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Arbuscular Mycorrhizal Fungi: Promoting Degradation of Petroleum Hydrocarbons

Ephraim Motaroki Menge*
Email: ephraimmenge@gmail.com

Abstract
The accidental release of crude oil and its byproducts into the environment has raised concerns mainly because of their serious consequences to the ecosystem. The adoption of Arbuscular Mycorrhizal Fungi (AMF) as a sustainable approach in dealing with these chemicals has revealed promising outcomes. These microbes can form symbiotic mycorrhizal relationships with the host plants facilitating the availability of nutrients to the plant and other soil microorganisms that facilitate hydrocarbon degradation. This review incorporates studies from Asia, Europe, and Africa, which together showcase the extraordinary capacity of AMF to decompose petroleum hydrocarbons. The analysis underscore AMF's ability to accelerate the breakdown of diverse hydrocarbon compounds typically present in petroleum, thus offering a promising strategy for bioremediation efforts. Future investigations in this field should focus on optimizing AMF strains to maximize their potential for petroleum hydrocarbon degradation. By identifying and selecting specific AMF strains that exhibit enhanced capabilities for breaking down hydrocarbons, it may be possible to transform their efforts towards more efficient bioremediation strategies.
***Keywords**: Bioremediation; degradation; Arbuscular Mycorrhizal Fungi; hydrocarbons;*

1. Introduction

1.1 Background

There has been a renewed interest in using AMF due to their ability to degrade petroleum hydrocarbons. Owing to their rampant use and unintentional release, these substances and their by-products, to a greater extent, pose an environmental challenge. The potential of AMF to break down these hydrocarbons has been widely studied and presents promising findings. Enzymes such as peroxidases and laccases produced by these soil microbes play a crucial role in the AMF-mediated decomposition of hydrocarbon molecules into less complex compounds [1]. The former enzyme, for example, oxidizes organic compounds, while the latter is specifically designed to oxidize phenolic compounds. Together, these enzymes serve as biocatalysts, speeding chemical reactions without being depleted.

A characteristic feature of AMF-mediated hydrocarbon compound interaction is the adherence of unique receptors to fungal cells. This attribute activates a series of chemical reactions, releasing various enzymes [2,3]. Gradually, the enzymes degrade the waste products, transforming them into simple and less harmful compounds. This process plays a fundamental role in sustaining ecological balance. In particular, it supports detoxifying polluted environments by converting harmful pollutants into less harmful forms. Most importantly, it plays a role in the recycling of nutrients by releasing valuable carbon substances that can be used by other living organisms in the ecosystem.

Studies have also shown that AMF can improve the soil quality for microorganism functioning by improving soil permeability and water retention potential [4,5]. Thus, the presence of these microbes can create an ideal habitat for the proliferation and functioning of bacteria that break down hydrocarbons. The potential use of AMF in approaches aimed at environmental restoration is exceptionally encouraging. By utilizing their innate capabilities, it might be feasible to expedite the breakdown process and alleviate the ecological concerns triggered by oil spills.

1.2 Search strategy

The study utilized English-language journals from 2015 to 2023. The search entailed the fragmentation of the topic into various search terms, namely "Arbuscular Mycorrhizal Fungi" and "Degradation of Petroleum Hydrocarbons." The adequacy of a study was solely dependent on its coverage of any of the keywords mentioned above. Upon completion of the search, 63 journal articles were found, but 3 were duplicates, resulting in 60 unique articles. The abstracts of all these journals were perused and pertinent papers were bookmarked for subsequent evaluation. The study employed an 8-year threshold as the primary criteria for inclusion and exclusion. Upon implementation of this requirement, a total of 52 journal articles were scrutinized to determine their pertinence to the research topic. At this point, 7 of these journals were dismissed as the analysis only incorporated peer-reviewed articles. 45 peer-reviewed journals were fully scrutinized to determine their eligibility for consideration in this analysis. Two of these journals were deemed insignificant as they did not assist in the identification of key words. Thus, the research strategy resulted in 43 publications reviewed, cited, and referenced in this analysis (Figure 1).

2. AMF in petroleum hydrocarbon degradation

2.1 Enhancement of hydrocarbon degradation

AMF assumes a significant function in enhancing the breakdown of petroleum hydrocarbons by fostering mutual associations with plants in the rhizosphere. This symbiotic relationship increases the availability of nutrients and oxygen, facilitating the multiplication of bacteria responsible for hydrocarbon degradation [6]. Petroleum contaminants in present-day society pose a considerable challenge to conservation efforts because of their detrimental characteristics. The degradation of these contaminants is mainly achieved by specific microorganisms. However, these bacteria require optimal conditions for growth and activity. AMF helps create such conditions by improving nutrient availability through its extensive hyphae network extending into the soil [7]. Therefore, they possess the ability to obtain crucial elements from natural substances and convey them to plants, thereby enhancing the availability of fundamental constituents for both plants and bacteria. Additionally, AMF have the capability to enhance oxygen levels in the rhizosphere through their respiratory process. The increased nutrient and oxygen accessibility provided by AMF stimulates the proliferation and operation of hydrocarbon-degrading bacteria, which can utilize petroleum hydrocarbons as a carbon source in energy production [8]. Thus, with optimized conditions provided by AMF, these bacteria can proficiently break down petroleum hydrocarbons in contaminated habitats.

2.2 Root system development

AMF play a crucial role in the growth of plant root structures, which in turn helps in the absorption and breakdown of petroleum products. AMF form a mutually beneficial symbiotic connection with plants, in which they establish colonies within the roots providing diverse benefits [9]. One such benefit is the extension of the root system. By dispensing the root system, AMF microbes enlarges the available space for hydrocarbon-metabolizing microorganisms to thrive and colonize various hydrocarbon substrates. The increased colonization leads to the rise in the number of beneficial microbes that break down petroleum hydrocarbons [10]. Additionally, the amplified expanse promotes a more efficient uptake of hydrocarbons by plants.

Additionally, AMF has the potential to boost plant resilience towards petroleum hydrocarbons by forming symbiotic relationships with roots. They have the ability to enhance plant nutrient uptake and water absorption, which are frequently hindered in polluted surroundings. This enhanced availability of nutrients aids plants in better withstanding the harmful impacts of petroleum hydrocarbons [11]. Besides their direct impact on plant root systems, AMF indirectly contribute to the breakdown of petroleum hydrocarbons by influencing soil composition and microbial populations [12]. They encourage soil cohesion and enhance microbial variety, establishing an advantageous habitat for hydrocarbon-consuming bacteria.

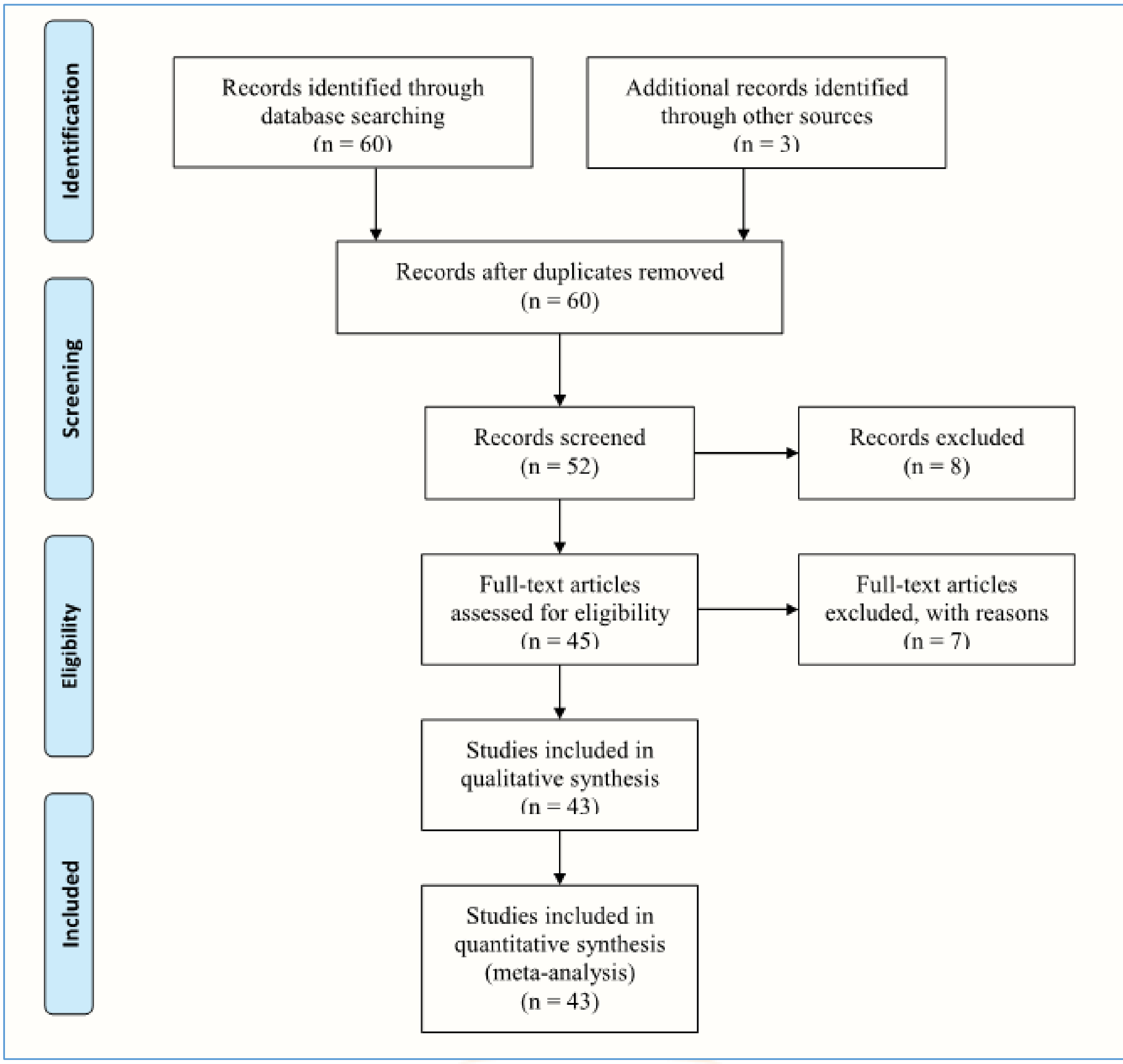

Figure 1: *PRISMA diagram showing how papers were selected, excluded and included*

2.3 Stress tolerance

Hydrocarbons originating from petroleum are a leading cause of ecological pollution, causing detrimental effects on flora and fauna alike. However, lately conducted research has uncovered that arbuscular mycorrhizal fungi (AMF) have the ability to mitigate this situation by enhancing plants' ability to withstand hydrocarbon contaminants [13]. AMF form a mutually beneficial association with plants, colonizing their roots and enhancing nutrient uptake. This association has been proven exceedingly beneficial in contaminated situations, as AMF aids vegetation in handling the existence of hydrocarbons [14]. This is accomplished by boosting the production of stress-responsive substances and plant growth regulators. Antioxidants have a vital function in neutralizing reactive oxygen species (ROS), which are byproducts of hydrocarbon exposure. By enhancing the generation of antioxidants, AMF assist plants in combating the oxidative stress caused by hydrocarbons [15]. Furthermore, phytohormones, including ethylene and jasmonic acid, play a pivotal role in controlling plant reactions to stress. AMF enable plants exposed to petroleum hydrocarbons to synthesize these hormones, improving their adaptability and survival in such situations [16,7]. This is particularly significant in polluted environments where the availability of nutrients may be limited due to hydrocarbon contamination.

3. Mechanisms of AMF-mediated hydrocarbon degradation

3.1 Hydrocarbon uptake and transport

AMF play a critical role in the redistribution of hydrocarbons, improving accessibility to microorganisms specialized in hydrocarbon degradation. The remarkable ability of these fungi lies in their capability to absorb hydrocarbons from the ground and facilitate their movement through the hyphal networks [17]. This elaborate process serves as an effective bridge, connecting hydrocarbon-contaminated regions to uncontaminated areas. By doing so, AMF facilitate the spread of hydrocarbon degradation throughout the ecosystem [18]. This mechanism is essential for maintaining a healthy environment and preventing further contamination.

The hyphal networks of AMF extend far beyond their host plants' root systems, allowing them to reach areas that would otherwise be inaccessible to other organisms. These interconnected systems efficiently redistribute organic compounds, increasing their biodegradability [19]. AMF can additionally enhance the growth and activity of microorganisms with the ability to decompose organic compounds by providing them with a nutrient-rich environment. The mutually beneficial association between AMF and plants enables the exchange of nutrients, with plants supplying carbohydrates to AMF in return for essential mineral nutrients such as phosphorus [20].

3.2 Enzymatic degradation

AMF generate diverse enzymes that actively disintegrate crude oil derivatives, such as hydroxylases, oxidases, and dehydrogenases. Hydroxylases are AMF enzymes that catalyze the addition of a hydroxyl group to a substrate, helping in breaking down long hydrocarbon chains into smaller compounds [21]. This oxidative process is necessary for the breakdown of poisonous substances found in unrefined oil. Oxidases is the other AMF group of enzymes that contribute to the degradation of crude oil derivatives [22]. These enzymes catalyze the transfer of electrons from one molecule to another, resulting in the transformation of harmful compounds into less toxic substances. Dehydrogenases are AMF catalysts that enable the elimination of hydrogen atoms from organic molecules [23]. In the context of petroleum degradation, dehydrogenases assist in breaking down complex hydrocarbon chains by removing hydrogen atoms from specific positions within these molecules. This process ultimately leads to the formation of less toxic compounds that can be easily metabolized by other microorganisms or assimilated into natural ecosystems.

3.3 Biofilm formation

The biofilms formed by AMF act as physical barriers, shielding the bacteria from the toxic effects of hydrocarbons [24]. Hydrocarbons are recognized to affect microbial cells negatively, impeding their development and metabolic functioning. Nevertheless, inside these biofilms, the microbes are safeguarded against such toxins and can prosper in an atmosphere favorable to their decomposition abilities. Furthermore, these biofilms also facilitate the exchange of metabolites between AMF and the associated bacteria [25]. This mutualistic relationship allows for a symbiotic interaction where both organisms benefit. The AMF provide a protective niche for the bacteria while receiving nutrients produced by bacterial metabolism. The formation of these biofilms is crucial in environmental remediation efforts as they enhance the efficiency of hydrocarbon degradation [18]. By creating microenvironments that support bacterial growth and shield them from toxicity, AMF play a vital role in facilitating bioremediation processes.

4. AMF-mediated hydrocarbon degradation: Findings from previous studies

A study conducted by Li et al. illustrates the effectiveness of AMF in facilitating the degradation of petroleum hydrocarbons. The researchers observed that the presence of AMF fungi amplified the proficiency of *Salix viminalis L*. to phytoremediate PAH-contaminated soils [26]. The study revealed that the fusion of plant-fungal symbiosis brought about an accelerated and efficient breakdown of PAHs compared to the lack of fungi in the control group (Table 1). The exact mechanism that underlies this enhancement is still unknown, but it may involve amplified nutrient availability or enzyme production catalyzed by the AMF fungi.

Another study [27] indicates that the application of AMF and Plant Growth-Promoting Rhizobacteria (PGPR), enhances the degradation potential of phenanthrene and pyrene, two persistent pollutants, in contaminated soils. This microbial combination also stimulates a diverse microscopic community, augmenting both microbe variety and efficacy. The reason behind this increase is because AMF form mutualistic associations with plant roots, providing them with nutrients while receiving carbon compounds in return. This symbiotic relationship not only benefits plants but also enhances microbial activity in the soil [27]. Similarly, PGPR promote plant growth by producing growth-promoting substances and suppressing pathogenic microorganisms. By introducing AMF and PGPR into contaminated soils, there was [27] an increase in microbial biomass, enzyme activity, and diversity. This is attributed to the ability of these beneficial organisms to enhance nutrient availability, stimulate root exudation, and produce enzymes that facilitate PAH degradation.

In their 2022 meta-analysis of 45 articles, Shi et al. revealed that AMF can increase plant biomass, enhance soil conditions, and significantly decrease the concentration of residual soil polycyclic aromatic hydrocarbons. The most significant decline was 48.5% in PAHs levels, a significant environmental risk [28]. The research additionally unveiled a noteworthy influence of AM fungi on the biomass of plants and the growth of roots, underscoring their crucial function in phytoremediation processes. Similarly, the research emphasized the enhancement of physical, chemical, and biological characteristics of soil due to AM inoculation, accentuating its potential as an effective approach for phytoremediation.

Zuzolo et al. conducted another study in 2021 that examined the effectiveness of phytoremediation in Northern Italy using Poaceae and Fabaceae species, as well as their role in supporting plant growth. They additionally assessed the consequences of native microorganisms and endo-mycorrhizae collaboration incorporations on the advancement of plant growth [29]. The results of this experimental test uncovered multiple noteworthy results. It was observed that incorporating indigenous microorganisms and AMF had a positive effect on the growth of vegetation. This implies that these microorganisms have a vital role in boosting the overall well-being and progress of plants. It was also revealed that soil enzymatic activities increased with hydrocarbon degradation rate after 60 days [29]. This indicates that the phytoremediation approach efficiently breaks down hydrocarbons found in polluted soil, resulting in an enhancement in the quality of the soil. These findings have significant implications for methods used in environmental remediation. The combination of phytoremediation and targeted microbe introduction presents a formidable technique for purifying contaminated areas and re-establishing ecological balance. The utilization of plants' inherent capabilities and symbiotic partnerships with beneficial microorganisms has the potential to mitigate the negative ecological effects of substances like hydrocarbons.

In 2016, Ingrid and her team conducted a research project on the efficacy of wheat plants colonized by arbuscular mycorrhizal fungi in reducing alkanes and PAHs in aged soils. The findings of this study revealed that inoculating wheat with *Rhizophagus irregularis* leads to better dissipation after 16 weeks, with degradation rates reaching 18% and 48% [30]. The process of mycorrhization, an interdependent relationship between plants and fungi, has long been recognized for its capacity to amplify plant growth and boost nutrient absorption. This study aimed to investigate whether mycorrhizal fungi colonization could also contribute to the breakdown of hydrocarbon pollutants discovered in the soil. The findings revealed that wheat plants that were introduced to *R. irregularis* exhibited significantly hastened dissipation rates of alkanes and PAHs in comparison to non-mycorrhizal plants. This suggests that mycorrhization plays a crucial role in enhancing the ability of plants to degrade these pollutants. This improved dissipation may be attributed to the heightened microbial activity associated with mycorrhizal colonization. The fungi establish a complex mesh of fine threads that expand into the soil, amplifying the nutrient supply for both the plant and associated microorganisms [30]. This enhanced microbial activity leads to increased degradation rates of hydrocarbon pollutants. These findings underscore the plausible application of arbuscular mycorrhizal fungi as a method for ecological rehabilitation in contaminated soils. By capitalizing on the intrinsic mutualistic relationship between plants and fungi, it is viable to alleviate the adverse consequences of hydrocarbon pollution in contaminated soils. However, more research is required to investigate alternative plant and fungi combinations, as well as their efficacy in remediating different kinds of pollutants.

In another study conducted by Balasubramaniyam in 2015 in Western Europe, it was found that AMF phytoremediation, a low-input biotechnology approach, can be effectively used to remediate contaminated sites. The effectiveness of this strategy hinges on the gradual decrease of pollutant levels via biodegradation and physicochemical mechanisms [31]. However, the plants' response to hydrocarbon pollution plays a vital role in the successful execution of AMF phytoremediation. The study highlights that different plant species exhibit varying responses to such contamination. Therefore, the effective remediation of polluted sites is contingent upon the judicious selection of plant species possessing sufficient morphological traits and physiological capabilities. The results of this research offer crucial remarks into the potential utilization of arbuscular mycorrhizal fungi (AMF) in mitigating environmental pollution through phytoremediation [31]. Possessing a comprehensive understanding of the diverse responses of plants to pollutants allows scientists to make well-informed decisions when selecting suitable plant species for specific polluted locations. Balasubramaniyam's research demonstrates that phytoremediation has great potential as a low-input biotechnology approach for remediating contaminated sites. It emphasizes the importance of selecting appropriate plant species with adequate morphological characteristics and physiological capabilities for effective pollutant reduction.

In their groundbreaking study, Abdel-salam and peers shed light on the remarkable findings regarding mycorrhizoremediation and its potential benefits in Saudi Arabia. The research findings revealed that the utilization of mycorrhizal fungi can effectively eradicate pollutants from polluted soil while concurrently augmenting the growth of host vegetation and fostering the development of non-mycorrhizal plants [32]. Mycorrhizal fungi form a mutually advantageous association with plant roots to foster their growth. They reside within the roots and construct elaborate hyphal networks, significantly expanding the available surface for nutrient uptake. This unique association allows for improved nutrient uptake by the host plant, leading to enhanced growth and development. However, Abdel-salam et al.'s research goes beyond this well-known aspect of mycorrhizal fungi. They [32] exhibit that these fungi display a remarkable capacity to restore contaminated soil by efficiently eliminating different pollutants, including heavy metals and organic toxins. The mechanisms behind this occurrence encompass the attachment of pollutants to fungal filaments or their conversion into less harmful forms. Additionally, scientists discovered that mycorrhizal fungi have the capability to interact with vegetation, promoting enhanced growth rates and expanding the potential for mycorrhizoremediation in the field of agriculture. This could lead to sustainable, environmentally friendly approaches in land remediation efforts.

Lenoir and peers conducted a research on the potential of AMF-assisted phytoremediation as a plausible approach for ecological restoration through plants. This study highlights the protective role of AMF fungi in shielding plants from the harmful effects of persistent organic pollutants (POPs) and their ability to enhance soil detoxification by stimulating underground microbial activity [33]. AMF mycelium have been acknowledged to establish a symbiotic relationship with plants, colonizing their roots and improving nutrient uptake. This advantageous partnership has been widely acknowledged for its valuable impact on plant development and progress. However, this investigation delves deeper into the potential advantages of AMF-assisted phytoremediation in aged polluted soils. They [33] discovered that AMF fungi not only protected plants from the toxic effects of POPs but also enhanced soil bioremediation by promoting microbial activity. This stimulation of telluric microbial communities resulted in increased degradation and detoxification of contaminants present in the soil. Despite these promising findings, the implementation of AMF for the purpose of phytoremediation is still in its preliminary stages. Additional studies are necessary to fully understand the efficacy of this approach, particularly in aged contaminated soils, where the process of remediation may be challenging due to the reduced contaminants.

In their research, Abbaspour et al. analyzed how the growth weight of indigenous plant species, including clover and mallow, was affected by the application of biochar, mycorrhizae, and a combination of the two [34]. According to the greenhouse findings, the shoot dry weight of native species, such as clover and mallow, was significantly improved by all three treatments. The research established that the implementation of biochar and mycorrhizae treatments had a positive influence on both plant development and biomass production. In spite of this, clover failed to yield any noteworthy outcomes, possibly due to genetic differences and growth requirements. This finding indicates that these treatments may influence plant metabolism or nutrient uptake processes. Interestingly, octacosane remained unaffected by any treatment [34]. This particular compound may have different interaction properties with plants compared to other long-chain alkanes. Overall, this study highlights the potential benefits of implementing biochar and mycorrhizae to enhance shoot mass in plants like mallow. However, additional analysis is needed to completely apprehend the impacts of these elements on diverse plant species and their underlying processes.

Nkereuwem and his team conducted a study with the aim of exploring the impact of AMF and mineral fertilizer (NPK 15 15 15 grade) on the growth and performance of African spiral ginger plants (*Costus lucanusianus*) in soil contaminated with crude oil [35]. The researchers contaminated the soil with Bonny Light crude oil at various concentrations and inoculated it with AM fungus. The findings of this study revealed several interesting results. The first observation revealed that the presence of AM fungus had a significant impact on the growth parameters of African spiral ginger plants in crude oil-contaminated soil. This implies that AM fungi contribute positively to plant growth, even under challenging environmental conditions. Additionally, the application of mineral fertilizer (NPK 15 15 15 grade) further improved the performance of African spiral ginger plants. The combination of AM fungus and mineral fertilizer resulted in increased plant height, leaf area, root length, and biomass production compared to control groups. It was noted that elevated levels of crude oil had a detrimental impact on plant growth parameters. However, the presence of AM fungus mitigated these negative effects to some extent [35]. Overall, this study underscores the viability of AM fungi and mineral fertilizers in augmenting plant performance in soils contaminated by crude oil. These findings add to our knowledge of how beneficial microorganisms can mitigate environmental pollution and promote plant growth under difficult conditions.

The research conducted by Bolaji and team highlights the potential of specific bacteria to effectively utilize oil and the contribution of AMF to this procedure. The study identified four bacteria, *Lysinibacillus fusiformis*, *Paraclostridium benzoelyticum*, *Bacillus enecimensis*, and an unknown species, all of which displayed significant biodegradation capabilities. Among these bacteria, *Lysinibacillus fusiformis* exhibited the highest biodegradation rate by disintegrating 40% of the spilled oil [36]. *Paraclostridium benzoelyticum* and *Bacillus enecimensis* also exhibited effective oil degradation, demonstrating rates of 30% and 20%, respectively, over 28 days. These findings underscore the prospect of utilizing these bacterial strains in attempts to mitigate the environmental impact of oil spills. By harnessing their innate ability to break down hydrocarbons present in crude oil, these bacteria can contribute to the restoration of impacted ecosystems. They [36] found that arbuscular mycorrhiza played a crucial part in the biodegradation process. AM epitomizes a mutually advantageous partnership between certain fungi and plant roots, augmenting nutrient acquisition and fostering plant proliferation. The study proposes that this symbiotic relationship may have enhanced the functionality of the acknowledged bacteria.

In their research, Hussein and team illustrate the efficiency of phytoremediation and bioremediation as economical and eco-friendly methods for the contamination from crude oil. The study provides an in-depth analysis of the effects of crude oil pollution and the efficacy of phytoremediation in revitalizing contaminated surroundings [37]. The authors discuss various mechanisms by which plants can remediate the environment, particularly through phytodegradation and stabilization. Phytodegradation involves the breakdown of pollutants by plant enzymes, while stabilization refers to the immobilization or containment of contaminants within plant tissues. These techniques have a crucial part in reducing the level of harmful substances and promoting the restoration of ecosystems. Moreover, [37] emphasize the importance of ecological factors in influencing the effectiveness of environmentally-friendly remediation methods. Factors such as soil makeup, atmospheric conditions, and the choice of flora species can significantly affect the efficiency of pollutant removal. A comprehensive comprehension of these elements is essential for devising efficient measures tailored to specific polluted areas. The extensive impact of crude oil pollution can be harmful to both the natural surroundings and human well-being. However, this study provides optimism by presenting how green remediation can be utilized to mitigate these effects effectively. Overall, Hussein et al.'s findings underscore the potential of green remediation and bioremediation as effective technologies for restoring crude oil-contaminated ecosystems. Due to their cost-effective and environmentally friendly attributes, they present themselves as enticing options in contrast to the standard remediation methods that frequently call for expensive infrastructure or chemical interventions. This research reveals novel pathways for sustainable environmental management practices that prioritize both human well-being and ecological sustainability.

Region	Microbial species	Effect	Reference
Asia	*Funneliformis mosseae*	Plant-fungal symbiosis accelerated the breakdown of PAHs	[26]
	Rhizophagus intraradices		
	Rhizophagus intraradices		
Asia	*G. versiforme*	Produce enzymes that facilitate PAH degradation	[27]
	P. fluorescens		
Asia	*phylum Glomeromycota*	Decrease residual soil polycyclic aromatic hydrocarbon	[28]
Asia	*Glomus caledonium*	Eradicate pollutants from hydrocarbon polluted soil	[32]
Europe	*Acaulospora colombiana*	Enzymatic activities increased with hydrocarbon degradation	[29]
	Rhizophagus clarus		
	Rhizophagus intraradices		
	Rhizophagus irregularis		
	Claroideoglomus etunicatum		
	Funneliformis mosseae		
	Funneliformis geosporum		
Europe	*Rhizophagus irregularis*	Reduce alkanes and PAHs in aged soils	[30]
Europe	*Glomus caledonium*	Remediate hydrocarbon polluted sites	[31]
Europe	*Glomus caledonium*	shielding plants from the harmful effects of (POPs)	[33]
Asia	*Rhizophagus irregularis*	AMF failed to degrade octacosane	[34]
Africa	*Glomus clarum*	Enhance plant performance in soils contaminated by crude oil	[35]
Africa	*Glomus clarum*	Enhance *Lysinibacillus fusiformis* bacteria to effectively utilize oil	[36]
Africa	*Rhizophagus irregularis*	Lessens the concentration of hydrocarbon substances	[37]

***Table 1**: Summary of previous findings on AMF-mediated hydrocarbon degradation*

5. Potential for future research

The research conducted in Asia, Europe, and Africa demonstrates the notable potential of AMF in augmenting the breakdown of oil hydrocarbons. Despite this, countless avenues for further study can enrich our understanding and utilization of bioremediation with AMF.

5.1 Enhancing AMF strains

AMF is renowned for its capacity to establish mutualistic associations with plants, enhancing nutrient uptake and promoting plant growth. Yet, not all AMF strains illustrate indistinguishable competencies for breaking down various forms of petroleum hydrocarbons [38]. Hence, analyzing the unique competencies of diverse individuals of AMF strains in breaking down different categories of petroleum hydrocarbons can provide valuable insights for identifying the most effective strains in designated pollution events. Researchers can evaluate the efficacy of different AMF strains in breaking down diverse types of oil-based substances like crude oil, gasoline, diesel, and polycyclic aromatic hydrocarbons (PAHs) through comprehensive bioassays. These experiments can potentially advance the identification of strains that excel in degrading specific pollutants.

Furthermore, understanding the mechanisms behind these degradation abilities can contribute to developing targeted strategies for bioremediation. Some AMF strains may produce enzymes that facilitate the breakdown of certain hydrocarbon compounds more efficiently than others [39]. By identifying these enzymes and their associated genes, scientists can potentially engineer more effective AMF strains or develop enzyme-based treatments for contaminated sites. Most importantly, considering site-specific factors such as soil characteristics and contaminant concentrations is crucial when selecting appropriate AMF strains for bioremediation efforts. Certain strains may perform better in acidic soils or under high contaminant concentrations than others. Therefore, tailoring strain selection based on site-specific conditions can significantly enhance remediation outcomes.

5.2 Evaluating plant-AMF interactions

Empirical evidence has demonstrated that the employment of AMF holds the promise of enhancing the degradation of petroleum hydrocarbons by reinforcing microbial activity in the rhizosphere [20]. The AMF's existence encourages the multiplication of bacteria that specialize in hydrocarbon breakdown, ultimately resulting in increased degradation rates. Additionally, AMF can also directly degrade certain types of hydrocarbons themselves [40]. Likewise, this mutualistic symbiosis between AMF and plants can enhance plant growth in contaminated conditions. Scientific research has proven that plants infused with AMF exhibit increased resilience against hydrocarbon pollutants.

The mechanisms behind this enhanced resistance include improved nutrient uptake from the soil by plants through fungal networks established by AMF. On top of this, AMF can also produce enzymes that detoxify harmful compounds present in petroleum hydrocarbons [41]. A comprehensive understanding of the interplay between AMF, host plants, and fossil fuel hydrocarbons is crucial in formulating eco-conscious and sustainable strategies for cleansing polluted habitats and fostering plant growth in such areas. By leveraging these symbiotic relationships, innovative and economical bioremediation methods can be developed, leading to environmentally sustainable solutions.

5.3 Evaluating field experiments

The efficacy of bioremediation methods can be precisely assessed through experimentation in natural settings. By conducting exhaustive field experiments to evaluate the efficiency of AMF-based bioremediation techniques, invaluable insights can be gained for the progression of viable and economical methods. Moreover, executing extensive field experiments, scholars can evaluate the efficacy of AMF-focused bioremediation strategies in real-world situations. This facilitates a more profound understanding of their operational capacity within complex ecosystems and provides crucial insights into their effectiveness. As [42] indicates field trials facilitate the assessment of the long-term outcomes of AMF-centered bioremediation approaches on soil quality, plant growth, and the elimination of pollutants. Through the execution of these trials, it is likely to achieve knowledge of the cost-effectiveness of bioremediation approaches that utilize

AMF. By evaluating factors like application rates, treatment duration, and maintenance requirements on a macro level, it is possible to establish the economic feasibility of these approaches for broad deployment.

5.4 Investigating innovative approaches

Combining AMF with phytoremediation or bioaugmentation makes it possible to harness each technique's strengths while mitigating their limitations. AMF technology utilizes electrogenic bacteria that generate electricity through the oxidation of organic compounds present in petroleum hydrocarbons [43]. This electrical energy can then be used by plants or other microorganisms involved in biodegradation processes. Integrating AMF with phytoremediation allows for enhanced plant growth and pollutant uptake through increased nutrient availability provided by electrogenic bacteria. Additionally, AMF can promote root exudate production that stimulates microbial activity, further enhancing degradation rates. Similarly, when combined with bioaugmentation, AMF provides an additional energy source for introduced microorganisms, ensuring sustained activity over time. The electrical energy generated by AMF also promotes electron transfer processes necessary for efficient biodegradation. Examining the likely synergistic outcomes of integrating AMF with other bioremediation techniques, like phytoremediation or bioaugmentation, may lead to the formulation of groundbreaking and comprehensive strategies for eradicating hydrocarbon pollutants.

6. Conclusion

Research conducted in Asia, Europe, and Africa point out the excellent capacity of AMF in accelerating the breakdown of petroleum hydrocarbons. The possibility of AMF to improve hydrocarbon breakdown and their mutually advantageous relationship with plants creates new avenues for eco-friendly and sustainable bioremediation practices. Future studies focusing on optimizing AMF strains, understanding plant-AMF interactions, and assessing field-scale applications will further contribute towards harnessing the full potential of AMF in petroleum hydrocarbon degradation.

7. Conflict of interest

The author declare no conflict of interest.

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