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Bacterial Response and Saline Adaptation Under Osmotic Stress from Magnetically Treated Produced Water in Arid Environments

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Index Terms

Water produce, bacterial activity , Al-Istiklal field, Zaltan field, magnetic treatment,

Abstract

Water produced alongside oil poses a pressing environmental challenge; however, water scarcity in arid regions compels us to seek innovative solutions for its agricultural use. The major obstacle lies in its high ionic content and the risks of alkalinity, which destroy the physical structure of the soil. Therefore, this study sought to evaluate the effectiveness of "magnetic treatment" as a physical remediation tool to mitigate these damages, using water extracted from the Zaltan and Al-Istiklal fields in Libya. To achieve this, a laboratory experiment was conducted to test four levels of water dilution (5%, 10%, 15%, 25%), both magnetized and non-magnetized, while monitoring changes in the soil's physicochemical properties specifically the sodium adsorption ratio (SAR) and the exchangeable sodium percentage (ESP) and their impact on bacterial community response. The results revealed a significant positive effect of magnetization; it improved ionic balance by increasing the bioavailability of calcium and reducing sodium accumulation. This was clearly evident in the Istiqlal field, where the SAR value decreased from dangerous levels (43.72) to (32.55). This chemical improvement created a supportive microenvironment that stimulated aerobic bacterial activity, with magnetized isolation water at a 5% concentration recording the highest bacterial density (1.36×10^{2}CFU/g). In contrast, the experiment showed that high dilution (25%) generated osmotic shock, leading to a sharp decline in total bacterial counts, paving the way for "ecological selection" and the dominance of halotolerant bacterial strains. The study concludes that magnetization technology can effectively improve soil health and partially alleviate chemical stress, which, when combined with careful management of dilution ratios (less than 15%), helps support microbial activity and the sustainability of water resources in oil-producing regions

الاستجابة البكتيرية والتكيف الملحي تحت تأثير الإجهاد الأسموزي للمياه المصاحبة المعالجة مغناطيسياً في البيئات الجافة

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الكلمات المفتاحية

المياه المصاحبة، الإجهاد البيئي، التكيف الملحي، المعالجة المغناطيسية، البكتيريا

الملخص

تمثل المياه المصاحبة لإنتاج النفط تحدياً بيئياً ومصدر مهدد للأنظمة البيئية الهشة. ومع ذلك، فإن النقص الحاد في الموارد المائية العذبة في المناطق الجافة وشبه الجافة يدفع الباحثين نحو استكشاف حلول مبتكرة لإعادة تدوير هذه المياه واستغلالها في القطاع الزراعي. تكمن خطورتها في محتواها الأيوني العالي وارتفاع مستويات الملوحة، ومخاطر الصودية التي تعمل على تدمير البناء الفيزيائي للتربة وتثبيط النشاط الحيوي فيها. هدفت هذه الدراسة إلى تقييم فعالية المعالجة المغناطيسية كأداة استصلاح فيزيائية للتربة وصديقة للبيئة. تم استخدام في هذه الدراسة مياه مصاحبة للنفط من حقلي زلطن والاستقلال في ليبيا، نُفذت تجربة مخبرية لاختبار أربعة مستويات لتخفيف المياه المصاحبة (5%، 10%، 15%، 25%)، بنوعيها الممغنط (1.45 تسلا) وغير الممغنط. تمت مراقبة التغيرات في الخصائص الفيزيوكيميائية للتربة، مع التركيز على نسبة امتزاز الصوديوم (SARونسبة الصوديوم المتبادلESP، وانعكاس ذلك على استجابة التجمعات البكتيرية باستخدام وسط أجار المانيتول الملحي MSAكوسط انتقائي. كشفت النتائج عن تأثير إيجابي للمغنطة، حيث ساعدت في تحسين التوازن الأيوني عبر زيادة التوافر الحيوي للكالسيوم وتقليل تراكم الصوديوم، حيث تراجعت قيمة SARمن مستويات خطرة (43.72) إلى (32.55) في الترب المروية بمياه حقل الاستقلال . مما أدى هذا التحسين الكيميائي بيئة دقيقة حفّزت النشاط البكتيري الهوائي عند التخفيف المنخفض (5%). في المقابل أنتج التخفيف المرتفع (25%) صدمة أسموزية أدت لظاهرة "الانتخاب البيئي" وسيادة السلالات البكتيرية المتحملة للملوحة Halotolerantوالتي نمت بكثافة على وسط MSA وختاماً فإن تقنية المغنطة قادرة على تحسين صحة التربة وتخفيف الإجهاد الكيميائي، مما يساهم مع الإدارة الدقيقة لنسب التخفيف في استدامة الموارد المائية.

1. INTRODUCTION

Soil health and microbial activity form the foundation of sustainable agricultural systems, particularly in arid and semi-arid environments characterized by high

evaporation rates and limited rainfall. In these environments, salinity and water stress top the list of challenges hindering agricultural development and food security. With the steady increase in demand for freshwater, the water scarcity crisis has worsened, prompting scientists to explore non-conventional water sources (Qadir *et al*., 2007). In this context, "oil production water" has emerged as one of the available options, given the vast quantities extracted as a byproduct of oil exploration and extraction operations (Al-Jubori *et al*., 2020). Despite its great potential, its application in irrigation is fraught with environmental risks due to its complex chemical composition, which includes extremely high levels of total dissolved salts, with sodium and chloride ions predominating. The introduction of sodium ions at concentrations exceeding those of divalent cations (calcium and magnesium) leads to a severe deterioration in the physical structure of the soil, as sodium replaces calcium in the exchange complex, thereby increasing the exchangeable sodium (ESP) and leads to the dispersion of clay particles and the formation of hard surface crusts that inhibit aeration (Ayers & Westcot, 1985).

This physicochemical degradation has a direct impact on the biological component of the soil. Aerobic microbial communities serve as the "biological engine" of nutrient cycles and a sensitive indicator for assessing the health of terrestrial ecosystems (Rietz & Haynes, 2003). A sudden increase in salinity and alkalinity causes an "osmotic shock" that draws water out of the bacterial cell, leading to cytolysis and a decrease in microbial biomass. To address this challenge, "magnetic water treatment" has been proposed as an innovative and environmentally friendly physical solution that relies on altering the physical and dynamic properties of water by breaking hydrogen bonds, thereby increasing water's ability to leach free sodium ions (Mosin & Ignatov, 2014; Khoshravesh *et al*., 2011).

The topic of oil-contaminated water utilization and the remediation of affected lands has received increasing research attention over the past two decades. (Osuji *et al.,*2006) demonstrated in their study of soils contaminated with hydrocarbons and associated water that chemical degradation is primarily characterized by ionic imbalance and reduced soil permeability, necessitating urgent remediation interventions. In a more recent study, (Zeng *et al*., 2020) assessed the long-term response of the soil microbial community to the application of associated water in agricultural fields and concluded that direct application without treatment leads to a sharp decline in microbial biodiversity and the inhibition of soil enzyme activity essential for the carbon and nitrogen cycles.

In terms of physical treatment, numerous studies have demonstrated the feasibility of using magnetic fields in agriculture. (Maheshwari & Grewal 2009) noted that irrigation with magnetically treated water led to a significant increase in crop yield and water use efficiency, attributing this to increased solubility of salts in the soil and facilitated nutrient uptake by plants. Similarly, (Ali *et al*., 2014) confirmed that magnetized water has a superior ability to drive precipitated calcium into the soil solution to replace sodium on the adsorption complex, which is considered a process of "self-remediation" for saline soil. Recently, (Fan *et al*.,2025) demonstrated that magnetized saline water improves soil aggregate stability and mitigates toxic effects, thereby enhancing microbial enzymatic activity in the soil.

From a purely microbiological perspective, the dynamics of halotolerance are a focal point of pioneering research. (Zahran, 1997) demonstrated that harsh saline environments act as an ecological filter, allowing only bacterial strains with enzymatic systems adapted to high osmotic pressure to survive. (Fathepure, 2014) reinforced this concept by elucidating the physiological mechanisms, demonstrating that bacteria in environments affected by oil and salt residues survive through the synthesis and accumulation of "Osmo protectants" such as the amino acid proline within the cytoplasm to prevent cellular water loss. These findings are consistent with the conclusions of (Al-Jabri *et al*., 2025) that irrigation with associated water radically reshapes the soil microbiome, creating a microbial community dominated by highly resistant strains, which presents a promising opportunity for the subsequent use of these strains in bioremediation.

1.2. Research Objective:

Based on the research gap identified in previous studies regarding the response of Libyan soils and local microorganisms to physical treatment techniques, the main objective of this study is to: To evaluate the integrative relationship between chemical changes in the soil (sodicity and salinity) resulting from Zaltan field water and magnetic treatment, and its direct impact on the physiological response and quantitative distribution of aerobic and halotolerant bacterial communities (using MSA medium), to determine the environmental and agricultural suitability of this technique in mitigating the osmotic and chemical stress of the associated water.

2. MATERIALS AND METHODS

Study Site and Characterization of Produced Water Samples of produced water from oil extraction operations were collected directly from the oil-water separation units at the Zaltan and Istiklal fields in Libya. The samples were stored in sterile containers and transported under standard laboratory refrigeration conditions. Preliminary analyses revealed clear hydrochemical differences; the Istiklal field is characterized by high salinity and very high ionic concentrations compared to the Zaltan field, providing an ideal test environment for studying the effect of magnetic treatment under varying levels of chemical and saline stress.

Magnetic treatment system and experimental design to induce physical changes in the structure of water molecules: Raw water was passed through a magnetic water conditioner with opposing poles that generates a constant magnetic field with a flux density of 14,500 gauss (equivalent to 1.45 tesla) . To avoid high direct toxicity that could immediately destroy microbial communities, four levels of gradual dilution were prepared using fresh water (5%, 10%, 15%, 25%). Two series of these dilutions were prepared: the first was magnetized before irrigation, and the second was left as a control sample (unmagnetized). Sandy soil mixed with organic compost in a 1:1 ratio was used as a clean growing medium to ensure a carbon content that supports initial microbial colonization, and was placed in experimental pots with drainage holes.

Physicochemical Analysis and Indicators of Soil Structural Degradation After the experimental period ended and ionic reactions stabilized, soil samples were taken from the rhizosphere. The samples were dried, ground, and sieved. A saturated soil paste extract was prepared to determine ion concentrations according to the methods of (Black *et al.*1965). Dissolved cations (calcium, magnesium, sodium, and potassium) and anions (carbonate and bicarbonate) were determined in units of (meq/L).

Biological sodicity indices were calculated to assess the structural risks of the soil based on the classifications of the U.S. Salinity Laboratory (USSL, 1954). The "sodium adsorption ratio" (SAR), which measures the relative activity of sodium compared to calcium and magnesium, was calculated using the following mathematical equation:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

The "exchangeable sodium percentage" (ESP), which reflects the proportion of exchange sites occupied by sodium on clay particles, was also determined.

$$ESP = \frac{Na}{CEC} x\ 100$$

Microbiological analysis and the use of selective media (MSA) to assess the microbiological response of the soil; the Total Plate Count (TPC) technique was employed (APHA, 2012). Cells were extracted from 1 g of moist soil taken from each treatment using 9 ml of sterile physiological peptone water. Following mechanical shaking, a series of successive decimal dilutions was carried out.

Key reliance on Mannitol Salt Agar (MSA) medium: At this stage of the methodology, the MSA culture medium was relied upon as a crucial differential and selective tool. This medium consists of a very high salt concentration of 7.5% sodium chloride (NaCl). This extreme concentration acts as a potent inhibitory agent, preventing the growth of the vast majority of non-halotolerant bacteria. Conversely, it provides an ideal and highly selective environment for the selection and isolation of 'halotolerant bacteria' capable of surviving under conditions of high osmotic stress resulting from soil irrigation with brine at a 25% dilution (Zahran, 1997).

Statistical Analysis The experiment was designed as a completely randomised block design (CRD) with a factorial arrangement. The data were analysed to assess the main and interaction effects of the diluent and treatment type using analysis of variance (ANOVA) via SPSS software. Means were compared to determine significant differences at a significance level of $P \leqslant 0.05$.

3. Results and Discussion

Physicochemical changes and soil salinity indices The hydrochemical properties of irrigation water are the determining factor that reshapes the ionic composition of the soil solution. Table 1 illustrates the detailed physicochemical effects of the different treatments at the end of the experiment.

TABLE 1: CHEMICAL INDICES AND SOIL SALINITY INDICES (MEQ/L) AT THE END OF THE EXPERIMENT

Sample		Na	K	Ca	Mg	HCO3	SAR	ESP	Soil classification
Zaltan	**Non-magnetic**	45.22	0.46	18.5	8.2	2.0	12.37	14.12	Sodic
	Magnetic	36.96	0.46	22.4	10.5	1.0	9.11	10.7	Sodic
Al-Istiqlal	**Non-magnetic**	134.78	0.90	12.6	6.4	3.0	43.72	41.5	Sodic
	Magnetic	117.39	1.08	16.8	9.2	1.0	32.55	32.2	Saline-Sodic

Sodium dynamics and the leaching effect of magnetization, The data reveal a significant decrease in the concentrations of dissolved Na in the soil solution as a direct response to magnetized water. In water from the Zaltan field, the sodium concentration fell from 45.22 in the control sample to 36.96 (meq/L) in the magnetized treatment. More dramatically, in the highly saline Istiqlal field, magnetization succeeded in reducing sodium concentrations from 134.78 to 117.39 (meq/L). This behavior is attributed, chemically and physically, to the magnetic field modifying the hydrogen bonds of water, imparting greater kinetic energy that weakens the attractive forces between sodium ions and clay minerals, thereby facilitating their expulsion and leaching into deeper zones (Khoshravesh *et al.*, 2011; Mosin & Ignatov, 2014).

Displacement of divalent cations and the self-remediation mechanism: In contrast to sodium, divalent calcium and magnesium cations showed a marked accumulation in the magnetically treated soil. In the control plot, calcium increased from 12.6 to 16.8 (meq/L), and magnesium from 6.4 to 9.2 (meq/L). This is explained by the increase in the solubility of calcium carbonate salts precipitated in the soil matrix due to magnetized water (Maheshwari & Grewal, 2009). This high availability of calcium, which has a higher substitution energy, enables it to displace sodium from cation exchange sites and flush it out with leachate, a mechanism central to the 'self-remediation' of saline soils (Ali *et al*., 2014).

Magnetization also led to a reduction in bicarbonate ion concentrations (from 3.0 to 1.0 in the control). This reduction is highly beneficial, as the treatment prevents bicarbonate from reacting with calcium to form carbonate precipitates, keeping the calcium in solution to lower the SAR (Ayers & Westcot, 1985; Fan *et al*., 2025). The final result was a reduction in the SAR value in the independence field from the highly hazardous value of 43.72 to 32.55, leading to a change in soil classification from 'sodic' to 'sodic-saline', thereby preventing the soil from complete physical disintegration due to the dispersion of its particles (Qadir *et al*., 2007).

The principal component analysis (PCA)

The provided a clear spatial distinction between soil samples irrigated with raw water and those receiving magnetically treated water (MWT) **Figure 1**, The dominant first axis (Dim1, accounting for 81.4\% of total variance) separated the treatments based on sodicity hazards and nutrient availability. The strong grouping of non-magnetic samples alongside high SAR, ESP, Na, and CO_3 vectors reflects the baseline degradation of arid soils receiving untreated brackish water. Conversely, the pronounced shift of MWT samples toward the negative quadrant of Dim1 strongly aligned with Ca and K demonstrates a systemic chemical remediation driven by magnetic conditioning.The observed reduction in sodicity parameters (SAR and ESP) under MWT can be explained by fundamental changes in water structure and ion mobility. Passing water through a static magnetic field disrupts intramolecular hydrogen-bonded networks, reducing large water clusters into smaller, more homogeneous configurations (Surendran *et al*., 2016; Hachicha *et al*., 2018). This structural alteration decreases surface tension and enhances the solvent power and hydration capacity of water. Consequently, MWT accelerates the dissolution of native soil minerals, particularly calcium carbonate CaCO, releasing free Ca ions into the soil solution (Maheshwari & Grewal, 2009).

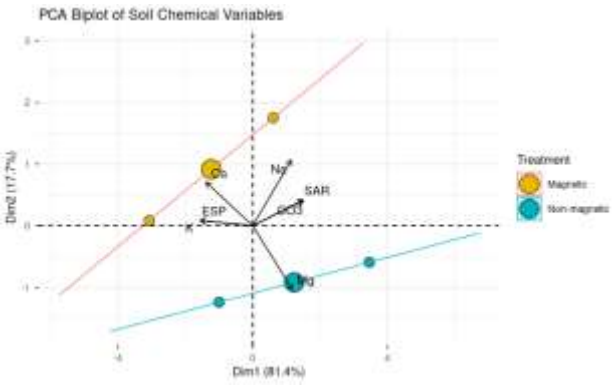
Because Ca possesses a higher valence and charge density than Na, the newly mobilized calcium preferentially occupies cation exchange sites on clay particles. This displacement mechanism follows standard lyotropic series rules, where divalent ions outcompete monovalent ions for adsorption sites:

$$\text{Clay- } 2\text{Na} + \text{Ca}_{(aq)} \leftrightarrow \text{Clay- Ca} + 2\text{Na}_{(aq)}$$

The displaced Na ions, once desorbed into the soil solution, associate with soluble anions such as CO_3 and are leached below the root zone due to the enhanced infiltration capacity imparted by MWT (Mostafa Zadeh-Fard *et al*., 2011). This active leaching mechanism accounts for the sharp decline in SAR observed in both Zaltan (from 14.12 to 10.7) and Al-Istiqlal (from 41.5 to 32.2) fields.

The vertical axis (Dim2, 17.7% of variance) captured site-specific geochemical variations between the two study locations. While both fields exhibited consistent responses to magnetic treatment, the initial severity of sodality at Al-Istiqlal resulted in a shift from a purely sodic classification to a saline-sodic status following treatment. This transitional phase suggests that in highly degraded soils (SAR > 40), MWT initially converts insoluble carbonates into soluble salt fractions before complete leaching is achieved (Mohamed, 2013). Furthermore, the concurrent increase in soluble K in MWT soils highlights an additional nutritional benefit, as magnetic treatment appears to promote the desorption of fixed potassium from clay interlayer spaces alongside calcium.

Figure 1. PCA biplot of soil chemical variables as affected by magnetic and non-magnetic water treatments



Microbiological response: dynamics and ecological selection on the MSA medium The microbial community is considered the most accurate reflection of microchemical variables in the soil. Table 2 shows changes in bacterial counts in response to dilution levels and physical treatment.

Bio stimulation at safe dilution levels (5–10%) under low stress conditions demonstrated the positive impact of balanced soil chemistry. The magnetized control field treatment (5%) recorded the highest bacterial density (1.36×10^2CFU/g). This is attributed to magnetization's ability to reduce salinity, thereby preserving soil porosity and providing optimal aeration for the respiration of microbial communities. This is consistent with the findings of (Zeng *et al*., 2020), who confirmed that improving the physical properties of treated water reduces the toxicity of associated compounds and enhances extracellular enzyme activity.

Dilution	Zaltan		Al-Istiqlal	
	Magnetic	Non-magnetic	Magnetic	Non-magnetic
5%	9.30×10	8.00×10	1.36×10^2	6.00×10
10%	2.80×10^2	2.56×10^2	4.00×10^2	4.48×10^2
15%	1.76×10^2	3.04×10^2	4.80×10^2	6.00×10^2
25%	1.00×10	3.76×10^2	3.56×10^2	6.80×10^2

Osmotic stress shock and microbial collapse (25% dilution) With the dilution ratio increased to 25%, a sharp collapse in bacterial count occurred in the magnetised Zaltan samples, reaching 1.00×10 CFU/g. This collapse represents a classic case of 'osmotic shock', whereby the accumulation of salts raises the osmotic pressure of the soil solution, drawing water from the bacterial cytoplasm and causing cytolysis and the cessation of enzymatic metabolism (Elmajdoub *et al*., 2015; Rath *et al*., 2016; Yuan *et al*., 2007).

Bacterial dominance and the phenomenon of salt adaptation through MSA colony growth In stark contrast, the non-magnetised independence field (with the highest sodium value, (SAR=43.72) exhibited exceptional bacterial growth at the highest dilution of 25%, reaching (6.80×10^2 CFU/g). This contradiction is scientifically explained by Darwin's phenomenon of 'natural selection'. Excessive stress eliminated sensitive strains, clearing the way for the dominance of halotolerant and halophilic bacteria.

This conclusion has been conclusively confirmed experimentally by the growth rates of these colonies on plates containing medium (MSA) with a high salt concentration (7.5% NaCl). The growth of these colonies, and the color change in some of them as a result of mannitol fermentation, demonstrates that these strains possess sophisticated physiological mechanisms to resist cellular dehydration by synthesizing 'compatible solutes' within their cells to maintain osmotic balance, exactly as noted by (Kempf & Bremer, 1998; Fathepure, 2014). This finding is consistent with the conclusions of a study by (Al-Jabri *et al*., 2025), which confirmed that associated water stress creates a soil microbiome characterized by reduced diversity but with the absolute dominance of highly resistant and adaptable strains, supported by statistical analysis results that showed significant differences ($P \leq 0.05$) in the bacterial response to mitigation and treatment interventions.

4. CONCLUSIONS

This experimental study provides solid evidence of the vital importance of the link between the physicochemical properties of soil and the evolutionary dynamics of its microbial communities. Magnetic treatment demonstrated clear operational efficiency in mitigating the chemical stress of the associated water, as it succeeded in removing toxic sodium, enhancing calcium availability, and reducing SAR and ESP values, thereby preserving the soil's pore structure. This chemical improvement had a positive effect on aerobic bacterial activity at safe dilution levels (less than 15%). In contrast, microbiological isolation techniques using a specialised medium (MSA) demonstrated their superior ability to track the phenomenon of 'ecological selection' resulting from osmotic shock at high irrigation concentrations (25%), where these concentrations led to the dominance of salt-tolerant bacterial strains as a survival mechanism. The study recommends that dilution ratios should be kept below 15%, in conjunction with magnetisation and the addition of chemical amendments, to ensure the sustainability of agricultural irrigation and prevent soil desertification in the areas surrounding oil fields. It also recommends the use of medium-isolated strains (MSA) in future bioremediation studies.

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