficiency ranged from 6-82% for fungi and 0.13-50% for bacteria [2,13].

The ability to degrade high molecular weight hydrocarbon pollutants depends on some advantages that were found in fungi. These include: (i) secretion of low substrate-specific enzymes (ii) ability to grow in an extreme environment than bacteria (iii) more access to hydrocarbon contaminants due to the formation of the mycelial network [2,13,15]. Fungi has been reported to produced biosurfactants which serve as a mechanism for achieving biodegradation of hydrocarbon, however, this is not open to all but rather some specific fungal organisms [2,16]. The objective of the study is to review and provide updated literature on the hydrocarbon biodegradation potentials of fungi, hence the study could be helpful to specialists and scientists working in this field.

Causes and effects of PAH's pollution

Polycyclic aromatic hydrocarbons are organic compounds consist of two or more aromatic rings of carbon and hydrogen atoms [11]. The causes of PAHs pollutions are as a result of combustion of organic molecules and their subsequent recombination, other sources of PAHs pollution includes: forest residue, agricultural residue and incineration of waste refuse [17]. Moreover, PAHs are also release into the environments after burning coal, petrol, wood. HMW-PAHs are more hydrophobic and recalcitrant, hence difficult to be degraded by bacteria [14,18]. PAHs are ubiquitous in the environments and therefore have serious health implications. According to in-vitro and in-vivo studies conducted on humans, animals and plants, PAHs was found to be carcinogenic, genotoxic, cytotoxic and ecotoxic [14,18,19]. Due to the environmental effects of PAHs, the US environmental agency classified it as a priority pollutant.

In the past, the treatment of PAH's pollution includes dilution, dispersion, volatilization, abiotic transformation etc. However, these methods are no longer reliable due to their detrimental effects on the environment after the treatments. Nowadays, fungal biodegradation is one of the reliable methods to reclaim PAHs contaminated environment because, its environmentally friendly [19]. Fungi have been reported to be capable of degrading PAHs, for example, *Monilinia strain W5-2* [15], *Scopulariopsis brevicaulis* and *non-white rot fungal strain PZ-4* [19]. The mechanisms by which fungi degrade PAHs involves the use of extracellular ligninolytic enzymes (LiP, MnP) and intracellular cellular cytochrome P450 as shown in Fig. 1 [14]. Recent studies have reported many ligninolytic fungal

species that can degrade different types of PAHs such as naphthalene, phenanthrene, chrysene, pyrene and etc. [14, 17,19].The advantage using fungi over bacteria is not only due to the presence of extracellular enzymes but also due to the presence of fungal mycelia which provide deeper penetration and larger surface area for degradation [17,19,20].

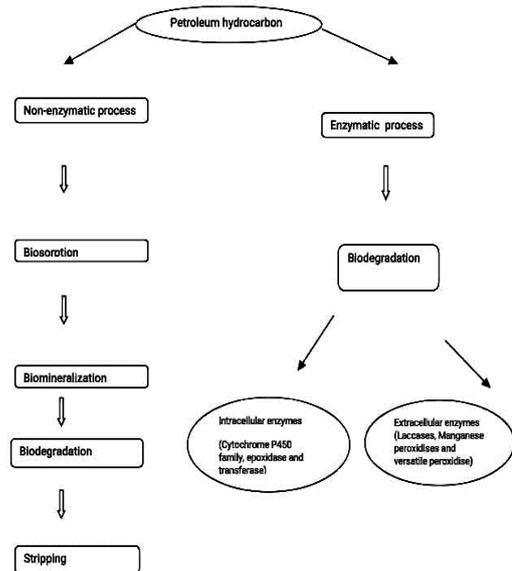


Fig. 1. General Mechanisms adopted by fungi for biodegradation of petroleum hydrocarbon.

Causes and effects of TPH's pollution

Total petroleum hydrocarbon is a term used to describe several chemical compounds that originated from crude oil. They are also called hydrocarbon because most of the constituents' elements are carbon and hydrogen [1,18]. The elemental composition of TPH is carbon 85-90%, hydrogen 10-14%, sulfur 0. 2-3%, nitrogen 0.1-2%, oxygen 1-1.5 and metals <1%. The causes of TPH pollution includes oil spill incidents, effluents of petroleum industries, oil ship operation and oil exploitation [1,13]. TPH is toxic and may causes detrimental effects on humans, animals and marine organisms, it may affect blood, immune system, liver, spleen, kidney, lungs and subsequently death [1,2]. Variety of methods has been employed for the treatment of pollution due to PAHs, including floating booms, oil combustion, absorbing materials and chemical dispersant, however, problems exist due to detrimental effects of these methods on the environments [2,17,19]. Fungi are capable of degrading TPH without causing any harm to the environments [1,9,11,13].

Mechanisms of fungal biodegradation of petroleum hydrocarbons

The mechanisms of fungal biodegradation of petroleum hydrocarbon depend mainly on the kind, nature, and quantity of the hydrocarbon mixtures present [9,3]. The first and most important mechanism is the attachment of fungal cells to the substrate. Similarly, the mechanism adopted by fungi during petroleum hydrocarbons degradation is the same mechanism applied during the degradation of other toxic and recalcitrant compounds, hence these mechanisms were extensively studied and reviewed by [2,10]. Several investigations and more recent literature on fungal bioremediation of petroleum hydrocarbon revealed that degradation was faster and efficient under aerobic conditions, furthermore, the degradation under aerobic

conditions gives better results than degradation under anaerobic conditions [3,13,14]. Similarly, the efficiency and effectiveness of fungal bioremediation of Petro-hydrocarbons depend largely on some important factors, these factors were also previously discussed and reviewed [2,3,13]. The factors include availability and types of nutrients, environmental conditions, temperature, salinity, oxygen level, and availability of water), and metabolic capabilities of the fungal isolate present [3, 9,12].

Biodegradation mechanisms for hydrocarbon degradation in fungi were categorized into two main processes, namely: enzymatic and non-enzymatic processes (Fig. 1). The non-enzymatic process is not mediated by enzymes but involved some series of biochemical reactions such as biosorption, biomineralization, and stripping [9]. However, the mechanism involving the enzymatic processes was mediated by some specific fungal enzymes, similarly, the roles played by these fungal enzymes in the bioremediation of Petro-hydrocarbons was previously described [3,2,16]. The mechanisms involving enzymes were further sub-grouped into extracellular and intracellular processes based on the sources of the fungal enzymes. The intracellular enzymes include cytochrome P450 family peroxidases and transferase, their participation and involvement in fungal bioremediation of petroleum hydrocarbon can lead to the activation of the hydrocarbon mixtures through oxidation, reduction, hydrolysis, and dehalogenation processes [2,3,9]. The activated hydrocarbon compounds are then converted to intermediate metabolites which are finally converted to excreted derivatives (Fig. 2). The extracellular enzymes, however, involved an enzymatic attack by some specific fungal enzymes, such as laccases, peroxidases, and oxidases, these aforementioned enzymes catabolized hydrocarbons into excreted derivatives [9,20,21]. Similarly, the mechanisms of fungal bioremediation of petroleum hydrocarbon under aerobic conditions were reviewed recently [3,8].

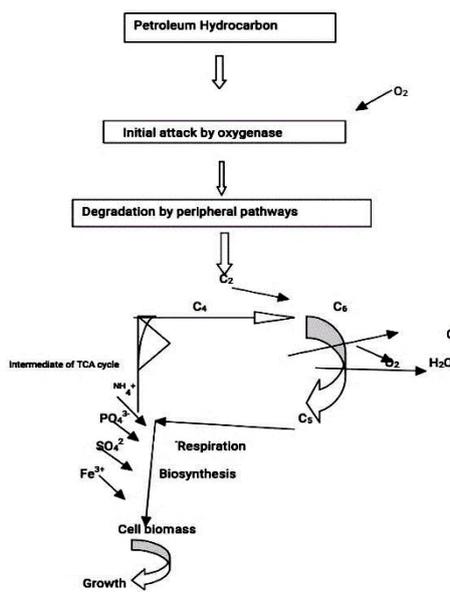


Fig. 2. Principle of aerobic fungal degradation of aliphatic hydrocarbons.

During aerobic degradation of petroleum hydrocarbon-pollutants, it begins with intracellular breaking down of hydrocarbons pollutants by oxidation processes which can be catalyzed by the enzymes oxygenase and peroxidases, hence aerobic degradation (Fig. 2). The pollutants are then gradually converted to different fragments through some central intermediary metabolisms (tricarboxylic acid cycle). Biological

fungal cell masses are then synthesized from the central precursors' metabolites (acetyl-CoA and succinate) [2,3,20]. The Gluconeogenesis process was then employed for the synthesis of sugars which are required for fungal biosynthesis and growth [3, 9].

In contrast to aerobic degradation of hydrocarbon pollutants, the mechanism involving anaerobic degradation of petroleum hydrocarbon pollutants shows a deficiency of addition of oxidized functional groups which can trigger or activate the hydrocarbons molecules, this results in the slow degradation of petroleum hydrocarbon by fungi under anaerobic conditions compared to that of aerobic condition [16]. Additionally, anaerobic fungi employed alternative terminal electron acceptors (NO₃, CO₂, etc.) other than oxygen during respiration [17,18 22,23]. The mechanism for PAH's degradation by fungi were previously reviewed [19,20,21,22]. Vast majority of fungi cannot use PAHs as sole source of carbon and energy; however, they can co- metabolize it to different variety of organic compounds and in some cases to CO₂ as shown in Fig. 3. Groups of fungi that can degrade PAHs includes: ligninolytic fungi and non-ligninolytic fungi [24].

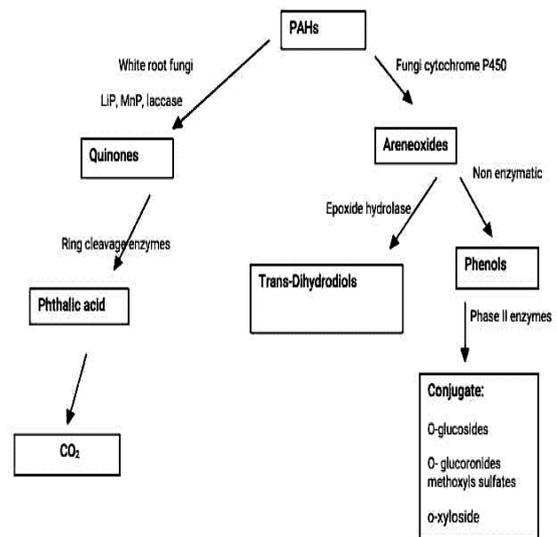


Fig. 3. Generalized pathways for the degradation of PAHs by fungi.

Current approaches in fungal bioremediation of Petro-hydrocarbons

Nowadays, biodegradation using fungi has been recognized as one of the most efficient and reliable methods for detoxification and removal of harmful pollutants resulting from contamination by petro-hydrocarbons [2,9,19]. Naturally occurring fungi present in Petro-hydrocarbons contaminated sites can break down total petroleum hydrocarbon fractions by natural attenuation process which normally takes a longer period due to sluggish degradation process [1,25]. Nowadays, the bioremediation process can greatly be enhanced by various methods to achieve efficient and cost-effective hydrocarbon-pollutants removal from the environment. Fig. 5 shows three (3) common and most widely available approaches of fungal bioremediation of petro-hydrocarbons, these approaches were recently reviewed [1,26,27]. The approaches include : bioaugmentation, biostimulation, and bioaugmentation-biostimulation [17].

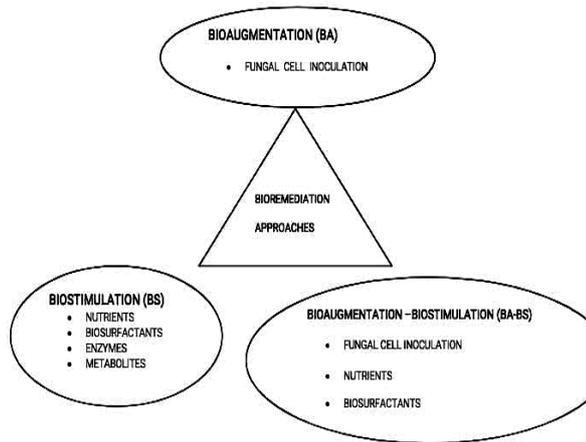


Fig. 5. Different approaches for fungal biodegradation of petroleum hydrocarbons.

Bioaugmentation approach

In bioaugmentation, potential hydrocarbons-degrading fungi are added in hydrocarbon pollutants to supplement the existing fungal population present, hence increasing the rate of petrohydrocarbons degradation by the exogenous fungi [1,28]. Bioaugmentation with fungi was now considered as a lasting solution for bioremediation of many recalcitrant compounds under extreme environmental conditions. The bioaugmentation approach is very efficient in transforming fresh oil spills into less harmful components, hence this process is known as polishing-up [1,15]. Similarly, bioaugmentation was described as the good method that can deal with oil spills associated with hydrocarbon contaminated soil [1,14].

During the bioaugmentation process, some fungi were reported to produce biosurfactants and enzymes which allow them to transform hazardous oil spills into less harmful components [29,30]. The effectiveness of this method was recently investigated by Myazin *et al.* [26] who conducted a study in the Russian subarctic and found that several species of microfungi were able to oxidize petrohydrocarbons mixtures from the soil. Bioaugmentation with fungi in an aged oil-polluted soil can facilitate the establishment of fungal and bacterial consortia responsible for more efficient oxidation and complete bioremediation of both total petroleum hydrocarbon and high molecular weight-polycyclic aromatic hydrocarbons [15]. Similarly, bioaugmentation using fungi have been a common practice by many researchers, especially when dealing with hydrocarbon contaminated water or industrial waste.

In the bioaugmentation approach researchers usually isolate and identify the fungal organisms from hydrocarbon-contaminated water or soil, it's then applied after providing growth conditions. Gargouri *et al.* [7] isolated and characterized some hydrocarbon-degrading yeast strain from petroleum-contaminated wastewater, their investigations show that *Candida tropicalis* and *Trichosporon asahii* could efficiently degrade total petroleum hydrocarbon by 97% and 95% respectively [7], this clearly showed the efficiency of bioaugmentation approach in the removal of hydrocarbons pollutants. Similarly, other findings have reported the isolation of *Candida tropicalis* and *Aspergillus clavatus* from used engine oil-polluted soil, bioaugmentation

using these two fungi have revealed their capabilities in the removal of polycyclic aromatic hydrocarbons, according to these laboratory investigations, *Candida tropicalis* and *Aspergillus clavatus* have both shown degradation efficiency of 70% after 16 days of incubation [4].

Bioaugmentation has also been applied as an efficient strategy for the bioremediation of heavy hydrocarbon polluted soil, recent report from these findings revealed that bioaugmentation with native fungi can ensure the removal of total petroleum hydrocarbon and alkane fractions by 39.90% after 120 days of incubation [5,15]. Asemoloye *et al.* [5] isolated *Aspergillus oryzae* and *Mucor irregularis* from Nigerian crude oil-polluted soil, bioaugmentation analysis using these two fungi revealed that they can significantly reduce benzene and naphthalene of the used engine oil after 15 days of incubation at 20% hydrocarbon concentration. Wu *et al.* [14] carried out bioaugmentation with *Monilinia* sp. to assess the bioremediation of polycyclic aromatic hydrocarbons, findings from this analysis showed a 35% decrease in total polycyclic aromatic hydrocarbons after 30 days of incubation with *Monilinia* sp. W5-2. **Table 1** shows some selected studies for fungal degradation of petroleum hydrocarbon using bioaugmentation approach.

Table 1. List of some selected studies for fungal degradation of petroleum hydrocarbons using bioaugmentation approach.

Fungi	Hydrocarbon Pollutant	Degrad. efficiency	Time	Ref.
<i>S. boydii</i>	1% v/v crude oil	81.45%	7 days	[25]
<i>C. tropicalis</i>	HC- wastewater	97%	-	[7]
<i>T. asahii</i>	HC- wastewater	95%	-	[7]
<i>C. tropicalis</i>	Engine oil polluted soil	70%	16 days	[4]
<i>A. clavatus</i>	Engine oil polluted soil	70%	16 days	[15]
<i>Penicillium</i> sp.	HC and alkane fractions	39.90%	120 days	[15]
<i>A. parasiticus</i>	HC and alkane fractions	39.90%	120 days	[15]
<i>P. chrysogenum</i>	HC and alkane fractions	39.90%	120 days	[15]
<i>F. oxysporum</i>	PAHs – contaminated soil	39.90%	120 days	[15]
<i>Monilinia</i> sp.	Crude oil polluted soil	35%	30 days	[14]
<i>A. oryzae</i>	Crude oil	25%	15 days	[5]
<i>Aspergillus</i> sp.	Crude oil	61%	16 days	[31]
<i>Penicillium</i> sp.	HC- contaminated soil	46%	16 days	[31]

Biostimulation approach

The biostimulation approach involves the addition of nutrients or growth-promoting substances to the hydrocarbon pollutants to stimulate the growth of indigenous hydrocarbon-degrading fungi [1,28]. Biostimulation solely depends on the stimulation of autochthonous fungi by the addition of nutrients, electron acceptor, electron donor, biosurfactants, metabolites, enzymes [15,32]. Recent laboratory investigations have demonstrated the role of the biostimulation approach in the soil remediation process using autochthonous soil fungi [26]. Comparatively, biostimulation has some advantages over bioaugmentation, the addition of nutrients offers an advantage since nutrients are important factor that affects the bioremediation process. The most important among these nutrients are nitrogen, iron, phosphorus, etc. These nutrients are commercially available in different formulations as stimulants for the biostimulation of hydrocarbon pollutants. During biostimulation, the source of carbon is not from the added nutrients but rather from petroleum hydrocarbon, while water is the source of hydrogen and oxygen [1].

The biostimulation approach was described as a suitable method for remediation of pollutants in marine and freshwater environments that are contaminated by oil spilled and effluent from petroleum industries and this may lead to a decrease in nitrogen and phosphorus content of aquatic environment and hence affect the process of bioremediation [1,15,26,32]. This is the reason why the addition of nutrients is necessary to stimulate the process of bioremediation. Medaura *et al.* [15] investigated the bioremediation efficiency of an aged industrially heavy hydrocarbon polluted soil using a biostimulation approach, findings from this study revealed that total petroleum hydrocarbon and alkane fractions were decreased (removed) by 24.17% after the addition of K₂NO₃ and K₂HPO₄ as the stimulants. Another finding conducted in 2007 reported degradation of total polycyclic aromatic hydrocarbons by 16% using ground corn cob as the stimulating agent [15]. Additionally, Mancera-lopez *et al.* [21] revealed their biostimulation study using sugarcane bagasse and moistened solid matrix as the stimulants, the results show that biostimulation removed aromatic hydrocarbons and polycyclic aromatic hydrocarbons by 59% and 34% respectively. Recently, myazin *et al.* [17] carried out experiments on the effectiveness of biostimulation of soil contaminated with petroleum hydrocarbon product in the Russian subarctic, their finding showed an increase in the rate of total petroleum hydrocarbon degradation by 47%, after 15 months of incubation with mineral fertilizer and dolomite flour as the stimulating agents. Another biostimulation study showed that *A. niger* degraded total petroleum hydrocarbon by 71.19 % in 60 days [28]. Many organic nutrients such as oleophilic nutrients products have recently been reported in the literature which are been marketed as biostimulating agents of biodegradation of hydrocarbon pollutants, these includes: Inipol Eapzz, Oil Spill Eater II, Bioren 1 and Bioren 2 [2]. **Table 2** summarized some few examples of biostimulating agents and their efficiencies.

Table 2. List of some selected studies for fungal degradation of hydrocarbons using biostimulation approach.

Stimulating agent	Hydrocarbon pollutant	Degradation efficiency	Ref.
Sugercane bagasse	Aromatic Hydrocarbon	9%	[27]
Moistened matrix	PAHs	34%	[27]
Ground corn cob	PAHs	16%	[14]
K ₂ NO ₃ and K ₂ HPO ₄	Total petroleum hydrocarbon	24.17%	[15]
Mineral fertilizer and dolomite flour	Total petroleum hydrocarbon	47%	[26]
MgSO ₂ .7H ₂ O, CaCl ₂ (NH ₄) SO ₄ and NaCl	Total petroleum hydrocarbon	65%	[28]
MgSO ₂ .7H ₂ O, CaCl ₂ (NH ₄) SO ₄ and NaCl	Total petroleum hydrocarbon	88%	[28]

Bioaugmentation-Biostimulation

In this approach, bioaugmentation and biostimulation are combined and used together to achieve good results that are better than the result obtained when only one method was used [1,28]. The bioaugmentation-biostimulation approach is not very common and its application is only limited to the degradation of hydrocarbons pollutants in seawaters or culture mediums. Furthermore, the degradation efficiency of these two combined methods depends on the types of total petroleum hydrocarbon present, the fungal strain used, and stimulants [26]. This approach has been applied by many researchers with a view of improving efficiency. According to a study conducted using *Aspergillus niger* and NPK stimulant, the finding from this study reported hydrocarbon degradation efficiency of 94.4% in 8 weeks [26,33]. Similarly, Mancera-lopez *et al.* [27] carried out fungal

bioremediation of an aged hydrocarbon contaminated soil using combined methods of bioaugmentation-biostimulation, hence the results show that combined methods of bioaugmentation-biostimulation with filamentous native fungi enhanced removal of total petroleum hydrocarbon by 16%, furthermore, the study identified some potential hydrocarbon-degrading fungi which can be considered an alternative treatment for hydrocarbon pollution including aromatic hydrocarbons and polycyclic aromatic hydrocarbons. Another bioremediation experiment conducted by in 2016 using bioaugmentation- biostimulation resulted in 79% degradation efficiency of petroleum hydrocarbon [1]. Other studies that show the effectiveness of combined approached of bioaugmentation and biostimulation revealed that several microfungi such as *Penicillium commune* has hydrocarbon degradation activity of 80-90% after 14 days of incubation [26].

Fungal enzymes for biodegradation of petroleum hydrocarbon

Fungal enzymes are largely involved in the bioremediation of petroleum hydrocarbon and their participation has also been reported [3,4,5]. Several fungi can employ several mechanisms which can allow them to synthesize enzymes that can degrade petroleum hydrocarbon [34]. Similarly, several studies have shown that fungi synthesized many valuable enzymes with industrial and commercial application, these enzymes are nowadays, available as bioremediation agents [1,2,39]. Bioremediation of petroleum hydrocarbon also depends on the types of the enzymes and presence of oxygen [9]. Enzymatic reactions are essential pathways for mediating a lot of mechanisms including the supply of oxygen during degradation under aerobic conditions [2,3]. Several investigations and more recent literature have reported many enzymes having industrial value, such as cytochrome P450, mono oxygenase family that can degrade petro-hydrocarbons including PAH [2,3,34]. Other notable fungal enzymes include laccases, manganese peroxidases, versatile peroxidase, epoxidase, and transferase [9].

Several recent research and reviews have reported the isolation of cytochrome P450 enzymes from yeast species such as *Candida maltose*, *Candida tropicalis*, and *Candida apicola* [3,15]. Several enzymes from fungi have been investigated for their roles in bioremediation of total petroleum hydrocarbon using enzymes immobilization. Similarly, recent studies have shown how some fungal enzymes catalyzed and facilitated the bioremediation of several hydrocarbon pollutants [23]. **Table 3** shows some genes that code for the production of some hydrocarbon degradative enzymes.

Table 3. Examples of some genes involves in hydrocarbon degradation [34].

Gene	Function	Types of Degradation
BssA gene	Degradation of toluene and xylene	anaerobic
Bam A gene	Dearomatization of benzoyl-CoA	anaerobic
ALKA gene	Encode enzymes for alkene degradation	aerobic
Catechol 2,3-dioxygenase gene	Degradation of aromatic compound	aerobic

Fungal biosurfactants and their application in Petro-hydrocarbons remediation

Biosurfactants are biological surface-active compounds produced by microorganisms [12]. Biosurfactants produced by fungi were extensively reviewed by Bhardwaj *et al.* [29] and have now replaced chemically synthesized surfactants in the oil and gas industry for many purposes, including enhancement of oil

recovery from oil reservoirs, remediation of oil-spill and detoxification of hydrocarbons pollutants from soil and water [29,30,33]. The properties and mechanisms of action of biosurfactants have been extensively studied and reviewed [2,3,12,29,30]. Fungal biosurfactants are heterogeneous molecules that can reduce surface tension, critical micelle concentration, and interfacial tension in both aqueous solution and hydrocarbon mixtures, these properties make biosurfactants to be an excellent and potential agent which can form microemulsion and hence hydrocarbon can be solubilized in water or water can be solubilized in hydrocarbon, based on these principles, biosurfactants played five (5) major roles in petroleum industries, namely: oil spilled pollution control, bioremediation of hydrocarbons contaminated soil and water, oil storage tank clean-up, enhancement of oil recovery from oil well, and stimulant in biostimulation [2,33].

Biosurfactants have many advantages over the chemically synthesized surface-active compound, these include (1) ability to be synthesized from renewable feedstock (2) high selectivity and specificity at extreme temperature, hydrogen ion concentration, and salinity (3) high foaming (4) better environmental compatibility (5) lower toxicity and (6) high biodegradability [32,33,34]. The ability to produce biosurfactants by fungi has been reported and various biosurfactants with their potential application in petroleum industries have been investigated [29,30]. Previous studies have reported the production of sophorolipids mainly by yeast such as *Torulopsis bombicola* and *Torulopsis apicola*. This sophorolipids has been shown to lower the interfacial tension between n-hexadecane and water from 40-5 mN/m [35]. In addition, fatty acid biosurfactants produced by *Aspergillus* sp. has been reported to reduced interfacial tension between water and hexadecane to less than 1mN/m [33,35]. Bhardwaj et al. [29] have similarly reported production of sophorolipids from *Candida lipolytica* and *Candida bombicola* which showed remarkable ability in the cleaning of oil tanks and degradation of hydrocarbon from polluted areas [29]. Another study also reported that rhamnolipids biosurfactant have degraded 36% aliphatic hydrocarbon and 40% aromatic hydrocarbon from a mixture of hydrocarbon contaminated soil [33]. However, few fungi are known to produce biosurfactants when compared with bacteria. The notable fungi that are capable of producing biosurfactants are *Candida lipolytica*, *Candida tropicalis*, *Candida ishiwadae*, *Candida batistae*, *Candida bombicola*, *Aspergillus ustus*, *Ustilago maydis*, *Trichosporonashii*, and *Penicillium spiculisporum* [16,29,30,33,35].

Bioemulsifiers are biosurfactants with high molecular weight biopolymers of polysaccharides, proteins, lipopolysaccharides, lipoproteins, or even a mixture of these compounds which are produced after fungal metabolisms of petro-hydrocarbons [32,35,36]. Production of emulsifiers by several fungi was previously reported, and their application in the oil and gas industry was investigated [2,29,30,31,35]. Bioemulsifiers are amphipathic molecules that stabilized and enabled the formation of oil-in-water or water-in-oil emulsions [36,37]. Bioemulsifiers are more complex than biosurfactants and they can efficiently emulsify two immiscible liquids (oil and water). Hence emulsifiers have a wider application in the bioremediation of petroleum hydrocarbon. According to a previous study, emulsifiers (exopolysaccharides molecules) can bind tightly to dispersed hydrocarbon and subsequently prevent the oil droplets from coalescing and bursting in an oil-polluted environment [16,33]. Bioemulsifiers offers three (3) major functions which are very crucial in the bioremediation of petroleum hydrocarbon, including (i) it increase the surface area

of the hydrophobic substrate (ii) increasing the bioavailability of hydrophobic substrate through solubilization, and (ii) regulation, attachment, and removal of microorganisms from the surface [30,33, 37].

Table 4. Various biosurfactant that are produced by fungi.

Biosurfactant	Fungal organism	Application	Ref.
Lipomannan	<i>C.tropicalis</i>	hydrocarbon pollution control	[2]
Mannosylerythritol-lipid	<i>C. Antarctica</i>	emulsification of HC	[33]
Spiculosporic acid	<i>P.spiculisporum</i>	HC pollution	[33]
Sophorolipids	<i>T.petrophilum</i>	enhanced oil recovery	[35]
Phospholipids	<i>Aspergillus spp.</i>	HC degradation	[33]
Sophorolipid	<i>C.bombicola</i>	Cleaning of oil tank	[33]
Sophorolipids	<i>A.ustus</i>	release of bitumen from HC	[30]
Sophorolipid	<i>C.lipolytica</i>	cleaning of oil tank	[33]
Sophorolipids	<i>T.bombicola</i>	release of bitumen from HC	[33]
Sophorolipids	<i>C.apicola</i>	treatment of HC pollution	[33]
Sophorolipids	<i>C.ishiwadae</i>	enatment of HC pollution	[30]
Sophorolipids	<i>C.batistae</i>	treatment of HC pollution	[30]
Glycolipids	<i>T.ashii</i>	treatment of HC pollution	[35]
Lipopolysacchrides	<i>C.lipolytica</i>	treatment of HC pollution	[30]
High molecular weight biosurfactant (Bioemulsifier)			
Fatty acid+carbohydrate	<i>T.mycotoxinavorans</i>	HC pollution	[36,37]
Liposan	<i>C. lipolytica</i>	treatments HC pollution	[37]
Lipids+carbohydrates	<i>Geotrichum sp</i>	HC pollution	[37]
Glycolipids	<i>A. niger</i>	treatments HC pollution	[36]
Manoproteins	<i>S.cerevisiae</i>	treatments of HC pollution	[36]
Polysaccharides+lipids	<i>C.lipolytica</i>	HC pollution	[36]
Glycolipid	<i>U.maydis</i>	HC pollution	[36,37]
Yasan	<i>Y. Lipolytica</i>	treatments of HC pollution	[36]

CONCLUSION

Biodegradation potentials of fungi were reviewed and discussed, based on our study, fungi are more efficient and effective in the removal of hydrocarbon contaminants from the environments viz., water and soil. However, the potentiality of fungi has not been exploited fully. Similarly, there have been many advancements in the bioremediation of hydrocarbon including the use of fungal enzymes and genetically modified fungi to reduce bioremediation time and cost, however, these advancements are inadequate, more efforts are needed in this field. Omics technology which comprises genomics, transcriptomics and proteomics has now been used to increase the biodegradation of fungi, genomics provides blueprint and biochemical pathways for the fungal organism, transcriptomics can provide information about active pathways during hydrocarbon degradation. Therefore, with the application of omics technology, the potentiality of fungi for biodegradation of hydrocarbon can be improve by discovering new pathways and functional genes that may code for the production of more biodegradative enzymes.

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