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Genetic and Environmental Factors Influencing Grain Quality in Maize

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Abstract Grain quality in maize (*Zea mays* L.) is influenced by a complex interplay of genetic and environmental factors. This review synthesizes current research on the genetic determinants and environmental conditions that affect maize grain composition and quality. Studies have shown that transcription factors and other regulatory proteins play a significant role in gene expression variability, which in turn impacts grain composition. Genetic control over kernel compositional traits has been extensively studied, revealing substantial phenotypic variation attributable to both genetic and environmental factors. Environmental variables such as soil type, rainfall, and management practices also significantly influence grain yield and quality. Recent findings suggest that while genetic improvements have contributed to yield gains, the role of agronomic practices and climate conditions is increasingly critical. This review highlights the need for integrated approaches combining genetic, molecular, and environmental strategies to enhance maize grain quality.

Keywords Maize grain quality; Genetic factors; Environmental influences; Transcription factors; Agronomic practices

1 Introduction

Maize (*Zea mays* L.) is one of the most significant crops globally, serving as a staple food for millions of people and a critical component in animal feed and industrial products. Its adaptability to diverse climatic conditions and its high yield potential make it a vital crop in both developed and developing countries. In regions like Argentina, maize production is undergoing changes with farmers planting later in the growing season, which necessitates an understanding of the influences of genotype, management, and environmental variables on grain yield (Lee and Tollenaar, 2007; Gambin et al., 2016). Similarly, in sub-Saharan Africa, maize is crucial for food security, and breeding programs have focused on developing cultivars that can withstand stress conditions such as drought and low soil fertility (Badu-Apraku et al., 2015; Mebratu et al., 2019).

Grain quality in maize encompasses a variety of traits, including kernel composition (e.g., protein, starch, and oil content), kernel hardness, and breakage susceptibility. These traits are influenced by both genetic and environmental factors. For instance, studies have shown that nitrogen application can significantly affect kernel hardness and breakage susceptibility, with genotype playing a larger role in determining grain quality parameters than nitrogen rate (Duarte et al., 2005). Additionally, the interaction between genotype and environment (GEI) is a critical factor in determining the stability and quality of maize grain across different environments (Katsenios et al., 2021; Renk et al., 2021).

The study provides a comprehensive analysis of the genetic and environmental factors influencing grain quality in maize. By examining various studies conducted across different regions and under varying conditions, can identify key factors that contribute to grain quality and yield stability. The scope of this study includes an evaluation of the effects of genotype, environmental conditions, and management practices on grain quality traits. It also explores the potential for breeding programs to develop high-yielding and stable maize hybrids that can thrive under both stress and non-stress conditions. This study will serve as a valuable resource for researchers, agronomists, and policymakers involved in maize production and breeding programs.

2 Genetic Factors Influencing Grain Quality

2.1 Key genetic traits

Grain quality in maize is significantly influenced by various genetic traits. Key traits include kernel composition, such as protein, starch, and oil content, which are critical for both nutritional value and industrial applications. Studies have shown that genetic variation plays a substantial role in determining these traits. For instance, a study evaluating 501 diverse temperate maize inbred lines found significant genetic control over 16 compositional traits, with 22.9-71.0% of phenotypic variation explained by genetic factors (Renk et al., 2021). Additionally, kernel depth and ear length have been identified as important genotypic covariates influencing yield and stability under stress conditions (Romay et al., 2010).

2.2 Molecular markers and QTL mapping

Molecular markers and quantitative trait loci (QTL) mapping are essential tools for understanding the genetic basis of grain quality traits. Genome-wide association studies (GWAS) have identified numerous single nucleotide polymorphisms (SNPs) associated with key compositional traits. For example, a GWAS conducted on a maize diversity panel identified 72 significant SNPs for 11 compositional traits, providing valuable insights for breeding programs aimed at improving grain quality (Renk et al., 2021). These molecular markers facilitate the selection of desirable traits, thereby enhancing the efficiency of breeding programs.

2.3 Genetic engineering and CRISPR/Cas9

Genetic engineering, including the use of CRISPR/Cas9 technology, offers promising avenues for improving maize grain quality. CRISPR/Cas9 allows for precise genome editing, enabling the modification of specific genes associated with desirable traits. This technology has the potential to enhance traits such as kernel composition, disease resistance, and stress tolerance. Although specific studies on CRISPR/Cas9 applications in maize grain quality are limited, the technology's success in other crops suggests significant potential for maize improvement.

2.4 Role of teosinte in genetic improvement

Teosinte, the wild ancestor of maize, plays a crucial role in the genetic improvement of modern maize varieties. The genetic diversity present in teosinte offers a valuable reservoir of traits that can be introgressed into maize to enhance grain quality. For instance, teosinte has been used to introduce traits such as drought tolerance and disease resistance into maize, thereby improving its adaptability and productivity under various environmental conditions. The integration of teosinte genes into maize breeding programs has the potential to enhance grain quality by introducing novel genetic variations (Russell, 1991).

3 Environmental Factors Influencing Grain Quality

3.1 Climate and weather conditions

Climate and weather conditions play a pivotal role in determining the grain quality of maize. Variations in temperature, precipitation, and other climatic factors can significantly impact the yield and quality of maize grains. For instance, high temperatures during critical growth stages can lead to reduced grain filling and lower quality grains. A study conducted in Spain highlighted that climatic variables such as days with mean temperatures over 15 ℃ and maximum temperatures in September were crucial for maize yield under stress conditions like drought and cold (Romay et al., 2010). Similarly, another study in Brazil found that differences in light, accumulated temperature, and precipitation were key factors affecting maize grain quality, with variations in these factors leading to differences in protein, starch, and fat content in the grains (Tian et al., 2021).

Drought conditions, in particular, have been shown to severely limit maize yield and quality. Research in Eastern and Southern Africa demonstrated that drought stress significantly affected the grain yield stability of quality protein maize hybrids, with certain hybrids performing better under drought conditions than others (Mebratu et al., 2019). This indicates that both the timing and intensity of drought can influence the final grain quality.

3.2 Soil characteristics

Soil characteristics, including soil type, nutrient availability, and soil texture, are critical determinants of maize grain quality. The presence of essential nutrients like nitrogen (N), phosphorus (P), and magnesium (Mg) in the soil can enhance grain quality by improving protein and fiber content. A study in Greece found that environments with high concentrations of nutrients like Mg and Ca, along with favorable soil texture, resulted in higher protein and fiber contents in maize grains (Katsenios et al., 2021).

Nitrogen availability, in particular, has a profound impact on grain quality. Research in Brazil showed that increasing N application rates led to higher grain yields and improved kernel hardness, while reducing breakage susceptibility (Chen et al., 2014; Duarte et al., 2005). However, the genotype of the maize also played a significant role, with some genotypes responding better to N application than others. This suggests that soil fertility management, particularly N management, is crucial for optimizing grain quality.

3.3 Agricultural practices

Agricultural practices, including planting density, herbicide application, and overall crop management, significantly influence maize grain quality. Planting density, for example, affects the availability of resources like light, water, and nutrients to individual plants, thereby impacting grain quality. A study comparing different planting densities in various ecological environments found that higher planting densities generally led to a decrease in grain protein content, although the trends for other nutrients like fat and starch were more complex (Tian et al., 2021).

Herbicide application is another critical factor. Research in contrasting climatic conditions showed that different herbicide treatments had significant effects on the hundred-grain weight and overall yield of maize genotypes. The study found that the genotype and the specific herbicide treatment both played significant roles in determining grain quality, with some genotypes showing more resilience to herbicide stress than others (Bozovic et al., 2022). Moreover, the timing of planting and other management decisions, such as stand density and soil P levels, were found to be crucial in determining grain yield and quality in late-sown maize in Argentina. The study highlighted the importance of optimizing these management variables to achieve better grain quality (Gambin et al., 2016).

3.4 Pest and disease management

Effective pest and disease management is essential for maintaining high grain quality in maize. Pests and diseases can cause significant damage to maize crops, leading to reduced grain quality and yield. For instance, the presence of pests like the European corn borer and diseases such as maize streak virus can lead to poor grain filling and lower nutritional quality. Research in West and Central Africa has shown that breeding for resistance to pests and diseases, such as Striga parasitism, can lead to substantial improvements in grain yield and quality. The study found that maize cultivars developed for resistance to Striga and other stress factors showed higher yield stability and better grain quality under both optimal and stress conditions (Badu-Apraku et al., 2015).

In addition to genetic resistance, integrated pest management (IPM) practices, including the use of biological control agents and cultural practices, can help mitigate the impact of pests and diseases on maize grain quality. For example, maintaining proper field hygiene, crop rotation, and timely application of appropriate pesticides can reduce pest and disease pressure, thereby enhancing grain quality. The grain quality of maize is influenced by a complex interplay of genetic and environmental factors. Climate and weather conditions, soil characteristics, agricultural practices, and pest and disease management all play crucial roles in determining the final quality of maize grains. Understanding and optimizing these factors can help improve maize grain quality, thereby enhancing its value for both human consumption and industrial use.

4 Interaction Between Genetic and Environmental Factors

4.1 Genotype-environment interaction

Genotype-environment interaction (GEI) plays a crucial role in determining the grain quality and yield stability of maize. The interaction between genetic makeup and environmental conditions can significantly influence the performance of maize hybrids. For instance, a study conducted in Eastern and Southern Africa evaluated 108 quality protein maize (QPM) hybrids across 13 environments under varying conditions such as drought, low nitrogen, and optimal environments. The results indicated that both the environment and the genotype significantly affected grain yield and stability, with certain hybrids like H40 showing outstanding performance across different management conditions (Stuber et al., 1987; Mebratu et al., 2019).

Similarly, another study analyzed the grain yield variation in 1918 maize hybrids across 65 testing environments. It was found that genetic-by-environment variances were more significant than genetic main effect variances, highlighting the importance of considering both additive and dominance relationships in modeling GEI patterns. This approach allows for better genomic prediction of hybrid performance across different environments (Zhang et al., 2019; Rogers et al., 2021).

In Greece, the interaction of genotype by environment was also evident in multi-environment trials of maize hybrids. The study used principal components analysis (PCA) and additive main effects and multiplicative interaction (AMMI) analysis to evaluate the performance of four maize genotypes across five locations. The results showed that certain environments provided higher yields and better grain quality, indicating the importance of selecting specific genotypes for specific environments to optimize grain quality (Figure 1) (Katsenios et al., 2021).

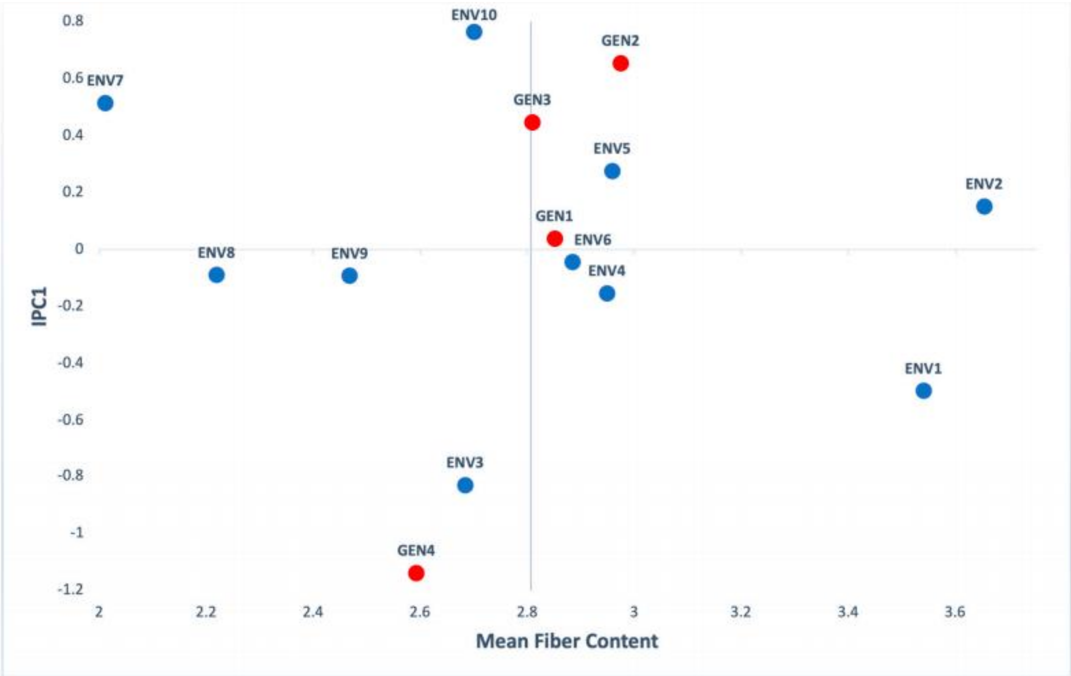

Figure 1 AMMI biplot presenting mean fiber content and the first interaction principal components axis (IPC1) for various genotypes in different environments (Adapted from Katsenios et al., 2021)

Image caption: AMMI biplot presenting mean fiber content and the first interaction principal components axis (IPC1) of 4 genotypes (red) evaluated in 10 environments (blue) (Adapted from Katsenios et al., 2021)

4.2 Breeding for adaptation

Breeding programs aiming to improve maize grain quality must consider the interaction between genetic and environmental factors. The identification of genotypes that perform well under specific environmental conditions is essential for developing stable and high-yielding hybrids. For example, a study on Spanish maize populations under stress conditions such as drought and cold found that commercial hybrids had higher yield and stability compared to most populations. The study emphasized the importance of considering climatic variables and genotypic traits like kernel depth and ear length in breeding programs (Svečnjak et al., 2007; Pok et al., 2009; Romay et al., 2010).

Another study focused on the adaptation of maize genotypes to environments with varying nitrogen availability. The research identified morpho-physiological traits associated with better performance in low nitrogen environments, such as efficient canopy to sustain resource capture up to maturity. These findings highlight the need for breeding programs to consider specific traits that enhance adaptation to different environmental conditions (Cirilo et al., 2009).

Furthermore, the evaluation of introduced nutrient-dense maize lines for adaptation through GEI analysis is crucial for breeding quality traits. A study in Zimbabwe assessed the grain yield performance of zinc-enhanced, provitamin A, normal, and quality protein maize lines across stress and non-stress environments. The results identified high-yielding and stable lines that could be used for developing nutrient-enhanced hybrids with improved seed producibility (Matongera et al., 2023).

In conclusion, understanding the interaction between genetic and environmental factors is vital for improving maize grain quality. Breeding programs should focus on selecting genotypes that perform well under specific environmental conditions and consider traits that enhance adaptation to varying environments. This approach will lead to the development of stable and high-yielding maize hybrids suitable for different growing conditions.

5 Case Studies and Practical Applications

5.1 Successful breeding programs

Successful breeding programs have significantly contributed to improving maize grain quality by focusing on both genetic and environmental factors. For instance, a study conducted in West and Central Africa demonstrated substantial genetic gains in maize cultivars developed over three breeding eras. These cultivars were bred for resistance to Striga parasitism, drought, and low soil nitrogen, resulting in an average yield increase of 40 kg ha-1 per year under optimal conditions and 30 kg ha-1 per year under stress conditions (Badu-Apraku et al., 2015). Similarly, in Eastern and Southern Africa, quality protein maize (QPM) hybrids were developed to withstand drought and low soil fertility. The hybrids H40, H41, H56, and H58 showed high yield stability across various environments, making them suitable for breeding programs aimed at stress and non-stress conditions (Mebratu et al., 2019).

In Greece, the interaction of genotype by environment was studied to evaluate grain quality traits. The study found that specific environments could enhance protein and fiber content, suggesting that targeted breeding programs could improve these quality traits by selecting appropriate genotypes for specific environments (Katsenios et al., 2021). Additionally, in Spain, breeding programs focusing on yield stability under stress conditions identified genotypes with desirable traits such as kernel depth and ear length, which contributed to higher yield stability (Romay et al., 2010).

5.2 Technological innovations

Technological innovations have played a crucial role in enhancing maize grain quality. For example, the use of near-infrared (NIR) spectroscopy in a study involving 501 diverse temperate maize inbred lines allowed for the prediction of 16 compositional traits, including carbohydrates, protein, and starch. This technology enabled the identification of significant genetic and environmental factors affecting grain quality, providing valuable insights for breeding programs (Renk et al., 2021).

In Brazil, the application of nitrogen (N) fertilizers was found to significantly influence grain quality. Studies showed that N application increased grain yield, N concentration, and kernel hardness while reducing breakage susceptibility. This highlights the importance of optimizing N application rates to improve both yield and grain quality (Duarte et al., 2005). Furthermore, a comparative analysis of maize grown under different planting densities and ecological environments revealed that factors such as light, accumulated temperature, and precipitation significantly affected grain quality. This information can be used to develop region-specific agronomic practices to enhance grain quality (Li et al., 2011; Tian et al., 2021).

5.3 Farmer experiences and insights

Farmers' experiences and insights are invaluable in understanding the practical applications of research findings. In central Argentina, on-farm multi-environmental trials were conducted to analyze the influences of genotype, management, and environmental variables on grain yield. The study found that management practices such as planting date, stand density, and nutrient availability significantly impacted grain yield, providing farmers with actionable insights to optimize their practices (Gambin et al., 2016).

In Nebraska, USA, a study distinguished the contributions of climate, agronomic management, and genetic technologies to maize yield gains. It was found that 48% of the yield gain was associated with climate trends, 39% with agronomic improvements, and only 13% with genetic technologies. This underscores the importance of agronomic practices and climate adaptation in achieving yield gains, offering farmers practical strategies to enhance productivity (Rizzo et al., 2022).

In conclusion, the integration of successful breeding programs, technological innovations, and farmers' experiences has significantly contributed to improving maize grain quality. By understanding and leveraging genetic and environmental factors, it is possible to develop targeted strategies that enhance both yield and quality, ultimately benefiting farmers and the agricultural industry as a whole.

6 Future Directions and Research Priorities

6.1 Emerging technologies

The future of maize grain quality improvement lies significantly in the adoption and integration of emerging technologies. Genomic selection and genome editing, such as CRISPR-Cas9, offer promising avenues for enhancing specific grain quality traits by directly targeting and modifying genes associated with these traits. For instance, the study by Renk et al. (2021) highlights the potential of genome-wide association studies (GWAS) in identifying significant single nucleotide polymorphisms (SNPs) that influence compositional traits like protein and starch content. Leveraging such technologies can accelerate the breeding process and improve the precision of selecting desirable traits.

Additionally, advancements in phenotyping technologies, including near-infrared (NIR) spectroscopy, can facilitate rapid and non-destructive assessment of grain quality traits, as demonstrated in Renk et al. (2021). These technologies can be integrated into breeding programs to monitor and select for high-quality grain traits more efficiently. Furthermore, the use of mixed-effects models and principal component analysis (PCA) to understand genotype by environment interactions (GEI) can help in identifying stable genotypes across diverse environments, as shown in1and Katsenios et al. (2021).

6.2 Policy and economic considerations

Policy frameworks and economic incentives play a crucial role in promoting the adoption of improved maize varieties and sustainable agricultural practices. Governments and international organizations need to invest in research and development to support the breeding of high-yielding and quality maize varieties. The study by Rizzo et al. (2022) emphasizes the importance of distinguishing the contributions of genetic, climatic, and agronomic factors to yield gains, suggesting that future investments should prioritize agronomic improvements alongside genetic advancements (Figure 2).

Economic policies should also focus on providing subsidies and financial support to farmers adopting new technologies and improved maize varieties. For instance, the findings in Bozovic et al. (2022) indicate that different herbicide treatments and management practices significantly affect maize yield and quality. Therefore, policies that support integrated pest management and sustainable farming practices can enhance grain quality and yield stability.

Moreover, international trade policies should consider the quality standards of maize grain to ensure that exported maize meets the nutritional and safety requirements of importing countries. This is particularly relevant for countries like Brazil, where maize is a significant export commodity, as discussed in Duarte et al. (2005).

6.3 Sustainability and food security

Sustainability and food security are paramount in the context of maize production (Ma et al., 2023). The increasing demand for maize as a staple food and its role in food security necessitate sustainable agricultural practices that ensure long-term productivity and environmental health. The study by Tian et al. (2021) highlights the impact of ecological factors such as light, temperature, and precipitation on maize yield and quality, underscoring the need for region-specific agronomic practices that optimize these factors.

Breeding programs should focus on developing maize varieties that are resilient to climate change and environmental stresses such as drought, low soil fertility, and pest attacks. The research by Romay et al. (2010) and Badu-Apraku et al. (2015) demonstrates the importance of selecting genotypes with stable performance under stress conditions, which is critical for maintaining yield and quality in the face of climate variability.

Furthermore, sustainable maize production should incorporate practices that enhance soil health, such as crop rotation, cover cropping, and reduced tillage. These practices can improve soil fertility and structure, leading to better water retention and nutrient availability, which are essential for high-quality grain production.

The integration of emerging technologies, supportive policy frameworks, and sustainable agricultural practices are essential for improving maize grain quality and ensuring food security. Future research should continue to explore the genetic and environmental factors influencing grain quality and develop strategies that address the challenges posed by climate change and resource limitations. The researchers can achieve a more resilient and productive maize production system that meets the nutritional needs of a growing global population.

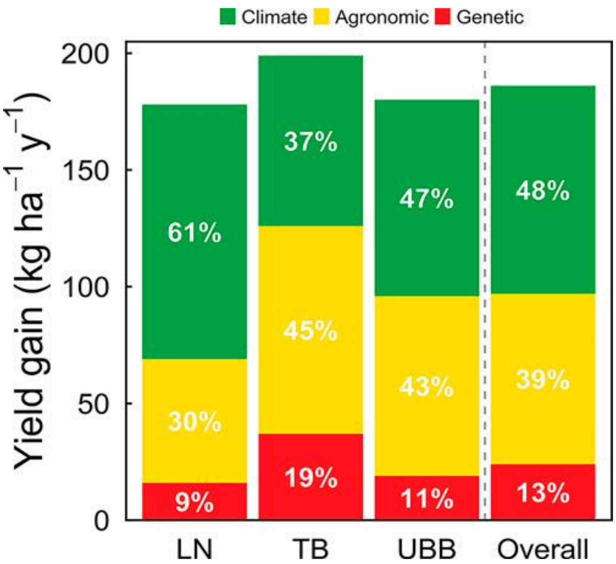

Figure 2 Contribution of Climate Change, Agronomic Management, and Genetic Improvement to Maize Yield Gain in Different Regions (Adopted from Rizzo et al., 2022)

Image caption: Total yield gain and contribution from changes in climate and adoption of agronomic and genetic technologies for each region; Lower Niobrara (LN), Tri-Basin (TB), and Upper Big Blue (UBB). Also shown are the averages across the three regions. Numbers inside bars indicate the relative contribution of climate (green), agronomic management (yellow), and genetic improvement (red) to the total yield gain (Adopted from Rizzo et al., 2022)

7 Concluding Remarks

The research on genetic and environmental factors influencing grain quality in maize has revealed several critical insights. Firstly, genotype and environmental interactions (GEI) play a significant role in determining maize grain yield and quality. Studies have shown that different genotypes respond variably to environmental conditions such as drought, low soil fertility, and planting density, which significantly affect grain yield and quality traits like protein, starch, and oil content.

In Argentina, late-sown maize trials indicated that management variables like planting date, stand density, and nitrogen availability, along with environmental factors such as soil type and rainfall, significantly influence grain yield. Similarly, in Eastern and Southern Africa, quality protein maize hybrids exhibited significant GEI, with certain hybrids performing better under specific stress conditions like drought and low nitrogen. In Greece, the stability of maize hybrids' yield and quality traits was also found to be highly dependent on the interaction between genotype and environment. Additionally, genetic studies have highlighted the substantial variation in grain compositional traits, with significant contributions from both genetic and environmental factors.

The findings underscore the complexity of breeding and managing maize for optimal grain quality. The significant influence of both genetic and environmental factors necessitates a multifaceted approach to maize cultivation. Breeding programs must focus on developing genotypes that are not only high-yielding but also stable across diverse environmental conditions. This includes selecting for traits that confer resilience to climatic stresses and optimizing agronomic practices to enhance grain quality.

Future research should continue to dissect the genetic basis of grain quality traits and their interaction with environmental variables. This will enable the development of more precise breeding strategies and management practices tailored to specific environments. Additionally, the integration of advanced genomic tools and phenotypic analyses will be crucial in accelerating the improvement of maize grain quality. In conclusion, achieving high-quality maize grain requires a synergistic approach that combines genetic improvement with optimized environmental management. By leveraging the insights gained from these studies, we can enhance maize production to meet the growing demands for food security and quality in various regions worldwide.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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