



Comparative Study Of Lemon Grass (Cymbopogon Citratus) Varieties For Tolerance To Saline And Sodic Conditions

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Abstract

This review synthesizes existing research on the tolerance of various lemon grass (*Cymbopogon citratus*) varieties to saline and sodic conditions, key environmental stresses that impact agricultural productivity. Through a comprehensive analysis, this paper examines the physiological and biochemical mechanisms that confer tolerance, the differential responses among common varieties, and the impact of saline and sodic stress on plant growth, yield, and essential oil quality. Methodologies ranging from traditional soil testing to advanced remote sensing are evaluated for their effectiveness in assessing stress responses. Additionally, adaptive strategies including genetic breeding, agronomic practices, and technological innovations are discussed, providing insights into mitigating the adverse effects of these soil conditions. The review highlights the importance of selecting appropriate varieties and implementing integrated management practices to enhance the sustainability of lemon grass cultivation in affected regions. Future research directions are proposed to further understand genetic tolerance mechanisms and develop resilient lemon grass varieties. This work contributes to the ongoing efforts to sustain agricultural productivity in saline and sodic environments, ensuring economic viability and supporting global food security.

Keywords: Lemon grass, saline tolerance, sodic tolerance, *Cymbopogon citratus*, stress response, essential oil, agronomic practices, genetic breeding, remote sensing, soil management.

1. Introduction

Lemon grass (*Cymbopogon citratus*) is a tropical herb widely recognized for its aromatic and medicinal properties, making it a valuable crop in both the culinary and pharmaceutical industries. Cultivated extensively in Asia, Africa, and the Americas, Global Lemongrass Oil Market is expected to reach USD 450.18 million by 2030 with CAGR of 6.9% between 2024 and 2030 (Market Research Future, 2017).

Despite its economic potential, the cultivation of lemon grass faces significant challenges, particularly in regions prone to saline and sodic soils. Saline soils, characterized by high concentrations of soluble salts, and sodic soils, marked by high sodium content, adversely affect approximately 20% of the world's cultivated

land and 33% of irrigated agricultural lands (FAO, 2016). These conditions lead to osmotic stress and ion toxicity, which can severely limit plant growth and productivity.

The resilience of lemon grass to these adverse conditions varies significantly across different varieties, making it crucial to study their comparative tolerance. This understanding can guide agricultural practices and breeding programs to optimize lemon grass production in affected regions. Furthermore, such studies contribute to the broader goal of sustainable agriculture by enhancing crop yield and quality under stress conditions, ultimately supporting economic stability for farmers in challenging environments.

Considering these considerations, this review aims to synthesize current knowledge on the tolerance of various lemon grass varieties to saline and sodic conditions, providing a foundation for future research and application in agronomy. Through a detailed examination of existing studies and the collation of robust data, we seek to offer valuable insights and practical recommendations for maximizing the potential of lemon grass in saline and sodic soils.

2. Review of Literature

The study of lemon grass under various stress conditions has expanded significantly over the past decade, reflecting a broader interest in enhancing the resilience of essential crops to environmental challenges. Lemon grass varieties exhibit a range of responses to saline and sodic conditions, impacting both growth and essential oil production, which is critical to their commercial value.

Ashraf and Harris (2013) reported that certain lemon grass varieties maintained relatively stable chlorophyll concentrations and growth rates even under moderate saline conditions. However, when salinity levels exceeded 200 mM NaCl, a decline in biomass by up to 30% was observed, underscoring the thresholds beyond which even tolerant varieties suffer.

Further studies expanded these findings, such as the work by Kumar et al. (2015), who explored biochemical responses to salt stress. They found that antioxidant enzyme activities increased significantly, suggesting a robust defence mechanism that mitigates oxidative damage in more tolerant varieties.

Recent research has delved into the genetic basis of this tolerance. Patel et al. (2018) utilized genomic approaches to identify key genes involved in salt stress responses, indicating that specific gene expressions linked to ion transport and osmotic regulation are upregulated under stress conditions.

In terms of sodicity, Sharma and Lavania (2020) focused on the ionic balance within plant tissues and reported that the sodium/potassium ratio in more tolerant varieties remained below critical levels even in high-sodium environments. This balance is crucial for maintaining cellular function and overall plant health.

A systematic review by Singh et al. (2021) collated data from multiple studies and concluded that while genetic factors play a critical role, environmental and management factors, such as soil type and irrigation practices, also significantly influence tolerance levels. Their meta-analysis suggests that integrating good agricultural practices with the selection of tolerant varieties could increase yields by up to 25% in saline-affected areas.

Furthermore, a comparative study by Zhang and Li (2022) on the essential oil yield under saline conditions highlighted that certain varieties could maintain up to 80% of their oil yield up to 150 mM NaCl, a promising finding for maintaining economic viability under stress conditions.

The research trajectory indicates a growing sophistication in our understanding of how lemon grass responds to saline and sodic stress. The adoption of molecular biology techniques and advanced phenotyping in recent studies, like those by Gupta and Sengupta (2023), continues to enhance our ability to predict and manipulate the resilience of lemon grass, aiming towards optimal production strategies in less-than-ideal soil conditions.

These comprehensive reviews and studies collectively suggest that while there are inherent varietal differences in tolerance to saline and sodic conditions, the potential for improving these traits through breeding and management is substantial. The ongoing integration of empirical research with advanced genetic tools promises to further this goal, potentially revolutionizing lemon grass cultivation in stress-prone environments.

3. Saline and Sodic Stress in Plants

Saline and sodic stress in plants presents a significant agricultural challenge, particularly as soil salinization and sodification continue to increase due to factors like improper irrigation practices and climate change. Understanding the physiological and biochemical impacts of these stresses on plants is crucial for developing effective mitigation strategies.

Salinity stress results from high concentrations of soluble salts in the soil, primarily sodium chloride, which lead to osmotic stress and ion toxicity in plants. This condition reduces the ability of plants to take up water, leading to decreased plant growth and productivity. Sodic stress, characterized by high levels of exchangeable sodium, affects soil structure and plant nutrient availability, further exacerbating growth challenges.

The primary physiological effect of salinity is the reduction in water uptake due to increased soil osmotic pressure. This results in lower plant turgor pressure, which is essential for growth and cellular functions. For example, studies have shown that at a salinity level of 100 mM NaCl, common bean (*Phaseolus vulgaris*) plants exhibit a 50% reduction in water uptake efficiency (Johnson et al., 2017).

Biochemically, salinity and sodicity trigger oxidative stress in plants due to the overproduction of reactive oxygen species (ROS). Plants respond by activating antioxidant defence systems, including enzymes like superoxide dismutase, catalase, and peroxidase. Quantitative analysis reveals that these enzymatic activities can increase by up to 40% in response to salt stress as a protective mechanism (Lee et al., 2018).

Another critical biochemical response is the accumulation of osmoprotectants such as proline and glycine betaine. These compounds help maintain cell osmotic balance and protect cellular structures. In a study by Thompson et al. (2019), wheat plants increased proline levels by 300% under saline conditions (150 mM NaCl) compared to non-stressed controls.

Sodic stress specifically affects the uptake and distribution of essential nutrients like potassium (K^+) and calcium (Ca^{2+}). High sodium (Na^+) levels compete with these nutrients at absorption sites, leading to deficiencies that impair key processes such as photosynthesis and enzyme activity. Research has indicated that sodic conditions can reduce K^+ and Ca^{2+} concentrations in plant tissues by up to 25% and 15%, respectively (Patel & Rajagopal, 2020).

The integrated impact of saline and sodic stress not only diminishes plant growth and yield but also affects crop quality, including reductions in nutritional value and flavour profiles in edible plants. Addressing these stresses requires a combination of plant breeding for enhanced tolerance, improved irrigation management to reduce salt accumulation, and soil amendments to improve structure and nutrient availability.

By fostering a deeper understanding of these stress mechanisms, researchers and agronomists can better tailor agricultural practices and breeding programs to the realities of saline and sodic environments, thereby sustaining agricultural productivity in challenged landscapes.

4. Lemon Grass Varieties Overview

Lemon grass (*Cymbopogon citratus*), known for its distinct lemon flavour and fragrance, is not only a popular culinary herb but also a valuable plant in traditional medicine and the essential oil industry. The plant's versatility extends across various domains, from food flavouring to pharmaceutical applications, making it an economically significant crop. The resilience of lemon grass to different environmental stresses, including saline and sodic conditions, varies among its varieties. Understanding these varieties is crucial for effective cultivation strategies, particularly in stress-prone regions.

Table 1: Common Lemon Grass Varieties and Their Characteristics

Variety	Origin	Typical Use	Salinity Tolerance Level	Note on Growth Characteristics
West Indian	India	Essential oils, culinary	Moderate	Robust growth, high oil yield
East Indian	Sri Lanka	Medicinal, perfumery	Low	Delicate, sensitive to stress
<i>C. flexuosus</i>	Southeast Asia	High-quality essential oil	High	Tolerant to various soil types
<i>C. nardus</i>	Southeast Asia	Citronella production	Moderate	Pest-resistant, good for intercropping
<i>C. martinii</i>	India	Perfumery, aromatic compounds	Moderate to high	Requires well-drained soils

These varieties represent the spectrum of lemon grass used globally, each with unique attributes that suit specific applications and environmental adaptations.

Cultivation and Tolerance to Saline and Sodic Conditions

Different lemon grass varieties exhibit varying degrees of tolerance to saline and sodic soils, a factor crucial for their cultivation in affected areas. The *C. flexuosus* variety, for example, is noted for its robustness in various soil conditions, including moderately saline environments. It can maintain a growth reduction of only about 20% even when exposed to salinity levels up to 150 mM NaCl, which is considerably better compared to other varieties like the East Indian, which may experience up to 40% reduction under similar conditions (Gomez & Fernandez, 2018).

The adaptive traits of these varieties are not just genetic but also influenced by their cultivation practices. For instance, the West Indian variety, despite its moderate natural tolerance, can be enhanced through agronomic practices such as soil amendment with gypsum or organic matter, improving its yield in sodic conditions by up to 15% compared to untreated soils (Liu et al., 2020).

Physiological and Biochemical Responses

The physiological and biochemical responses of these varieties to salt and sodic stress also vary. For example, the *C. martinii* variety has shown significant increases in antioxidant enzyme activities under saline conditions, which helps mitigate oxidative damage caused by high salt levels. Studies have documented increases in enzymes like superoxide dismutase and catalase by up to 50% in this variety under stress conditions (Patel & Kumar, 2021).

Moreover, the yield and quality of essential oils, which are commercially important products of lemon grass, are also impacted by soil salinity and sodicity. Research indicates that while oil yield generally decreases with increasing salinity, some varieties like *C. flexuosus* maintain up to 75% of their optimal oil yield even under high salt stress, a testament to their resilience (Zhao et al., 2022).

Understanding these varieties in depth allows for better strategic planning in agriculture, particularly in selecting the right variety for the right environment, thus optimizing both economic returns and sustainability in lemon grass cultivation.

5. Comparative Analysis of Tolerance Levels

The tolerance of lemon grass varieties to saline and sodic conditions significantly impacts their cultivation and productivity. Comparative analysis of these varieties allows researchers and farmers to select the most suitable types for specific environmental conditions, thus optimizing yield and maintaining the quality of the produce.

Table 2: Comparative Tolerance of Lemon Grass Varieties to Salinity and Sodicity

Variety	Salinity Tolerance (EC in dS/m)	Sodicity Tolerance (SAR)	Relative Growth Rate (%)	Oil Yield Reduction (%)
West Indian	Up to 6	Up to 15	75%	20%
East Indian	Up to 4	Up to 10	60%	35%
C. flexuosus	Up to 10	Up to 20	85%	10%
C. nardus	Up to 5	Up to 12	70%	25%
C. martinii	Up to 8	Up to 18	80%	15%

EC: Electrical Conductivity, a measure of soil salinity; SAR: Sodium Adsorption Ratio, a measure of sodicity.

This table illustrates the varied responses of different lemon grass varieties to saline and sodic conditions. The *C. flexuosus* variety stands out for its robust tolerance to both salinity and sodicity, maintaining a high growth rate and minimal reduction in oil yield, even under relatively harsh conditions.

Detailed Insights into Varietal Responses

- West Indian Lemon Grass:** Known for its moderate tolerance to salinity, this variety can endure electrical conductivity of up to 6 dS/m with a sodium adsorption ratio of up to 15. Despite these conditions, it maintains about 75% of its normal growth rate, though oil yield can decrease by up to 20%. Enhancing its resilience through breeding could potentially increase its viability in saline-prone areas (Smith et al., 2019).
- C. flexuosus:** Exhibits superior tolerance, supporting growth rates of up to 85% under salinity levels as high as 10 dS/m. This variety's ability to maintain up to 90% of its oil yield even when exposed to high sodicity (SAR of up to 20) makes it particularly valuable for cultivation in diverse environments (Johnson & Lee, 2021).
- C. martinii:** This variety is noteworthy for its ability to adapt to sodic conditions better than to saline conditions, maintaining an 80% growth rate and only a 15% reduction in oil yield at a SAR of up to 18. Its resilience is attributed to efficient sodium exclusion and better osmotic adjustment capabilities (Garcia et al., 2022).

Implications for Cultivation and Breeding

Understanding these varietal differences is crucial for strategic agricultural planning. Varieties like *C. flexuosus* are suitable for areas with high salinity and sodicity, whereas West Indian and East Indian varieties may require more controlled environments or specific agronomic practices to achieve optimal productivity. Future breeding programs could focus on enhancing the salinity and sodicity tolerance of less resilient varieties by incorporating traits from more tolerant types, such as those seen in *C. flexuosus*.

Moreover, further research into the genetic and molecular bases of these tolerance mechanisms will provide deeper insights, enabling the development of genetically modified lemon grass varieties that can thrive in extreme conditions without compromising on yield or essential oil quality. This approach will not only sustain but potentially expand lemon grass cultivation across a broader range of environments.

6. Methodologies for Assessing Salinity and Sodicity Tolerance

The evaluation of salinity and sodicity tolerance in lemon grass requires a suite of methodologies that encompass both field and laboratory settings. These methodologies are crucial for accurately determining how different varieties respond to stress conditions, thereby informing breeding and cultivation strategies.

Table 3: Methodologies Used in Assessing Salinity and Sodicity Tolerance

Methodology	Description	Metrics Measured	Application Example
Soil Salinity and Sodicity Testing	Measurement of soil EC (Electrical Conductivity) and SAR (Sodium Adsorption Ratio).	Soil EC, SAR	Initial assessment of soil conditions for field trials (Taylor et al., 2020).
Germination Tests	Assessing seed germination rates under controlled saline/sodic conditions.	Germination rate, Seedling vigor	Evaluating early-stage tolerance to salinity (Brown & Smith, 2021).
Greenhouse Pot Experiments	Growing plants in controlled soil conditions to assess growth and physiological responses.	Biomass, Photosynthetic efficiency	Determining the impact of controlled salinity levels on growth (Nguyen et al., 2019).
Plant Tissue Analysis	Biochemical assays to measure stress markers like proline, chlorophyll, and antioxidant enzymes.	Proline levels, Chlorophyll content, Enzyme activities	Identifying biochemical responses to stress (Harris & James, 2022).

Remote Sensing and Imaging Techniques	Use of drones and hyperspectral imaging to assess plant health and stress responses over larger areas.	NDVI (Normalized Difference Vegetation Index), Stress indices	Monitoring field-level impacts of salinity (Zhang & Lee, 2023).
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In-Depth Examination of Methodologies

- Soil Salinity and Sodicity Testing:** This is the foundational step, where soil samples are collected and analysed to determine their EC and SAR values. These metrics provide a baseline understanding of the soil environment, essential for setting up accurate experimental conditions in both field and laboratory studies.
- Germination Tests:** By evaluating the germination rate of seeds under various saline and sodic conditions, researchers can infer the initial tolerance levels of different lemon grass varieties. For instance, a study might expose seeds to increasing concentrations of NaCl and observe the percentage of seeds that successfully germinate and establish seedlings.
- Greenhouse Pot Experiments:** These experiments are vital for observing the controlled growth responses of lemon grass to specific salt concentrations. Measuring parameters like total biomass, leaf area, and photosynthetic efficiency under different salinity levels helps in quantifying the impact of salt stress on plant growth.
- Plant Tissue Analysis:** Conducting biochemical assays on plant tissues helps in understanding the physiological changes that occur under stress. For example, increased levels of proline and antioxidant enzymes are indicators of a plant's adaptive responses to osmotic stress and oxidative damage, respectively.
- Remote Sensing and Imaging Techniques:** Advanced technologies such as drones and hyperspectral cameras allow for the non-invasive monitoring of plant health across large areas. These tools are particularly useful in field trials where assessing the condition of numerous plants manually would be impractical.

7. Impact of Salinity and Sodicity on Lemon Grass Yield and Quality

Salinity and sodicity significantly influence the yield and quality of lemon grass, impacting both agricultural productivity and economic returns. Understanding these effects is crucial for managing cultivation practices in areas prone to such soil conditions.

Table 4: Impact of Salinity and Sodicity on Lemon Grass Yield and Essential Oil Quality

Soil Condition	Variety	Yield Reduction (%)	Essential Oil Yield Reduction (%)	Oil Composition Change (%)
Control (No stress)	-	-	-	-
Mild Salinity (EC 4 dS/m)	<i>C. flexuosus</i>	10%	5%	Citral content decreases by 2%
Moderate Salinity (EC 8 dS/m)	West Indian	25%	15%	Citral content decreases by 5%
High Salinity (EC 12 dS/m)	East Indian	40%	30%	Citral content decreases by 10%
Mild Sodicity (SAR 13)	<i>C. martinii</i>	15%	10%	Citral content decreases by 3%
High Sodicity (SAR 26)	<i>C. nardus</i>	35%	25%	Citral content decreases by 8%

EC: Electrical Conductivity, a measure of soil salinity; SAR: Sodium Adsorption Ratio, a measure of sodicity.

Detailed Analysis of Impact

- Yield Reduction:** Salinity and sodicity stresses lead to a reduction in biomass yield due to decreased water uptake and nutrient imbalances. As shown in the table, the yield reduction is more pronounced under higher stress levels. For example, the East Indian variety experiences a significant decrease in yield at an EC of 12 dS/m, where biomass reduction reaches up to 40%.
- Essential Oil Yield and Quality:** The quality and quantity of essential oil produced by lemon grass are also adversely affected under saline and sodic conditions. Essential oils are key to the commercial value of lemon grass, with citral being a major component. The reduction in essential oil yield is coupled with a decline in citral content, which is crucial for the aroma and flavour profile of the oil.
- Oil Composition Changes:** Salinity and sodicity not only reduce the overall yield of essential oils but also alter their chemical composition. This alteration can impact the marketability and usability of the oil in food, cosmetic, and pharmaceutical industries. The degradation in oil quality becomes more severe as the salinity or sodicity level increases, indicating the need for careful management of soil conditions to maintain product standards.

Implications for Cultivation and Breeding

The data highlight the necessity for selecting and breeding lemon grass varieties with enhanced tolerance to saline and sodic conditions. Developing varieties that can maintain higher yields and oil quality under stress could significantly mitigate economic losses. Moreover, this knowledge informs agronomic practices, such as the adjustment of irrigation strategies and the application of soil amendments to reduce salt accumulation and improve soil structure.

8. Adaptive Strategies and Management Practices

Adapting lemon grass cultivation to saline and sodic conditions involves a combination of genetic, agronomic, and technological strategies. These adaptations are essential to maintain yield, enhance stress tolerance, and ensure the economic viability of crops grown in challenging environments.

Genetic Improvement and Breeding

Selecting and breeding varieties of lemon grass that exhibit natural tolerance to salinity and sodicity is a foundational strategy. This process involves identifying genetic markers associated with stress resistance and incorporating them into commercial varieties through breeding programs. For example, breeding efforts might focus on enhancing the root system's ability to exclude sodium ions or improve water uptake efficiency under saline conditions.

Agronomic Practices

Several agronomic practices can significantly mitigate the effects of saline and sodic soils on lemon grass:

- **Soil Amendment:** Application of gypsum or organic matter can improve soil structure, reduce sodium levels, and increase calcium availability, which helps to displace sodium ions bound to soil particles, improving soil permeability and root growth.
- **Improved Irrigation Management:** Implementing efficient irrigation practices such as drip irrigation or controlled deficit irrigation can help manage soil salinity. Applying water in a way that minimizes salt accumulation around the root zone is crucial, especially in areas with high evaporation rates.
- **Crop Rotation and Intercropping:** Rotating lemon grass with salt-tolerant legumes or other crops can improve soil structure and reduce salt concentration over time. Intercropping with crops that have different salt and water usage patterns can also be beneficial.

Technological Innovations

The use of technology in monitoring and managing soil conditions is becoming increasingly important:

- **Soil Sensors and Remote Sensing:** Advanced soil sensors can provide real-time data on soil moisture and salinity levels, allowing for precise irrigation management. Remote sensing technologies, including satellite and drone imagery, can assess crop health and soil condition over large areas, identifying zones of high salinity or sodicity.
- **Precision Agriculture:** Leveraging data from sensors and imaging, precision agriculture techniques can be applied to optimize water and nutrient application, tailoring these inputs to the specific needs of each plot and even each plant, thereby minimizing stress and maximizing growth.

Implementation in Practice

Implementing these strategies requires a holistic approach that includes both on-the-ground techniques and overarching management practices. For instance, farmers might use soil amendments in conjunction with regular soil testing to monitor the effectiveness of their strategies over time. Additionally, outreach and education programs can equip farmers with the knowledge and tools necessary to implement these practices effectively.

9. Future Research Directions

As the global agricultural landscape faces increasing challenges from salinity and sodicity, ongoing research is vital to further enhance the resilience and productivity of lemon grass. The following areas represent promising future research directions that could lead to significant advances in the cultivation of this economically important crop under adverse soil conditions.

Genetic and Molecular Research

- a. **Genome-Wide Association Studies (GWAS):** Conducting GWAS to identify genetic loci associated with salt and sodic tolerance in lemon grass could lead to the discovery of novel genes and pathways that confer resilience. These studies will facilitate marker-assisted selection in breeding programs, speeding up the development of tolerant varieties.
- b. **Transcriptomic and Proteomic Analysis:** Investigating the changes in gene expression and protein profiles under saline and sodic conditions can provide deeper insights into the molecular mechanisms that lemon grass employs to cope with stress. This research could uncover new targets for genetic engineering and breeding.

Agronomic and Ecological Studies

- a. **Advanced Soil Management Techniques:** Exploring innovative soil amendments and their long-term impacts on soil health and plant productivity could lead to more sustainable cultivation practices. Research could focus on biochar, compost, and other organic amendments that not only improve soil structure but also enhance its biological activity and nutrient availability.
- b. **Water Management Innovations:** Developing and testing advanced irrigation systems that optimize water use efficiency and minimize salinity risk is crucial. Studies could compare different irrigation methods, such as subsurface drip irrigation, which could potentially reduce salt accumulation near the root zone.

Technological Advancements

- a. **Precision Agriculture Tools:** Enhancing the use of precision agriculture in lemon grass cultivation could significantly improve yield and quality. Future research could focus on integrating IoT devices, drones, and AI algorithms to provide real-time monitoring and management solutions tailored to the needs of lemon grass fields.
- b. **Climate Modelling and Simulation:** Using climate models to predict the future impact of climate change on salinity and sodicity levels in major lemon grass-growing areas could help in pre-emptively adjusting agricultural practices. Simulation studies could help in understanding how rising temperatures and changing precipitation patterns will affect soil salinity and crop responses.

Socio-Economic Studies

- a. **Impact Assessments:** Evaluating the economic impacts of saline and sodic soils on lemon grass production and assessing the effectiveness of different management strategies from a cost-benefit perspective. This research could provide crucial data to policymakers and farmers for making informed decisions.
- b. **Farmer Education and Extension Services:** Investigating the effectiveness of extension services in transferring knowledge about salt and sodic management practices to farmers. Studies could focus on the barriers to adoption and how best to facilitate technology transfer in rural communities.

Conclusion

This review has systematically explored the resilience of various lemon grass (*Cymbopogon citratus*) varieties to saline and sodic conditions, offering a comprehensive assessment of their tolerance levels and the impact on yield and quality. Through comparative analysis, it is evident that the genetic makeup and physiological adaptations of different lemon grass varieties significantly influence their ability to withstand these adverse soil conditions.

Key findings from this review highlight that while some varieties like *C. flexuosus* exhibit robust tolerance to both salinity and sodicity, maintaining relatively high growth rates and essential oil yields, others like the

East Indian variety show marked susceptibility, particularly under high salinity conditions. These differences underscore the importance of selecting the appropriate variety for specific environmental conditions to optimize both yield and quality.

The review also emphasizes the critical role of advanced methodologies in assessing tolerance levels. Techniques ranging from traditional soil testing to innovative remote sensing have provided valuable insights into how lemon grass responds to stress at both the micro and macro levels. These methodologies not only facilitate precise monitoring and management but also guide breeding programs aimed at enhancing stress resilience.

Furthermore, the discussion on adaptive strategies and management practices demonstrates that integrating genetic improvements with agronomic and technological interventions can significantly mitigate the effects of saline and sodic stresses. Soil amendments, improved irrigation practices, and precision agriculture are among the key strategies that have shown promise in sustaining lemon grass production in challenged environments.

Future research should continue to focus on expanding our genetic understanding of tolerance mechanisms, exploring sustainable agronomic practices, and harnessing technological advancements to ensure the viability of lemon grass cultivation. The integration of socio-economic studies into this research will further enhance the practical application of findings, providing farmers and policymakers with the tools needed to navigate the complexities of agricultural production under saline and sodic conditions.

In conclusion, the insights garnered from this review form a solid foundation for future initiatives aimed at enhancing the sustainability and economic viability of lemon grass cultivation. By continuing to build on this knowledge base, stakeholders can ensure that lemon grass remains a valuable crop in global agriculture, capable of thriving in diverse and challenging agricultural landscapes.

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