

Artículo original / Original article

Morphological response of *Hordeum vulgare* cv. La Molina 96 and *Chenopodium quinoa* cv. La Molina 89 to varying concentrations of petroleum sludge

Respuesta morfológica de *Hordeum vulgare* cv. La Molina 96 y *Chenopodium quinoa* cv. La Molina 89 a diferentes concentraciones de borra petrolera

Aldo Alberto Cabrera-Berrocal ^{1*}; Ronald Rolando Mori-Pezo ²; Pedro Mendoza-Tamani ²

¹Universidad Nacional Agraria La Molina, Lima, Peru

²Universidad Nacional Autónoma de Alto Amazonas, Yurimaguas, Peru

ABSTRACT

The contamination of agricultural soils with petroleum residues poses a threat to plant development and agroecological productivity. This study aimed to evaluate the morphological response of barley (*Hordeum vulgare* cv. La Molina 96) and quinoa (*Chenopodium quinoa* cv. La Molina 89) to different concentrations of petroleum sludge in the soil. A completely randomized design was employed with six treatments (0 %, 0.5 %, 1 %, 2 %, 4 %, and 6 %) and three replicates per treatment, conducted under controlled conditions. Morphophysiological variables such as plant height, number of leaves, leaf length, number of grains (in barley), and estimated leaf area were measured. The results showed that both crops failed to germinate from 4 % contamination. Barley exhibited reductions of up to 81 % in height and 84 % in leaf area at 2 % petroleum sludge. Quinoa germinated in all treatments; however, at 2 %, its height was reduced by 87 %, and the number of leaves dropped by 90 %. It is concluded that petroleum sludge causes severe phytotoxic effects in both species, with quinoa being relatively more tolerant. These findings suggest its potential use in contaminated soils or as a bioindicator species.

Keywords: asphaltenes; bioindicators; phytotoxicity; heavy hydrocarbons; soil contamination; plant tolerance.

RESUMEN

La contaminación de suelos agrícolas con residuos de petróleo representa una amenaza para el desarrollo vegetal y la productividad agroecológica. El presente estudio tuvo como objetivo evaluar la respuesta morfológica de la cebada (*Hordeum vulgare* cv. La Molina 96) y la quinua (*Chenopodium quinoa* cv. La Molina 89) frente a diferentes concentraciones de borra petrolera en el suelo. Se empleó un diseño completamente aleatorizado con seis tratamientos (0 %, 0.5 %, 1 %, 2 %, 4 % y 6 %) y tres repeticiones por tratamiento, bajo condiciones controladas. Se midieron variables morfofisiológicas como altura, número de hojas, longitud foliar, número de granos (en cebada) y área foliar estimada. Los resultados mostraron que ambos cultivos no germinaron a partir del 4 % de contaminación. La cebada presentó reducciones de hasta 81 % en altura y 84 % en área foliar con 2 % de borra. La quinua germinó en todos los tratamientos, aunque a 2 % su altura se redujo un 87 % y el número de hojas cayó un 90 %. Se concluye que la borra petrolera genera un efecto fitotóxico severo en ambas especies, siendo la quinua relativamente más tolerante, permitiendo sugerir su uso potencial en suelos contaminados o como especie bioindicadora.

Palabras clave: asfáltenos; bioindicadores; contaminación del suelo; fitotoxicidad; hidrocarburos pesados; tolerancia vegetal.

Cómo citar / Citation: Cabrera Berrocal, A. A., Mori Pezo, R. R. & Mendoza Tamani, P. (2025). Respuesta morfológica de *Hordeum vulgare* cv. La Molina 96 y *Chenopodium quinoa* cv. La Molina 89 a diferentes concentraciones de borra petrolera. *Revista Peruana de Investigación Agropecuaria*, 5(1), e124. <https://doi.org/10.56926/repia.v5i1.124>

Editor: Dr. Fred William Chu Koo 

Received: 28/08/2025

Accepted: 01/04/2026

Published: 20/04/2026

* aldocabreraberrocal@gmail.com (corresponding author)



© Authors. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International License.

1. INTRODUCTION

Soil contamination by petroleum hydrocarbons is a serious environmental problem that affects soil fertility and plant growth (Barati et al., 2020). Petroleum hydrocarbons present in soils exert phytotoxic effects that can inhibit germination and significantly reduce biomass (Kamranifar et al., 2025; Khatibi & Hosseini, 2018). Rivera-Cruz & Trujillo-Narcía (2004) observed that in soils with extremely high concentrations of petroleum hydrocarbons, vegetation biomass production was reduced by approximately 50% compared to soils with lower levels of contamination.

Within the Peruvian regulatory framework, Supreme Decree No. 011-2017-MINAM establishes an Environmental Quality Standard (EQS) for agricultural soils of 3000 mg/kg for the F3 fraction, corresponding to hydrocarbon chains ranging from 28 to 40 carbon atoms. However, no specific limit is defined for heavier hydrocarbons (>C40), such as those typically found in petroleum sludge. This regulatory gap represents a significant limitation in the environmental management of highly contaminated soils and highlights the need for studies evaluating their effects on plant biota.

Petroleum sludge, a heavy residue derived from crude oil processing, typically contains high concentrations of asphaltenes—compounds that are highly recalcitrant and resistant to biological degradation. Navas-Cáceres et al. (2023) indicate that asphaltenes are the most polar and heaviest fraction of petroleum, characterized by complex structures and high toxicity, which explains their persistence in contaminated soils and resistance to microbial catabolism. Previous studies confirm these characteristics, describing asphaltenes as highly polarized, high-molecular-weight compounds with low biodegradability (Chand et al., 2022; Kashi et al., 2018; Liao et al., 2009; Tavassoli et al., 2012). Furthermore, it has been observed that during the biodegradation of petroleum-contaminated soils, the proportion of asphaltenes increases as lighter fractions are preferentially degraded, leaving behind heavier residues (>C40) (Tavassoli et al., 2012).

The presence of petroleum in soil can interfere with water and nutrient uptake by roots and induce oxidative stress in plants (Korshunova et al., 2021). In barley (*Hordeum vulgare*), crude oil contamination has been reported to inhibit root and shoot growth, reduce leaf size, and decrease chlorophyll content (Korshunova et al., 2021). These effects result in smaller, chlorotic plants with reduced vigor in contaminated soils. Korshunova et al. (2021), also documented that oil contamination inhibited root and stem length and biomass throughout a field experiment, in addition to reducing leaf area and greenness. Such morphological damage reflects the difficulty many plant species face in establishing under hydrocarbon-contaminated conditions.

Phytoremediation has emerged as a viable strategy for rehabilitating contaminated soils by utilizing plants capable of tolerating and even degrading organic pollutants (Barati et al., 2020). This approach involves identifying resistant plant species that can grow in the presence of petroleum residues and contribute to the degradation or stabilization of hydrocarbons (Barati et al., 2020). Some short-cycle grasses, such as barley and oats, have been shown to enhance petroleum hydrocarbon biodegradation in soil by stimulating microbial activity in the rhizosphere. However, contamination generally limits plant growth. Barati et al. (2020), reported reductions in plant height and biomass in barley and oats as petroleum levels increased. Thus, even species with phytoremediation potential experience stress under high contaminant loads, which may reduce their effectiveness.

On the other hand, quinoa (*Chenopodium quinoa*) is an Andean pseudocereal known for its remarkable tolerance to adverse conditions such as high salinity, drought, and frost (Abbas et al., 2023; Hinojosa et al., 2018; Pathan et al., 2023). Recent studies suggest that quinoa can also tolerate soils contaminated with heavy metals and petroleum drilling residues, maintaining relatively stable growth where other species experience severe stress (Amjad et al., 2022; Haseeb et al., 2022; Matías et al., 2024). Khalili et al. (2024) found that quinoa exhibited exceptional tolerance and a high capacity for metal accumulation in soils containing up to 15% drilling cuttings, whereas barley showed visible stress symptoms under high contamination levels. This capacity makes quinoa a potential candidate for phytoremediation or as a bioindicator in petroleum-contaminated environments. It has also been reported that although quinoa is resistant, its growth and biomass ultimately decline under extreme contamination conditions (Alharby et al., 2022); however, under moderate stress levels, it outperforms many conventional crops. Its tolerance mechanisms—similar to those of halophytic plants—include ion exclusion or controlled accumulation of toxic elements and a robust antioxidant system, which may explain its superior performance in degraded soils (Nikalje & Suprasanna, 2018).

In this context, the present study aims to evaluate the morphological response of barley (*Hordeum vulgare* cv. La Molina 96) and quinoa (*Chenopodium quinoa* cv. La Molina 89) when grown in soil contaminated with petroleum sludge. It is hypothesized that increasing concentrations of petroleum sludge in soil will negatively affect the morphological growth and development of both barley and quinoa, with quinoa expected to exhibit greater tolerance to heavy hydrocarbon contamination due to its physiological stress-resistance mechanisms.

2. MATERIALS AND METHODS

Study area and research design

The study was conducted in the gardens of the Universidad Nacional Agraria La Molina (UNALM), specifically in the area located in front of the Faculty of Sciences. It was designed as an applied, explanatory-level study with a completely randomized experimental design, aimed at evaluating the morphological response of two plant species to different concentrations of soil contaminants.

Experimental design

A completely randomized design (CRD) was employed, consisting of six treatments with three replicates per treatment. The treatments involved mixing soil with different concentrations of petroleum sludge: 0 % (control), 0.5 %, 1 %, 2 %, 4 %, and 6 %. The experimental units consisted of plastic pots with a capacity of 700 g, containing homogeneously treated soil.

Variables

The dependent variables were morphophysiological and were evaluated separately for each plant species:

Maximum height (cm).

Last internode length (cm).

Number of leaves.

Mean length of lower leaves (MLL) (cm).

Maximum length of the upper leaf (MLU) (cm).

Number of grains (in barley).

Initial vigor (cm² of estimated leaf area).

Population and sample

The sample consisted of two plant species: barley (*Hordeum vulgare* cv. La Molina 96) and quinoa (*Chenopodium quinoa* cv. La Molina 89), developed by the UNALM Cereal Program. A total of 18 pots were used per species (6 treatments × 3 replicates), resulting in 36 experimental units.

Soil conditions and measurements

The soil was classified as sandy loam with medium fertility. Its physicochemical characteristics are presented in **Table 1**. Variables related to plant vigor and growth were measured at the end of the vegetative cycle. Leaf area (initial vigor) was estimated using the formula proposed by Isla Climente (1996):

$$\text{Area} = \text{Length} \times \text{Maximum width} \times 0.665$$

Table 1.

Initial characteristics of the soil used in the experiment.

Parameter	Value
pH	7.8
Electrical conductivity (1:1)	0.87 dS/m
Free CaCO ₃	2.57 %
Organic matter	1.3 %
Available phosphorus	2.2 ppm
Total nitrogen	0.04 %
Available potassium	96 ppm
Texture	64 % sand, 14 % clay, 22 % silt
Wilting point	0.10 cm ³ water/cm ³
Field capacity	0.21 cm ³ water/cm ³
Bulk density	1.51 g/cm ³
Particle density	2.65 g/cm ³
Porosity	0.43 cm ³ water/cm ³
Available water	0.10 cm ³ water/cm ³

Preparation of treatments

The petroleum sludge, obtained from the Conchán refinery (Lima, Peru), was homogeneously mixed with the soil prior to sowing. The actual hydrocarbon concentration in the mixtures was determined using Soxhlet extraction with diethyl ether as the solvent. The solvent was subsequently evaporated, and the residue was weighed until constant weight was achieved.

During the experiment, no active bioremediation techniques (e.g., soil turning or aeration) were applied. Soil moisture was maintained close to field capacity through daily irrigation. No additional fertilizers were applied to avoid bias in the effects of petroleum sludge.

Data collection techniques

Measurements were taken manually using a millimeter ruler and calipers. The variables were recorded in field sheets specifically designed for the experiment. Seedlings were monitored until the completion of the vegetative cycle or until growth was interrupted due to the effects of the contaminant.

Statistical analysis

Data were processed using RStudio software version 4.2.2. Descriptive statistics (mean \pm standard error) were applied for each treatment to summarize central tendencies and variability of the morphophysiological variables evaluated in barley and quinoa.

To analyze the relationship between petroleum sludge concentration and morphophysiological variables, Pearson's correlation coefficient (r) and its corresponding coefficient of determination (R^2) were calculated. A correlation was considered significant when $|r| \geq 0.80$ and $R^2 > 0.65$, indicating a strong association between variables.

3. RESULTS AND DISCUSSION

3.1. Barley development

Table 2 shows the behavior of morphophysiological variables in *Hordeum vulgare* cv. La Molina 96 plants under different concentrations of petroleum sludge. The evaluated variables included maximum height, last internode length, number of grains, and initial vigor. Plants did not germinate at concentrations of 4 % and 6 %; therefore, these treatments were excluded from the measurement of the aforementioned variables.

Table 2.

Morphophysiological variables in barley (Hordeum vulgare cv. La Molina 96) exposed to petroleum sludge.

Treatment	Maximum height (cm)	Last internode (cm)	Number of grains	Initial vigor (cm ²)
Testigo	42.6 \pm 1.5	9.0 \pm 0.2	4	8.91 \pm 0.1
T1 (0.5 %)	37.0 \pm 2.0	9.3 \pm 0.3	4	8.80 \pm 0.3
T2 (1.0 %)	21.6 \pm 1.9	–	–	8.30 \pm 0.1
T3 (2.0 %)	8.05 \pm 2.1	–	–	1.41 \pm 0.2
<i>r</i>	-0.985	–	–	-0.908

Morphological response of barley (*Hordeum vulgare* cv. La Molina 96) to different concentrations of oil sludge

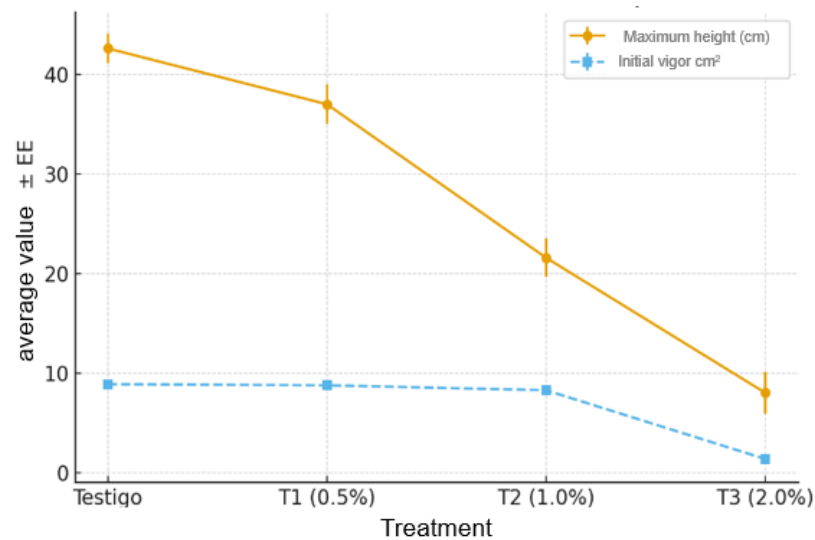


Figure 1. Variation in maximum height and initial vigor of *Hordeum vulgare* cv. La Molina 96 as a function of petroleum sludge concentration

The data showed a progressive decrease in plant height and initial vigor as petroleum sludge concentration increased. Pearson's correlation between contaminant concentration and maximum height and initial vigor was strong and negative ($r = -0.985$ and -0.908 , respectively).

These results indicate that petroleum sludge exerts a severe phytotoxic effect on barley, affecting germination, growth, and reproduction. At concentrations of 4 % and 6 %, plants failed to germinate, indicating a critical toxicity threshold, consistent with findings reported by Kamranifar et al. (2025) in halophytic species exposed to hydrocarbons.

Maximum height decreased significantly with increasing contaminant concentration ($r = -0.985$), confirming a strong negative relationship. This pattern is consistent with the inhibitory effects described by Korshunova et al. (2021), who reported similar reductions in barley exposed to petroleum contamination.

The number of grains and last internode length were affected in the most contaminated treatments, reflecting disruption of the reproductive cycle due to environmental stress, as reported by Rivera-Cruz & Trujillo-Narcía (2004).

Initial vigor (estimated leaf area) also decreased markedly ($r = -0.908$), suggesting damage to the photosynthetic apparatus due to oxidative stress, as supported by studies on quinoa and heavy metal exposure (Alharby et al, 2022).

3.2. Quinoa development

Quinoa showed initial germination in all treatments; however, plants did not survive at concentrations of 4 % and 6 %. **Table 3** presents the results of the evaluated morphophysiological variables: maximum height, number of leaves, mean length of lower leaves, and maximum length of upper leaves.

Table 3.

Morphophysiological variables in quinoa (Chenopodium quinoa cv. La Molina 89) exposed to petroleum sludge.

Treatment	Maximum height (cm)	Number of leaves	MLL (cm)	MLU (cm)
Testigo	10.7 ± 0.5	20.7 ± 1.2	1.6 ± 0.1	1.3 ± 0.1
T1 (0.5 %)	3.46 ± 0.1	13.0 ± 1.0	1.1 ± 0.1	0.9 ± 0.1
T2 (1.0 %)	2.27 ± 0.1	7.7 ± 0.6	0.9 ± 0.1	0.5 ± 0.1
T3 (2.0 %)	1.43 ± 0.1	2.0 ± 0.0	0.7 ± 0.0	–
<i>r</i>	-0.807	-0.970	-0.922	-0.992
R²	0.652	0.941	0.941	0.983

Morphological response of barley (*Chenopodium quinoa* cv. La Molina 89) to different concentrations of oil sludge

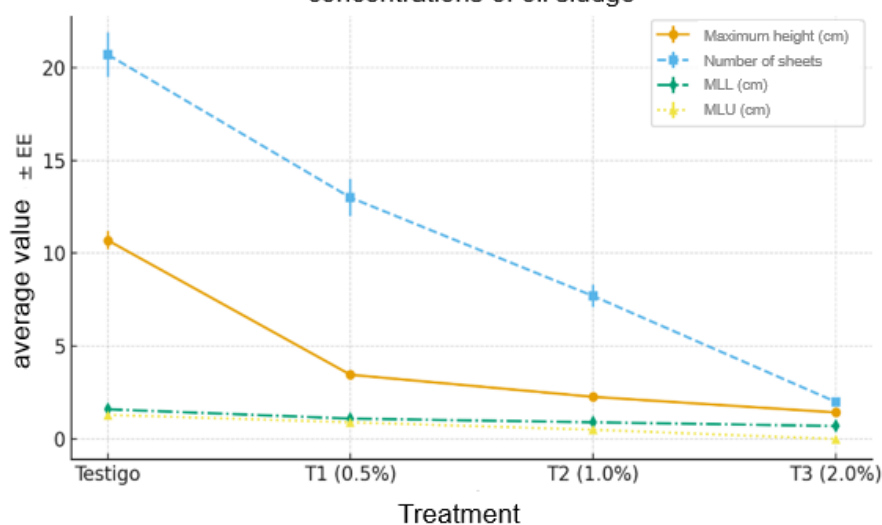


Figure 2. Effect of petroleum sludge on plant height, number of leaves, and leaf length in quinoa (*Chenopodium quinoa* cv. La Molina 89)

All evaluated variables in quinoa showed inverse correlations with petroleum sludge concentration. The maximum length of the upper leaf exhibited an almost perfect correlation ($r = -0.992$; $R^2 = 0.983$), confirming its sensitivity as an indicator of physiological stress.

Unlike barley, quinoa was able to germinate and partially develop under all treatments, supporting its relative tolerance to organic contaminants (Amjad et al., 2022; Haseeb et al., 2022; Matías et al., 2024). However, the results of this study demonstrate that petroleum sludge significantly affects its morphological development, and that variables such as number of leaves and upper leaf length are reliable indicators of physiological damage. The reduction in leaf area directly compromises photosynthesis and overall plant development, as documented in other species under hydrocarbon stress (Kamranifar et al., 2025). This general pattern of decline is consistent with studies such as Alharby et al. (2022), which reported that quinoa reduces leaf size and biomass production under heavy metal stress, although it maintains some structural integrity due to antioxidant and ion-exclusion mechanisms. In this study, quinoa showed better tolerance at low concentrations (0.5 %), maintaining relatively stable morphology; however, at concentrations of 1.0 % to 2.0 %, the impact was severe.

These findings are consistent with those reported by Navas-Cáceres et al. (2023), who state that heavy hydrocarbons such as asphaltenes affect vegetative growth by altering cellular physiology and hormonal balance in plants.

CONCLUSIONS

The study demonstrates that petroleum sludge exerts a progressive phytotoxic effect on the morphological development of both barley and quinoa, affecting key variables such as germination, vegetative growth, and initial vigor. Barley (*Hordeum vulgare* cv. La Molina 96) showed high sensitivity to contamination, with developmental disruption occurring at concentrations equal to or greater than 1 %, whereas quinoa (*Chenopodium quinoa* cv. La Molina 89) exhibited relatively greater tolerance, particularly at low levels of petroleum sludge.

These results provide valuable evidence for the management and monitoring of soils contaminated with petroleum residues. Quinoa may be considered a bioindicator species of intermediate tolerance, useful for identifying moderate levels of contamination, while barley can serve as a sensitive indicator in toxicity assessments. The selection of these species could be incorporated into passive phytoremediation strategies or early-stage revegetation of degraded soils, contributing to ecological and productive recovery in areas affected by the petroleum industry.

RECOMMENDATIONS

Further research is recommended to evaluate the physiological mechanisms underlying tolerance in quinoa, as well as larger-scale trials that incorporate interactions with rhizospheric microorganisms or the use of amendments to enhance bioremediation. These approaches would contribute to a deeper understanding of the sustainable management of contaminated soils and optimize the use of native and adapted species in environmental restoration programs.

The study was conducted under controlled pot conditions, which limits the direct extrapolation of the results to field conditions. In addition, physiological parameters (e.g., chlorophyll content, lipid peroxidation, or antioxidant activity) were not evaluated, which could provide a more detailed explanation of the observed tolerance mechanisms.

Future studies integrating biochemical and microbiological measurements, as well as field trials involving different soil types and local cultivars, are recommended to validate the applicability of quinoa as a bioindicator species.

ACKNOWLEDGMENTS

The authors would like to thank the Universidad Nacional Agraria La Molina for allowing this research to be conducted on its campus.

FUNDING

The authors received no financial support for the conduct of this study.

CONFLICT OF INTEREST

Conceptualization and manuscript preparation: Cabrera-Berrocal, A.A, Mendoza-Tamani, P.

Data collection: Cabrera-Berrocal, A.A., Mori-Pezo, R.R.

Data analysis: Cabrera-Berrocal, A.A, Mendoza-Tamani, P.

Results discussion: Cabrera-Berrocal, A.A, Mendoza-Tamani, P.

Review and approval: Cabrera-Berrocal, A.A, Mori-Pezo, R.R.

REFERENCES

- Abbas, G., Areej, F., Asad, S. A., Saqib, M., Anwar-ul-Haq, M., Afzal, S., Murtaza, B., Amjad, M., Naeem, M. A., Akram, M., Akhtar, N., Aftab, M., & Siddique, K. H. M. (2023). Differential Effect of Heat Stress on Drought and Salt Tolerance Potential of Quinoa Genotypes: A Physiological and Biochemical Investigation. *Plants*, *12*(4), 774. <https://doi.org/10.3390/plants12040774>
- Alharby, H. F., Al-Zahrani, H. S., & Abbas, G. (2022). Potassium and Silicon Synergistically Increase Cadmium and Lead Tolerance and Phytostabilization by Quinoa through Modulation of Physiological and Biochemical Attributes. *Toxics*, *10*(4), 169. <https://doi.org/10.3390/toxics10040169>
- Amjad, M., Iqbal, M. M., Abbas, G., Farooq, A. B. U., Naeem, M. A., Imran, M., Murtaza, B., Nadeem, M., & Jacobsen, S.-E. (2022). Assessment of cadmium and lead tolerance potential of quinoa (*Chenopodium quinoa* Willd) and its implications for phytoremediation and human health. *Environmental Geochemistry and Health*, *44*(5), 1487–1500. <https://doi.org/10.1007/s10653-021-00826-0>
- Barati, M., Safarzadeh, S., Mowla, D., & Bakhtiari, F. (2020). Effect of Barley and Oat Plants on Phytoremediation of Petroleum Polluted Soils. *Pollution*, *6*(4), 695–703. <https://doi.org/https://doi.org/10.22059/poll.2020.297258.746>
- Chand, P., Dutta, S., & Mukherji, S. (2022). Slurry phase biodegradation of heavy oily sludge and evidence of asphaltene biotransformation. *Journal of Environmental Management*, *324*, 116315. <https://doi.org/10.1016/j.jenvman.2022.116315>
- Haseeb, M., Iqbal, S., Hafeez, M. B., Saddiq, M. S., Zahra, N., Raza, A., Lbrahim, M. U., Iqbal, J., Kamran, M., Ali, Q., Javed, T., Ali, H. M., & Siddiqui, M. H. (2022). Phytoremediation of nickel by quinoa: Morphological and physiological response. *PLOS ONE*, *17*(1), e0262309. <https://doi.org/10.1371/journal.pone.0262309>
- Hinojosa, L., González, J. A., Barrios-Masias, F. H., Fuentes, F., & Murphy, K. M. (2018). Quinoa Abiotic Stress Responses: A Review. *Plants*, *7*(4), 106. <https://doi.org/10.3390/plants7040106>
- Isla Climente, R. (1996). *Efecto de la salinidad sobre la cebada (Hordeum vulgare L.). Análisis de caracteres morfo-fisiológicos y su relación con la tolerancia a la salinidad* [Universitat de Lleida]. <http://hdl.handle.net/10803/8324>
- Kamranifar, M., Pourzamani, H., Khosravi, R., Ranjbar, G., & Ebrahimpour, K. (2025). Phytotoxic effects of petroleum hydrocarbons on germination and growth of the native halophyte *Salicornia sinus persica* in oil contaminated soil. *Scientific Reports*, *15*(1), 8459. <https://doi.org/10.1038/s41598-025-92512-9>
- Kashi, M. H., Tabatabaee, M. S., & Soleimani, N. A. (2018). Biodegradation of the Most Heavier

Fraction of Crude Oil, Asphaltene, by *Bacillus toyonensis* BCT-7112. *Journal of Chemical Health Risks*, 8(1). <https://jchr.org/index.php/JCHR/article/view/87>

- Khalili, P., Hoodaji, M., Nadoushan, M. A., & Chamani, A. (2024). Assessing some Cereals and Quinoa as Bioindicators and Phytoextractors of Heavy Metals in Soils Contaminated with Drill Cutting Waste. *Journal of Soil Science and Plant Nutrition*, 24(2), 3631–3648. <https://doi.org/10.1007/s42729-024-01782-1>
- Khatibi, S., & Hosseini, H. M. (2018). Assessment of Certain Plant Species degrading Total Petroleum Hydrocarbons in Contaminated Soil. *Grassroots Journal of Natural Resources*, 1(1), 69–82. <https://doi.org/10.33002/nr2581.6853.01017>
- Korshunova, T. Y., Vysotskaya, L. B., Arkhipova, T. N., Kuzina, E. V., Rafikova, G. F., Chetverikova, D. V., Bakaeva, M. D., & Chetverikov, S. P. (2021). Morphological and physiological-biochemical response of plants to treatment with hydrocarbon bacteria on the background of oil contamination. *ĖKOBIOTEH*, 4(2), 72–80. <https://doi.org/10.31163/2618-964X-2021-4-2-72-80>
- Liao, Y., Geng, A., & Huang, H. (2009). The influence of biodegradation on resins and asphaltenes in the Liaohe Basin. *Organic Geochemistry*, 40(3), 312–320. <https://doi.org/10.1016/j.orggeochem.2008.12.006>
- Matías, J., Cruz, V., Rodríguez, M. J., Calvo, P., Maestro-Gaitán, I., & Reguera, M. (2024). Evaluating Yield, Nutritional Quality, and Environmental Impact of Quinoa Straws across Mediterranean Water Environments. *Plants*, 13(6), 751. <https://doi.org/10.3390/plants13060751>
- Navas-Cáceres, O. D., Parada, M., & Zafra, G. (2023). Development of a highly tolerant bacterial consortium for asphaltene biodegradation in soils. *Environmental Science and Pollution Research*, 30(59), 123439–123451. <https://doi.org/10.1007/s11356-023-30682-7>
- Nikalje, G. C., & Suprasanna, P. (2018). Coping With Metal Toxicity – Cues From Halophytes. *Frontiers in Plant Science*, 9. <https://doi.org/10.3389/fpls.2018.00777>
- Pathan, S., Ndunguru, G., Clark, K., & Ayele, A. G. (2023). Yield and nutritional responses of quinoa (*Chenopodium quinoa* Willd.) genotypes to irrigated, rainfed, and drought-stress environments. *Frontiers in Sustainable Food Systems*, 7. <https://doi.org/10.3389/fsufs.2023.1242187>
- Rivera-Cruz, M. del C., & Trujillo-Narcía, A. (2004). Estudio de toxicidad vegetal en suelos con petróleo nuevo e intemperizado. *Interciencia*, 29(7). https://ve.scielo.org/scielo.php?script=sci_arttext&pid=S0378-18442004000700007
- Tavassoli, T., Mousavi, S. M., Shojaosadati, S. A., & Salehizadeh, H. (2012). Asphaltene biodegradation using microorganisms isolated from oil samples. *Fuel*, 93, 142–148. <https://doi.org/10.1016/j.fuel.2011.10.021>