Applying the Ten Principles of Ecotoxicology to Assess Alkaline Stress Responses in *Vigna radiata* Micro-Ecosystems

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Abstract: This study evaluates the phytotoxic impact of varying alkalinity levels on the germination and early development of mung beans (*Vigna radiata*) through the lens of the 10 Principles of Ecotoxicology. Utilizing a laboratory-controlled micro-ecosystem, seedlings were exposed to a pH gradient ranging from 6.80 (control) to 12.0 over a five-day duration. Results demonstrate a clear dose-response relationship, where optimal growth and morphological integrity were maintained at pH 6.80 and 8.00. However, significant growth inhibition and reduced leaf emergence were observed at pH 10.0 and 11.0, culminating in near-total developmental cessation at pH 12.0. The observed toxicity highlights critical concepts of bioavailability and toxicodynamics, as the high concentration of hydroxide (OH^-) ions likely disrupted the "acid growth" mechanism and nutrient uptake pathways. This research identifies a critical alkalinity threshold (pH > 10.0) that poses a severe hazard to primary productivity. As an ecologically relevant indicator species, the failure of *V. radiata* under extreme alkaline stress suggests significant risks to terrestrial nitrogen-fixing communities and soil stability. These findings provide a biological basis for environmental risk assessment and the establishment of safe discharge limits for industrial alkaline effluents to protect agricultural ecosystems.

Keywords: *Vigna radiata*, Alkalinity, Dose-Response, Phytotoxicity, Risk Assessment.

1. INTRODUCTION

The preservation of agricultural productivity and soil health is increasingly challenged by chemical stressors, among which high alkalinity stands as a significant environmental concern. Ecotoxicology, the study of how toxic substances impact living organisms and their ecosystems, provides a robust framework for assessing these threats (Yap *et al*., 2025a, 2025b). In terrestrial environments, excessive alkalinity, often resulting from industrial discharge, improper irrigation, or natural mineral weathering. The alkalinity stress can fundamentally alter the chemical landscape and disrupt plant physiological processes, particularly those related to ion balance, nutrient availability, and cellular metabolism (Atta *et al*., 2023; Balasubramaniam *et al*., 2023; Pandit *et al*., 2024). Mung bean (*Vigna radiata*) serves as an ideal model organism for evaluating these impacts due to its rapid germination cycle and its vital role as a primary producer and nitrogen-fixer in global food systems (Yap *et al*., 2024; Mohd Hadir *et al*., 2025).

Understanding the interaction between a chemical stressor and a biological receptor is central to the Source–Pathway–Receptor model. When alkalinity increases, the concentration of hydroxide (OH^-) ions in the growth medium creates a hostile environment that can disrupt the internal pH homeostasis of developing seedlings. This experiment utilizes a controlled laboratory setting to observe the Dose–Response relationship across a pH gradient from 6.80 to 12.0. By monitoring parameters such as hypocotyl elongation and leaf emergence over a five-day period, we can identify the specific thresholds at which alkaline stress transitions from a manageable physiological burden to a lethal toxicological event.

The broader ecological relevance of this study lies in its ability to inform Risk Assessment and Management strategies. Because legumes like *V. radiata* are foundational to nutrient cycling, their failure to thrive under alkaline conditions signals a potential collapse of community-level functions, including soil stabilization and nitrogen availability for subsequent trophic levels. By applying the 10 Principles of Ecotoxicology, this paper aims to bridge the gap between observed physical stunting and the underlying biochemical mechanisms of toxicity.

While previous studies have examined alkalinity stress in *Vigna radiata*, the present study introduces a novel integrative approach by explicitly applying the Ten Principles of Ecotoxicology as a unifying interpretative framework. This allows the experimental observations to be systematically translated into ecological risk concepts, bridging laboratory-scale responses with ecosystem-level understanding."

The primary objective of this study is to systematically evaluate the phytotoxic impact of increasing alkalinity gradients (pH 6.80 to 12.0) on the germination and early morphological development of *V. radiata* over a 5-day exposure period. By applying the 10 Principles of Ecotoxicology, the research aims to define the specific Dose–Response relationship and identify the critical physiological thresholds—such as

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the No Observed Effect Concentration (NOEC) and the point of severe growth inhibition—where hydroxide ion concentration disrupts cellular elongation and nutrient uptake. Ultimately, this analysis seeks to provide a biological basis for environmental Risk Assessment, establishing how alkaline chemical stressors influence the structural and functional dynamics of leguminous plants within a terrestrial micro-ecosystem. This study is intentionally structured to prioritize conceptual integration, using experimental observations as anchors for illustrating the Ten Principles of Ecotoxicology.

2. IMPACT OF ALKALINITY ON MUNG BEAN DEVELOPMENT: A SIMPLE EXPERIMENTAL STUDY

The experimental results in Figure **1** indicate that *V. radiata* exhibits a specific range of tolerance to alkalinity, with optimal growth observed near the neutral control (pH 6.80) and moderate alkalinity (pH 8.00). As the pH increases from 9.0 to 11.0, there is a visible maintained growth in shoot length, suggesting that mung beans possess certain physiological mechanisms to mitigate moderate alkaline stress. This is consistent with findings that mung beans can initiate antioxidant enzyme activities to combat reactive oxygen species (ROS) generated by high-pH environments (Sehrawat *et al*., 2019). However, even within this range, subtle signs of chlorosis and reduced leaf expansion begin to appear compared to the control group.

At the extreme end of the scale (pH 12.0), there is a significant inhibition of both germination and seedling vigour. The image reveals stunted shoots and a marked decrease in the number of viable leaves. This decline is likely due to the high concentration of OH^- ions, which interferes with the plant's ability to maintain ion homeostasis and nutrient uptake. High alkalinity often leads to the precipitation of essential micronutrients like iron and phosphorus, making them unavailable to the developing seedling (Anand, 2026). This nutrient deficiency, coupled with osmotic stress, severely restricts the elongation of the hypocotyl and the expansion of the primary leaves.

The structural integrity of the seedlings also appears compromised at higher pH levels. At pH 11.0 and 12.0, the stems appear thinner and less erect compared to the robust seedlings at pH 6.80. Scientific literature suggests that high alkalinity damages the root hair zone, which is the primary site for water absorption, leading to physiological drought even in moist conditions (Hanumantha Rao *et al*., 2016). The observed reduction in leaf number is a classic adaptive response to minimize transpiration when the root system is under stress, prioritizing survival over biomass accumulation.

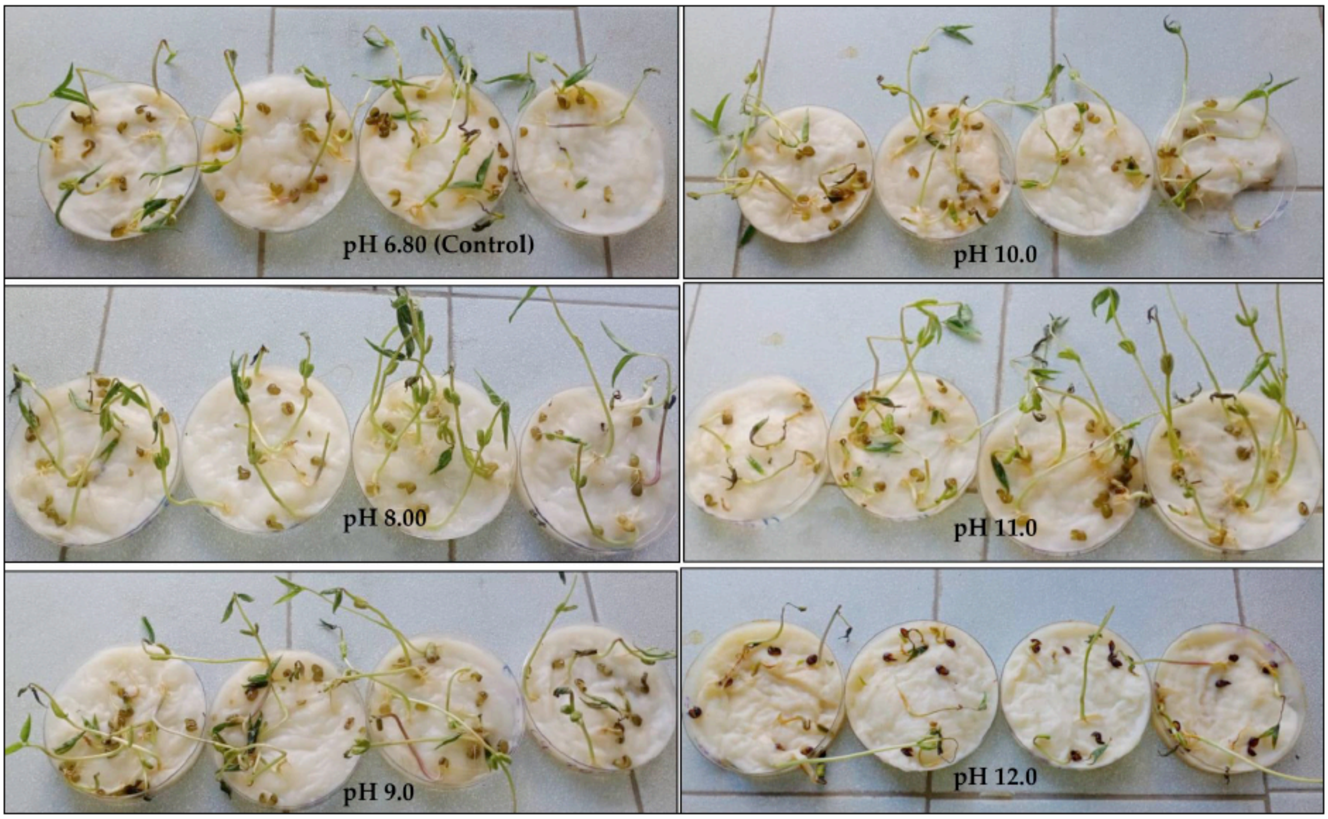

Figure 1: The growth and number of leaves of mung beans after 5 days exposure to different alkalinity levels under experimental laboratory conditions.

The observed stunting at pH ≥ 11.0 is not merely a theoretical outcome but directly corresponds to the visible reduction in hypocotyl elongation and leaf formation, indicating a failure of cellular expansion processes under extreme alkaline conditions. At pH 12.0, more than 80% of seedlings exhibited complete growth inhibition, with negligible hypocotyl elongation and absence of leaf expansion, compared to the control (pH 6.80), where 100% of seedlings developed normally.

Each pH treatment consisted of three independent replicates, with five seeds per replicate (n = 15 per treatment). Observations were conducted over a 5-day exposure period under identical laboratory conditions. Growth parameters, including shoot length and leaf number, were recorded daily. Due to the exploratory and conceptual nature of this study, the data were interpreted using descriptive trends supported by ecological principles rather than inferential statistical testing. This study does not aim to derive LC50 values or predictive regression models, as pH represents a logarithmic environmental parameter rather than a linear toxicant concentration. Instead, the focus is on identifying ecological thresholds relevant for risk interpretation.

Furthermore, the drastic reduction in growth at pH 12.0 highlights the "alkaline threshold" for *V. radiata*. While many legumes are known for their resilience, the chemical stress of pH 12.0 likely causes irreversible damage to the cell membranes and enzymatic proteins required for metabolism (López-Millán *et al*., 2000). The inability of the mung beans to thrive at this level confirms that while they are somewhat alkali-tolerant, extreme hydroxide concentrations create a toxic environment that exceeds the plant's natural buffering capacity.

3. APPLICATION TO UNDERSTAND THE TEN PRINCIPLES OF ECOTOXICOLOGY

3.1. Source–Pathway–Receptor

Based on Figure **2**, the Source–Pathway–Receptor framework illustrates the mechanism of alkaline-induced damage, beginning with the Source (alkaline solution) and its movement through the Pathway (moistened cotton wool and the seed testa). High concentrations of OH^- ions facilitate a chemical degradation of the protective wax layers of the testa, increasing its permeability and allowing for direct ion flooding into the internal tissues. As the Receptor (mung bean embryo and cotyledons) is exposed to this influx, the storage proteins within the cotyledons undergo premature degradation, as noted by Muccifora and Bellani (2013). This structural and biochemical breakdown occurs before successful metabolic mobilization can be initiated, ultimately leading to the failure of seedling development.

In this laboratory setup, the Source is the alkaline solution added to the petri dishes. The Pathway is the moistened cotton wool facilitating diffusion, and the Receptor is the mung bean embryo. Beyond simple contact, the pathway involves the movement of hydroxide (OH^-) ions across the seed coat (testa). Research indicates that the permeability of the testa can be compromised by high alkalinity, which alters the protective wax layers and allows toxic ions to flood the internal tissues. This direct pathway often leads to the degradation of storage proteins within the cotyledons

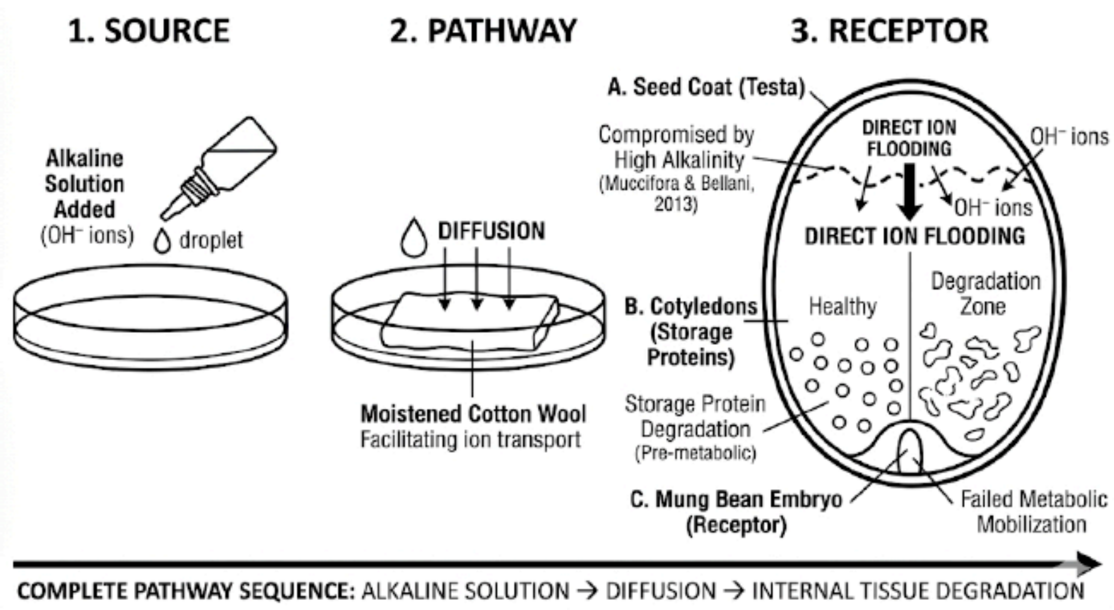

Figure 2: The Source–Pathway–Receptor model of alkaline stress in *Vigna radiata* during early germination.

before the receptor can even begin successful metabolic mobilization (Muccifora and Bellani, 2013).

3.2. Dose–Response Relationship

Figure **3** presents a sigmoidal dose-response curve and associated cellular mechanics that define the impact of external alkalinity on mung bean development. Within the low-dose range of pH 6.80 to 8.00, physiological responses remain healthy, masking a threshold beyond which cellular repair mechanisms are overwhelmed. The critical inhibitory mechanism is linked to the "dose" of OH^- ions, which are hypothesized to inactivate the plasma membrane ATPase pump (Xiao *et al*., 2022). This pump failure disrupts the electrochemical gradient vital for nutrient and water influx, often marking the point where the LC_{50} is reached and initiating the significant decline in biological response that results in the stunted phenotype observed in the pH 12.0 treatment group. The observed responses may be associated with disruptions in membrane transport systems and cell wall extensibility, as suggested in previous studies, although these mechanisms were not directly measured in the present experiment.

The image illustrates a classic Dose-Response curve. At low doses (pH 6.80 to 8.00), growth is healthy, while at high doses (pH 11.0 to 12.0), biological response becomes negative. The "sigmoidal" nature of dose-response in plants often masks a threshold beyond which cellular repair mechanisms fail. In mung beans, the LC_{50} (lethal concentration) for pH stress is often reached when the external alkalinity inhibits the ATPase pump activity in the plasma membrane. When this pump fails due to the "dose" of OH^- ions, the cell cannot maintain the electrochemical gradient necessary for nutrient uptake, leading to the stunted phenotype seen in the pH 12.0 group (Xiao *et al*., 2022).

3.3. Bioavailability

Figure **4** compares the bioavailability of the alkaline stressor in different environmental matrices, defining it as the fraction of the OH^- ions available for uptake. In Section 1, the experimental aqueous-petri dish model uses moistened cotton wool, a substrate that lacks clay particles or significant organic matter, preventing any "buffering" or binding of the hydroxide ions. The visual evidence at pH 12.0 demonstrates that the stressor is highly bioavailable and overwhelming to the plant. This model exposes the mung beans to the maximum theoretical bioavailability, facilitating direct ion flux and explaining the rapid onset of toxicity symptoms, such as severely stunted growth, within just five days (Mazhar *et al*., 2023). In contrast, Section 2 illustrates a complex soil matrix where multiple mechanisms, including binding to clay and organic matter or precipitation of minerals, minimize the effective concentration and buffer the onset of toxicity.

Bioavailability refers to the fraction of the alkaline stressor available for uptake. The visual evidence at pH 12.0 suggests the alkalinity is highly bioavailable and overwhelming to the plant. Bioavailability in paper or cotton-based substrates is often higher than in complex soils because there are no clay particles or organic

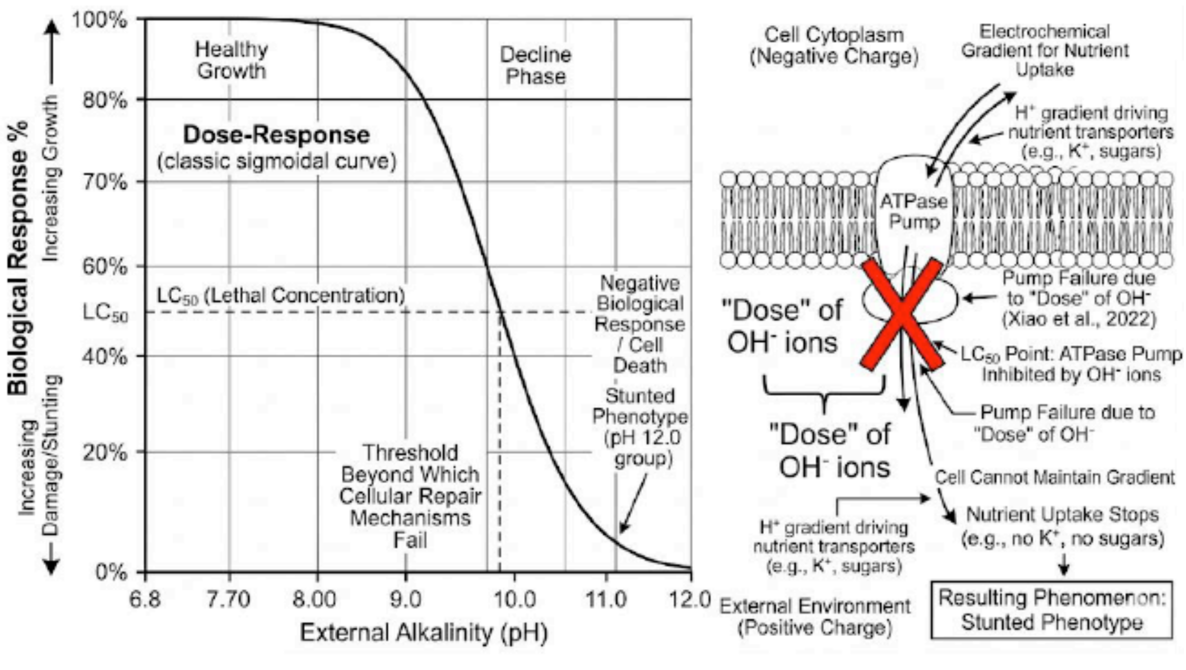

Figure 3: Dose–Response Relationship between alkalinity (pH) and biological response in *Vigna radiata*.

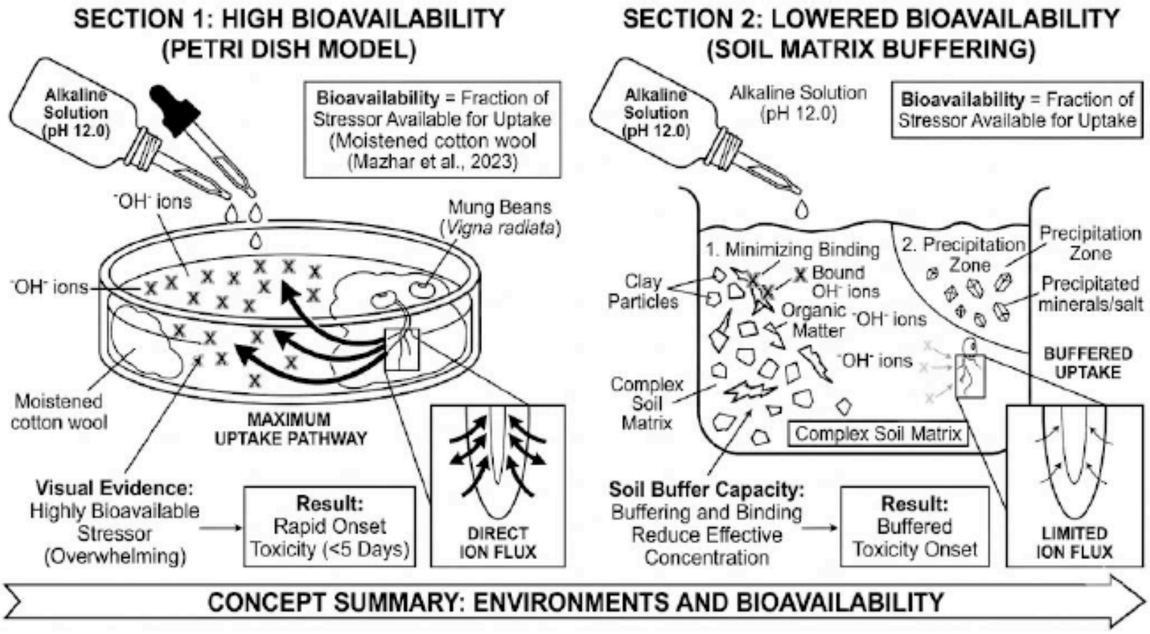

Figure 4: Comparative bioavailability of alkaline stress (OH^- ions) in aqueous-cotton versus complex soil systems.

matter to "buffer" or bind the hydroxide ions. In a soil matrix, minerals might precipitate out, reducing the effective concentration. However, in this aqueous-petri dish model, the mung beans are exposed to the maximum theoretical bioavailability, explaining the rapid onset of toxicity symptoms within just five days (Mazhar *et al*., 2023).

3.4. Accumulation and Biomagnification

Figure **5** illustrates the transition from a defensive survival strategy to systemic failure during prolonged alkaline exposure. Section 1 depicts the continuous bioaccumulation of OH^- ions from the substrate into the seedling over a 5-day period, where ions are initially sequestered in vacuoles to maintain osmotic balance. Section 2 details the cellular tipping point: when the rate of internal OH^- accumulation exceeds the plant's metabolic capacity to synthesize neutralizing organic acids, such as malate or citrate, "alkaline toxicity" occurs (Zhang & Mu, 2009). This buildup causes a critical disruption of the cytoplasmic pH and damages vacuolar integrity, leading to the loss of osmotic control. These internal biochemical breakdowns manifest physically as the leaf chlorosis and necrosis observed in the high-pH replicates.

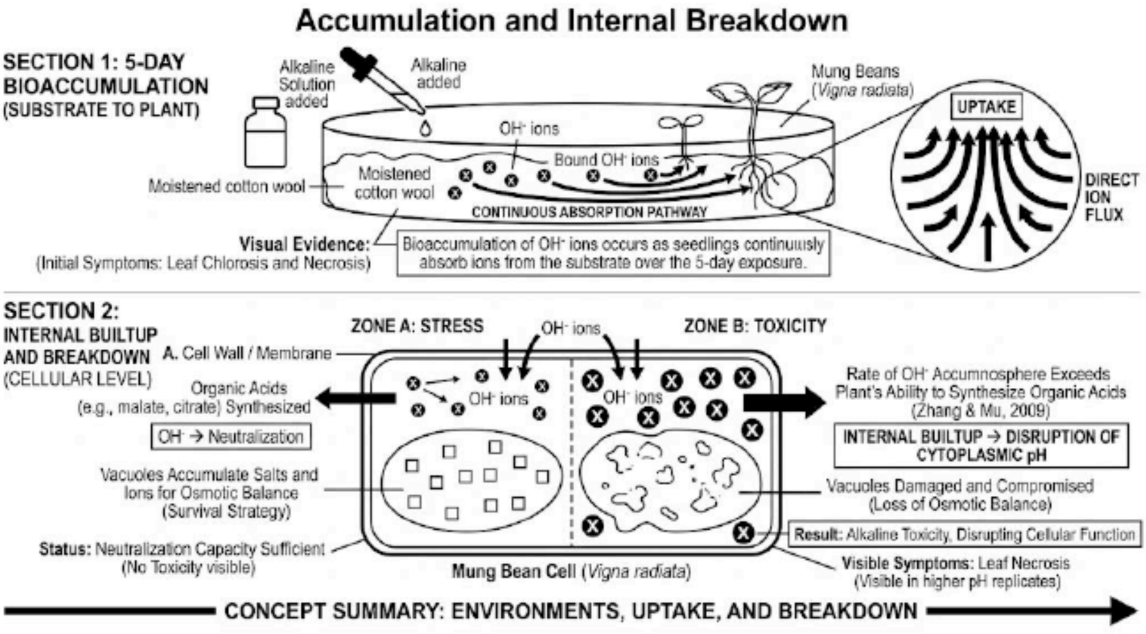

Figure 5: Bioaccumulation and cellular mechanisms of alkaline toxicity in *Vigna radiata* cells.

While Biomagnification is not visible here, Bioaccumulation occurs as seedlings continuously absorb ions from the substrate over the 5-day exposure. The bioaccumulation of salts and ions in the vacuoles of *V. radiata* cells is a survival strategy to maintain osmotic balance. However, when the rate of OH^- accumulation exceeds the plant's ability to synthesize organic acids (like malate or citrate) for neutralization, "alkaline toxicity" sets in. This internal buildup disrupts the cytoplasmic pH, eventually leading to the leaf chlorosis and necrosis visible in the higher pH replicates (Zhang and Mu, 2009).

3.5. Mode of Action

Figure **6** contrasts the mechanical stretchability of the cell wall under healthy and alkaline conditions, illustrating the specific mode of action responsible for the observed vertical stunting. In the Healthy Development panel, the acidic environment of the apoplast (driven by H^+ pumps) activates expansin proteins, allowing them to loosen the cellulose microfibril and hemicellulose network to facilitate normal cell elongation. In the Alkali-Induced Stunting panel, the excessively high pH created by external OH^- ions floods the apoplast (Pramsohler *et al*., 2022). This alkaline environment effectively "locks" the cell wall matrix by preventing expansin activation. Despite adequate internal turgor or moisture, the structural network remains rigid, mechanically blocking the vertical expansion required for hypocotyl elongation and resulting in a structurally compromised, stunted seedling phenotype.

The Mode of Action likely involves the disruption of the "acid growth hypothesis," where cell wall loosening is hindered by high external pH. The Mode of Action underlying the observed stunting involves the disruption of the "acid growth hypothesis," a critical physiological process for plant development. Specifically, high alkalinity targets expansin proteins within the cell wall, which typically require an acidic environment to loosen cellulose microfibrils and facilitate cell elongation. By maintaining an excessively high pH in the apoplast—the intercellular space outside the cell membrane—the alkaline treatments at pH 11.0 and 12.0 effectively "lock" the cell wall matrix. This biochemical interference prevents the mechanical stretching necessary for hypocotyl expansion, explaining why the seedlings remain vertically stunted and structurally compromised despite the presence of adequate moisture (Pramsohler *et al*., 2022).

3.6. Ecological Relevance of Test Organisms

Figure **7** illustrates why *Vigna radiata* is a standardized and ecologically critical test organism for assessing terrestrial ecosystem risks. Section 1 outlines the benefits of its rapid 5-day generation time and documented genome, positioning it as a foundational representative for the Fabaceae family. Section 2 highlights its "indicator function," where healthy leguminous development signifies normal nitrogen fixation. Section 3 details the cascading ecological consequences if the test organism fails due to alkaline stress: the entire local community is at risk of structural collapse. As a vital nitrogen-fixer, the sensitivity of the mung bean reflects broader potential risks to terrestrial plant communities, indicating that

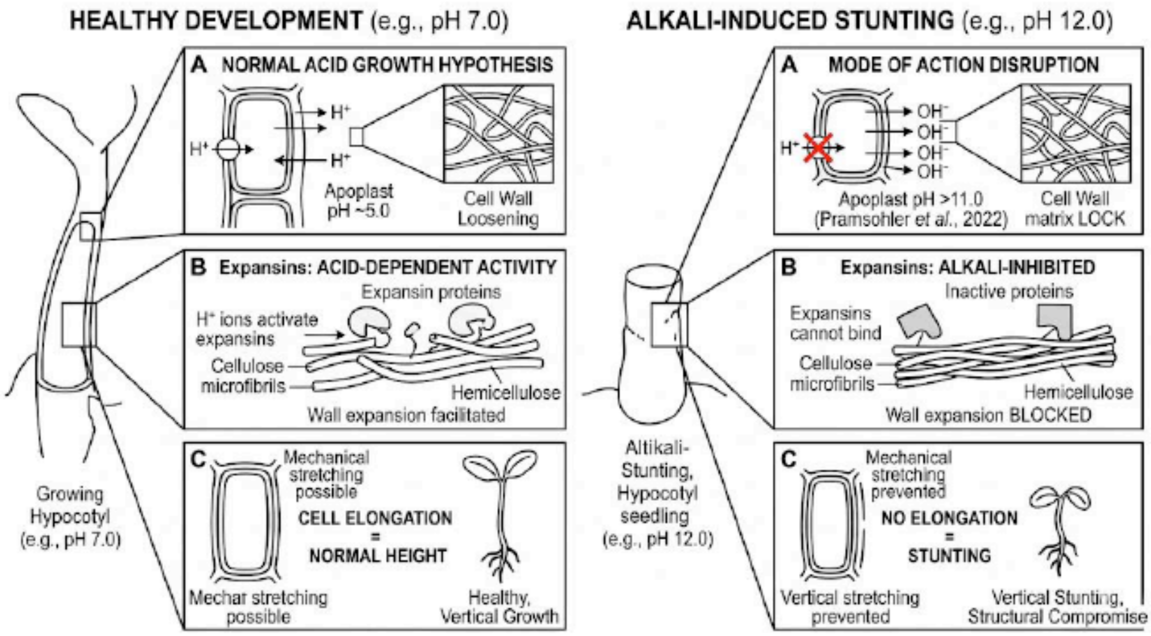

Figure 6: The biochemical mode of action of alkaline stress: Inhibition of the Acid Growth Hypothesis in *Vigna radiata* hypocotyl cells.

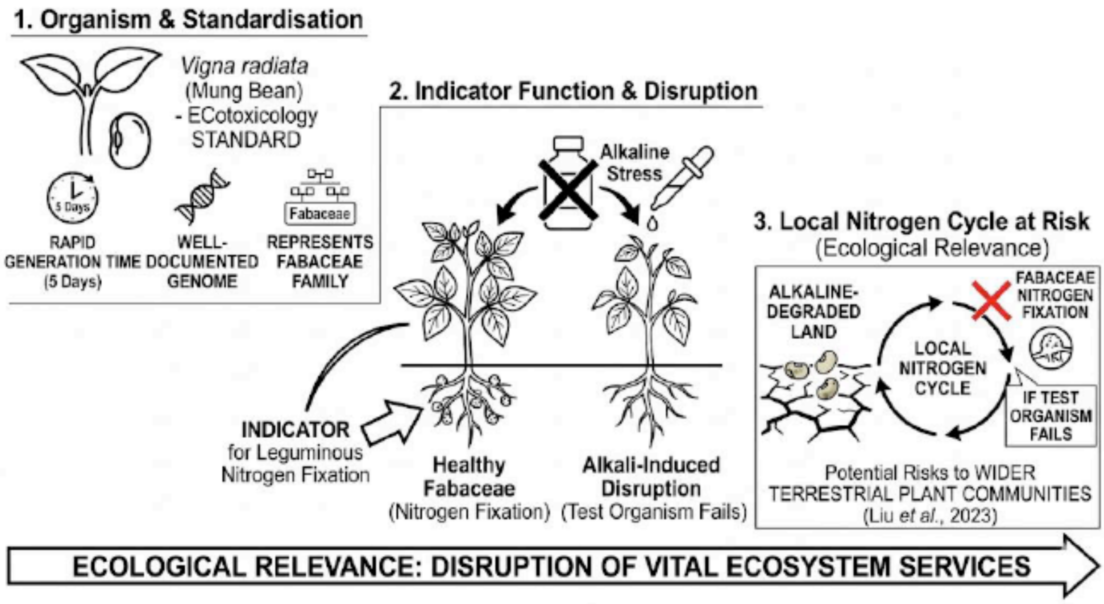

Figure 7: Ecological relevance of *Vigna radiata* as an indicator species for nitrogen cycle disruption.

when leguminous nitrogen-fixation—a critical ecosystem service—is disrupted, the essential nitrogen cycle for the wider ecosystem may be severely compromised (Liu *et al*., 2023).

Mung beans are an ecologically relevant Test Organism because they are vital nitrogen-fixers. Their sensitivity reflects potential risks to wider terrestrial plant communities. The use of *V. radiata* is standardized in ecotoxicology due to its rapid generation time and well-documented genome. Because it represents the Fabaceae family, its response to alkalinity provides an "indicator" for how leguminous nitrogen-fixation—a critical ecosystem service—might be disrupted in alkaline-degraded lands. If the test organism fails, the entire nitrogen cycle of that local community is at risk (Liu *et al*., 2023).

3.7. Mixture Toxicity

Figure **8** illustrates the concept of mixture toxicity, where the physiological impact of alkalinity is compounded by its interaction with internal nutrient reserves. Section 1 shows a synergistic stress model where the combined effect of high pH and nutrient deficiency is more damaging than the sum of their individual effects. Section 2 details the proposed cellular mechanism: as OH^- ions accumulate, the resulting high internal pH causes essential trace minerals, specifically iron (Fe) and phosphorus (P), to

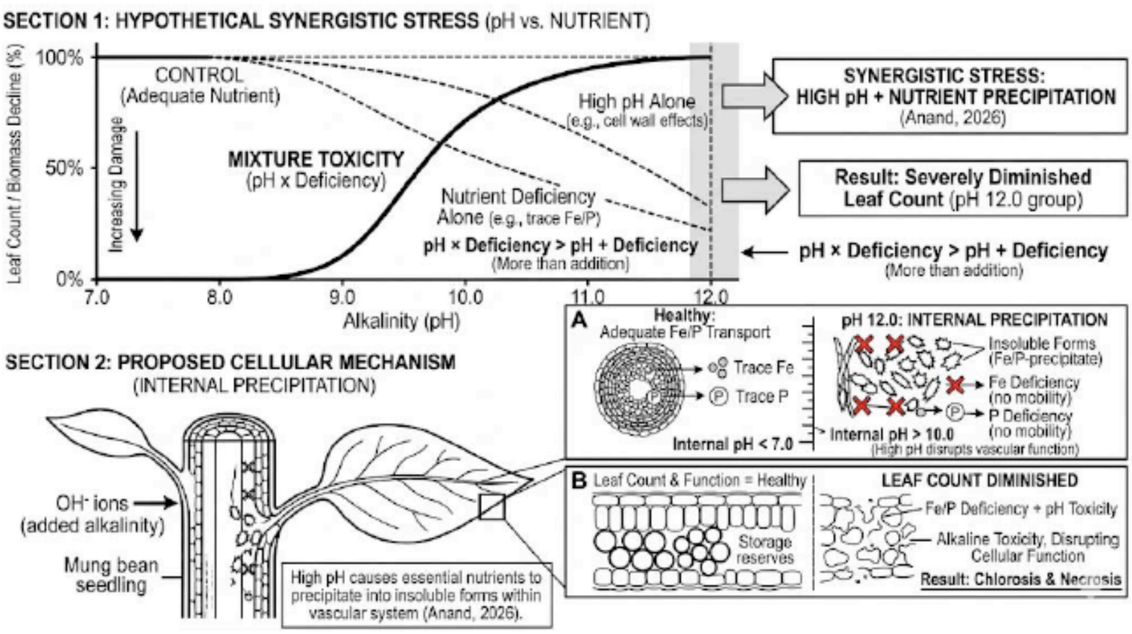

Figure 8: Mixture toxicity and synergistic stress of alkalinity and nutrient precipitation in *Vigna radiata*.

precipitate into insoluble forms within the seedling's vascular system (Anand, 2026). This "internal mixture" of alkalinity and nutrient unavailability disrupts vascular function and metabolic mobilization, providing a biochemical explanation for the severely diminished leaf count and advanced chlorosis observed at pH 12.0.

Mixture Toxicity considers how alkalinity interacts with other factors. Real-world scenarios involve complex interactions between pH and nutrient solubility.

In this experiment, the alkalinity likely interacts with the trace minerals present in the seed's own reserves. High internal pH can cause essential iron (Fe) and phosphorus (P) to precipitate into insoluble forms within the plant's vascular system. This "internal mixture" of high pH and nutrient deficiency creates a synergistic stress effect that is more damaging than either factor alone, resulting in the severely diminished leaf count at pH 12.0 (Anand, 2026).

3.8. Ecosystem and Community-Level Effects

Figure **9** characterizes the petri dishes as "micro-ecosystems" to illustrate the broader ecological implications of chemical stress on community structure. In Section 1, the healthy control represents a functioning primary production layer where the establishment of a "canopy" provides organic litter and stabilizes the substrate. Conversely, the pH 12.0 treatment demonstrates a complete community-level collapse where high alkalinity prevents germination and the establishment of pioneer species. Section 2 translates these observations to a natural environment, showing how the failure of primary producers triggers a trophic cascade (Pimentel *et al.*, 1992). Without pioneer species to provide organic matter and stabilize the soil, the microbial community declines and herbivores lose their primary food source, leading to a systemic failure of the local nitrogen cycle and terrestrial plant community.

Observing the dishes as "micro-ecosystems," we see Community-Level Effects where high pH prevents the establishment of a "canopy." In a natural ecosystem, the failure of primary producers like these beans to germinate at pH 12.0 would trigger a trophic cascade. Without the "pioneer" species to stabilize the soil and provide organic litter, the microbial community in the soil would decline, and herbivores would lose their food source. The petri dishes illustrate the "bottom-up" collapse of a community when a chemical stressor eliminates the primary production layer (Pimentel *et al.*, 1992). While the laboratory micro-ecosystem provides controlled insights into alkaline stress responses, extrapolation to field conditions should be made cautiously due to the buffering capacity and complexity of natural soils.

3.9. Toxicokinetics and Toxicodynamics

Figure **10** distinguishes between the movement of stressors and the resulting physiological damage during alkaline exposure. The toxicokinetics phase involves the rapid uptake of OH^- ions through the radicle (initial root) and their subsequent distribution throughout the plant tissues. The toxicodynamics phase refers to the specific cellular and systemic failure that follows this internal accumulation (Wang *et al.*, 2024). A primary target of this toxicity is the

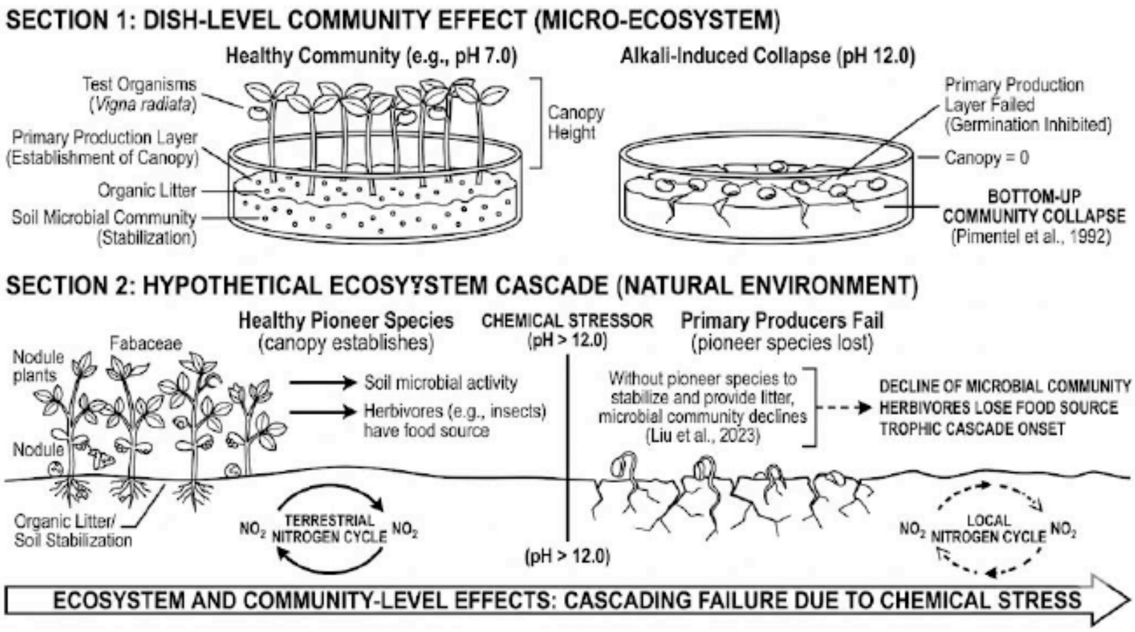

Figure 9: Ecosystem and community-level effects of alkaline stress: A "bottom-up" trophic cascade model.

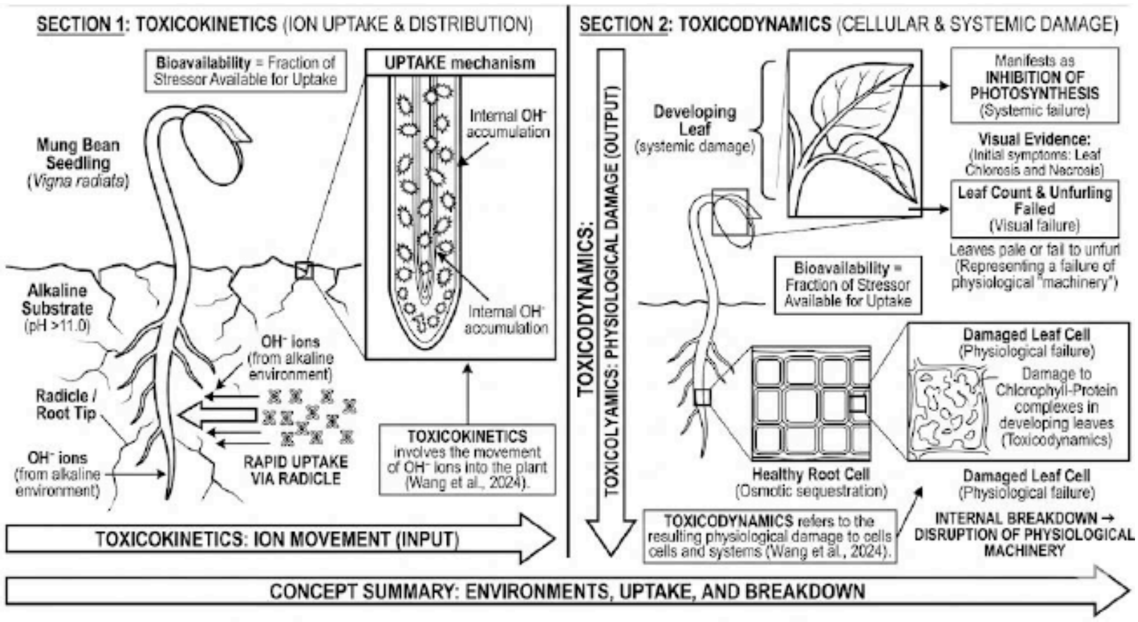

Figure 10: Toxicokinetics and toxicodynamics of OH^- ions in *Vigna radiata* seedlings.

chlorophyll–protein complexes within developing leaves; high alkalinity disrupts these complexes, leading to an inhibition of photosynthesis. This failure of the physiological "machinery" explains why leaves in the pH 11.0 and 12.0 treatments are not only reduced in size but also manifest as pale, chlorotic organs that frequently fail to unfurl.

Toxicokinetics involves the movement of ions into the plant, while Toxicodynamics refers to the resulting physiological damage to cells and systems. The toxicokinetics of OH^- ions in mung beans involve rapid uptake through the radical (initial root). Once inside, the toxicodynamics manifest as the inhibition of photosynthesis. High alkalinity damages the chlorophyll-protein complexes in the developing leaves. This is why the leaves at pH 11.0 and 12.0 are not just smaller, but often appear paler or fail to unfurl, representing a failure of the physiological "machinery" (Wang *et al*., 2024).

3.10. Risk Assessment and Management

Figure **11** outlines a structured approach to environmental protection by identifying alkaline hazard levels and proposing mitigation strategies. Risk Assessment (Section 1) identifies pH levels above 10.0 as a critical hazard, associated with an 80–90% loss in

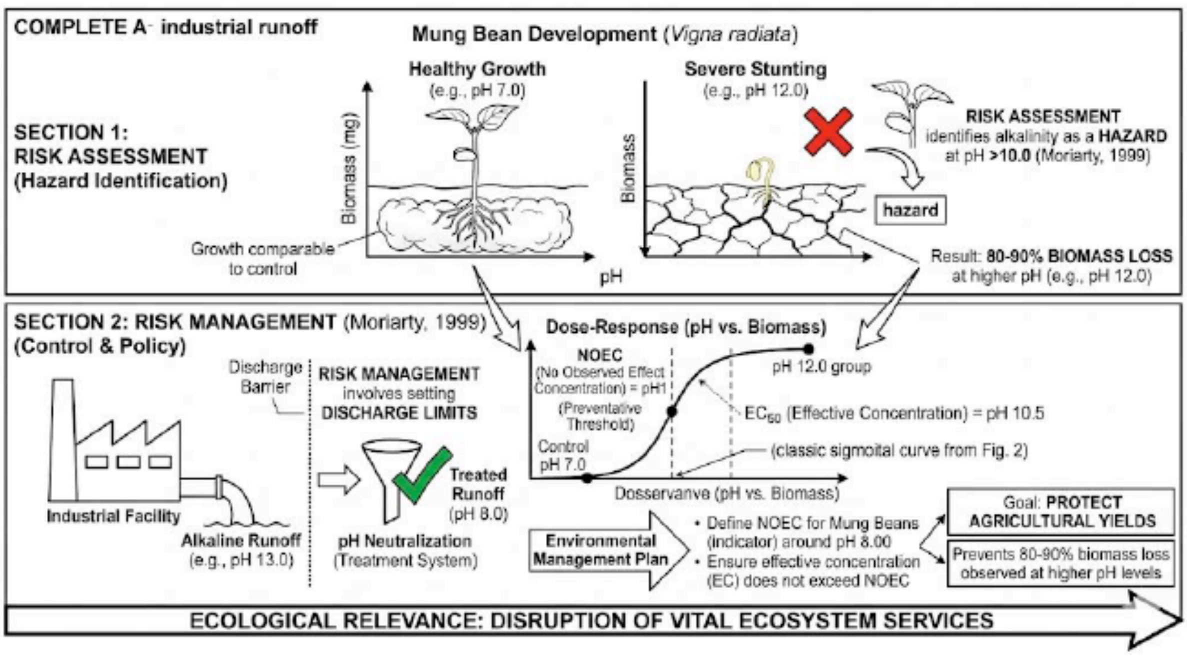

Figure 11: Risk assessment and management framework for industrial alkaline runoff using *Vigna radiata* as a bio-indicator.

biomass. Risk Management (Section 2) utilizes these toxicological data to establish a "No Observed Effect Concentration" (NOEC), which for mung beans is identified at approximately pH 8.00, where growth remains comparable to the control. To protect agricultural yields and ecosystem services, environmental management plans must set strict discharge limits for industrial facilities, ensuring that the effective concentration (EC) in the receiving environment does not exceed this NOEC threshold (Moriarty, 1999). The NOEC identified at approximately pH 8.00 should be interpreted as an observational threshold rather than a statistically derived value, serving as a preliminary ecological reference point.

Risk Assessment identifies pH >10.0 as a hazard. Risk Management would involve setting discharge limits to protect agricultural yields. Effective risk management requires defining the "No Observed Effect Concentration" (NOEC). Based on Figure **1**, the NOEC for mung beans appears to be around pH 8.00, as growth there is comparable to the control. Any environmental management plan for industrial runoff would need to ensure that the "Effective Concentration" (EC) does not exceed this threshold to prevent the 80-90% biomass loss observed at the higher pH levels (Moriarty, 1999).

CONCLUSION

The experimental evaluation of *V. radiata* under varying alkaline gradients provides a clear visual and physiological demonstration of the thresholds governing plant survival and development. The results confirm that while mung beans exhibit a degree of resilience up to pH 9.0, there is a sharp decline in biological performance as alkalinity increases toward pH 12.0. The control group (pH 6.80) and the pH 8.00 treatment produced the most robust seedlings, characterized by elongated hypocotyls and fully expanded primary leaves. In contrast, the pH 12.0 treatment resulted in severe growth retardation, manifesting as stunted stems and a failure to unfurl leaves, which aligns with the ecotoxicological principle of a threshold-dependent dose-response relationship.

These findings highlight the significant risk that high alkalinity—often a byproduct of industrial runoff or improper soil management—poses to agricultural productivity and ecosystem stability. The observed inhibition at pH 11.0 and 12.0 suggests that extreme hydroxide concentrations disrupt essential toxicodynamic processes, likely interfering with nutrient bioavailability and the "acid growth" mechanisms necessary for cellular expansion. Because *V. radiata* serves as an ecologically relevant indicator species, its failure to thrive under these conditions suggests that similar alkaline stress in natural environments would lead to a loss of primary productivity and a disruption of the nitrogen-fixing services provided by leguminous plants.

Ultimately, this study underscores the necessity for rigorous risk assessment and environmental management of alkaline substances. To ensure the sustainability of crop yields and the health of terrestrial communities, industrial and agricultural practices must aim to maintain environmental pH levels within the NOEC range identified here (approximately pH 6.80 to 8.00). Future research should focus on the synergistic effects of alkalinity and salinity to better simulate real-world contaminated sites and to develop more robust, alkali-tolerant crop varieties.

DECLARATION ON THE USE OF ARTIFICIAL INTELLIGENCE

The author declares that generative artificial intelligence tools were used in a supportive capacity during the preparation of this manuscript. These tools assisted with language refinement, structural organisation, and stylistic clarity of the text. All ideas, interpretations, commentary, understanding, and conclusions presented in this paper are the author's own and are grounded in personal experience and scholarly judgment. The author retains full responsibility for the content, accuracy, originality, and integrity of the manuscript.

REFERENCES

[1] Anand, S. (2026). Effects of salinity stress on seedling growth of Vigna radiata (L.) Wilczek. IJARMS, 8(2), 154-158.

[2] Atta, K., Mondal, S., Gorai, S., Singh, A. P., Kumari, A., Ghosh, T., Roy, A., Hembram, S., Gaikwad, D. J., Mondal, S., Bhattacharya, S., Jha, U. C., & Jespersen, D. (2023). Impacts of salinity stress on crop plants: Improving salt tolerance through genetic and molecular dissection. Frontiers in Plant Science, 14, 1241736. https://doi.org/10.3389/fpls.2023.1241736

[3] Balasubramaniam, T., Shen, G., Esmaeili, N., & Zhang, H. (2023). Plants' response mechanisms to salinity stress. Plants, 12(12), 2253. https://doi.org/10.3390/plants12122253

[4] Hanumantha Rao, B., Nair, R. M., & Nayyar, H. (2016). Salinity and high temperature tolerance in mungbean [Vigna radiata (L.) Wilczek] from a physiological perspective. Frontiers in Plant Science, 7, Article 957. https://doi.org/10.3389/fpls.2016.00957

[5] Liu, J., Khan, S., Hu, Y., Yin, L., & Huang, J. (2023). Physiological mechanisms of exogenous organic acids to alleviate aluminum toxicity in seedlings of mungbean, buckwheat, and rice. Plant Physiology and Biochemistry, 203, Article 108031. https://doi.org/10.1016/j.plaphy.2023.108031

[6] López-Millán, A. F., Morales, F., Abadía, A., & Abadía, J. (2000). Effects of iron deficiency on the composition of the leaf apoplastic fluid and xylem sap in sugar beet: Implications for iron and carbon transport. Plant Physiology, 124(2), 873-884. https://doi.org/10.1104/pp.124.2.873

[7] Mazhar, M. W., Ishtiaq, M., Maqbool, M., Ajaib, M., Hussain, I., Hussain, T., Parveen, A., Thind, S., Sardar, T., Akram, R., Azeem, M., & Gul, A. (2023). Synergistic application of calcium oxide nanoparticles and farmyard manure induces cadmium tolerance in mung bean (Vigna radiata L.) by influencing physiological and biochemical parameters. PLOS ONE, 18(3), Article e0282531. https://doi.org/10.1371/journal.pone.0282531

[8] Mohd Hadir, M,I., Noraini, A. B., Chengai, Z., Ramlee, M. A., Syukran Baharuddin, M. A., Mohd Latif, M., Nulit, R., Mohd Syazwan, W., Dwi Setyawan, A., & Yap, C. K. (2025). Effects of the toxicities of Zn and Fe exposure on the growths of mung bean (Vigna radiata): An experimental laboratory study. Malaysian Journal of Sustainable Agriculture (MJSA), 9(1), 10-15. https://doi.org/10.26480/mjsa.01.2025.10.15

[9] Moriarty, F. (1999). Ecotoxicology: The study of pollutants in ecosystems (3rd ed.). Academic Press.

[10] Muccifora, S., & Bellani, L. M. (2013). Effects of copper on germination and reserve mobilization in Vicia sativa L. seeds. Environmental Pollution, 179, 68-74. https://doi.org/10.1016/j.envpol.2013.03.061

[11] Pandit, K., Chandni, Simrandeep Kaur, Kumar, M., Bhardwaj, R., & Kaur, S. (2024). Salinity stress: Impact on plant growth. In Advances in food security and sustainability (Vol. 9, pp. 145-160). Elsevier. https://doi.org/10.1016/bs.af2s.2024.07.002

[12] Pimentel, D., Acquay, H., Biltonen, M., Rice, P., Silva, M., Nelson, J., Lipner, V., Giordano, S., Horowitz, A., & D'Amore, M. (1992). Environmental and economic costs of pesticide use. BioScience, 42(10), 750-760. https://doi.org/10.2307/1311994

[13] Pramsohler, M., Lichtenberger, E., & Neuner, G. (2022). Seasonal xylem sap acidification is governed by tree phenology, temperature and elevation of growing site. Plants, 11(15), Article 2058. https://doi.org/10.3390/plants11152058

[14] Sehrawat, N., Yadav, M., Sharma, A. K., Kumar, V., & Bhat, K. V. (2019). Salt stress and mungbean [Vigna radiata (L.) Wilczek]: Effects, physiological perspective and management practices for alleviating salinity. Archives of Agronomy and Soil Science, 65(9), 1287-1301. https://doi.org/10.1080/03650340.2018.1562548

[15] Wang, D., Song, F., Zhou, Y., Zhong, T., Zhang, Y., Deng, Q., Wang, X., Wang, S., Wang, D., Zhu, X., Jiang, N., & Liu, X. (2024). Effects of alkaline salt stress on growth, physiological properties and medicinal components of clonal Glechoma longituba (Nakai) Kupr. BMC Plant Biology, 24(1), Article 965. https://doi.org/10.1186/s12870-024-05668-3

[16] Xiao, X., Wang, J. L., Li, J. J., Li, X. L., Dai, X. J., Shen, R. F., & Zhao, X. Q. (2022). Distinct patterns of rhizosphere microbiota associated with rice genotypes differing in aluminum tolerance in an acid sulfate soil. Frontiers in Microbiology, 13, Article 933722. https://doi.org/10.3389/fmicb.2022.933722

[17] Yap, C. K., Tiamiyu, M. A., Abu Bakar, N., Wan Mohd Syazwan, Azrizal-Wahid, N., Nulit, R., Setyawan, A. D., *et al*. (2025a). Reframing the collapse of the Aral Sea through the principles of ecotoxicology: A critical synthesis of toxicological governance, environmental justice, and restoration. Cornous Biology, 3(3), 14-32.

[18] Yap, C.K., *et al*. (2024). The Effects of Water Stress on Mung Bean (Vigna radiata L.): Variability in the Growth, Biomass & Stomatal Opening. Journal of Agriculture Research 9(2): 000369. https://doi.org/10.23880/oajar-16000369

[19] Yap, C.K., Kumar, K., Nulit, R., Syazwan, W.M., Bakar, N.A., Hee, W., Cheng, M.A.T., Setyawan, A.D. and Aguol, K.A. (2025b). Reinterpreting World War II Atrocities through the Principles of Ecotoxicology: A Critical Historical-Ecological Framework. BAUET Journal 5(1), 1-17. https://doi.org/10.59321/BAUETJ.V5I1.12

[20] Zhang, J. T., & Mu, C. S. (2009). Effects of saline and alkaline stresses on the germination, growth, photosynthesis, ionic balance and anti-oxidant system in an alkali-tolerant leguminous forage Lathyrus quinquenervius. Soil Science and Plant Nutrition, 55(5), 685-697. https://doi.org/10.1111/j.1747-0765.2009.00411.x

https://doi.org/10.12974/2311-8741.2025.13.11