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Improved Technological Processes on the Nutritional Quality of Maize

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Abstract

As global food security and staple food, maize has become one of the most widely used cereals for fundamental research. Several important discoveries are reported, some of which are technological processes being used to improve maize crops' dietetic, phenotypic, genotypic, and organoleptic properties. This chapter provides insight into improved technological techniques such as crossbreeding, genetic cloning, and functional genomics and how they improve the nutritional quality of maize crops. The use of these technological processes could be one of the sustainable strategies in meeting the dietary needs and livelihood of Africa, Mexico, and Latin America's growing populace.

Keywords: breeding, genomics, functional genomics, improved technological processes, maize nutritional quality

1. Introduction

Maize (*Zea mays ssp.*) is one of the widely-spread staple cereals globally since its introduction to the New World by Christopher Columbus in the fifteenth century [1, 2]. Maize originated from central Mexico 7000–9000 years ago as a wild grass known as teosinte [3]. Today, maize is a cereal that serves as a significant food source in animal and human nutrition, playing an essential role in feeding the world. It is the most researched cereal due to its significant strategic role in social and economic development, mainly in Asia and Africa [4], impacting economic growth activities, including employment. Based on FAOSTAT [5] report, maize and its products contributed 6.5%, 30%, and 38% of food supply to Asia, the Americas, and Africa. Africa's farmland used for maize cultivation is 24% [5]. Although maize production has made a critical contribution to food security and poverty in many African countries, there have been persistent challenges, causing a low maize yield and poor crop nutritional quality.

Nevertheless, Otekunrin et al. [6] assert that maize production can still play an essential role in achieving poverty alleviation and zero hunger. They illuminated the importance of channeling the support from the agricultural ministry on educated maize farmers from an empirical study conducted in Ghana. They argue that knowledgeable farmers can effectively use new technologies. Technical efficiency, which is the ability to use available resources for maximum output, influences the choices for the strategies used for productivity improvement.

Maize evolved enormously, alienating itself from some key traits of teosinte. For example, teosinte has abundant branches and tillers, increased number of ears per plant, reduced number of kernels per ear (5–12 per ear for teosinte and several hundred for maize), and small kernels with a hardened fruit case (reviewed in [7]). About 40 years ago, Beadle [8] observed that after he planted a teosinte–maize F₂ population consisting of 50,000 individuals, the frequency of parental types was ~1 in 500, then estimated that there were four or five major loci involved in maize domestication. Later, Doebley and Stec [9] mapped five major quantitative trait loci (QTLs) plus some minor-effect QTLs for key traits in which teosinte and maize differ. This result was consistent with Beadle’s estimation and indicated that a small number of loci were responsible for the teosinte–maize morphological difference. Wright [10] investigated 774 genes and estimated that 2–4% of maize genes were selected during maize domestication and subsequent improvement. According to recently released gene annotations of high-quality maize genomes, modern maize contains ~39,000–42,000 protein-coding genes [11–14], indicating that ~800–1700 protein-coding genes ($39,000 \times 2\% = 800$; $42,000 \times 4\% = 1700$) underwent selection during the process of domestication (**Figure 1**).

Recently, two researchers [16, 17] used chromatin interaction analysis by paired-end tag sequencing (ChIA-PET) technology to map genome-wide chromatin interactions. They revealed their connections to gene-expression regulation (**Figure 1**), including the chromatin interactions in which TB1, UB3, ZmCCT9, Vgt1 were involved. Likely, population-scale identification of chromatin interactions would allow the detection of many more important regulatory elements, providing several useful selection targets for improving future maize, which is essential in addressing poverty alleviation and zero hunger (sustainable development goals, 1 and 2, set by the United Nations in 2015 to achieve global food security by 2030) [18]. The current low in the maize crop yield calls for more comprehensive and more consistent crop production strategies. A newly introduced program named clustered regularly interspaced short

Figure 1. Genomic sequence variants in the *tb1* regions of teosinte and tropical and temperate maize lines [1]. (A) The red rectangles indicate the position of *tb1*, and the blue rectangles indicate the position of the hopscotch TE. This TE is the functional variant of *tb1* and is absent in teosinte [14]. (B–D) the increased expression levels of representative selected genes (*tb1* in B, *ZmSWEET4c* in C, *ra1* in D) in modern elite maize lines compared with teosinte, the ancestor of maize. The expression profile was obtained by analyzing RNA-seq data generated by Lemmon et al. [15].

palindromic repeats-associated protein (CRISPR-Cas) technology is widely used for plant genome editing. It can be hoped that the CRISPR-Cas system will accelerate the breeding of improved crop cultivars compared with conventional breeding and help to address the zero-hunger goal.

Although maize protein is high in the ratio of leucine to isoleucine, it lacks tryptophan and lysine, making it poor nutritionally. Also, threonine is found in a reduced quantity in common maize [19]. However, Mertz et al. [20] discovered an improved nutritional quality of maize mutant called *opaque 2* (O2). This O2 maize has 95% casein and 43% higher protein quality than common maize. Hence, efforts were made to integrate O2 as a commercialized variety but hindered by processing and agronomic problems [21]. O2 was characterized by the dull and chalky kernel, reduced grain yield, and susceptibility to stored grain pests and soft endosperm, making it unacceptable to farmers and consumers. Hence, quality protein maize (QPM) emerged. QPM is a genotype that incorporated modified *opaque 2*. QPM improved the poor keeping quality, deficient agronomic attributes of *opaque 2*, and the truncated nutritive value of normal endosperm; hence, it contained double tryptophan and lysine when juxtaposed with common maize endosperm [22]. Conventional breeding was used to develop QPM that possessed high lysine and complex endosperm characters by International Centre for Maize and Wheat Research (CIMMYT), Mexico, in 1993.

The breeding of QPM was introduced to improve the nutritional composition of protein in maize grain. Maize seeds contain an alcohol-soluble protein called zein [19]. QPM has a protein profile of 90% milk protein compared to the 40% milk biological value protein found in common maize [19]. Zein is more in the endosperm than in the embryo and constitutes 50–70% endosperm protein. Zeins are high in leucine, proline, and glutamine but are lack in tryptophan and lysine. Therefore, zein compositions are altered to enhance maize nutritional quality [19].

Maize products are shaped to make nutritious foods more available by using desirable characteristics and traits. Therefore, new varieties with high yields became the focus of maize breeders [23]. Information on the needs of maize users can be incorporated into the products' characteristics by the breeders. This information will increase the use of maize varieties and, most importantly, improve nutrition [24]. Worldwide, maize varieties vary genetically by hardness, sweetness, and grain's size and color, and this genetic variation results in diversity in nutritional properties of the whole maize grain. Maize endosperm is made up of 82% composition of maize kernel, which is mainly starch. Hence, the endosperm' protein profile of the maize kernel was improved by the QPM. The breeding of this QPM has been achieved through alteration in the recessive mutant allele of the O2 gene, a specific set of amino acid modifier genes and pair of endosperm hardness modifier genes. The kernels can be flint, pop, waxy, floury, or dent and provide micronutrients and macronutrients. There is a high level of antioxidants and minerals in the aleurone; minerals and fiber in the pericarps; antioxidants, protein starch, and vitamins in the endosperm; vitamins like vitamin E, fat, and minerals are rich in the germs [25]. The primary compounds in the kernels are cellulose and lignin, while secondary compounds are hemicellulose, β -glucans, and arabinoxylans. In maize, the presence of phytochemicals (anthocyanins, phlobaphenes, carotenoids, phenolic acids, nonpolar and polar lipids) prevents diseases and strengthens health.

2. Technologies on the nutritional quality of maize crop

This technological processing for increasing the nutritional quality of maize as a potential solution for nutritional deficiency can be classified into two main groups, preharvest technology and postharvest technology.

2.1 Preharvest technology

Preharvest technology discussion will include crossbreeding and genetic manipulation, functional genomics and transgenic crop technology, biofortification, functional genomics and transgenic crop technology, and soil improvement.

2.1.1 Crossbreeding and genetic manipulation

Crossbreeding method is used to transfer micronutrients density in unac-customed sources into genetic with a high-yielding competitive background. For the farmers to accept and adopt the newly developed trait, end-use quality and agronomic attributes must be considered during crossbreeding [26]. An increase in protein content such as methionine, tryptophan, and lysine is evidence for advancement in diet's nutritional content through breeding that fundamentally focuses on nutritional quality.

Physical appearance, cooking and eating quality, milling trait, and nutritive value are those parameters used to determine grain's overall quality [18]. These properties are to a large extent, especially the eating and cooking qualities, influenced by the amylose content of the maize, and thus open to genetic manipulation. Amylose, a polysaccharide that is made up of 20–30% starch, is a significant form of resistant starch. However, the amylose biosynthesis is modulated by the enzyme granule-bound starch synthase 1 (GBSS1) and encoded by the Waxy gene. Gao et al. [27], and Wang et al. [28] disrupted the GBSS1 with clustered interspaced and short palindromic repeats-associated protein (CRISPR-Cas) to produce elect maize that contains low amylose content. Also, CRISPR-Cas to encode isoamylase-type debranching enzyme been edited with isoamylase 1 (ISA1) produced low amylose content [29]. CRISPR-Cas uses the system of knock-out and knock-in to improve the quality of crops.

Phytate, an antinutrient content in maize, also referred to as inositol 1,2,3,4,5,6-hexakisphosphate, forms insoluble complexes with minerals and protein and reduces their absorption when consumed. Zinc finger nucleases (ZFNs) blocked gene coding IPK1 for enzyme inositol-1,3,4,5,6-pentakisphosphate 2-kinase to reduce the phytate concentration in maize [30]. Also, Qi et al. [31] used CRISPR-Cas and RNA interference (RNAi) which targeted the gene ZmMADS47 encoding a MADS-box protein that interacts with O2 to switch on zein gene promoter so that reduced zein protein content can be reduced. However, the decrease in zein content was 12.5% and 16.8% in the kernel of MADS/Cas9-21 and ZmMADS47 lines, respectively [31].

2.1.2 Functional genomics and transgenic crop technology

Genome editing is the principle on which functional genomics is based. It is based on nuclease-based forms of engineering like transcription activator-like effector nucleases (TALENs), clustered regularly interspaced short palindromic repeats (CRISPR) with the concerns of creation of mutations, precise incisions, and substitutions in eukaryotic and plant cells [32]. Transgenic crop technology directly inserts genes of interest into the plant genome. These are the only viable alternative for biofortifying crops with micronutrients that naturally do not exist in the crop [26]. Transgenic crop technology can be achieved at a low cost, short time, and without nutrition-based programs and ease the concurrent incorporation of the genetic system to reduce antinutrients, increase micronutrient concentration, and promote bioavailability.

A hybrid of QPM and provitamin A was developed by Zunjare et al. [33], which was speculated to help fight malnutrition among the populace where maize is used as a primary staple food. Based on QPM analysis, the required amount of tryptophan and lysine was achieved when switching conventional maize with a lesser amount of QPM [34]. Also, orange maize improved vitamin A in children's diet in Zambia [35].

Many kinds of cereal contain a high prevalence of phytic acid (PA), a significant zinc absorption inhibitor. Minerals like iron and zinc are bound by PA and prevent mineral absorption in the gastrointestinal tract. Some researchers like Brnić et al. [36] have reduced the PA in maize due to its nutritional consequences. Chemicals such as acetic acid and hydrochloric acid, microwave treatment or heat methods, and recombinant microbial phytate exogenously reduce PA in grains [37]. Transgenic corn expression phytate from *Aspergillus niger* was created to raise mineral availability by limiting PA through microbial phytate enzymes [38]. Eventually, low PA (lpa) phenotype cereal mutants have been developed in wheat, maize, and rice. The primary concern about this transgenic expression is its negative impact on agronomic performance and crop yield.

2.1.3 Biofortification

Biofortification is a primary means of fighting micronutrient deficiency in the world. Biofortification and supplementation are the traditional means of adding minerals and vitamins to food crops. The three essential means of biofortifying crops are biotechnology, conventional plant breeding, and adding an inorganic or mineral compound to fertilizer [37]. Essential micronutrients and β -carotene have been used to biofortified maize in order to maintain healthy living. In the 1970s, researchers developed quality protein maize (QPM) to increase maize's tryptophan and lysine content. These newly developed biofortified crops have a tremendous amount of micronutrients in the edible parts of the crops. Conventional breeding in maize has also been used to upgrade its nutritional content [25].

Nutritionally improved crops, such as orange maize (enhanced with zinc and biofortified with provitamin A carotenoids), quality protein maize (QPM) (biofortified with amino acids), have been developed by plant breeders. The commercialization of maize with provitamin A carotenoid is gaining traction in Western and Southern Africa [38]. Sowa et al. [39] reported 85% retention of carotenoid provitamin A in biofortified flour in the preparation of muffin and porridge. Adoption of biofortified crops is mainly tested by consumer acceptability of rural households where it is used to produce the different menus and prepared in their local ways. Consumers need to accept and use biofortified crops to prepare local foods to make the most of them. However, QPM was preferred by rural mothers in Ethiopia to conventional maize in the preparation of complementary food for children and infants [40]. Li et al. [41] and Muzhingi et al. [42] proved that biofortified maize efficiently converted provitamin A carotenoid to vitamin A. Hence, the daily requirement of vitamin A may be met by consuming biofortified maize.

Although the stability of carotenoids during storage is a significant challenge in provitamin A maize, consumption without dehulling improved the storage stability of carotenoids. Taleon et al. [43] studied different processing methods and storage environments of hybrid maize in Zambia. They proposed that maize biofortified with provitamin A should be sold just before consumption as whole grain and milled as such. Carotenoid degrades over time; therefore, fortified maize variety should be consumed before the white-unfortified maize.

The milling process, mode of cooking (refined versus whole grain flour), and container used for cooking will determine the zinc retention in biofortified maize. Zinc absorbed by Zambia children through zinc-biofortified maize helped to meet their zinc requirement [44]. QPM boosts tryptophan; hence, niacin (vitamin B3) can be partially met [25] because tryptophan is free by changing the leucine— isoleucine ratio for niacin biosynthesis.

2.1.4 Soil improvement

Protein content and yield react positively to nitrogen fertilizer used to supplement the soil in which maize was planted. This is the advantage of adding nitrogen fertilizer to low-nitrogen soil. Fertilizers that are biofortified with micronutrients and applied to the soil are the simplest biofortification method [37]. This practice has been affected by the regular application of micronutrients to the soil, increasing labor and cost, accumulation and mobility of minerals among plants, and variations in soil composition at a specific location. It also increases the micronutrients temporarily as there is a need to apply the fertilizer constantly. These micronutrient fertilizers raise molybdenum, nickel, copper, selenium, iodine, and zinc in different levels in their edible parts [26].

People in low-income countries whose diet is based on cereal grains low in zinc (Zn) are affected by Zn deficiency. Zn deficiency can cause poor immunity, birth complications, impaired mental development, and stunted growth [37]. Zinc concentration in grain crops has been improved by nitrogen management improvement through the availability of Zn in the soil. Nitrogen availability in the soil represents a significant component in the biofortification of zinc in grains and, therefore, enhances residence's nutritional status in developing countries. Another micronutrient in low quantity in grain due to its insufficient amount in the soil is selenium (Se) [45]. The organic form of Se (selenocysteine and selenomethionine) are more significantly bioavailable than inorganic selenium (Se). According to Poblaciones et al. [45], Se-rich fertilizer increases Se's bioavailability in grain and boosts total yield. The author discovered that chickpea could store a high concentration of Se in the grain after applying fertilizer.

2.2 Postharvest technology

Reducing the wastage and losses of food becomes crucial in ensuring adequate nutrition, food security, improvement in rural livelihood, poverty, and food availability among the populace. However, food wastage can result from poor grain storage affected by temperature, relative humidity and grain moisture. Microorganisms, insects, and rodents are maize biological deteriorating agents [25]. *Penicillium*, *Fusarium* and *Aspergillus* are the general mycotoxigenic fungi of importance in maize. The most prominent mycotoxins in foods, aflatoxin is produced as secondary metabolites by *Aspergillus flavus* sp. The contribution of aflatoxins to crops losses has a negative effect, either directly or indirectly, on general nutrition, health, food security, and the economy at large [46]. The prevalence of aflatoxin can be reduced by both post and pre-harvest intervention. The preharvest intervention could be in the form of developing insect and *Aspergillus* resistant, heat, and drought-tolerant varieties [47]. According to Suwarno et al. [48], provitamin A carotenoid enriched maize can reduce aflatoxin contamination. Postharvest interventions include suitable moisture at harvest, humidity and temperatures during storage, and suitable containers and space.

2.2.1 Processing and utensils used

When maize is processed into staple foods, it lacks tryptophan, lysine, and methionine [34]. Different cooking and processing methods, degermed and decorticated kernels in maize products cause additional loss of nutrients. Some processing methods and menus where maize is served as raw materials can still enhance the nutritional properties of the final product and overcome nutrient deficiencies [25]. Fermentation and nixtamalization as processing methods increase bioavailability and bioaccessibility of maize and can also cause a decrease in some compounds.

2.2.2 Unrefined grains

These are grains that their germ and bran had not been removed through processing methods. They help to reduce the risk of type 2 diabetes, heart disease. Overall mortality is positively associated with high unrefined grain and nonfiber consumption. According to Willett et al. [49], preferred foods and shelf-life are the social and technological challenges faced when consuming whole grain. Most consumers of these products have adapted the fine texture and color of most refined flour, especially maize. However, there is a need for promotion and expansion in situations where unrefined maize has been consumed to increase its nutritional impact and meet consumer preferences [50]. These situations include roasted kernels, green maize, popcorn, wet-ground foods, and nixtamalization, along with short soaking time. The aleurone, germ, and pericarp of refined maize have been removed together with minerals and vitamin B. If this maize is not enriched after milling, the consumer's nutritional status will be negatively affected. There are little or no changes in the nutrient content of refined maize if it has been biofortified. Gannon et al. [51] compared the bioavailability of provitamin A from refined and whole maize grain with biofortified maize flours as there was no difference between their β -carotene bioefficiency. Furthermore, milling does not affect the bioavailability of zeaxanthin and β -cryptoxanthin in refined and whole-grain biofortified orange maize [52].

2.2.3 Fresh maize

Any variety of maize harvested at the milky stage and prepared by boiling or roasting is referred to as fresh or green maize. Compared to conventional maize, QPM has higher glutelins, reduced zein protein, peak tryptophan, and lysine [25]. Alamu et al. [53] reported variations in the minerals and macronutrients retention of boiled and fresh maize in yellow, white, and high provitamin A carotenoid. The boiling of maize preserved lysine, zinc, and carotenoids at the milk stage.

2.2.4 Nixtamalization

Nixtamalization is when lime, grounded shellfish shell, or ash is added to hot water in which whole grains have been soaked for 8 hours or more. Any process used to modify grain fat components, remove the pericarp, and produce changes in starch and protein content of any grain is called nixtamalization [50]. There is a better characteristic of the kernels of processed maize through nixtamalization as compared to unprocessed ones. Nixtamalization causes physicochemical changes (losses in the pericarp) in maize kernels because of changes in the functionality and chemical composition (decrease in phytic acid) [25]. Nixtamalized kernel is characterized by reduced mycotoxin content, increased product shelf-life and nutritional value, easy mill kernel, and improved aroma and flavor. The significant nutritional changes that occur because of the nixtamalization process

in maize and its products include greater bioavailability of iron and niacin, increased resistance starch content and calcium [25].

2.2.5 Fermentation

Latin America and African countries have a lot of maize food products that are acidic and nonalcoholic fermented. Marco et al. [54] stated that probiotics from fermented products promote a healthy microbiome. Lacto-fermentation is a process by which starch and sugar are converted to lactic acid by bacteria. The nutritional bioavailability of niacin and iron from beverages is increased by fermentation [55]. Furthermore, mycotoxins, antinutrients, and natural toxicants are reduced or removed through fermentation processing, thus improving the maize products' safety and nutritional quality [56].

3. How technological processes improve the nutritional quality of maize crops

Based on the report of Mertz et al. [20], opaque 2 (O2) lysine content in the endosperm (3.3–4.4 g lysine/100 g of endosperm) is double that of the normal maize (1.3 g lysine/100 g endosperm protein). The O2 maize protein has a biological value of 90% of milk protein, while normal maize protein has 40%. The body utilized 74% of O2 maize protein intake, while only 37% was used in normal maize protein [19].

In comparing the protein content of QPM with normal maize, the QPM protein contains 38% lesser leucine, 55% higher tryptophan, and 30% higher lysine than normal maize. Bressani [57] reported that 8 g/kg body weight of QPM is needed for nitrogen equilibrium compared to the 24 g/kg body weight of normal maize. The QPM has greater niacin availability due to lower leucine content, utilization of carotene, and higher tryptophan content [19]. QPM maize can be processed without a decrease in its acceptability and quality. Bressani [57] report in Columbia showed that O2 maize was used as therapeutic food for children suffering from protein deficiency diseases and kwashiorkor and brought about normalcy in them. Also, Anon [58] reported that QPM increased the weight and height of preschool children that used it as a major starchy staple by 20% faster than those that used normal maize. Based on the report of Muzhingi et al. [42], porridge made from biofortified yellow maize provide 40–50% vitamin A of recommended dietary allowance (RDA) for Zimbabwean men. Similarly, North American females consuming porridge from biofortified maize had 3:1 fold of vitamin A equivalence when a fraction of the blood triglycerol-rich lipoprotein was measured compared to the traditional white maize porridge [41].

The high amount of ascorbate, folate, and β -carotene in triple-vitamin fortified maize has been developed through metabolic engineering in the endosperm [59]. The transgenic kernels have a double, 6-fold and 169-fold normal amount of folate, ascorbate, and β -carotene as traditionally bred crops. These crops can offer a nutritionally complete meal. There was a grain yield of about 145.3% in transgenic maize compared to wild maize due to upgraded grain number and size [60]. Total starch content was improved by constitutive expression of invertase in the transgenic kernels, which showed that genes could boost grain quality and yield in crop plants.

4. Conclusion

Malnutrition and hunger alleviation can be achieved through fortified maize and continuous advancement in crop yields. It is not enough to generate micronutrients

at a higher level in plants. Their bioavailability, absorption, and utilization in the body are crucial to increase the consumer's micronutrient status after cooking and processing the food in their local ways. Also, the biofortified crops must be accepted by consumers and adopted by a significant number of farmers to increase the nutritional health of the community. Biotechnology through biofortified maize can be used to improve the vitamin A status of the populace.

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