Colegio de Postgraduados

Challenges and Opportunities in the Specialization of Maize Cultivation

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ABSTRACT

Objective: To identify current scientific information on maize (*Zea mays* L.) in relation to the challenges and opportunities associated with the specialization of this crop.

Design/methodology/approach: A bibliographic search was conducted in high-impact journals focusing on the difficulties and opportunities in maize cultivation.

Results: Several key challenges in maize cultivation were identified, including the impact of climate change, limited access to technologies for small and medium producers, variability in grain price, and the availability of improved seed to increase yields in their reproductive zones. One potential solution involves access to improved short-cycle varieties with tolerance to adverse factors (both biotic and abiotic), combined with sustainable agricultural techniques such as conservation agriculture.

Limitations on study/implications: Despite existing research on maize cultivation, its composition, nutritional contribution and economic importance, the profitability of this crop is affected by factors such as price variation, climate change, and the incidence of pests and diseases. Therefore, further research is needed to identify varieties with more competitive markets to enhance sustainability.

Findings/conclusions: Maize is a globally important crop with industrial applications and uses for both human and livestock consumption. The increasing demand underscores the need to improve its performance and profitability. A strategy to increase production involves promoting diversification through the specialization of varieties with more competitive markets and the adoption of sustainable agricultural techniques.

Keywords: Maize, stress, climate change, hybrids, profitability.

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INTRODUCTION

Globally, maize (*Zea mays* L.) is recognized as one of the most important cereals, playing a fundamental role in human consumption and the livestock sector. Projections for the 2030 decade estimate that maize will be the crop with the highest production, consumption, and commercialization worldwide (Erenstein *et al.*, 2022).

The prominent position of maize cultivation is directly linked to its versatility in uses and adaptability. In addition to its significant role in nutrition, maize also represents a key raw material in the industry, as it is used in edible products, biofuels, plastics, and other

industrial products (Ruan *et al.*, 2019). In countries like Mexico, maize is not only a staple food (Eakin *et al.*, 2014) but also a fundamental part of the country's history and culture (Cervantes *et al.*, 2014). Mexico hosts a great diversity of maize, with 59 recognized races (Duncan *et al.*, 2019) and thousands of varieties adapted to different climatic conditions and altitudes, representing approximately 50% of the genetic diversity of maize in the American continent (Ureta *et al.*, 2020).

The increase in global population and the growing demand from industries such as food and energy pose a significant challenge to increase the productivity and efficiency of maize cultivation (García-Lara and Serna-Saldivar, 2019; Ruan *et al.*, 2019). To meet this demand, it is necessary to innovate in crop management to explore specific market niches that encourage its development. One of the promising strategies focuses on the specialization of cultivation, which involves the development of maize varieties adapted to specific needs in terms of yield, nutritional quality, resistance to pests, diseases, and adverse environmental conditions (Bekele and Rao, 2013), coupled with special technological applications of industrial interest.

While the specialization of maize cultivation has generated significant advances such as the development of hybrids and improved varieties to meet the specific demands of the industrial sector, it also poses important challenges regarding the loss of genetic diversity (Darrah *et al.*, 2019). Therefore, it is essential to adopt a balanced approach that allows for the preservation of this diversity while also offering the market the advantages and opportunities of maize cultivation specialization. In this context, the aim of this analysis was to identify the current scientific information on maize (*Zea mays* L.) regarding the challenges and opportunities associated with the specialization of this crop.

MATERIALS AND METHODS

A search on the specialization of maize (*Zea mays* L.) cultivation was conducted using the keywords: *Zea mays* L., maize cultivation, maize cultivation specialization, maize issues, climate change, food security, genetic improvement, and maize uses, in the databases of ScienceDirect, Wiley, Springer, Google Scholar, Scielo, and MDPI. Scientific articles from 2013 to 2024 were selected, prioritizing updated information on the topic.

RESULTS AND DISCUSSION

Challenges in maize cultivation; climate change in production

Constant changes in markets exert significant pressure on the agricultural production sector. In particular, the increase in demand and uncertain prices of maize grain drive the search for alternatives, such as cultivation specialization. This strategy aims to obtain economic advantages, improve production efficiency, and access higher value-added markets. However, this process faces a series of challenges that require attention and appropriate solutions (Bekele and Rao, 2013).

One of the greatest challenges for agriculture is climate change, which is expected to have increasingly intense effects on cultivation environments. In the first two decades of the 21st century, a global surface temperature increases of 0.99 °C compared to the 1850-1900 period has been recorded, along with an increase in CO_2, CH_4, and N_2O levels due to intense human activity (Intergovernmental Panel on Climate Change: IPCC, 2023). This has increased the incidence of climatic events such as droughts, variations in precipitation (Sharma *et al.*, 2022), floods, tropical cyclones (Murray-Tortarolo *et al.*, 2018), heatwaves, and cold waves (IPCC, 2023). Together, these factors increase the incidence of damage from biotic factors in crops like maize (Erenstein *et al.*, 2022), and pose future displacements of pests and diseases, along with a reduction of beneficial soil microorganisms (Sharma *et al.*, 2022).

In Mexico, a reduction in rainfall distribution and quantity, along with an increase in temperature, more droughts, and tropical cyclones is forecasted (Cervantes *et al.*, 2014). These phenomena will affect maize productivity, projecting a near 10% reduction in Latin America by 2055 (Murray-Tortarolo *et al.*, 2018).

Specifically, increased temperature has been associated with a decrease in maize yield (Ureta *et al.*, 2020), as it directly affects the vegetative period, pollination, and grain filling (Noriega-Navarrete *et al.*, 2021). This represents an inherent risk and directly impacts food security. Food security aims to ensure that, for foods such as maize, there is supply, access, availability, and affordability exist to achieve consumption and nutrition for the population. Given the high dependency on this crop in sectors such as livestock and industry, production for human consumption is likely to be reduced.

Additionally, it is relevant to note that climate change has a significant effect on rain-fed agriculture. In Mexico, approximately 80% of the maize cultivation area is dependent on these conditions (Cervantes *et al.*, 2014). Authors such as Ureta *et al.* (2020) mention that local varieties face greater difficulties adapting to higher temperatures and combined with reduced water access during flowering and grain filling stages, this results in a negative impact on yield (Sharma *et al.*, 2022).

Maize Production by Small and Medium Farmers; Grain Price Variation and Imports

Another aspect to consider in the challenges is that at least one-third of maize production in Mexico comes from small producers, whose cultivation areas are less than 5 hectares (Ureta *et al.*, 2020). This production is mainly focused on self-consumption, mostly under a rain-fed production system (Ibarrola-Rivas *et al.*, 2020). Producers face significant limitations in available resources such as access to inputs, improved seeds, agrochemicals, and fertilizers. They also have limited agricultural mechanization capacity and access to competitive markets (Eakin *et al.*, 2014). In contrast, in countries such as the United States, China, and Brazil, large producers have access to technology, extensive land, and hybrid and genetically modified seeds, which gives them a considerable advantage in crop efficiency and profitability (Erenstein *et al.*, 2022).

In the international market, Mexico's dependence on maize creates constant concern for small and medium producers due to falling prices. For example, at the beginning of 2024, a large supply of maize from other producing countries reduced the price from \$244.08 to \$182.47 per ton, representing a decline of more than 20% (García, 2024). These variations are related to market expectations about increased demand, speculation from major traders, and global maize supply. In a speculative environment, production cannot be estimated accurately, which disrupts supply and impacts maize marketing prices (Shobande and Shodipe, 2021), placing national production at a significant disadvantage.

Low maize prices leave producers with minimal or no profit margins, affecting food security in maize-dependent countries like Mexico and impacting other industries related to this cereal (Sayed and Auret, 2019). This volatility in maize prices is closely linked to various factors such as climate change, tariff and import costs, production costs, and productivity, among others. In relation to the major maize producers, the United States, Brazil, and Argentina account for approximately 70% of global maize exports (Ruan *et al.*, 2019; Sayed and Auret, 2019).

Although Mexico is the seventh-largest producer worldwide (SADER, 2023), it shows continuous dependency. In 2022, maize imports reached nearly 17 million tons, equivalent to 57.1% of national production (Ramírez-Díaz *et al.*, 2023). These imports are primarily of yellow grain destined for the livestock sector.

The Challenge of Genetic Improvement and Transgenic Materials

Regarding the development of improved maize germplasm, this has marked a turning point in the agro-food production system of this crop. The development of maize hybrids involves the selective combination of inbred parent lines to find heterosis or hybrid vigor (Tripathy *et al.*, 2017). This process requires years of work by breeders in the search for parents that contribute the necessary characteristics to increase yield (Fromme *et al.*, 2019), tolerance to biotic and abiotic factors, higher plant density (Haegele *et al.*, 2013), as well as adaptability and ease of production (Kutka, 2011). This involves a considerable investment in resources, time, and research.

Additionally, water supply, soil type, and nutrient availability must be considered (Assefa *et al.*, 2016). These conditions are not present in all environments, so varieties must be carefully selected for specific regions, representing a constant challenge for breeders. It should also be considered that intensive production systems can contribute to soil degradation in the medium and long term due to the reduction of organic matter and nutrients, affecting soil fertility. This problem increases the dependence on inputs such as fertilizers, which, when used for extended periods, will have negative impacts on the environment (Erenstein *et al.*, 2022).

To increase yields and crop resistance, transgenic maize varieties have also been developed. These genetically modified varieties contain genes that confer resistance to insects, tolerance to herbicides such as glyphosate, and some tolerance to abiotic factors such as drought. These advances are mainly adopted in major producing countries such as the United States and Brazil, where transgenic maize cultivation represents about 90% (Duncan *et al.*, 2019). This approach focuses primarily on benefits such as increased yields, reduced use of agricultural inputs (pesticides), and resistance to pests and diseases (Yadava *et al.*, 2017). However, the adoption of these materials can have an ecological, socioeconomic, and cultural impact in a country like Mexico, which is the main center of origin and domestication of maize, as its use could cause contamination of native maize with transgenes (Luna and Altamirano, 2015). In this regard, the acceptance and regulation of these crops in Mexico generates debates about the effects and repercussions on food security, biodiversity, and farmers' sovereignty (Erenstein *et al.*, 2022), suggesting that the acceptance of genetically modified material may not be viable or imminent for future scenarios. Currently, approximately two-thirds of the production comes from open-pollinated local varieties, valuable for their genetic diversity, adaptation, and particular characteristics (Duncan *et al.*, 2019).

In the maize improvement approach, Quality Protein Maize (QPM) varieties have been developed, with the aim of enriching diets for human consumption by increasing the content of essential amino acids (lysine and tryptophan). However, the initial experiments exhibited undesirable characteristics such as unpleasant taste, soft and floury endosperm, leading to increased susceptibility to pests and diseases, and reduced yield at harvest (Tripathy *et al.*, 2017). This case highlighted some of the difficulties encountered in obtaining specific desired characteristics in the crop. Currently, efforts continue to develop protein-quality maize with agronomic characteristics and acceptance for commercialization.

In this context, the research and adoption of viable technologies are fundamental for the sustainable production of maize. To adequately address the identified challenges, an integrated approach is required, which also includes sustainable agricultural practices (conservation agriculture), as activities such as plowing and harrowing have caused the deterioration of soil structure and quality (Martínez-Gamiño *et al.*, 2020). Additionally, there is a need to provide access to technologies for small producers, training programs, and agricultural sector policies that promote inclusion and equity in access to more competitive markets for maize. These measures can significantly contribute to improving and incentivizing maize production.

Opportunities in Maize Cultivation

The global importance of maize cultivation is based on its versatility and broad usage, attributed to its genetic diversity. Its applications range from livestock feed to food and non-food uses. This crop plays a crucial role in food security and nutrition, contributing directly and indirectly to the human diet (Ranum *et al.*, 2014). For example, it is estimated that approximately 3 kg of maize and soybean grain is estimated in ruminant diets that produce around 1 kg of meat (Erenstein *et al.*, 2022), mainly due to the energy contribution of lipids and proteins present in the grain.

To strengthen sustained maize production and contribute to future food security, it is essential to involve and integrate research, development, and technology transfer, as well as the implementation of public policies and training for producers to identify development opportunities for maize cultivation. In this regard, it is important to clarify that information on maize for special uses is limited. According to the SIAP database (2023), the existing information on maize production is categorized into three major groups: green fodder maize, grain maize, and popcorn maize. For this last case, the data on the platform reported a production of 246.72 tons of popcorn maize. Regarding grain maize, 27,549,917.53 tons were recorded, of which, as specialty maize, only the categories of colored maize (59,747.74 tons), blue maize (12,073.39 tons), and pozole maize (26,960.81 tons) are presented. These data allow us to see that the reported production of specialty maize in Mexico represents less than 0.5% of the national production, with these types of maize having the highest commercialization value. With this in mind, the promotion of specialty maize is proposed as an opportunity to boost production and the economic advantages that they can bring. To achieve this, specific programs must be developed and collaboration between academic institutions, governmental bodies, and the private sector to successfully drive this initiative.

Grain prices and crop specialization

Faced with eventualities, especially variations in the sale price of maize grain, various alternatives can be considered. Establishing a minimum sale price (Shobande and Shodipe, 2021), paying for risk coverage, or using sales contracts (Harčariková, 2018) are strategies that can be employed to minimize the effect of falling maize crop prices. Reyes-Santiago *et al.* (2022) mention that in Mexico, guaranteed prices are defined as an economic policy instrument aimed at increasing the price received by producers (above the market equilibrium) while maintaining the price for consumers (below the market level), with the government covering the difference. These same authors emphasize that guaranteed prices in Mexico encourage maize production, although in a conservative manner. They recommend interaction with other support programs for the agricultural sector, such as fertilizer subsidies. Regarding the price of maize grain, it should be noted that it varies according to the type of grain being sold. In this sense, those focused on specialized applications command better prices than those intended for the livestock sector. For example, in Mexico, in 2023, popcorn maize had an average rural price of $8,283.94 per ton, pozole maize $7,244.92 per ton, blue grain maize $6,406.64 per ton, while white and yellow grain sold for $6,253.34 per ton (SIAP, 2023). This highlights the opportunity presented by specialty maize as a proposal to diversify production and identify the most profitable markets for producers.

Under this approach, it is important to highlight the existing diversity in maize in terms of color, ranging from white to dark blue, and varieties of maize with unique characteristics such as sweet maize, waxy maize, high oil content, high amylose content, high protein content, among others (Serna-Saldivar, 2019). The use of these specialized crops offers advantages for more profitable trades and the promotion of niche markets, such as snacks, cereals, and preserves, among others.

Examples of Recognized Specialty Maize Types

The so-called specialty maize varieties are those that present specific characteristics making them useful for applications in both food and industrial sectors. These differences are closely related to variations in the endosperm, pericarp, and germ, as well as the starch composition and proximate analysis (Serna-Saldivar, 2019). These specific attributes provide the opportunity to identify and penetrate markets with higher profitability for maize.

Among these types of specialty maize of interest is the variety used for higher oil extraction. This component is primarily found in the germ of the grain. For this purpose, the oil content must be above 6% (García-Lara and Serna-Saldivar, 2019). This variety of maize has a high content of monounsaturated fats with a high content of oleic acid, which has demonstrated cardiovascular health benefits (Darrah *et al.*, 2019). Among the industrial advantages of fatty acids obtained from maize, oleic acid, for example, exhibits greater oxidative stability, thus a longer shelf life, making it suitable for frying processes and high-temperature conditions (Barrera-Arellano *et al.*, 2019).

In Mexico, a highly recognized type of specialty maize is the one used for pozole, which has specific characteristics such as large, starchy kernels, like Cacahuacintle, Ancho, and Western maize varieties. These kernels, after cooking, open like a flower and produce foam when boiled (pozolli comes from the Nahuatl word meaning "foamy"). This type of maize can be sold in its unprocessed form, which means selling the maize grain as-is without added value, as well as precooked and dehulled maize for pozole (García-Lara and Serna-Saldivar, 2019).

Also known as "popcorn maize," this is a yellow or white grain of maize with a high proportion of vitreous endosperm and a hard pericarp. When this type of grain is subjected to elevated temperatures, the moisture content turns into steam, causing the grains to explode. They exhibit a high endosperm expansion rate, expanding 30 to 40 times their original size (García-Lara and Serna-Saldivar, 2019). This type of maize is highly valued for producing snacks such as those consumed in cinemas and recreational events.

Another type of maize used for specific industrial purposes is known as "hard corn". It features a corneous or vitreous endosperm proportion greater than 90% and a high starch content (Tagmano *et al.*, 2016). This type of maize is utilized in the production of semolina, flours, and starch, and is employed in the production of ethanol and sweeteners such as maize syrup. These derivative products are obtained from the processing of maize grain, where the components are separated, and starch-forming endosperm serves as an essential substrate for glucose products (sweeteners) and those processed by fermentation (ethanol) (Ruan *et al.*, 2019).

Pigmented maize varieties are another example of a specialization in maize cultivation. These varieties exhibit colors such as red, blue, and purple in various shades and intensities. The presence of these pigments is found in the aleurone layer and the pericarp. The phytochemical compounds present in higher proportions are anthocyanins, which have demonstrated nutraceutical properties (García-Lara and Serna-Saldivar, 2019). In this regard, their application as pigments can be varied, both in the food and non-food sectors. The advantage is that, in addition to providing color, they also possess antioxidant activity. These examples of maize types provide a broad and complex landscape in which production can be promoted to enter these developing markets in Mexico or for export to countries where these maize types are already industrialized (biofuels, breakfast cereals, snacks, beverages, etc.). As mentioned, these markets require specific characteristics in maize, which are dictated by the industries that demand them. In this regard, current tools enable the improvement and development of materials with the highest possible quality.

Genetic improvement as a tool for specialization

The application of maize in processed products varies according to region, country, and local customs. In some countries, maize is a central part of the diet and is used in various edible products (Ranum *et al.*, 2014). However, maize specifically provides minimal amounts of essential amino acids such as lysine and tryptophan, representing a nutritional challenge. To address this problem, quality protein maize (QPM) varieties have been developed, which contain a higher proportion of these essential amino acids (Tripathy *et al.*, 2017), with the aim of improving nutritional intake (Maqbool *et al.*, 2021). The development of important varieties such as QPM represents a significant advance in genetic improvement and another example of maize crop specialization, which aims to address the nutritional deficiencies of populations that rely on this crop as their main food source (Tandzi *et al.*, 2017). This approach highlights the opportunities that can contribute to boosting the agricultural sector and counteracting the nutritional deficiencies of the population.

Waxy maize, high-amylose, and sweet maize varieties are other examples of genetic modifications and improvements developed to provide specific characteristics to this cereal. In the food sector, waxy maize is a variety modified so that the main component of endosperm, called starch, is almost entirely amylopectin, with a content greater than 95% (in contrast to normal starch, which has approximately 75% amylopectin and 25% amylose). The characteristics of this type of starch, which are of industrial interest, are that when extracted through the wet milling process (in waxy maize), it allows for the formation of viscous pastes, low tendency to retrogradation, ease of enzymatic hydrolysis, and the formation of soft, transparent gels that easily disintegrate. Therefore, it is ideal for food applications such as desserts, frozen products, and dressings (García-Lara and Serna-Saldivar, 2019).

High-amylose maize (amylomaize) features a recessive gene that expresses high production of linear amylose, which is stored as starch in the endosperm. Its content ranges between 37% and 65%. Its industrial importance lies in the technological and functional properties provided by amylose, including the formation of rigid, opaque gels with a high tendency to retrogradation. Its potential applications are found in the textile, paper, adhesives, and biodegradable foam packaging industries, as well as in the confectionery industry (García-Lara and Serna-Saldivar, 2019).

Some varieties, such as sweet maize, are sought for consumption in their immature state. This variety has been developed through genetic modification and features recessive genes that reduce starch synthesis in the endosperm, resulting in maize kernels with a higher sugar content (Dong *et al.*, 2019). This variety is consumed as maize on the cob, when the kernels are tender and have a high water and sugar content, providing the characteristic flavor (Singh *et al.*, 2014). It is primarily consumed fresh but can also be found frozen, canned, and pickled, and is used in dishes, salads, sauces, etc. (García-Lara and Serna-Saldivar, 2019).

It should be recognized that, in addition to the characteristics provided by genetic improvement in maize, it has also contributed to increased and stable yields, particularly in areas prone to variations in water availability (Cooper *et al.*, 2014), such as rainfed maize cultivation areas. In this sense, hybrid varieties show superiority in aspects such as efficient nitrogen use, higher leaf photosynthesis rates, increased plant density, and tolerance to adverse environmental conditions, all as a result of the rigorous selection process (Fromme *et al.*, 2019). However, to ensure the optimization of available resources, they must be accompanied by appropriate agronomic practices that develop their potential, thus contributing to food security and the sustainability of agricultural production (Darrah *et al.*, 2019).

Industrial Uses of Specialty Maize

The primary use of maize is focused on livestock feed production, where it can constitute up to 70% of the diet (García-Lara and Serna-Saldivar, 2019). This cereal, in its dry form, has an approximate composition of proteins (≈9%), oil (≈4%), fiber (≈10%), starch (≈75%), and ash (≈2%). Therefore, maize has a wide range of both food and non-food applications (Ruan *et al.*, 2019). In this context, products can be obtained from immature and sweet maize to starches, flours, and semolinas, which are the base for bakery products, snacks, breakfast cereals, beer supplements, tortillas, and various other snacks.

An interesting industrial component is the oil contained in the germ of the maize kernel. This oil is in high demand, which has driven the development of specialized hybrid materials to increase content and optimize extraction. These maizes have an oil content greater than 6% and are obtained from hybrids specifically developed and selected for this purpose. The sought-after and recommended fatty acids are oleic or linoleic acid, palmitic, and stearic acids, which are associated with the reduction of arterial blockages (Darrah *et al.*, 2019).

On the other hand, the starch present in the endosperm of the grain is used as a base to produce maize syrup (Singh *et al.*, 2014), a sweetener in high demand by the beverage and soft drink industry (White, 2008), due to its sweetness comparable to sucrose, stability, and ease of use. The type of maize used for this purpose is hard maize, due to its starch and flour yield, as well as the quality and high purity obtained from it.

The starch from the endosperm of grain is also used by the distilling industry to produce alcoholic beverages and biofuels such as bioethanol (Ruan *et al.*, 2019). For this, the material is conditioned and hydrolyzed by yeasts to ultimately be distilled and recover the alcohol. During this process, high-nutritional-value by-products are generated, consisting of grain residues enriched during fermentation with the addition of biomass, vitamins, and amino acids, which are specifically used for the livestock sector.

Technological advancements and genetic improvements are closely linked to the specialization of maize cultivation, particularly in the focus on grain intended to produce a variety of products such as flours, starches, oils, protein, fiber, and maize semolina (Ruan *et al.*, 2019). These advances allow greater competitiveness and sustainability in maize cultivation, helping to meet the growing demand for maize-related products both nationally and globally.

This integrated approach to research and development is crucial for advancing food security and sustainability, as well as promoting economic prosperity in the agricultural sector. In this context, the specialization of maize cultivation in different products and specific uses allows its utilization according to the demands of specialized markets. In this regard, the selection of varieties and genetic improvement are of utmost importance to increase yield, tolerance to biotic and abiotic factors, and focus on specific applications, with the goal of contributing to the competitiveness and sustainability of the agricultural sector and the development of maize-producing regions.

These described examples highlight opportunities to diversify and revitalize maize production, which is a significant resource for farmers. The cultivation of specialty maize varieties meets specific market demands, offering greater profitability for this crop. Therefore, diversifying maize cultivation in Mexico represents an innovative and adaptive strategy in the agricultural production sector to address the changing needs of the consumer market.

CONCLUSIONS

Maize is a crop of significant global importance due to its use in human consumption, livestock feed, and various industries. In recent decades, there has been a notable increase in its demand, opening opportunities to enhance its performance and profitability. In Mexico, where challenges in maize production are prevalent, there is potential to encourage diversification of this crop through specialization. This involves promoting the production of varieties with specific uses, such as popcorn, pozole, and colored maize, which can offer higher profitability. Specialized maize production not only presents an alternative for meeting specific market niches but also serves as a means to diversify farmers' incomes and improve the profitability of maize production in Mexico. Identifying and promoting maize varieties with special uses can be a strategy to address the current challenges in maize production and advance towards food security and sovereignty for the country.

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