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Research Article

Influence of Crabgrass Root Exudates on the Hydrocarbons Degrading Microorganisms in Crude Oil Contaminated Soil

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Abstract

Understanding plant–microbial interactions in petroleum-contaminated soil is critical for enhancing phytoremediation technology. In this study, the root exudate of crabgrass (*Digitaria ciliaris*) was collected hydroponically, and its dominant composition was identified via GC–MS. A soil microcosm study was subsequently conducted to evaluate the influence of crabgrass root exudates on microbial growth, dehydrogenase activity, and biodegradation of total petroleum hydrocarbons by the petroleum-degrading bacteria *Micrococcus luteus* WN01 and *Acinetobacter lwoffii* A07. The amendment of crabgrass root exudates significantly promoted microbial degradation in both *A. lwoffii* A07 (47.98%) and *M. luteus* WN01 (62.78%), which were 8.47% and 15.78% greater than those in the nonamended treatments, respectively. The dehydrogenase activity and microbial population were highest in the presence of root exudates. The crabgrass root exudates were predominantly composed of organic acids, phenolic compounds, and fatty acids, namely, 2-ketoisovaleric acid, acetylmethylcarbinol, ribitol, cinnamic acid, palmitic acids, and stearic acids, respectively. These chemical compounds in crabgrass root exudates can stimulate microbial dehydrogenase activity and total petroleum hydrocarbon (TPH) degradation in crude oil-contaminated soil. Further studies on how these individual chemicals may promote the degradation activity of hydrocarbon-degrading bacteria could provide a better understanding of the phytostimulatory effect of crabgrass during the phytoremediation of petroleum-contaminated soil.

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Introduction

Soil contamination with petroleum hydrocarbons is a serious environmental problem worldwide. Large quantities of petrochemicals are released into the environment during oil transportation, refining, and processing activities, accidental spills, and pipeline breakages. Many forms of petroleum hydrocarbons, such as polycyclic aromatic hydrocarbons (PAHs), are toxic, carcinogenic, mutagenic, and persistent due to their hydrophobicity [1–2].

Phytoremediation is a promising green technology that uses plants to promote the ability of rhizosphere microorganisms to degrade organic pollutants in the soil. Plants remediate organic pollutants by recruiting microorganisms in the rhizosphere through the secretion of various chemical compounds, also known as root exudates [3]. Root exudates are composed of organic acids, amino acids, phenolic compounds, and other macromolecules, such as mucilage and root lysates, that can serve as simple carbon sources for rhizosphere microorganisms [3–4]

The plant–microbial interaction in petroleum-contaminated soil is a complex phenomenon, and little is known about it [5]. Studies have shown that the mineralization of total petroleum hydrocarbons (TPHs) is directly influenced by the chemical constituents of

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root exudates [6–7]. For example, the presence of phytochemicals such as flavones, maleic acid, palmitic acid, and hydroxycinnamic acids is positively correlated with TPH degradation [7–8]. On the other hand, amendments of simple carbon substrates such as fumarate, mannitol, and sucrose, which are often found in plant root exudates, decreased the hydrocarbon removal efficiency in TPH-contaminated soil, presumably due to increased competition for carbon sources [9]. In general, the contaminant removal rate is negatively correlated with the distance from the roots [2, 5–6]. It is also known that root exudates generally increase the microbial population and bioavailability of petrochemicals, which subsequently increase the degradation of petrochemicals in the soil [2, 6].

Crabgrass (*Digitaria ciliaris*) is an annual grass species native to Asia, and it is widely distributed throughout the tropics and subtropical regions. It is a robust species that can tolerate petroleum toxicity and promote the biodegradation of petroleum hydrocarbons in its rhizosphere [10–11]. Understanding the chemical constituents and mechanisms underlying the accelerated degradation of petrochemicals is critical for enhancing phytoremediation technology. *Micrococcus luteus* WN01 and *Acinetobacter lwofii* A07 are hydrocarbon-degrading bacteria isolated from the activated sludge of Map Ta Phut Olefin Company (MOC), Rayong, Thailand. The ability of these bacteria to colonize the plant rhizosphere and degrade petroleum hydrocarbons has been previously documented [5, 12, 16]. However, no studies have reported the effects of crabgrass root exudates on hydrocarbon-degrading bacteria. Therefore, this work aimed to determine the dominant composition of crabgrass root exudates and evaluate the influence of crabgrass root exudates on the biodegradation of petroleum hydrocarbons via *Acinetobacter lwoffii* A07 and *Micrococcus luteus* WN01.

Materials and methods

1) Bacterial preparation

The petroleum hydrocarbon-degrading microorganisms *Acinetobacter lwoffii* A07 and *Micrococcus luteus* WN01 were obtained from the Bioremediation, Phytoremediation, and Bioenergy Laboratory, Department of Biology, Faculty of Science, Mahidol University, Thailand. These hydrocarbon-degrading bacteria were previously isolated from the activated sludge of Map Ta Phut Olefin Company (MOC), Rayong, Thailand. The bacteria were cultivated in LB broth at 30°C for 48 hours at 150 rpm.

2) Root exposure collection and analysis

Crabgrass (*Digitaria ciliaris*) was obtained from Chai Nat Provincial Rice Experimental Station, Chai Nat, Thailand. The root exudates were hydroponically collected as described previously [12]. In brief, the roots of the crabgrass were carefully rinsed and transferred to 1/10 strength Hoagland's solution for acclimatization. The plants were grown for 14 days at 25±2°C under fluorescent 16/8 h light/dark conditions in the presence of aeration for root formation. After acclimatization, the root exudates were collected by submerging 2–3 plants in 300 mL of sterile distilled water in a 500 mL beaker for 6 hours. The solutions were lyophilized, filter sterilized with a 0.20 µm membrane filter, and stored at -20°C until analysis.

The composition of the root exudates was analyzed via gas chromatography–mass spectrometry (GC–MS) (GC 7890A series MSD 5975C, Agilent Technology, USA). The freeze-dried root exudates were derivatized via the use of methoxamine hydrochloride and N-methyl-N-(trimethylsilyl) trifluoroacetamide (MSTFA). In brief, the dried samples were mixed with 40 µL of methoxamine (MOX) reagent (Thermo Fisher Scientific, Bellefonte, PA, USA) for 90 min at 40°C. The samples were then gently mixed with 70 µL of MSTFA (Macherey-Nagel, Düren, Germany) and incubated at 40°C for 30 minutes. The derivatized samples were subsequently injected into the GC/MS instrument. The injection temperature was 280 °C, and the injection mode was split at a ratio of 5:1. The column temperature was held at 50 °C for 1 min, then increased to 200 °C (30 °C min^{-1}), then increased to 250 °C (6 °C min^{-1}), and finally increased from 250 to 270 °C. The auxiliary heater temperature was set at 280 °C. Ionization was achieved with a 70 eV electron beam. The compounds were identified on the basis of the NIST08 mass spectral library, NIST Chemistry WebBook, and SRD69 database.

3) Soil preparation and experimental setup

Agricultural soil with no background of petroleum contamination was purchased from Ratchaburi Province, Thailand. The soil was sieved at 2 mm to remove all the rock and plant debris. The physical and chemical characteristics of the soil were analyzed by the Department of Soil Science, Faculty of Agriculture, Kasetsart University, Thailand (Table 1). The rhizosphere experiment was performed on 125 mL tall wide-mouth glass vials containing 50 g of soil. The soil was artificially contaminated with 1% Tapis crude oil (v/w) dissolved in acetone to increase homogeneity. The crude oil-spiked soil was incubated in the dark for 72 hours at room temperature to reach equilibrium, and the soil water-holding capacity was adjusted to 50% for each microcosm. Four conditions were established in the microcosm study: natural attenuation (C), soil with root exudates (CR), soil augmented with *A. lwoffii* A07 (CB1), soil augmented with *M. luteus* WN01 (CB2), soil augmented with *A. lwoffii* A07 with root exudates (CRB1), and soil augmented with *M. luteus* WN01 with root exudates (CRB2). The augmented treatments were inoculated with approximately 6 × 105 CFU per gram soil. The initial root exudate concentration in the soil was set as 40 µg per gram soil to

mimic the average rhizosphere [12]. The freeze-dried root exudate powder was weighed and resuspended in distilled water at a concentration of 1 mg mL^{-1}. Two millimeter of root exudates was added each week (days 7, 14, and 21) to maintain the concentration of the root exudates. The experiments were performed in triplicate. The soil was incubated at 30°C in the dark, and the experiment was conducted for 28 days.

4) Microbial enumeration and enzymatic activities

The soil samples were collected on days 0, 3, 7, 14, 21, and 28, and microbial enumeration (CFU) was performed via the plate counting method. In brief, 9 ml of 0.85% NaCl was added to 1 g, which was subsequently serially diluted and spread on LB agar. The microbial dehydrogenase activities were determined via the 2(p-iodophenyl)-3-(p-nitrophenyl)-5-phenyl tetrazolium chloride (INT) method as described previously [5]. The iodonitrophenyl formazan (INTF) formed by dehydrogenase activity was determined at 464 nm against the blank. The dehydrogenase activities were expressed as µg INTF/g soil/24 hr.

5) TPH analysis

The total petroleum hydrocarbons in the soil were extracted following the US EPA method 3550C with slight modifications as described by Yang et al. [12]. In brief, 10 mL of acetone:dichloromethane (1:1, v/v) was added to 2 g of soil, after which the samples were subjected to ultrasonic extraction for 15 min via an ultrasonicator (Bandelin Sonorex RK 156 BH). The supernatants were filtered through No. 4 Whatman filter paper with anhydrous Na_2SO_4. The cycle was repeated with 10 ml of DCM. The extractants were subsequently concentrated with Multivapor P12 (Buchi, Switzerland) and transferred to the GC vials. The residual alkanes (C8-C40) and polycyclic aromatic hydrocarbons (16 US EPA priority PAHs) were identified and quantified via a GC-FID (Agilent Technology 6890 N, USA) equipped with a DB5-MS fused silica capillary column (30 m × 0.25 mm × 0.25 µm, Agilent J & W Scientific Co., Folsom, CA, USA). An external standard mixture of alkanes (C8-C40, Sigma–Aldrich) and 16PAHs (SRM® 1647f, NIST) was used for multilevel calibration. The total TPHs were defined as the sum of the total concentrations of alkanes and PAHs.

6) Data and statistical analysis

The data were analyzed via one-way ANOVA via the SPSS 18.0 statistical software package. Pearson's product–moment correlation was used to determine the associations between the parameters. The analysis was performed at a 95% confidence level ($p < 0.05$) by the least significant difference (LSD) test. All values from the analysis are presented as the means ± standard deviations. The TPH degradation efficiency was calculated as shown in Eq.1.

$$\text{Degradation efficiency (\%)} = 100*[(C_i-C_f)/C_i] \quad \text{(Eq.1)}$$

where C_i = initial concentration and C_f = final concentration.

Results and discussion

1) Physiochemical properties of the soil

The physicochemical properties of the soil used in this study are shown in Table 1. The results revealed that the soil was a neutral clay. The essential nutrient contents, especially the available potassium (244 mg kg^{-1}) and total nitrogen (960 mg kg^{-1}) contents, were high.

Table 1 Soil physicochemical properties

Properties	Value
pH	7.2
Organic matter (%)	2.48
Soil texture	Clay
Total N (mg kg^{-1})	960
Available P (mg kg^{-1})	28
Available K (mg kg^{-1})	244

2) Root exudate composition

The crabgrass root exudates were analyzed via GC–MS. The dominant constituents of crabgrass root exudates were ketone (acetylmethylcarbinol), organic acids (2-ketoisovaleric acid), sugar alcohol (ribitol), phenolics (cinnamic acid), and fatty acids (palmitic and stearic acids) (Table 2). Some other peaks also appeared, but only the dominant peaks with high spectral similarities (> 90%) are presented. Root exudates often induce contradictory results depending on the plant species [13], which is primarily due to the different chemical constituents of different plant species [12]. Crabgrass root exudates are rich in cinnamic acid and palmitic acid, which are chemicals that have been suggested to increase the degradation of TPHs [8]. Liu et al. [8] reported that amendment with palmitic acid promoted the colonization and growth of the plant growth-promoting bacteria *Klebsiella* sp. D5A. These authors further demonstrated that palmitic acid stimulated petroleum degradation in the soil. Yang et al. [12] reported that 4-methoxy-cinnamic acid and terephthalic acid stimulated the catabolic activities and degradation of petroleum hydrocarbons by oil-degrading bacteria in crude oil-contaminated soil. Therefore, the cinnamic acids and palmitic acids in crabgrass root exudates may function as key stimulators of the biodegradation of petroleum hydrocarbons in the soil.

Other dominant compounds, such as ribitol, acetylmethylcarbinol, and 2-ketoisovaleric acid, may also stimulate growth or degradative pathways. Many forms

of low-molecular-weight compounds, such as ketones, sugar alcohols, and organic acids, have been reported to increase the microbial population and activities of petroleum hydrocarbons [6, 8]. Further studies on how these individual compounds influence microbial activities and TPH dissipation will provide a better understanding of this complex interaction.

3) Effects of root exudates on TPH dissipation

A microcosm study was conducted to determine the influence of crabgrass root exudates on the hydrocarbon-degrading bacterial isolates *A. lwoffii* A07 and *M. luteus* WN01. Figure 1 shows the degradation efficiency of TPH for the treatments in time intervals. The natural attenuation (control) lost approximately 4.09% of the TPH from the initial concentration. The highest TPH degradation was achieved in the root exudates + *M. luteus* treatment (CR2), with an overall removal efficiency of 62.78%. Root exudate amendment significantly promoted the TPH removal efficiency of both *A. lwoffii* A07 and *M. luteus* WN01 by 8.47% and 15.78%, respectively ($p < 0.05$). The final remediation efficiencies were highest in the order of CBR2 > CBR1 > CB2 > CB1 > CR and C. Not surprisingly, the indigenous soil microbes were incompetent in the removal of petroleum hydrocarbons, even with root exudates.

The amendment of crabgrass root exudates significantly enhanced TPH degradation for both bacterial species. These findings prove that the observed increase in petroleum removal in the crabgrass root exudate-amended treatments was not species specific. Similar results were reported for cowpea root exudates amended with *M. luteus* WN01 and *Bacillus cereus* W2301 [12]. Compared with the nonamended treatment, the addition of cowpea root exudates to *M. luteus* WN01 and *B. cereus* W2301 increased PAH degradation by 21.42% and 27.90%, respectively.

Root exudates can increase the bioavailability of organic contaminants by changing the soil microenvironment [6, 14–15]. In the soil, hydrophobic contaminants such as petroleum hydrocarbons are tightly adsorbed onto soil particles and organic matter, impeding microbial biodegradation. Root exudates can change the solubility and surface tension of organic contaminants, increasing the availability of petroleum hydrocarbons [12]. Although the magnitude of petroleum availability depends on various environmental factors, such as soil pH, texture, organic matter, and temperature, increased concentrations of different organic acids in root exudates generally promote the desorption of petroleum hydrocarbons in the soil [9]. Since the amendment of crabgrass root exudates increased the concentration of 2-ketoisovaleric acids in the soil, more petroleum hydrocarbons were desorbed from the soil particles, allowing rapid biodegradation.

Table 2 Dominant composition of crabgrass root exudates

No.	Compounds	Relative abundance (%)	Retention time	Group
1	Acetylmethylcarbinol	9.06	4.431	Ketone
2	2- ketoisovaleric acid	13.03	4.471	Organic acid
5	Ribitol	7.87	4.973	Sugar alcohol
6	Cinnamic acid	7.33	7.022	Phenolics
7	Palmitic acid	8.16	11.069	Fatty acids
8	Stearic acid	4.25	13.469	Fatty acids

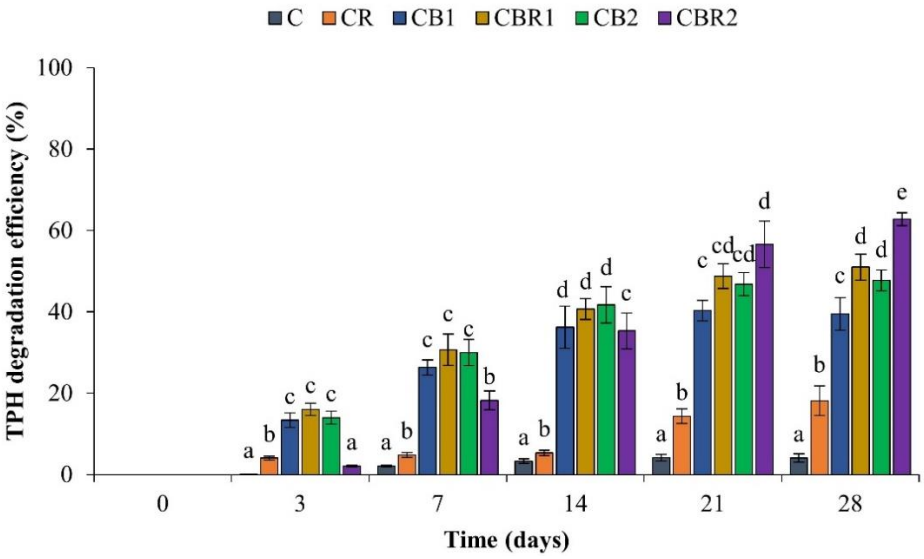

Figure 1 TPH degradation efficiency in the soil microcosm over 28 days. The data are the mean values of triplicate samples (n=3). Letters indicate the statistical significance of the LSD test ($p < 0.05$).

Interestingly, the degradation of CBR2 (*M. luteus* + root exudates) was low during the first seven days of the incubation period. One potential explanation is the increased competition between indigenous microorganisms and the augmented bacteria [16]. The bioaugmented microorganisms need to acclimate successfully in the soil before they can grow in the population. Since the doubling time of *M. luteus* is relatively slower than that of *A. lwoffii* in the soil [12], a prolonged acclimatization step of *M. luteus* was observed. However, after *M. luteus* rapidly recovered its population and degradative activities after day 7, rapid removal of TPH was observed, indicating that it served as a key player in the biodegradation of petroleum hydrocarbons in the soil.

4) Effects of root exudates on the microbial population and DHA activity

The influence of crabgrass root exudates on the microbial population and dehydrogenase activity was determined at different time intervals (Figures 2 and 3). The microbial population increased progressively during the first 14 days. A significantly greater microbial population was observed in the CBR1 and CBR2 treatment groups. The population was highest in the order of CBR1 > CBR2 > CB2 > CB1> CR and C, respectively. The soil dehydrogenase (DHA) content increased concurrently with the population of microorganisms. Significantly higher DHA activities were observed in the presence of root exudates for both bacteria. The highest activity of DHA was achieved in CBR1 on day 14.

Crabgrass root exudates also serve as cometabolites for microbes in the soil. Compared with the nonamended control (C), the root exudate amendment (CR) significantly increased the contaminant bioavailability, microbial population, and soil dehydrogenase activity. The increased DHA activities observed in this study indicate that crabgrass root exudates also promoted the cometabolic degradation of petroleum hydrocarbons. Phenolic compounds such as cinnamic acids can induce the upregulation of degradative enzymes such as catechol 2,3 dioxygenase and soil dehydrogenase activities [12], which are particularly important in the cleavage of complex alkanes and aromatic hydrocarbons [2, 7]. Thus, crabgrass root exudates are composed of metabolites that can promote the initiation of degradative activities of bioaugmented bacteria, which subsequently enhances the removal of petroleum hydrocarbons.

Notably, although plant root exudates have been reported to promote the growth of microorganisms in the soil, these microorganisms are not necessarily petroleum-degrading communities [5, 17]. Plant root exudates can alter soil microbial communities and the diversity of catabolic genes without increasing the degradation rate of petroleum hydrocarbons [17]. This is apparently due to increased competition among the soil microbes induced by an increased diversity of compatible carbon sources [18]. Hence, the positive influence of root exudates observed in the present study provides evidence that metabolites in crabgrass root exudates can promote growth, DHA activity, and the degradation rate of petroleum hydrocarbons by bioaugmented microbes.

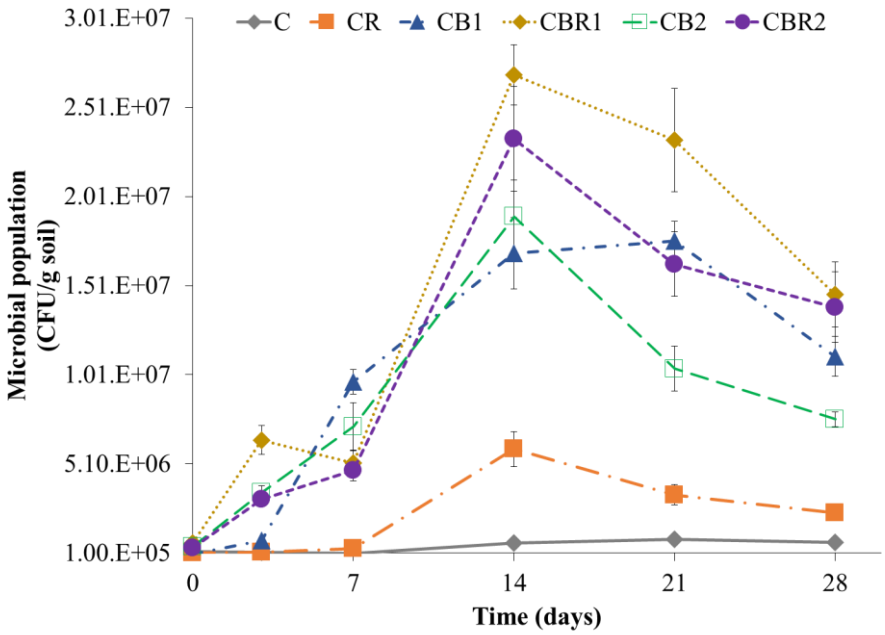

Figure 2 Microbial population in the soil microcosm during 28 days of incubation. The data are presented as the mean values of triplicate samples (n=3). Letters indicate the statistical significance of the LSD test ($p< 0.05$).

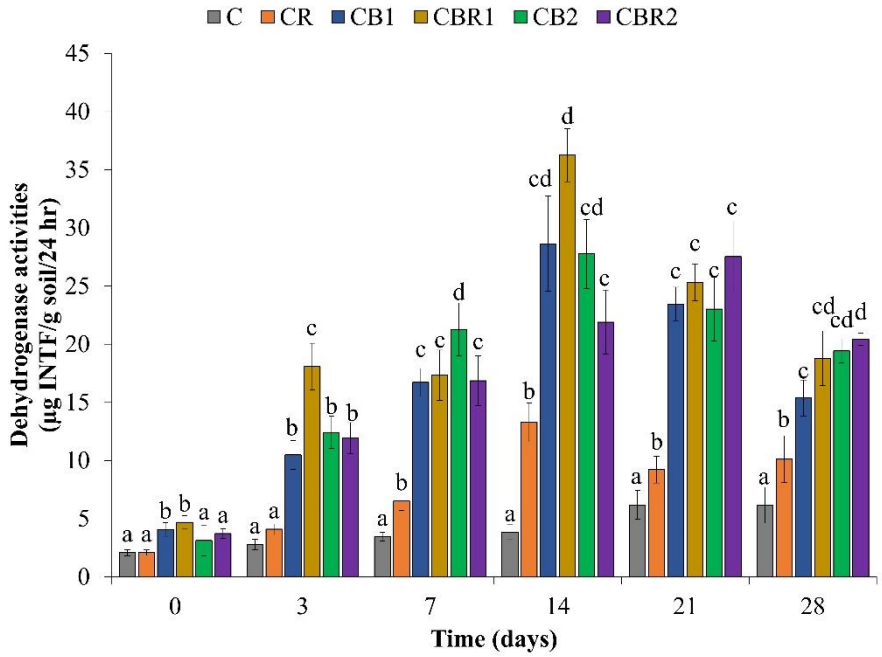

Figure 3 Microbial dehydrogenase activities in soil microcosms during 28 days of incubation. The data are presented as the mean values of triplicate samples (n=3). Letters indicate the statistical significance of the LSD test ($p < 0.05$).

Overall, the findings from this study indicate the potential for the use of root exudate constituents to accelerate the bioremediation process. In many cases, the landscape of the contaminated soil and contaminant toxicity impede the use of plants to remove petroleum hydrocarbons [19–20]. Phytochemicals from root exudates can overcome these limitations, and they can be applied at the field scale. Some studies have attempted to synthesize artificial root exudates to mimic the rhizosphere effect to overcome the variability of soil physicochemical properties [21–23]. Therefore, the results of this study could lead to a more practical approach than plant-centric remediation technologies.

Conclusions

This study demonstrated that crabgrass root exudates facilitate the degradation of hydrocarbon-degrading bacteria by promoting growth and DHA activity. The dominant metabolites in the crabgrass root exudates were 2-ketoisovaleric acid, acetylmethylcarbinol, ribitol, cinnamic acid, palmitic acid, and stearic acid, which are potent chemical compounds associated with increased TPH degradation. These compounds may serve as simple substrates that enhance microbial growth or trigger cometabolic pathways to promote TPH removal. In addition, the combination of *M. luteus* and the root exudates achieved the greatest removal after 28 days of incubation. These results suggest the phytoremediation potential of crabgrass and contribute to the understanding of plant–microbial interactions in crude oil-contaminated soil. Further studies on how these individual compounds interact with pollutants and microorganisms are needed to understand the mechanism behind plant–microbial interactions in TPH-contaminated soil.

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