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Review: Impact of Drought and Salinity on Microbial Dynamics in Soil and Water Ecosystems from Central to Southern Iraq: Implications for the Safety and Security of Agricultural Raw Materials in the Food Industry

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ABSTRACT

Drought and salinity rank among the most significant environmental stresses, altering ecosystem structure and function in arid and semi-arid regions worldwide. In central and southern Iraq, terrestrial and aquatic environments were dramatically transformed due to long-term water shortages, reduced river flows, rising temperatures, and increasing soil and water salinization. This paper presents a review of microbial community structure dynamics in soil and aquatic systems under conditions of drought and salinity stress, with special attention to central and southern Iraq, virtually the only region for which information is available, although it comes from unpublished gray literature sources. As opposed to baseless claims of immediate relevance for food safety, this paper tentatively links microbially mediated processes (cycling of carbon, nitrogen, and phosphorus) with indirect effects on soil fertility and the quality of raw agricultural materials and water. This review explicitly states that there is no direct transfer of pathogens and no data on endpoints for food safety from Iraqi ecosystems; therefore, it proposes a hypothesis-generating framework instead of definitive conclusions. In linking, albeit cautiously, environmental microbiology with food safety considerations, this review attempts to provide some basis for subsequent hypothesis-driven research under the present climate change situation in Iraq.

1- INTRODUCTION

Water resource stress and its relationship with salinity are mainly in dry and semi-dry areas [13]. This is particularly for transboundary river basins with irrigated agriculture, a pressure on hydrological systems that manifests within the existing water scarcity framework as salinity. Iraq is one of the countries where these pressures are converging. Land degradation, along a north-south transect in Iraq, also comes about due to climatically induced hydrological shifts [2].

In the past, the Tigris and Euphrates rivers have served as the primary sources of fresh water available for agriculture and ecosystems in central and southern Iraq. Major causes of the recent sharp decline in river flow include less upstream inflow, recurring droughts, and mismanagement of water [3]. Increased evaporation has worsened the problem of salinity by causing surface water and soil to accumulate salts. Salinity has left canals that supply agricultural lands, rivers, marshes, and groundwater systems heavily damaged, causing a vast loss of aquatic habitat. Such changes will surely have an effect on many trophic levels, where microorganisms are the most abundant and functionally diverse biological components of soil and aquatic systems [4].

Microbial communities are responsible for driving nearly all major ecosystem processes, including nutrient cycling, organic matter decomposition, soil aggregation, water purification, and primary production, while controlling the rate of carbon sequestration as well as most nutrient availabilities (including nitrogen to support crop productivity and soil fertility) [5]. Microbial communities in aquatic ecosystems play a direct role in ecosystem stability through the regulation of biogeochemical fluxes and water quality at the ecosystem level. Owing to fast generation times and high metabolic versatility, microbial communities can quickly respond to disturbances and thus make good bioindicators for changes in ecosystems [6].

Drought and salinity have direct effects on terrestrial and aquatic systems through water availability, osmotic potential, and nutrient diffusion. Thus, microbial communities are under strong selective pressures from these factors. Low soil moisture under drought immobilizes most microbes because there is little available substrate; overall activity is therefore by stress-tolerant taxa. Osmotic stress and ion toxicity from high salinity will support halotolerant and extremely halophilic microbial groups, while salt-sensitive populations will be inhibited. Aside from their impact on microbial diversity and community structure, the above-mentioned factors will also change functional pathways related to carbon mineralization, nitrogen transformation, and phosphorus availability [7].

Salinity and drought are more severe in the south and center of the country, where high rates of evaporation, shallow groundwater tables, and a long history of irrigation practice that promotes salt accumulation exist. Periodic fluctuations in water levels and intrusion by salinity from rivers into marshes, as well as the irrigation networks, will periodically restructure microbial assemblages and impose new functional processes. Functions driven by microorganisms hold critical ecological importance, yet, at best, studies on microbial communities in the soil and water ecosystems of Iraq remain fragmented; most available studies are on physicochemical parameters. Information on the response of microorganisms to environmental stressors is very limited [8,9].

This shows a gap in knowledge with respect to the integrated assessment of soil and aquatic microbial communities under drought and salinity stress in Iraq. Fast environmental changes are not well-documented in the country. Therefore, we recommend that the review be done right away to fill this knowledge gap and provide a scientific baseline for future research and environmental management strategies [10,11].

The food industry has always viewed the quality and safety of agricultural raw material from the health of soil and water ecosystems. There is no evidence available in Iraq on the movement of pathogens to crops or food safety endpoints, or how changes in microbial communities under drought and salinity conditions relate to contamination of raw materials. Therefore, these are assumed to be hypothetical links for future testing in this review. Water scarcity and salinity also negatively influence the quality of irrigation water. The Iraqi system has not documented how specifically the introduction of foodborne pathogens through irrigation water can happen within the food supply chain [12,13].

This review aims to give an initial narrative integration of the existing scientific literature on the dynamics of the microbial community in soil and aquatic ecosystems under drought and salinity stress, with special reference to central and southern Iraq. Since the available data are in pieces, no quantitative meta-analyses or causal inferences can be claimed to be presented in this review. Instead, it tries to:

1. Trends in microbial diversity and functional dynamics under water and salinity stress are reported. Lack of standardized methodologies is a major issue in most studies; There is very little information on patterns between terrestrial and aquatic systems. Major data gaps are noted.
2. Empirical studies should focus on what needs to become the priorities of future empirical studies rather than provide management recommendations that can be supported with direct evidence.

2- Framework: How Drought and Salinity Drive Changes in Microbial Communities

Drought and salinity are two environmental filters that are tightly interconnected in determining the assembly and functional dynamics of microbial communities across soil and aquatic ecosystems [14]. This review applies a conceptual framework from the global literature since no mechanistic studies have been conducted for Iraq to develop a region-specific framework. The heuristic use of the framework in this review is to organize existing observations and not to test causal relationships. Drought decreases water availability, thereby reducing both microbial dispersal and enzymatic activity. In contrast, high salt osmotically stresses the cells, thus inhibiting metabolism and growth. This should elicit a response from the microbial communities, shifting from highly diverse functionally redundant populations to more specialized stress-tolerant populations. Any change in the structure of microbial communities will change the functioning of the ecosystem in terms of nutrient cycling and organic matter turnover, thus changing overall resilience. In the soil-water system, hydrological connectivity allows stress-induced changes to cascade from one compartment to another, magnifying impacts at the ecosystem level under prolonged drought and salt stress [15].

3-Microbial Responses in Soil Ecosystems Under Drought and Salinity Stress

Microbial communities are one of the most diverse and functionally complex components of soil ecosystems. They are involved in making nutrients available, decomposing organic matter, and maintaining the stability of soil structure. However, this enormous diversity is significantly reduced under environmental stress such as drought and salinity, which exerts powerful selective pressures. In the arid and semi-arid climatic conditions of central and southern Iraq, both drought and salinity prevail as stressors, causing significant shifts in the microbial community's composition, diversity, and functional potential [16].

3.1 Impact of Drought on Soil Microbial Communities

The primary driver of terrestrial microbial community change in terrestrial ecosystems is drought. Reduced water availability limits the mobility of substrates and diffusion, as microbial activity can only occur in thin water films, resulting in decreased microbial activity and biomass [17]. Over longer periods of drought, there seems to be a decline in alpha diversity, where sensitive taxa are lost, and stress-tolerant microorganisms become dominant; these may include unknown taxa that are newly abundant under such conditions [18].

Taxonomic compositions in dryland ecosystems are usually dominated by groups capable of physiological or biochemical adaptation to desiccation, notably spore-forming organisms. Actinobacteria and Firmicutes, which are thick-walled Gram-positive bacterial taxa, exhibit high resistance to drought [19]. Gram-negative bacteria generally possess high sensitivity to osmotic stress and desiccation; hence, their abundance decreases significantly under dry conditions [20]. The main reason why fungal communities have relatively high resistance to drought is that most of them are filamentous, which allows them to access water in small soil pores, increasing the fungal-to-bacterial ratio under dry conditions [21].

Drought also depresses the activity of extracellular enzymes within microbial communities, reducing mineralization of soil organic matter and disrupting carbon cycling. Water limitation restricts microbial respiration and the enzymatic breakdown of organic substrates. It is well known that nitrogen cycling processes, including nitrification and denitrification, are inhibited in dry soil due to reduced microbial activity and altered oxygen diffusion. Functional nitrogen cycling was not restored immediately after rewetting; thus, the results indicate long-term nitrogen cycling legacy effects of drought on soil ecosystems [22,23].

Drought periods would reduce the frequency of irrigation in the agricultural soils of central and southern Iraq, thus exposing them to more severe drying cycles. This would encourage episodic microbial stress and recovery, often leading to unstable communities with low functional redundancy [24, 25]. Little research has been conducted on the direct effects of drought stress on microbial communities in the soil of Iraq. However, the decreased fertility and organic matter content in soil under prolonged drought can be taken as an indicator or proxy for microbial functional impairment [3].

3.2 Impact of Salinity on Soil Microbial Communities

Soil salinity is another major constraint on microbial life in arid environments. High concentrations of soluble salts in the soil increase its osmotic potential, thereby reducing the availability of water to organisms, and at the same time, it leads to ion toxicity, which affects the metabolism and survival of microorganisms [10]. As salinity increases, there is a general shift in community composition towards halotolerant and halophilic taxa that can maintain homeostasis at higher salt concentrations [11].

Several studies have reported a strong negative correlation between soil salinity and microbial diversity. It was further found that along the gradients of salinity, there were considerable reductions in the richness of bacteria and fungi. Halophilic taxa replace salt-sensitive microorganisms progressively. Those include Proteobacteria, Halobacteria, and some Actinobacteria selected for an environment with osmotic stress. This shift in composition will alter network interactions in the microbial community, resulting under saline conditions in less complex interaction networks centered on a few dominant taxa.

Salinity selects for microbial functional traits that have to do with osmoprotection, such as the synthesis of compatible solutes like glycine betaine, trehalose, and ectoine [27]. All these features allow survival under saline conditions but place high thermodynamic costs, hence reduced growth efficiencies and decreased enzymatic activity rates. As a result, organic matter decomposition and nutrient cycling rates are also reduced in saline soils. Microbial respiration rates and nitrogen transformation have been reported to be lower in saline soils, especially nitrification and biological nitrogen fixation [28, 29].

Land salinization in central and southern Iraq is mainly attributed to high rates of evaporation, shallow groundwater levels, and the type of irrigation system that involves the use of saline or brackish water [30]. These factors result in patches of heterogeneity within agricultural fields in terms of salinity and, therefore, generate heterogeneity in microbial communities. The spatial heterogeneity poses a challenge in developing effective management strategies aimed at achieving uniform productivity across fields. Thus, there is a need to understand how microorganisms respond to salinity at both fine and coarse scales in the field.

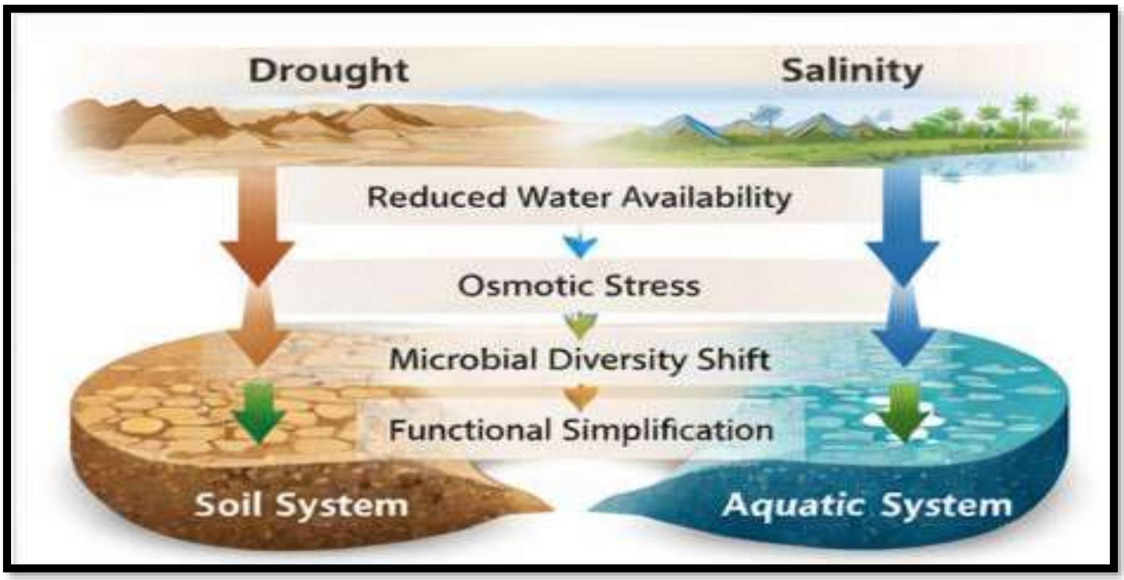

Figure 1. Conceptual framework showing the interaction between drought and salinity in soil- and water-associated microbial communities within dryland systems.

3.3 Combined Effects of Drought and Salinity on Soil Microbes and Their Functional Roles

Drought and salinity affect microbial communities in different ways, but the compounded impact of the two factors usually increases microbial stress in a synergistic manner greater than the sum of each factor. Compounded stress also imposes higher energetic demands on cellular maintenance because microorganisms have to cope with increased osmotic pressure due to decreased substrate diffusion and accelerated loss of diversity that favors highly specialized, narrow-functioning taxa.

Drought and salinity together decrease microbial biomass and enzymatic activities sharply, with a more pronounced effect on the activities of enzymes of carbon and phosphorus cycling. Functional redundancy declines under such conditions, rather than being maintained as in ideal conditions, making the system more vulnerable to additional disturbance and less resilient to perturbations. The recovery of the microbial community after relief from stress is slow and incomplete due to the persistent alteration of the assembly process of the community.

In Iraqi soils, drought and salinity are the major factors that occur simultaneously. This combined phenomenon threatens soil health and agricultural sustainability by increasing land degradation that manifests through loss of microbial functional capacity, reduced structural stability, and diminished nutrient availability for crops and land productivity, which in turn perpetuates cycles of degradation. Despite its immense ecological significance, integrated assessments on the combined effects of drought and salinity on soil microbiomes in Iraq are extremely scanty, marking a critical research gap (Figure 2).

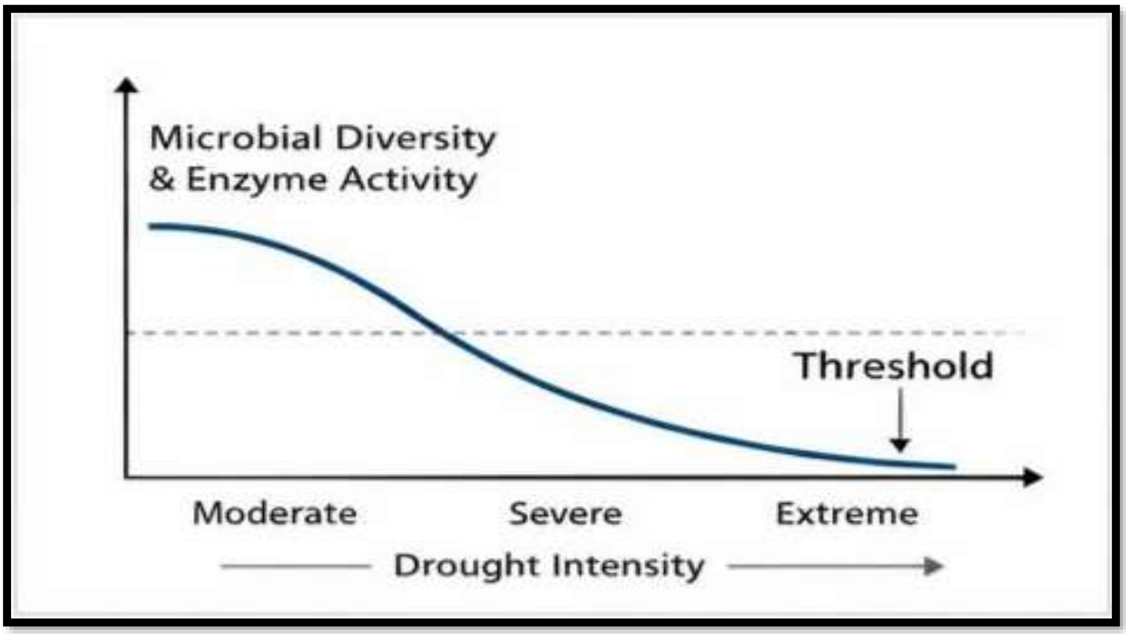

Figure 2. An overview of how soil microbial diversity and activity change with increasing drought intensity.

4. A conceptual diagram can be represented as a declining trend of microbial diversity and functional activity along increasing gradients of drought intensity and salinity.

A conceptual diagram is a simplification of the hypothetical trend of microbial diversity and functional activity along drought and salinity gradients. Under moderate stress, microbial communities may have adaptive responses, with partial functional compensation; however, beyond a critical threshold, community collapse occurs with a clear dominance of stress-tolerant taxa, resulting in minimal ecosystem services [9]. Direct evidence for threshold values in the soils of Iraq is completely lacking at the present time.

4. Aquatic Ecosystems

The vulnerability of aquatic ecosystems in arid and semi-arid regions to drought and salinity impacts on hydrology is very high. Microbial life in rivers, marshes, irrigation canals, surface reservoirs, and groundwater systems depends on a constant supply of water and the physicochemical conditions that can be considered suitable for microbial life to undertake its activities within ecosystem processes [34]. The aquatic environment in central and southern Iraq has experienced significant changes during the recent long dry period of low river discharge and high evaporation rates. These changes take the form of fluctuating water levels, changing nutrient availabilities, and increased salinity, which strongly suppresses the normal aquatic microbial community structure that acts as the ultimate regulator of biogeochemical cycling and water quality.

4.1 Impact of Drought on Aquatic Microbial Communities

Drought has a primary influence on aquatic microbial communities through the diminution of water volume, flow velocity, and hydrological connectivity. Low river discharge and the shrinkage of water bodies raise the concentration of dissolved salts and nutrients and the level of thermal stratification; they create oxygen-deficient conditions, all directly impacting microbial metabolism and community composition [35]. In drought conditions, microbial communities tend to shift toward taxa capable of tolerating wide ranges of oxygen concentration, high temperatures, and low nutrient fluxes.

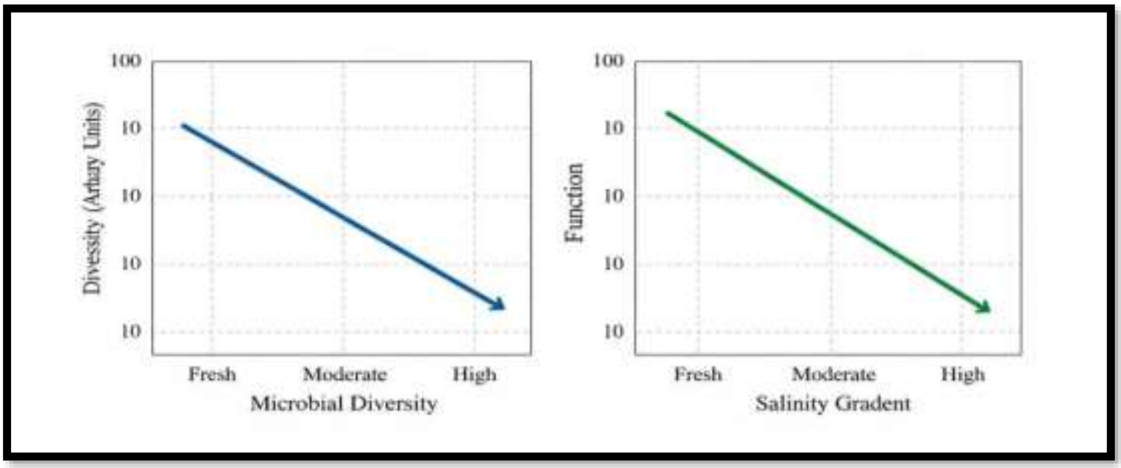

Figure 3. Variations in soil microbial community makeup and roles across a salinity gradient.

In central and southern Iraq, a drought has diminished the flow of the Tigris and Euphrates rivers in their lower reaches. This has changed microbial dynamics in both lotic and lentic systems. Reduced inflows to marshlands disrupt the natural flooding cycle, leading to drying events, then followed by rewetting episodes that impose repeated stress on aquatic microbial communities [13]. Such fluctuations favor the fast-growing stress-tolerant microbes at the expense of community stability and functional diversity.

The high abundance of bacteria in rivers and lakes declines during prolonged drought because of reduced substrate input and low primary productivity. However, some microbial groups increase in abundance as competitive pressure increases. Heterotrophic bacteria that are adapted to low-flow, high-residence-time conditions often become the dominant types in such water bodies during drought; however, those types associated with high-flow environments decrease. Drought-warming is associated with drought increases microbial metabolic activity, accelerating organic matter decomposition and oxygen consumption, which ultimately leads to hypoxic conditions.

Drought in central and southern Iraq has also reduced the flow of the Tigris and Euphrates rivers at their lower reaches, thereby changing microbial dynamics in both lotic and lentic systems. Reduced inflow to marshlands breaks the natural flooding cycle and initiates drying events, followed by rewetting episodes, so it's a repeated stress for the aquatic microbial community [13]. Under fluctuating conditions, fast-growing, stress-tolerant microbes outcompete stable communities and functional diversity.

4.2 Salinity Intrusion and Its Impact on Aquatic Microbial Communities

Salinity intrusion is one of the major stresses on the aquatic ecosystems of southern Iraq, especially in the downstream river sections, marshlands, and estuarine or tidal areas influenced by seawater. The increased salinity is accompanied by reduced freshwater inflow, upstream seawater intrusion, and evaporative salt concentration. Increased salinity comes with reduced freshwater inflow, upstream seawater intrusion, and evaporative salt concentration [38].

Freshwater microbial populations gradually give way to halotolerant and then halophilic populations with increased salinity. Communities of Proteobacteria, Bacteroidetes, and haloarchaea often become important components of these communities [11]. These organisms have physiological adaptations allowing their growth under high salt concentrations, including specific ion pumps and systems for accumulating compatible solutes. However, in general, high dominance by these groups is associated with reduced overall diversity of the community and a simple network structure among taxa.

Salinity changes microbially mediated nutrient conversions in the water. High levels of salts can stop nitrification and denitrification simply because they prevent salt-sensitive nitrifiers and denitrifiers. This changes the form of nitrogen available and encourages the accumulation of nutrients. In highly saline waters, the cycling of phosphorus may be increasingly controlled by microbial mineralization processes, further affecting primary productivity and algal growth. High salinity in the marshlands and irrigation waters of Iraq has been linked with a trend towards cyanobacteria and other phototrophs that can tolerate high salt concentrations, thereby increasing the potential for algal blooms under conditions of stagnant water and high nutrients [40]. These events of blooms change organic matter input and oxygen dynamics in a way that creates feedback loops that further intensify ecosystem degradation.

4.3 Groundwater Microbial Communities under Drought and Salinity Stress

Historically, microbial ecologists have paid little attention to groundwater systems, though these are of crucial importance in arid regions for drinking water supplies and irrigation. Drought conditions reduce recharge, increase the time water stays in the system, and increase salinity through evaporation concentration as well as the upward movement of saline water tables [2]. Groundwater microbial communities, which are generally adapted to stable environmental parameters and nutrient-limited conditions, undergo marked changes when these stressors are imposed.

Higher salinity selects for more oligotrophic and slow-growing taxa that have higher metabolic efficiency and can survive under saline conditions [41]. This reduced diversity and activity of microbes will most probably affect the natural attenuation process that degrades most organic contaminants and nitrate in groundwater, and eventually has an impact on water quality. In the central and southern part of Iraq, where shallow groundwater is widespread, the increasing threat of drought-induced salinization on the ecosystem services of microbes and human water security is already looming [30].

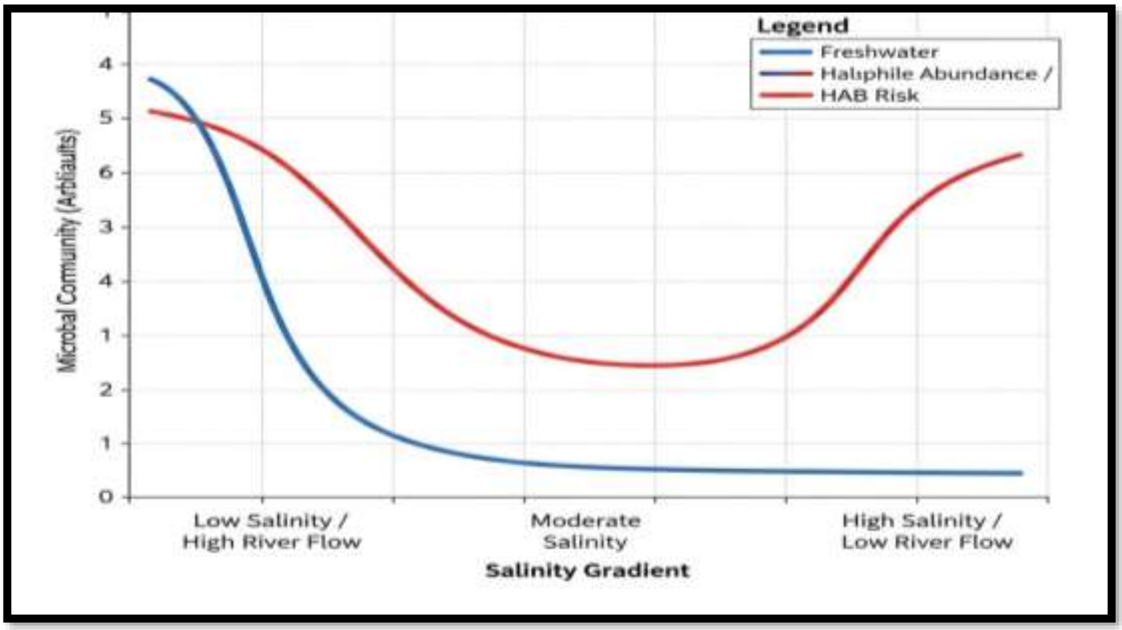

Figure 4. Changes in aquatic microbial communities as flow decreases and salinity goes up.

4.4 Comparative Responses of Soil and Aquatic Microbial Communities to Drought and Salinity

Both soil and water microbial communities face similar environmental stressors, but their responses are different due to differences in physical structure, connectivity, and resource dynamics. Microbes at the microscale within soil exhibit considerable heterogeneity, and most are physically protected within the structure of aggregates. In contrast, microbes in overlying water are directly exposed to changes in its chemistry and hydrology, leading to rapid community reorganization under stress [42]. Comparative studies have shown that microbial communities in soil recover slowly after drought and salinity stress compared to those in water, where recovery under favorable conditions is relatively easy. The microbial community in the soil is more resistant to drought and salinity stress than the microbial community in water, but recovery is slower under favorable conditions [43]. The recovery of the microbial community in water is easier under favorable conditions. Terrestrial and aquatic responses are connected by hydrological soil, rivers, and an irrigation network in Iraq, which allows microbial exchange among different compartments [9]. For example, saline irrigation return flows carry soil-associated microbes into aquatic systems, where they may therefore influence microbial community dynamics as well as water quality. Data on microbial fluxes between compartments in Iraq are not available. A conceptual diagram would show a gradual shift in the composition of the aquatic microbial community along two gradients: water availability and salinity. It would illustrate the transition from a highly diverse freshwater community to a less diverse halotolerant community under high salinity and oxygen-limited conditions, where alternative nutrient cycling pathways are available. Reduced flow brings about increased salinity since it invokes feedback mechanisms between hydrological conditions and microbial metabolic activity (Figure 5).

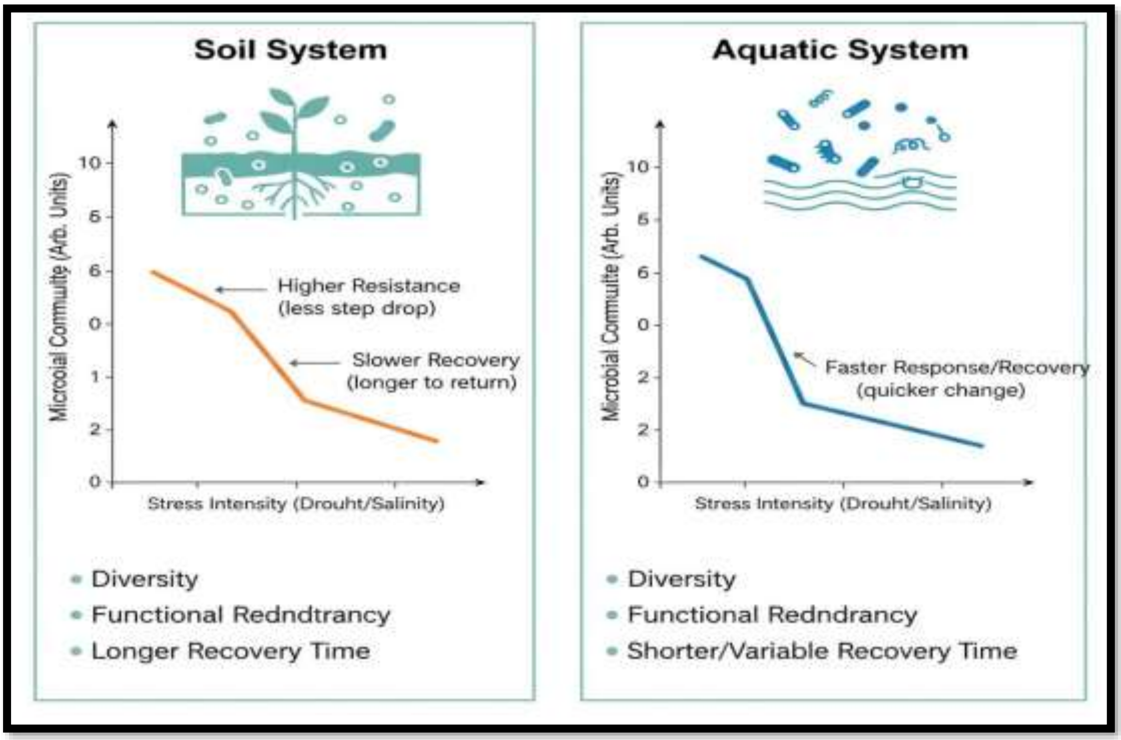

Figure 5. How soil and water microbes react differently when there's less rain or more salt.

5. Synthesis: Microbial Responses in Soil and Water Ecosystems under Drought and Salinity Stress

Terrestrial and aquatic microbial responses were synthesized to demonstrate that drought and salinity are major environmental filters that structurally and functionally alter microbial communities in all compartments of the ecosystem. Despite differences in physical structure and hydrological connectivity between land and water, severe and long-term stress makes more similarities than differences between their microbial communities. Reduced diversity and functional simplification characterize these shared communities, with a few taxonomic groups dominating high-stress niches [9, 15]. Most importantly, the above synthesis is based on ecosystems outside Iraq, and there is no direct validation in Iraq.

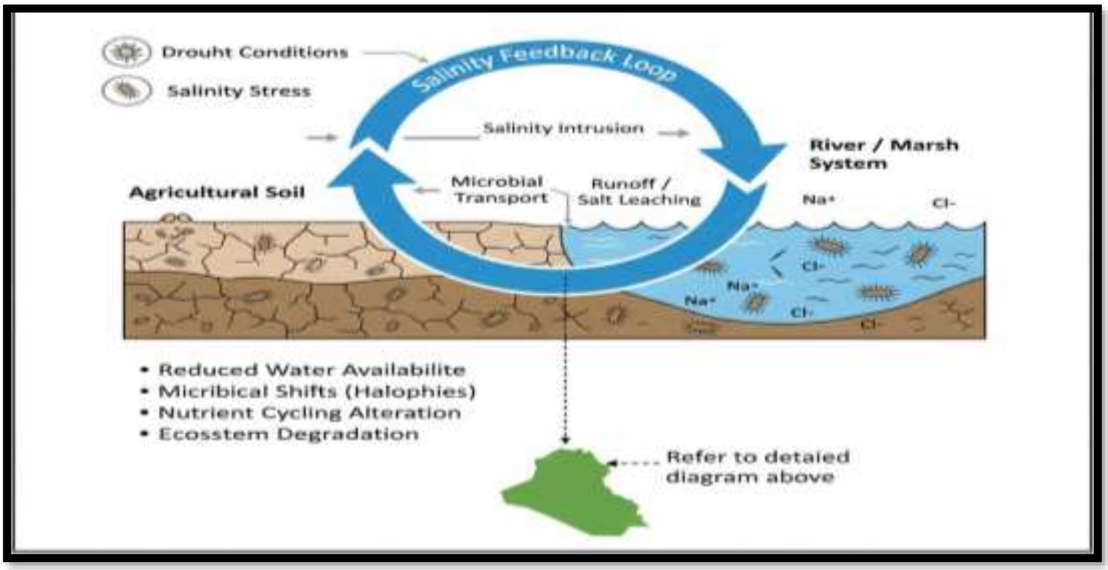

Figure 6. Connectivity between water, soil, and microbial systems in feedback loops of drought and salinity conditions for central and southern Iraq.

Drought and salinity mainly limit the activity of soil microbes by reducing water availability, imposing osmotic stress, and restricting the diffusion of substrates [17, 12]. In aquatic systems, these stressors are expressed as a contraction of the hydrology concomitant with intrusion salinity, and changes in oxygen dynamics that quickly reshape microbial communities to dominant metabolic pathways [36, 37]. Functional redundancy is gradually lost in both compartments under sustained disturbance, making them more vulnerable to additional stress.

Hydrological connectivity is the most important connection between soil and water systems in central and southern Iraq. Infiltration and surface runoff, and exchange processes between shallow groundwater and surface water bodies, provide pathways for microbial transport and nutrient fluxes between soil and water bodies [2]. Under saline irrigation conditions, halotolerant microbes developed in the soil may enter the water system, playing a role in salinity-induced changes to the community structure downstream (Figure 6). Decreased river flow due to drought increases the dispersal limitation of microbes in the upper part of the river, thereby affecting the possibility of recolonization and recovery of both compartments.

Drought and salinity interact as driving factors on the microbially mediated nutrient cycling, eventually leading to reduced soil fertility, lowered crop productivity, and impaired functioning of the aquatic system, which manifests as poor water quality, imbalance in oxygen, and enhanced risk of harmful algal blooms [33, 44]. This is a very important, but usually ignored, form of environmental damage in a country like Iraq, where agriculture and freshwater ecosystems are tightly linked (Figure 7).

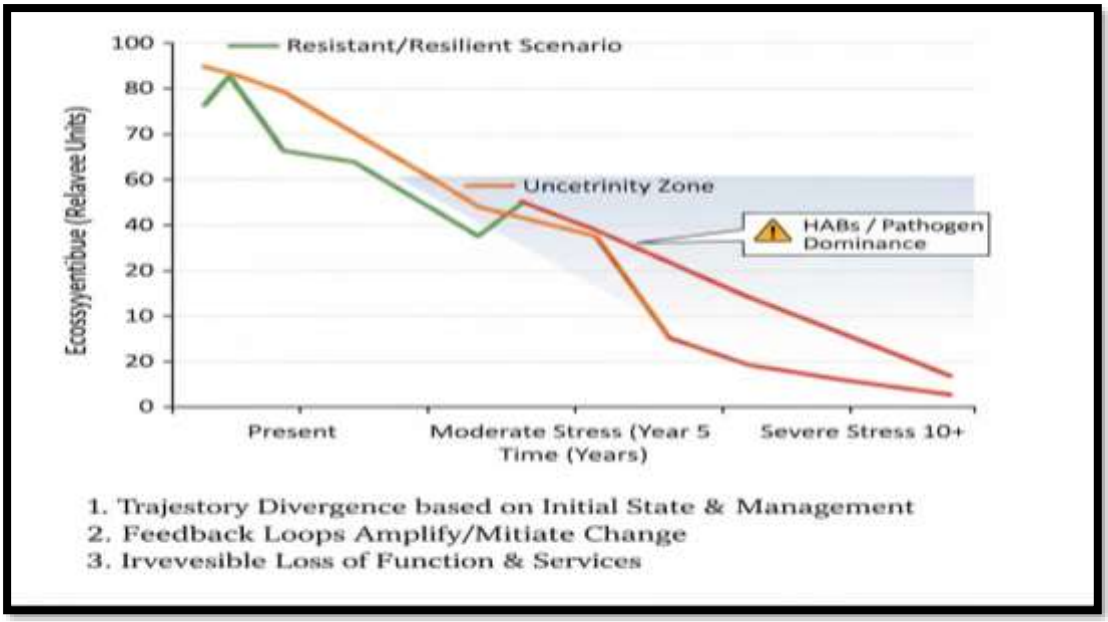

Figure 7. Microbial ecosystem trajectories under increased scenarios of drought and salinity

5-Conclusions

This review paper suggests that drought and salinity may be the key determinants of the microbial community in the soil and water ecosystems of the drylands of central and southern Iraq. However, because there are no data available, neither directly nor indirectly through observations made in the region on the transfer of pathogens to crops, endpoints for food safety (e.g., prevalence of Salmonella, E. coli O157:H7, Listeria in fresh produce), and causative links between changes in the microbiota and contamination of raw materials, no conclusive evidence can be drawn about the implications for food safety. The literature, which is mainly from non-Iraqi ecosystems, indicates decreased diversity and increased dominance of stress-tolerant taxa under conditions of drought and salinity. These patterns should be applied to Iraq very cautiously. The review does not claim to demonstrate actual impacts on the stability of the food supply chain or on foodborne pathogen prevalence in Iraq, or direct risks to the food industry. Instead, it provides a framework for generating hypotheses and identifies critical knowledge gaps that should be addressed by future empirical research.

Recommendations:

To address the knowledge gaps identified in this review (specifically the complete lack of data on pathogen transfer to crops and food safety endpoints in Iraqi ecosystems), the following recommendations are proposed for future research funding and study design. No policy or management recommendations are made here due to insufficient evidence.

1. Baseline data on microbial community composition of Iraqi soils and waters using standardized, reproducible molecular methods, such as 16S rRNA amplicon sequencing and metagenomics, must be established by future empirical studies before making any claims regarding their relevance to food safety.
2. In the future, studies should immediately address the need for direct measurement of food safety endpoints, which can include, but are not limited to, the survival of foodborne pathogens on crops irrigated with saline water, transfer rates from soil to produce, and the prevalence of virulence factors in microbial isolates from Iraqi agricultural systems. This review does not provide such data.

3. Long-term monitoring programs should be set up to examine temporal variability and legacy effects of repeated drought and salinity events on microbial community structures. These programs should include explicit food safety endpoints from the outset. Intervention strategies are not recommended at this stage because the necessary baseline data do not exist. Future research should prioritize descriptive, hypothesis-generating studies over prescriptive recommendations.

Future Perspectives

Without any applied or translational perspectives to be discussed, it is recommended that future work should focus on more descriptive hypothesis-generating studies of microbial communities under severe drought-salinity conditions in Iraq. Quantitative microbial risk assessment (QMRA), pathogen transfer experiments, and direct measurements of food safety endpoints are urgently required since they are absent from the current literature. The long-term objective is to integrate microbial ecology with climate modeling and land-use planning, but this should only begin once baseline empirical data become available. A much broader cross-disciplinary international cooperation approach will be essential in Iraq to develop primary data supporting sustainable land and water management under continued climate change. Until such data exist, this review is a roadmap for future data collection, not a source of actionable conclusions.

Ethical Approval

This study did not involve human participants or animals. All experimental procedures were conducted in accordance with institutional and laboratory biosafety guidelines.

Conflict of Interest

The authors declare that they have no conflict of interest.

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This research received no external funding.

Data Availability

All data supporting the findings of this study are available within the manuscript.

6-REFERENCES

[1] IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

[2] Scanlon, B. R., Jolly, I., Sophocleous, M., & Zhang, L. (2017). Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. Water Resources Research, 53(5), 3605-3627.

[3] Al-Ansari, N., Adamo, N., & Sissakian, V. (2021). Water resources of Iraq: A review. Journal of Earth Sciences and Geotechnical Engineering, 11(1), 133-165.

[4] Issa, I. E., Al-Ansari, N., & Knutsson, S. (2020). Changes in the Tigris River flow and water quality in Iraq. Engineering, 12(3), 143-160.

[5] Abbas, J. K., Al-Ansari, N., & Knutsson, S. (2018). Water quality of the Tigris River in Iraq: A review. Journal of Advanced Research in Science and Engineering, 7(2), 45-58.

[6] Falkowski, P. G., Fenchel, T., & Delong, E. F. (2008). The microbial engines that drive Earth's biogeochemical cycles. Science, 320(5879), 1034-1039.

[7] Schimel, J. P., & Schaeffer, S. M. (2012). Microbial control over carbon cycling in soil. Frontiers in Microbiology, 3, 348.

[8] Azam, F., & Malfatti, F. (2007). Microbial structuring of marine ecosystems. Nature Reviews Microbiology, 5(10), 782-791.

[9] Allison, S. D., & Martiny, J. B. H. (2008). Resistance, resilience, and redundancy in microbial communities. Proceedings of the National Academy of Sciences, 105(Supplement 1), 11512-11519.

[10] Rietz, D. N., & Haynes, R. J. (2003). Effects of irrigation-induced salinity and sodicity on soil microbial activity. Soil Biology and Biochemistry, 35(6), 845-854.

[11] Oren, A. (2011). Thermodynamic limits to microbial life at high salt concentrations. Environmental Microbiology, 13(8), 1908-1923.

[12] Zhang, K., Shi, Y., Cui, X., Yue, P., Li, K., Liu, X., & Tripathi, B. M. (2019). Salinity is a key determinant for soil microbial communities in a desert ecosystem. mSystems, 4(1), e00225-18.

[13] Hussain, N., Abbas, A., & Al-Ansari, N. (2022). Salinity and water quality dynamics in southern Iraq marshlands. Iraqi Journal of Environmental Science, 8(2), 112-125.

[14] Chase, J. M. (2007). Drought mediates the importance of stochastic community assembly. Proceedings of the National Academy of Sciences, 104(44), 17430-17434.

[15] Schimel, J. P. (2018). Life in dry soils: Effects of drought on soil microbial communities and processes. Annual Review of Ecology, Evolution, and Systematics, 49, 409-432.

[16] Fierer, N. (2017). Embracing the unknown: Disentangling the complexities of the soil microbiome. Nature Reviews Microbiology, 15(10), 579-590.

[17] Manzoni, S., Schimel, J. P., & Porporato, A. (2012). Responses of soil microbial communities to water stress: Results from a meta-analysis. Ecology, 93(4), 930-938.

[18] Evans, S. E., & Wallenstein, M. D. (2014). Climate change alters ecological strategies of soil bacteria. Ecology Letters, 17(2), 155-164.

[19] Bouskill, N. J., Lim, H. C., & Borglin, S. (2013). Pre-exposure to drought increases the resistance of tropical forest soil bacterial communities to extended drought. The ISME Journal, 7(2), 384-394.

[20] Naylor, D., & Coleman-Derr, D. (2018). Drought stress and root-associated bacterial communities. Frontiers in Plant Science, 8, 2223.

[21] de Vries, F. T., Griffiths, R. I., & Bailey, M. (2012). Soil bacterial and fungal communities across a pH gradient in an arable soil. The ISME Journal, 6(6), 1118-1129.

[22] Butterbach-Bahl, K., & Dannenmann, M. (2011). Denitrification and associated N2O emissions are limited by phosphorus availability in a grassland soil. Biogeosciences, 8(8), 2143-2157.

[23] Hawkes, C. V., Waring, B. G., & Rocca, J. D. (2017). Historical climate controls soil respiration responses to current climate precipitation. Global Change Biology, 23(4), 1645-1656.

[24] Heal, O. W., Anderson, J. M., & Swift, M. J. (1997). Plant litter quality and decomposition: An historical overview. Driven by Nature: Plant Litter Quality and Decomposition, 3-30.

[25] Bastida, F., Torres, I. F., & Moreno, J. L. (2017). The active microbial community responds differently to drying and rewetting than the total community. Soil Biology and Biochemistry, 114, 178-186.

[26] Zhao, S., Liu, J., & Banerjee, S. (2020). Soil pH is a major driver of soil bacterial community structure in salinized agroecosystems. Science of the Total Environment, 708, 134-145.

[27] Empadinhas, N., & da Costa, M. S. (2008). Osmoadaptation mechanisms in prokaryotes: Distribution of compatible solutes. International Microbiology, 11(3), 151-161.

[28] Setia, R., Marschner, P., & Baldock, J. (2013). Salinity effects on carbon mineralization in soils of varying texture. Soil Biology and Biochemistry, 57, 654-660.

[29] Rath, K. M., & Rousk, J. (2015). Salt effects on the soil microbial decomposer community and their role in the carbon cycle: A review. Soil Biology and Biochemistry, 81, 108-123.

[30] Al-Tamimi, A. H., Al-Ansari, N., & Knutsson, S. (2019). Salinity mapping and management in Iraqi agricultural lands. Journal of Agricultural Science, 11(4), 245-258.

[31] Maestre, F. T., Eldridge, D. J., & Soliveres, S. (2016). Structure and functioning of dryland ecosystems in a changing world. Annual Review of Ecology, Evolution, and Systematics, 47, 215-237.

[32] Wang, X., Li, Y., & Wang, J. (2021). Combined effects of drought and salinity on soil microbial communities: A meta-analysis. Soil Biology and Biochemistry, 158, 108-119.

[33] Sardans, J., & Peñuelas, J. (2013). Plant-soil interactions in Mediterranean forest and shrublands: Impacts of climatic change. Plant and Soil, 365(1), 1-33.

[34] Wetzel, R. G. (2001). Limnology: Lake and River Ecosystems (3rd ed.). Academic Press, San Diego.

[35] Lake, P. S. (2011). Drought and Aquatic Ecosystems: Effects and Responses. Wiley-Blackwell, Oxford.

[36] Paerl, H. W., Gardner, W. S., & Havens, K. E. (2018). Microbial responses to drought and nutrient loading in aquatic ecosystems. Frontiers in Microbiology, 9, 2315.

[37] Hall, E. K., Singer, G. A., & Kainz, M. J. (2016). Warming effects on microbial metabolism in aquatic ecosystems. Global Change Biology, 22(8), 2789-2803.

[38] Al-Fartusie, F. S., & Al-Saadi, H. A. (2013). Salinity intrusion in the Shatt Al-Arab River and its impact on aquatic ecosystems. Mesopotamian Journal of Marine Science, 28(1), 45-58.

[39] Rysgaard, S., Thastum, P., & Dalsgaard, T. (2004). Effects of salinity on nitrification and denitrification in estuarine sediments. Marine Ecology Progress Series, 283, 1-13.

[40] Al-Handal, A. Y., & Wulff, A. (2014). Cyanobacterial blooms in Iraqi marshlands: Causes and consequences. Journal of Environmental Biology, 35(4), 721-728.

[41] Griebler, C., & Lueders, T. (2009). Microbial biodiversity in groundwater ecosystems. Freshwater Biology, 54(4), 649-677.

[42] Young, I. M., & Ritz, K. (2000). Tillage, habitat space and function of soil microbes. Soil and Tillage Research, 53(3-4), 201-213.

[43] Shade, A., Peter, H., & Allison, S. D. (2012). Fundamentals of microbial community resistance and resilience. Frontiers in Microbiology, 3, 417.

[44] Paerl, H. W., & Otten, T. G. (2016). Harmful cyanobacterial blooms: Causes, consequences, and controls. Microbial Ecology, 65(4), 995-1010.