Physiological and microbiological hormesis in sedge *Eleocharis palustris* induced by crude oil in phytoremediation of flooded clay soil

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Abstract

Soil contamination with petroleum hydrocarbons affects plants and rhizospheric microorganisms. Microbial activity participates in important biochemical processes that stimulate, together with plants, the modification of toxic compounds for organisms. A nine-month experiment was set up to study the effect over time of oil on plant height (cm), formation of new plants, plant matter production (gravimetry), and population of rhizospheric microorganisms (serial dilution) in the sedge *Eleocharis palustris*. Removal of total petroleum hydrocarbons (soxhlet and gravimetry) from the soil was also evaluated. The means of the evaluated variables registered significant statistical differences (Duncan, *p* < 0.05) regarding the age of the plant and the amount of crude oil. There was a high correlation between oil and plant height (0.848) and with new plants (0.994). 60 mg oil dose promoted the greatest statistical difference in the amounts of roots and plant biomass (*p* < 0.05). *E. palustris* exposed to 60 and 75 mg of oil stimulated high densities of microalgae, actinomycetes, fungi, hydrocarbonoclastic bacteria and *Pseudomonas* spp; the overall ratio was 2:1 relative to natural attenuation. Plant and microorganism variables evaluated registered physiological and microbiological horsematic indices ≥1, showing a positive linear relationship. Natural attenuation was more efficient in removing crude oil. We conclude that *E. palustris* is tolerant to oil exposure. It is suggested to combine it with natural attenuation for the optimization of soils contaminated with crude oil.

Keywords Crude oil. Growth phase. *Pseudomonas*. Microbiological hormesis index

Introduction

A long-standing problem in the tropical wetlands is the contamination of Gleysol soils with hydrocarbons associated with the extraction and transportation of crude oil (CO). Due to the flooded conditions of these soils, the underground pipelines are frequently damaged, which can lead to the accidental release of oil into the environment (Rodríguez-Rodríguez et al. 2016). CO is made up mainly of total petroleum hydrocarbons (TPH) as well as saturated hydrocarbons, aromatic compounds, asphaltenes, and resins. These groups of hydrocarbons and their epoxides are toxic, mutagenic, and/or carcinogenic, and cause damage both to microorganisms and higher organisms, including humans (Moubasher et al. 2015). In wetland Gleysols, the presence of CO induces structural changes in soil, air, and water, altering their original physicochemical properties (Iturbe et al., (2007)). The biological balance of...
oil-contaminated soil changes according to the living organisms that inhabit it. Soil contamination with hydrocarbons can even have a positive effect on the biology of the organisms that inhabit historically contaminated environments (González-Moscoso et al. 2017; Orocio-Carrillo et al. 2019; Alanbary et al. 2019; Rodríguez-Uribe et al. 2021).

The positive effect of CO on plants and various beneficial microorganisms has been studied by considering the relationship between oil quantity, composition, and degree of affectation. The use of physiological and microbiological bioindicators to measure the toxicity and hormesis of CO hydrocarbons in plants and microorganisms has several advantages, compared to the use of physicochemical indicators since the first have greater sensitivity, flexibility, and higher response speed than the latter (Pentreath et al. 2015). The physiological response of plants and microorganisms can be expressed as an absolute numerical value that indicates the harm and/or benefits they derive from exposure to the pollutant. This value depends on the type of soil and pollutant (Calabrese and Blain 2009). Indicators of hormesis show the typical dose-response relationship for low and high doses that have a stimulating effect on living beings (Calabrese 2013). Hormesis is an evolutionary response of organisms that had to adapt to stressful conditions, has implications for ecology, toxicology, risk assessment, and other disciplines (Agathokleous and Calabrese 2020a; Calabrese and Agathokleous 2020). Hormesis plays a crucial role in the control and remediation of soil contamination (Agathokleous and Calabrese 2020b; Fan et al. 2021).

The response variables of plant and soil and rhizospheric microorganisms exposed to oil include plant growth, root density, accumulation of plant biomass, and the population densities of microorganisms (Vázquez-Luna et al. (2011); Agathokleous et al. 2020). Tropical wetlands are home to C3 plants of the Cyperaceae family, which have short growth cycles, accumulation of aerial plant matter, and abundant roots. These properties are due to their high photosynthetic and transpiration rates, which give these plants the cellular capacity to synthesize sugars, proteins, and high polysaccharides (Salisbury and Ross 2000). Cyperaceae plants have a fibrous root system that holds onto the flooded soil to form the rhizosphere. The roots release organic and inorganic exudates into the rhizosphere that act as inducers of the growth of microalgae, actinomycetes, fungi, and TPH-degrading bacteria (Cao et al. 2012; Tang et al. 2011; Neumann and Römheld 2012). Microalgae play an important role in the rhizosphere by capturing inorganic carbon through photosynthesis. The metabolism of these autotrophic microorganisms releases carbonic acid into the soil, increasing its acidity (Pepper and Gentry 2015). Fungi, actinomycetes, and bacteria with heterotrophic metabolism oxidize and/or reduce carbon of biogenic origin or from petroleum in soil and sediment. They also provide NH$_3$, H$_2$PO$_4$, and SO$_4^{2−}$ to plants and microorganisms (Madigan et al. 2015; Smith et al. 2015).

Various plants adapted to petroleum-induced stress inhabit tropical and subtropical wetlands. Some of these plants are *Scirpus grossus* (Al-Baldawi et al. 2015), *Ludwigia octovalvis* (Al-Mansoory et al. 2017), *Scirpus mucronatus*, *Cyperus laxus*, *C. esculentus*, and *L. peploides* (Al-Mansoory et al. 2021). The roots of these plants host nitrogen-fixing bacteria, *Pseudomonas* spp, and *Rhodococcus* spp, which show increased growth when exposed to hydrocarbon stress, compared to soil without roots (Vázquez-Luna et al. (2011); Rodríguez-Uribe et al. 2021). In Gleysol, petroleum hydrocarbons are absorbed into organic matter and sediment. This slows down the metabolism and biodegradation of said hydrocarbons (Madigan et al. 2015). During the anaerobic biodegradation of TPH, fungi, actinomycetes, and bacteria use H$_2$, SO$_4^{2−}$, Fe$^{3+}$, and NO$_3$ as electron donors (Maier and Gentry 2015). In these environments, the rhizosphere is reported to stimulate the flow of oxygen, organic molecules, nutrients, and facultative anaerobic microorganisms. Microorganisms release enzymes that oxidize high molecular weight hydrocarbons and arrange them, in the aqueous phase, in the form of polycyclic hydrocarbons that are dissolved or absorbed in solubilized organic matter (Brady and Weil 2008; Madigan et al. 2015).

In recent decades, different public and scientific organizations have taken an interest in the decontamination of wetland soils polluted with CO. The use of phytoremediation with native plants has been one of the preferred alternatives since it has several advantages, including ecological ones (Calabrese and Agathokleous 2021). Phytoremediation under anaerobic conditions is slower than under aerobic conditions but it has the potential to reduce the harmful impact of petroleum pollution by mineralizing hydrocarbons (Ławniczak et al. (2020)). The following native wetland plants have shown the ability to remove TPH from flooded soils contaminated with oil, gasoline, or diesel: *L. octovalvis* (Alanbary et al. 2019; Al-Mansoory et al. 2017), *Spartina alterniflora* (Fleeger et al. 2015), and *S. grossus* (Al-Baldawi et al. 2015).

*E. palustris* is a Cyperaceae that grows in large wetland areas used for livestock production in the humid Mexican tropics. This plant grows underground storage organs such as basal bulbs and tubers. In stressful environments (soil contaminated with CO), young plants regenerate from these storage organs (Rivera-Cruz et al. 2016). The physiological and microbiological response that allows *E. palustris* to survive in Gleysol soils contaminated with CO is still unknown. The present work aimed to identify indicator variables of physiological and microbiological hormesis in
response to oil-induced stress. Together with the ability of the rhizosphere of E. palustris to remove TPH, these variables could serve to develop a biological technology to remediate Gleysol soil from contaminated wetlands in the Mexican humid tropics.

**Materials and methods**

**Collection of soil and rhizomes**

Uncontaminated soil (250 kg) was collected in January 2020 from a site on the surface horizon (0–30 cm) of a Gleysol located at Paso and Playa village, Huimanguillo municipality, Tabasco, México (17°57′41″N and 92°21′38″W) at 17 masl. Soil was dried, ground and sieved (5 mm in diameter) before subjecting it to analysis to determine the properties of a composite sample. The collected soil was then mixed with different concentrations of fresh oil to establish the experiment. Soil properties were as follows: clay texture (12% sand, 51% clay, and 37% silt), SOC 3.5%, TPH 1024 mg/kg, pH 6.4; electrical conductivity 0.3 dS/m, exchangeable cation capacity 9.6 Cmol/kg, NO3 55.5 ppm, available P 30.1 ppm, Ca 3.7 meq/100 g, Mg 2.2 meq/100 g, K 0.4 meq/100 g, and extractable sodium 27% (Rodríguez-Uribe et al. 2021). E. palustris rhizomes were collected from wetland soil contaminated with weathered oil in José Narciso Rovirosa village, southeast of the “La Venta” gas processing complex, Tabasco state (18°04′40″ N and 94°02′38″ W). E. palustris had been exposed to chronic contamination as-a-result of crude oil spills (Rivera-Cruz et al. 2016), this condition suggests plant adaptation to polluted habitat. Rhizomes were cut with a stem length of 5 cm for use in the experimental bioassay.

**Contaminated soil and experimental design** CO was obtained from the Ogarrio 2 oil battery in Huimanguillo, Tabasco state (18°02′12″ N and 93°55′40″ W). Oil is of medium grade, Isthmus type, 1.8 sulfur content, with an American Petroleum Institute gravity of 32–33 degrees. The chemical composition of CO is saturated hydrocarbons (61.2%), aromatic hydrocarbons (24.8%) and asphaltenes and resins (13.4%). Experiment 1 (Exp-1), which evaluated the growth of E. palustris, was conducted under a completely randomized design using a 7 × 37 factorial arrangement. Experiment included seven oil concentrations (0, 3, 15, 30, 45, 60, and 75 mg/kg soil) and 37 exposure times (2 to 38 weeks after transplantation). Experiment 2 (Exp-2), evaluated the production of plant material, the population densities of microorganisms, and the phytoremediation of TPH, was conducted under a random design using a 7 × 2 factorial arrangement and oil concentrations similar to those used in Exp-1. Two remediation techniques were evaluated: phytoremediation (PR) with E. palustris and natural attenuation (NA), in both experiments four repetitions per treatment were used. CO were used because they showed that E. palustris tolerates 76 g of CO (Rivera-Cruz et al. 2016). During 38 weeks the plant height (PH) was measured and the new plants (NP) of each experimental unit were also counted. Root and aerial biomass, microbial population densities, and oil removal were determined at week 38. Vegetable variables studied were the number of primary roots (NPR), root dry matter (RDM), and aerial dry matter (ADM). Population densities of microorganisms counted were 14 treatments with PR and NA. Microorganisms evaluated were microalgae (Mi) (cells/mL), heterotrophic fungi (HF), total actinomycetes (ACT), Pseudomonas spp (PsB), and hydrocarbonoclastic bacteria (HB) (CFU/g soil or dry rhizosphere). Removal of TPH (%), organic carbon (%), total nitrogen (%) and sulfate (mg/kg) from the soil and rhizosphere of E. palustris were also quantified.

All treatments were established in a greenhouse at an average temperature of 34 °C in soil permanently saturated with water (5 cm subsurface water level). Initial oil concentrations were 0, 3, 15, 30, 45, 60, and 75 mg/kg soil. Each oil concentration level was manually homogenized. TPH concentration was determined by extraction for 8 h using soxhlet equipment (USEPA-3540C (1996)) with analytical grade dichloromethane. Experimental unit consisted of a container (16 height × 40 length × 28 cm width) with 9000 g of dry soil, an E. palustris plant for PR, and no plant for NA.

**Plant growth and new plants**

Plant height was measured weekly with a ruler graduated in cm and mm, from the base of the stem to the apical meristem; new plants emerged from the rhizome were also counted each week. The ADM (stems, new plants) and the RDM were determined after drying the fresh material at 65 °C for 72 h. The dry material was weighed on a semi-analytical balance (Ohaus, Scout Pro SP202) with a readability of 0.01 g.

**Population densities of microorganisms**

Population densities (cells/mL) of Mi was determined in soil and rhizosphere samples collected at the end of week 38, by direct microscopic cell count in 0.1 mL of dilution 101 in a Neubauer chamber (Madigan et al. 2015). Populations (CFU/g dry weight) of HF, HB, PsB, and ACT were determined with the viable count technique and serial dilution using specific culture media (Madigan et al. 2015). Potato dextrose agar (Baker®) was used for HF, arginine-glycerol-salt agar for ACT (Johnson and Curl 1972),
To measure the effect of the treatments, the PHI (control (0 g/kg TPH). The PHI was calculated as the sum of all the MHI (x). The hormesis index (TPHI) was calculated as the sum of all the logical response to contaminated soil. Total physiological hormesis index (PHI) and the microbiological hormesis index (MHI) were calculated for each variable under study, as well as the dry plant material. The following equations were used:

\[
\text{PHI}(x) \text{ and } \text{MHI}(x) = \frac{TcR1}{\text{TcR1}}
\]

\[
\text{TPHI}(x) = \sum_{i=1}^{n} \left( \frac{\text{PHI}(x)}{n} \right) \quad \text{......} i = 1, 2, 3 \ldots t
\]

\[
\text{TPHI}(x) = \sum_{i=1}^{n} \left( \frac{\text{MHI}(x)}{n} \right) \quad \text{......} i = 1, 2, 3 \ldots t
\]

where: PHI(x): physiological hormesis index for variable x, and MHI (x): microbiological hormesis index for variable x; Tco: crude oil concentration; Tc: control; R1: repetition 1…n; N = number of variables

\[
\text{TPHI}_{(x)} = \sum (\text{PHI} + \text{PHIN} + \text{PHINPR} + \text{PHIRDM} + \text{PHIADM})/n
\]

where: PHI: physiological hormesis index of the plant height variable, NP: new plant, NPR: number of primary roots, RDM: root dry matter; ADM: aerial dry matter, n = number of variables. The total microbiological hormesis index (TMHI) represents the sum of the MHIMi (x) of mL⁻¹ of microalgae cells, the CFU g⁻¹ of fungi, actinomycetes, Pseudomonas bacteria, and hydrocarbonoclastic bacteria in the rhizosphere. It was calculated using the following formula

\[
\text{TMHI} = \sum (\text{MHIMa} + \text{MHTF} + \text{MHIACT} + \text{MHIPS}B + \text{MHIHB})/n.
\]

### Organic carbon, nitrogen, and sulfate

Organic carbon was determined by combustion with K₂Cr₂O₇ (Walkley and Black 1934), and total nitrogen through micro-Kjeldahl technique and digestion with H₂SO₄ (Page et al. 1982). Assimilable sulfate in buffer solution (K₂SO₄, 2 N glacial acetic acid and distilled H₂O) and a standard solution [Ca(H₂PO₄)₂.H₂O, 2 N glacial acetic acid and distilled H₂O]. Sulfate quantification was performed by the turbidimetric method in a spectrophotometer at 670 nm (Etchevers 1992).

### Removal of total petroleum hydrocarbons

Crude oil removal was evaluated based on the percentage of TPH removed from the soil (NA) and the rhizosphere of E. palustris (PR). Simple soil samples, from each experimental unit, were collected on day 1 of week 1 and also on the last day of week 38. TPH extraction was carried out, with analytical dichloromethane, for eight hours in soxhlet equipment (USEPA-3540C (1996)). The amount of TPH removed was calculated by gravimetry based on the amounts extracted on day 1 with respect to the value of week 38 (González-Moscoso et al. 2019).

### Hormesis indices

Physiological hormesis index (PHI) and the microbiological hormesis index (MHI) were calculated for each variable (x). To measure the effect of the treatments, the PHI (x) and MHI (x) of each variable were compared with those of the control (0 g/kg TPH). The PHI (x) and MHI (x) were obtained by dividing the values corresponding to the treatments with crude oil between the values corresponding to the control treatment. This allowed us to evaluate the biological response to contaminated soil. Total physiological hormesis index (TPHI) was calculated as the sum of all the PHI (x), while the total microbiological hormesis index (TMHI) was calculated as the sum of all the MHI (x) divided by the total of the variables under study, whose value represents the response of plants (PHI) and rhizospheric microorganisms (MHI) to the contaminant as a function of all the physiological and/or microbiological variables under study, as well as the dry plant material. The following equations were used:

\[
\text{PHI}(x) \text{ and } \text{MHI}(x) = \frac{TcR1}{\text{TcR1}}
\]

\[
\text{TPHI}(x) = \sum_{i=1}^{n} \left( \frac{\text{PHI}(x)}{n} \right) \quad \text{......} i = 1, 2, 3 \ldots t
\]

\[
\text{TPHI}(x) = \sum_{i=1}^{n} \left( \frac{\text{MHI}(x)}{n} \right) \quad \text{......} i = 1, 2, 3 \ldots t
\]

where: PHI(x): physiological hormesis index for variable x, and MHI (x): microbiological hormesis index for variable x; Tco: crude oil concentration; Tc: control; R1: repetition 1…n; N = number of variables

\[
\text{TPHI}_{(x)} = \sum (\text{PHI} + \text{PHIN} + \text{PHINPR} + \text{PHIRDM} + \text{PHIADM})/n
\]

where: PHI: physiological hormesis index of the plant height variable, NP: new plant, NPR: number of primary roots, RDM: root dry matter; ADM: aerial dry matter, n = number of variables. The total microbiological hormesis index (TMHI) represents the sum of the MHIMi (x) of mL⁻¹ of microalgae cells, the CFU g⁻¹ of fungi, actinomycetes, Pseudomonas bacteria, and hydrocarbonoclastic bacteria in the rhizosphere. It was calculated using the following formula

\[
\text{TMHI} = \sum (\text{MHIMa} + \text{MHTF} + \text{MHIACT} + \text{MHIPS}B + \text{MHIHB})/n.
\]

### Statistical analysis

The normal distribution of the data was assessed using the Shapiro-Wilk test. While the homogeneity of the data was evaluated with the Bartlett test. An analysis of variance was also applied, and Duncan’s test was used to compare the means (p < 0.05). The pairwise correlation was evaluated with Pearson’s correlation coefficient, using linear regression, for normally distributed variables with a statistical significance of p < 0.05 and 0.01. All tests were run using the statistical program SAS v.9.4 (SAS Statical Analysis Systems (2005)).

### Results

#### Plant height and new plants

The data for plant height and number of new plants registered statistical differences (Duncan p < 0.05) from week 2 of the experiment. In treatments without and with CO, the logarithmic phase of PH occurred between weeks 2 and 8; the linear phase between weeks 9 and 29, and the senescence or asymptotic phase started at week 30 and ended at week 38 (Fig. 1A). Values of PH were higher in the
treatments with CO. The highest plant height was recorded during weeks 30 to 38, it occurred in the plant exposed to 60 g/kg of CO, on the other hand, the lowest height in the same period corresponded to the plant established in soil without oil. It is interesting that the control plant had the lowest growth during the entire experimental cycle with respect to the six oil treatments. Data show that the \textit{E. palustris} plant was tolerant to oil exposure during the 38 weeks, equivalent to nine months.

As in the PH, the increase of NP also showed means with highly significant differences and correlation values close to 1.0 (Fig. 1B). The growing trend of plant formation shows that this biological process of repopulating areas contaminated with up to 75 g of oil will not yet diminish. During the 38 weeks the vegetative multiplication of new organisms, typical of hydrophytic individuals belonging to the botanical family Cyperaceae, maintained a logarithmic trend in all the evaluated treatments, only the plant exposed to 60 mg of oil decreased the vegetative slope from week 36. Like height, the number of seedlings was higher in plants exposed to 60 g of oil.

\textbf{Physiological and microbiological hormesis in sedge \textit{Eleocharis palustris} induced by crude oil in...} 1245

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Weekly average height of plant (A) and new plants (B) of \textit{Eleocharis palustris} exposed to seven concentrations of crude oil during May 2020 to January 2021. *Treatment means with statistical significant differences (Duncan, $p < 0.05$, $n = 4$)}
\end{figure}

Physiological and microbiological hormesis in sedge \textit{Eleocharis palustris} induced by crude oil in... 1245

Physiological hormesis indices for plant height and number of new plants

With the exception of plants exposed to 30 and 75 g of oil that showed hormesis, the other four doses inhibited plant growth during the first four weeks of the bioassay (Fig. 2A). The general trend of hormesis, in all treatments, began at week 10 and remained with small changes until the end of the experiment. The highest hormentic height index (Duncan $p < 0.05$) occurred in the plant exposed to 60 g of oil, this happened from week 33 with a physiological index of 1.5 (Fig. 2A). The new plants variable was more sensitive than the plant height variable. Statistically significant differences were identified at three stages of the experimental cycle: weeks 13, 21 to 25, and 60 (Fig. 2B). The highest physiological hormentic index of the new plants variable also corresponded to \textit{L. hexandra} exposed to 60 g of oil for 38 consecutive weeks. The hormetic index varied from 1.74 to 1.77 units.

\textbf{Physiological hormesis indices for number of roots and dry matter accumulation}

The analysis of variance of the hormentic physiological indices of the variables number of primary roots (NPR), root dry matter (RDM) and aerial biomass matter (ADM) (stem, sepal and inflorescence) registered statistical differences (Duncan $p < 0.05$) due to the effect of exposure to crude oil for 38 weeks (Fig. 3). The highest indices were related to greater amounts of root in the plant exposed to 60 g of oil, radical dry matter was formed in the plant established in 75 g of oil, finally, in terms of aerial biomass,
the highest index corresponded to the plant that grew in soil with 30 g of the contaminant. The values of the physiological indices were 2.37, 1.45, and 1.4, respectively. Regarding the total hormesis of the three variables, the index was 1.63 in soil with 60 g of oil.

**Microbiological hormesis indices for rhizospheric microorganisms**

Microbiological index data for microalgae (Mi), total fungi (TF), actinomycetes (ACT), Pseudomonas spp (PsB) and hydrocarbonoclastic bacteria (HB) also show significant statistical differences in *E. palustris* plants exposed to different doses of crude oil (Fig. 4A, B). The horneric response of the four groups of microorganisms occurred in the two highest doses evaluated. The fungi and actinomycetes with the highest indices occurred in the plant exposed to 60 g of oil, the indices were 3.1 and 2.2, respectively; the indices were higher in microalgae and *Pseudomonas* spp under the effect of 75 g of oil, the microbiological indices were 3.3 and 6, respectively. Hydrocarbonoclastic bacteria were also more abundant in plants established in 45 to 75 g of oil, statistically the populations were similar, consequently the indices were also similar (Fig. 4B).

**Population densities of microorganisms according to remediation technology**

The population means of Mi, ACT, TF, HB and PsB registered significant statistical differences (Duncan *p* < 0.05) induced both by crude oil and by the two technologies (NA and PR) for treating soil contaminated with crude oil (Table 1). Microorganisms were more abundant in the rhizosphere of *E. palustris*, where microbial multiplication was higher in soil contaminated with ≥15 g of crude oil. The highest population densities of TF (22 × 10² CFU/g) grew in rhizospheric soil exposed to 15 g of oil and ACT (507 × 10³ CFU/g) in soil with 60 g of oil. As for the soil with 75 g oil, it favored the most numerous populations of Mi (94 × 10³ cells/mL), PsB (64 × 10² CFU/g) and HB (1885 × 10² CFU/g). Global statistical analysis showed that the PR stimulated higher densities of the five microbial groups compared to the NA, the increase was 120%.

**Removal of total petroleum hydrocarbons**

Results of oil removal, in the treatments with PR and NA, show statistically significant differences (Duncan *p* < 0.05) (Fig. 5A, B). The highest percentage of removal (85%)
occurred in soil with 3 g of CO treated with NA, 16% higher than the RP result; in contrast, the lowest removal (23%) occurred in soil with 75 g treated with PR (Fig. 5A). In general, it was identified that soils containing between 3 and 75 g of CO, PR eliminated 21.7% less TPH than NA (Fig. 5B). Oil removal recorded highly significant (** negative correlations between doses regarding the type of microorganism: Mi = −0.341**, ACT = −0.365**, PsB = −0.624**, and HB = −0.791**. The relationship between organic carbon and total nitrogen and sulfate was negative (SOC/TN = −0.409**, and SOC/SO$_4^{2−}$ = −0.466**) (Table 2). These results suggest that biogenic COS and petroleum-derived COS are mineralized at the same time as TPH are degraded. This process made TN and sulfate aerobically available to plants and microorganisms.

**Discussion**

TPH accumulated in soil contains complex recalcitrant chemical structures with low water solubility. They remain for a long time absorbed in the soil and organic matter (Jacques et al. 2007). TPH changes the organic, macro and micronutrient carbon content (Shukry et al. 2013) of the soil and its biological balance (Labud et al. 2007); they also reduce or increase plant growth according to the plant species (González-Moscoso et al. 2019; Orocio-Carrillo et al. 2019). The results of the present study indicate that *E. palustris* adapts to grow in artificial wetland soil containing between 3 and 75 g/kg of CO. The variables NP and PH showed a linear trend from 2 to 37 weeks. *E. palustris* has three growth phases, a...
logarithmic one, a linear one, and a senescent one (Fig. 1A, B). These phases are similar to those of plants that grow in environments without stress (Salisbury and Ross 2000; Hauser 2006; Ogle et al. 2012). On the other hand, Rivera-Cruz et al. (2016) reported that E. palustris covers large areas of wetland soil. It adapts to unfavorable conditions induced by man in soil and water.

Hormesis is a positive response of some living organisms to soil contamination (Calabrese 2013). This is shown by the results of the present study, with PHI values ≥ 1 for the

| Crude oil (g/kg)/Technology | Microalgae (10^3 cell/mL) | Actinomycetes (10^3 CFU/g) | Fungi (10^2 CFU/g) | Pseudomonas spp | Hydrocarbonoclastic bacteria |
|-----------------------------|--------------------------|----------------------------|-------------------|----------------|-----------------------------|
| Natural attenuation         |                          |                            |                   |                |                             |
| 0                           | 26fgh                    | 492abc                     | 11b               | 17c            | 53c                         |
| 3                           | 18gh                     | 451c                       | 4df               | 11c            | 59c                         |
| 15                          | 15h                      | 18g                        | 9bc               | 11c            | 20c                         |
| 30                          | 40de                     | 40g                        | 8cd               | 16c            | 20c                         |
| 45                          | 48cd                     | 204c                       | 6de               | 13c            | 150c                        |
| 60                          | 33ef                     | 105f                       | 4fg               | 24b            | 864b                        |
| 75                          | 30def                    | 33g                        | 2g                | 15c            | 1426ab                      |
| Phytoremediation            |                          |                            |                   |                |                             |
| 0                           | 23gh                     | 372d                       | 10b               | 11c            | 10c                         |
| 3                           | 73b                      | 492abc                     | 8cd               | 13c            | 74c                         |
| 15                          | 73b                      | 475abc                     | 22a*              | 14c            | 32c                         |
| 30                          | 60bc                     | 401d                       | 12cd              | 16c            | 253c                        |
| 45                          | 55c                      | 462cd                      | *10c              | 26b            | 1572a*                      |
| 60                          | 69b                      | 507a*                      | 12b               | 23c            | 1629a*                      |
| 75                          | 94a*                     | 475abc                     | 13b               | 64a*           | 1885a*                      |
| Natural attenuation         | 30B                      | 187B                       | 5B                | 15B            | 370B                        |
| Phytoremediation            | 64A*                     | 455A*                      | 12A*              | 24A*           | 779A*                       |

*Different letters in columns are statistically different (Duncan, p < 0.05, n = 9, a > b)

Fig. 5 Removal of total petroleum hydrocarbons from soil contaminated during May 2020 to January 2021. A Effect of crude oil concentration, and B Technology type effect. *Treatment means with statistical significant differences (Duncan, p < 0.05, n = 4)
PH and NP of *E. palustris* at the 37 measurement times. The 60 g TPH dose increased PH and NP by 34 and 43.8%, respectively. Similar results were reported by Cedergreen et al. (2007), who found a hermetic response of 13% in the aquatic plant *Lemma minor* when exposed to herbicide. Orocio-Carrillo et al. (2019) reported a hermetic response of 7.4% in the stolon length of *L. minor* when exposed to 7.9 g TPH. The increased growth of *E. palustris* when exposed to crude oil in wetland clay soil shows its sustainability under stress. Calabrese and Blain (2009) reported exposed to crude oil in wetland clay soil shows its susceptibility to *E. palustris* 7.9 g TPH. The increased growth of *E. palustris* 7.4% in the stolon length of aquatic plant *Lemna minor* when exposed to herbicide. Escaso et al. (2010), auxins are hormones that are activated under stress conditions and promote cell expansion and division in the apical meristem of young plants, as well as root elongation. The hermetic response of the roots of *E. palustris* at 38 weeks, when exposed to CO, is possibly influenced by the high content of organic carbon that characterizes Gleysol contaminated with petroleum. Segura (2008) indicated that the aromatic cytokinin 6-amino purine stimulates cell division. This hormone comes from the degradation of organic material and plant synthesis. Eichert, Fernández (2012) reported that cytokinin synthesis is activated in plants by stress. The meristem at the base of the root activates genetic signals for the biosynthesis of higher amounts of phytohormones and cytokinins. Likewise, according to Escaso et al. (2010), auxins are hormones that are activated under stress conditions and promote cell expansion and division in the apical meristem of young plants, as well as root elongation.

The rise of the radical system can also be explained by plant-microbe interactions. The results of the present study indicate a positive relationship between RDM and Mi (0.926**), TF (0.633**), PsB (0.457**), and HCB (0.395**) (Table 2). Rhizospheric microorganisms are plant growth promoters that influence root growth by providing nutrients and phytohormones, and inhibiting pathogens (Marschner 2012).

### Table 2 Correlation coefficients between total petroleum hydrocarbons, soil variables and plant variables

|         | REM    | SOC    | SOC/TN  | SOC/SO  | RDM    | ADM    | Mi     | TF     | ACT    | PsB    | HB     |
|---------|--------|--------|---------|---------|--------|--------|--------|--------|--------|--------|--------|
| CO      | −0.814**| 0.827**| 0.610** | −0.752**| NS     | NS     | 0.266* | NS     | −0.272*| 0.609**| 0.768**|
| PR      | −0.334* | 0.311* | −0.460**| 0.973** | NS     | −0.976**| 0.636**| 0.612**| 0.822**| 0.368* | 0.320* |
| REM     | −0.813**| −0.409**| −0.466**| −0.400**| −0.369**| −0.341**| NS     | −0.365**| −0.624**| −0.791**| NS     |
| SOC     | 0.617** | 0.470**| 0.380** | 0.342*  | 0.409**| NS     | NS     | 0.743**| 0.775**| NS     | NS     |
| SOC/TN  | −0.472**| NS     | NS      | NS     | 0.346* | 0.658**| 0.413**| NS     | NS     | NS     | NS     |
| SOC/SO  | 0.362*  | 0.371**| 0.926** | 0.633** | 0.807**| 0.457**| 0.395**| NS     | NS     | NS     | NS     |
| RDM     | 0.976** | 0.926**| 0.633** | 0.801**| 0.353* | 0.351* | NS     | NS     | NS     | NS     | NS     |
| ADM     | 0.638** | 0.465**| 0.466** | 0.458**| 0.401**| 0.359* | NS     | NS     | NS     | NS     | NS     |
| Mi      | 0.448** | 0.465**| 0.466** | 0.458**| 0.401**| 0.359* | NS     | NS     | NS     | NS     | NS     |
| TF      | 0.461** | NS     | NS      | NS     | NS     | NS     | NS     | NS     | NS     | NS     | NS     |
| ACT     | NS     | NS     | NS      | NS     | NS     | NS     | NS     | NS     | NS     | NS     | NS     |
| PsB     | 0.671**| NS     | NS      | NS     | NS     | NS     | NS     | NS     | NS     | NS     | NS     |

CO crude oil, PR phytoremediation, REM removal TPH, SOC soil organic carbon, TN total nitrogen, SO sulphate, RDM aerial dry matter, Mi microalgae, TF total fungi, ACT actinomycetes, PsB *Pseudomonas* bacteria, HB hydrocarbonoclastic bacteria, NS not significant

*Correlation with significant statistical difference (Duncan, *p* < 0.05)

**Correlation with highly significant statistical difference (Duncan, *p* < 0.01)
abiotic stress due to their ability to solubilize phosphate, produce 1-aminocyclopropane-1-carboxylic acid deaminase, biosurfactants, phytohormones, and exopolysaccharides, fix biological nitrogen, produce siderophore and volatile compounds, and express various stress-related genes (Rastogi et al. 2021).

Values of the physiological hor metric index of ADM of *E. palustris* were ≥ 1 when exposed to 3, 15, 30, 45, 60, and 75 g of CO in artificial wetland soil. This response differs from that of other plants that inhabit the wetland. González-Moscoso et al. (2017) reported that in Gleysol with 90 g/kg of CO, the ADM of *L. hexandra* decreased by 16% compared to the control. Alanbary et al. (2019) reported that the dry matter of *L. octovalvis* decreased when growing on drilling mud with 14,700 mg/kg of TPH. Al-Mansoory et al. (2017) reported that the dry matter of *L. octovalvis* increased by 66%, compared to the control, after 42 days of exposure to 2 g/kg of gasoline. The toxicity response of foliage to the presence of petroleum has been explained by the alteration of stomatal conductance, which regulates the rate of diffusion of carbon dioxide in the leaves for photosynthesis, and by loss of water through transpiration (Rebetzke et al., 2000).

We assume that the increase in ADM of *E. palustris* was due to the highly significant positive relationship between RDM (0.976**) and rhizospheric microbial activity found in the present study. This is because the density of roots and long root hairs are important factor in the absorption of nutrients supplied by diffusion. There is a linear relationship between root density and the absorption rate of nutrients (Marschner and Rengel 2012). The growth of the root system increases the number of sites that can be colonized by microorganisms that provide nutrients for the cellular metabolism of the plant (Neumann and Römheld 2012). In this regard, ADM is very positively related to the population of Mi (0.638**), TF (0.628**), ACT (0.801**), but only positive with PsB (0.353*) and HCB (0.351*) (Table 2).

Under anaerobic conditions, roots provide the rhizosphere with exudates rich in amino acids, organic acids, and carbohydrates (Dagher et al. 2019). Mi provide nitrogen and sulfate, while fungi provide water-soluble carbon. Actinomycetes and bacteria help in the fixation of nitrogen, the degradation of carbon of biogenic and petroleum origin, and the mineralization of essential nutrients (Pepper and Gentry 2008). The present study found a negative relationship between SOC/TN and SOC/SO4 −2 (Table 2). NA induced the efficiency of NA compared to PR when using *E. palustris* for the removal of TPH in the wetland coincides with the results of González-Moscoso et al. (2019), who reported that NA was 15.8% more efficient than PR in the removal of TPH after nine months. In this regard, it is known that the efficiency of oil removal depends on the processes of photooxidation, evaporation, volatilization, and biodegradation by indigenous microorganisms (Abu and Diki 2008). In the wetlands, the water surface hosts autochthonous microorganisms that have been shown to degrade hydrocarbons to a greater percentage than biostimulation (Fodelianakis et al. 2015). Carbon oxidation by microorganisms has been shown to be associated with the availability of nitrogen and sulfate (Brady and Weil 2008). The present study found a negative relationship between SOC/TN and SOC/SO4 −2 (Table 2). NA induced by microbial activity (Gerba and Pepper 2015) in wetland
soil was not favored by Mi, ACT, Pseudomonas spp, and HB (Tables 1 and 2). It is possible that other microbial groups that mineralize nitrogen and sulfate were also established in the same wetland soil favoring the degradation of CO.

Phytoremediation removed only 49.6% of the TPH found in soil contaminated with 3–75 g of petroleum at week 38. Various authors have reported that PR is a non-destructive technology in wetland that requires a long time to decontaminate soil, depending on the concentration of crude oil (Agarry et al. 2018; Alanbary et al. 2019). Different wetland plants have shown to be able to remove TPH from soil: Scirpus grossus removed 66.6% of TPH in soil contaminated with 0.25% diesel-water; Typha domingensis, Phragmites australis, Leptochloa fusca, and Brachiaria mutica removed 99.13% of hydrocarbons in wetland soil contaminated with 319 mg/L of petroleum at month 18 (Al-Mansoory et al. 2017; Alanbary et al. 2019). These authors argue that the use of PR in contaminated wetlands stabilizes the petroleum through the influence of the abundant root systems, retaining and enveloping hydrocarbons, which in turn favors the establishment of microorganisms with CO metabolic capacity that can use carbon of biogenic and petroleum origin (Atlas and Bartha 2002; Rivera-Cruz et al. 2016).

Conclusions

Eleocharis palustris, a plant native to wetlands, was exposed to crude oil contamination for 38 weeks. A hormetic effect was observed in all the physiological variables evaluated from week 2 through week 38. The production and microorganisms evaluated at week 38 showed a hormesis index ≥ 1 to oil. Plant height and new plant production showed an increase at most of the 37 evaluation time points, with statistically significant differences due to the effect of petroleum concentration. The number of primary roots, root dry matter and aerial dry matter increased up to 138, 38 and 45%, respectively in plants exposed to 75 g of crude oil compared to the control. These results were associated with high concentrations of petroleum, indicating a hormetic effect. The same trend was observed in the rhizospheric population of microorganisms, with 75 g of petroleum yielding hormetic index values ≥1 for microalgae, total fungi, actinomycetes, Pseudomonas spp, and hydrocarbonoclastic bacteria. The amount of microalgae, Pseudomonas spp and hydrocarbonoclastic bacteria increased by 69.3, 83.3 and 99.4% respectively when the rhizosphere of E. palustris was exposed to 75 g of oil, while the amount of total fungi and actinomycetes increased by 67.9 and 73.5% when exposed to 60 g of oil. The population of the five microbial groups under study increased in the rhizospheric system of E. palustris used for phytoremediation. The removal of petroleum was greater in soil subjected to natural attenuation. In soil contaminated with 3 g of petroleum, phytoremediation showed a negative relationship between TPH removal and petroleum concentration. At week 38, the effect of phytoremediation on petroleum removal was lower than with natural attenuation. The correlation between the removal of total petroleum hydrocarbons and the population of microalgae, actinomycetes, Pseudomonas spp, and hydrocarbonoclastic bacteria was highly significant and negative. The hormetic effect induced by petroleum in the physiological and microbiological variables of the rhizosphere of E. palustris, as well as the removal of TPH stimulated by it, support the potential of this Cyperaceae as a biological technology for the remediation of contaminated wetlands in the Mexican humid tropics.

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Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

References

Abu GO, Dike PO (2008) A study of natural attenuation processes involved in a microcosm model of a crude oil-impacted wetland sediment in the Niger Delta. Biore sour Technol 99(11): 4761–4767. https://doi.org/10.1016/j.biortech.2007.09.09
Afzal M, Rehman K, Shabir G, Tahseen R, Ijaz A, Hashmat JA, Brix H (2019) Large-scale remediation of oil contaminated water using floating treatment wetlands. npj Clean Water 2(1):3. https://doi.org/10.1038/s41545-018-0025-7
Agarry SE, Ogbenioboh KM, Latinwo GK, Owabor CN (2018) Biotreatment of petroleum refinery wastewater in vertical surface-flow constructed wetland vegetated with Eichhornia crassipes: lab-scale experimental and kinetic modelling. Environ Technol 41(14):1793–1813. https://doi.org/10.1080/09593330.2018.1549106
Agathokleous E, Calabrese EJ (2020a) A global environmental health perspective and optimisation of stress. Sci. Total Environ 704:135263. https://doi.org/10.1016/j.scitotenv.2019.135263
Agathokleous E, Calabrese EJ (2020b) Environmental toxicology and ecotoxicology: How clean is clean? Rethinking dose-response analysis, Sci Total Environ 746:138769. https://doi.org/10.1016/j.scitotenv.2020.138769
Agathokleous E, Barcelo D, Tsatsakis A, Calabrese JE (2020) Hydrocarbon-induced hormesis: 101 years of evidence at the margin. Environ Pollut 265:114846. https://doi.org/10.1016/j.envpol.2020.114846
Alanbary SRN, Abdullah SRS, Al-Baldawi IAW, Hasan HA, Anuar N, Othman AR, Suja F (2019) Phytotoxicity of contaminated sand containing crude oil sludge on Ludwigia octovalvis. J Ecol Eng 20(11):246–255. https://doi.org/10.12911/22998993/113189
Ali-Baldawi AI, Abdullah SRS, Anuar N, Suja F, Mushrifah I (2015) Phytodegradation of total petroleum hydrocarbon (TPH) in diesel-contaminated water using Scirpus grossus. Ecol Eng 74:463–473. https://doi.org/10.1016/j.ecoleng.2014.11.007
Al-Mansoory AF, Idris M, Abdullah SRS, Anuar N (2017) Phyto-
remediation of contaminated soils containing gasoline using Ludovi-
gia octovalvis (Jacq.) in greenhouse pots. Environ Sci Pollut Res
24(13):11998–12008. https://doi.org/10.1007/s11365-015-5261-5
Al-Mansoory AF, Idris M, Abdullah SRS, Anuar N, Kurniawan BS
(2021) Response and capability of Scirpus mucronatus (L.) in phy-
отreating petroleum-contaminated soil. Chemosphere 269:128760:1–9.
https://doi.org/10.1016/j.chemosphere.2020.128760
Atlas MR, Bartha R (2002) Ecología Microbiana y Microbiología
Ambiental. Pearson Educación S.A. Madrid, España
Azcón-Bieto J, Talón M (2013) Fundamentos de Fisiología Vegetal.
McGraw-Hill. Interamericana de España, S.L, Madrid, España
Brady CN, Weil RR (2008) The nature and properties of soils. Pear-
son, Prentice Hall, New Jersey, Columbus Ohio, USA
Calabrese EJ (2013) Hormetic mechanisms. Crit Rev Toxicol
43(7):580e606. https://doi.org/10.3389/fmicb.2019.02144
Calabrese EJ, Blain RB (2009) Hormesis and plant biology. Environ
Pollut 157(1):42–48. https://doi.org/10.1016/j.envpol.2008.07.028
Calabrese EJ, Agathokleous E (2020) Theodosius Dobzhansky’s view
on biology and evolution v.2.0: “Nothing in biology makes sense
except in light of evolution and evolution’s dependence on
hormesis mediated acquired resilience that optimizes biological
performance and numerous diverse short and longer term pro-
tection strategies”. Environ Res 186:109559. https://doi.org/10.1016/
1096.186.2020.109559
Calabrese EJ, Agathokleous E (2021) Accumulator plants and horm-
esis. Environ Pollut 274:116526. https://doi.org/10.1016/j.envpol.
2021.116526
Cao Z, Liu X, Zhang X, Chen L, Liu S, Hu Y (2012) Short-term effects of
diesel fuel on rhizosphere microbial community structure of
native plants in Yangtze estuarine wetland. Environ Sci Pollut Res
19(6):2179–2185. https://doi.org/10.1007/s11356-011-0720-4
Cedergreen N, Streibig JC, Kudsk P, Mathiassen SK, Duke SO (2007)
The occurrence of hormesis in plants and algae. Dose-Response
5(2):150–162. https://scholarworks.umass.edu/dose_response/vol5/iss2/8
Dagher DJ, de la Providencia IE, Pitre FE, St-Arnaud M, Hijji M
(2019) Plant identity shaped rhizospheric microbial communities
more strongly than bacterial bioaugmentation in petroleum
hydrocarbon-polluted sediments. Front Microbiol 10:2144.
https://doi.org/10.3389/fmicb.2019.02144
Durenne B, Druarta P, Blondela A, Fauconnier ML (2018) How cad-
mium affects the fitness and the glucosinolate content of oil-
seed rape plantlets. Environ Exp Biol 155:185–194. https://doi.
org/10.1016/j.envexpbot.2018.06.008
Eichert T, Fernández V (2012) Uptake and release of elements by
leaves and other aerial plant parts. In: Marschner P (ed.)
Marschner’s mineral nutrition of higher plants, 3rd edn.
Aca-
demic Press, San Diego, CA, p 71-84 https://doi.org/10.1016/B978-
0-12-384905-2.00004-2 Corpus ID: 88795032
Escaso SF, Martínez GJL, Planelló CMR (2010) Fundamentos Básicos
de Fisiología Vegetal y Animal. Pearson Educación, S.A, Madrid,
España
Etchevers BJD (1992) Manual de métodos para análisis de suelos,
plantas agua y fertilizantes. Análisis rutinarios en estudios y
programas de fertilidad. Laboratorio de Fertilidad, Centro de
Edafología. Colegio de Postgraduados en Ciencias Agrícolas.
Montecillos. edo, México
Fan D, Wang S, Gao Y, Liu J, Agathokleous E, Zhu Y, Han J (2021) The
role of bacterial communities in shaping Cd-induced hormesis in
‘living’ soil as a function of land-use change. J Hazard Mater
409:124996. https://doi.org/10.1016/j.jhazmat.2020.124996
Fleeger JW, Carman K, Riggio A, Mendelsson I, Lin Q, Hou A, Deis
L, Zengel S (2015) Recovery of salt marsh benthic microalgae
and meiofauna following the Deepwater Horizon oil spill linked
to recovery of Spartina alterniflora. Mar Ecol Prog Ser
536:39–54. https://doi.org/10.3354/meps11451
Fodoralianakis S, Antoniou E, Mapelli F, Magagnini M, Niko-
lopoulou M, Marasco R, Barbato M, Tsiola A, Tsikopouloue I, Giacca-
gi L, Mahjoubi M, Jauanii A, Amer R, Husseinj E, Al-Horani FA,
Benzhal F, Blaghenl M, Malkawu IH, Abdel-Fattahi Y, Cherif A,
Daffonchio D, Kalegorakis N (2015) Allochthonous bioaug-
mentation in ex situ treatment of crude oil-polluted sediments in
the presence of an effective degrading indigenous microbiome. J
Hazard Mater 287:78–86. https://doi.org/10.1016/j.jhazmat.2015.
01.03
Fu J, Huang B (2001) Involvement of antioxidants and lipid perox-
adation in the adaptation of two cool season grasses to localized
drought stress. Environ Exp Bot 45(2):105–114. https://doi.
org/10.1007/S0098-8472(00)00084-8
Garrity GM, Bell JA, Lilburn T (2005) Pseudomonadales Orla-Jensen
1921. 270AL. In: Brenner DJ et al. (eds.) Bergey’s Manual of
Systematic Bacteriology. Springer, Boston, MA. https://doi.
org/10.1007/0-387-28022-7–9
George E, Host W, Neumann E (2012) Adaptation of Plants to
Adverse Chemical Soil Conditions. In: Marschner P (ed.)
Marschner’s Mineral Nutrition of Higher Plants. 3rd edn.
Aca-
demic Press, San Diego, CA, USA, p 409–455
Gerba PC, Pepper LI (2015) Drinking Water Treatment and Distribu-
tion. In: Pepper LI, Gerba PCh, Gentry JT (eds.) Environmental Micro-
biology. Academic Press, San Diego, CA, p 663-642
González-Moscoco M, Rivera-Cruz MC, Delgadillo-Martínez J,
Lagunes-Espinoza LC (2017) Growth analysis and plant pro-
duction of Leersia hexandra Swartz in tropic wet mexican
fication on petroleum and surfactant. Polibotánica 43:177–196.
https://doi.org/10.18387/polibotanica.43.8
González-Moscoco M, Rivera-Cruz MC. Trujillo-Narcia A (2019)
Decontamination of soil containing oil by natural attenuation,
phytoremediation and chemical desorption. Int J Phytoremedi-
et 21(8):768–776. https://doi.org/10.1080/15226514.2019.1566879
Hauser AS (2006) Eleocharis palustris. In: Fire Effects Information
System, [Online]. U.S. Department of Agriculture, Forest Ser-
vice, Rocky Mountain Research Station, Fire Sciences Labora-
(tory (Producer). https://www.fs.fed.us/database/feis/plants/grain
moid/elepalep.html [2021, November 17]
Iturbe R, Flores C, Castro A, Torres LG (2007) Sub-soil contamination
due to oil spills in zones surrounding oil pipeline-pump stations and oil
pipeline right-of-ways in Southwest-Mexico. Environ Monit Assess
133(1-3):378–398. https://doi.org/10.1007/s1137p.006-9593-3
Jacques RJS, Bento FM, Antonielli ZI, Camargo FAO (2007) Bior-
remediação de solos contaminados com hidrocarbonetos áro-
micos policíclicos. Ciência Rural 37(4):1192–1201
Jeffrey AA (2002) Catalase activity, hydrogen peroxide content and
thermotolerance of pepper leaves. Sci Hort 95(4):277–284.
https://doi.org/10.1016/S0304-4288(02)00076-6
Jia L, Liu Z, Chen W, Ye Y, Yu S, He XY (2015) Hormesis effects
induced by cadmium on growth and photosynthetic performance in
a hyperaccumulator, Lonicera japonica. Thunb. J Plant Growth
Regul 34(1):13–21. https://doi.org/10.1007/s10661-006-9433-1
Johnson LF, Curl EA (1972) Methods for research on the ecology of
soil-borne plant pathogens. Burgess Publishing Company. Min-
neapolis, MN, USA
Labad V, García C, Hernández T (2007) Effect of hydrocarbon pol-
lution on the microbial properties of a sandy and a clay soil.
Chemosphere 66(10):1863–1871. https://doi.org/10.1016/j.
chemosphere.2006.08.021
Ławniczak L, Wozniak-Karczewska M, Loibner AP, Heipieper HJ,
Chrzanoski L (2020) Microbial degradation of hydrocarbons-
basics principles for bioremediation: A review. Molecules
25(4):856. https://doi.org/10.3390/molecules25040856
Physiological and microbiological hormesis in sedge Eleocharis palustris induced by crude oil in...