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Effects of Different Processing Methods on the Micronutrient and Phytochemical Contents of Maize: From A to Z

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Abstract: Maize is a staple human food eaten by more than a billion people around the world in a variety of whole and processed products. Different processing methods result in changes to the nutritional profile of maize products, which can greatly affect the micronutrient intake of populations dependent on this crop for a large proportion of their caloric needs. This review summarizes the effects of different processing methods on the resulting micronutrient and phytochemical contents of maize. The majority of B vitamins are lost during storage and milling; further loss occurs with soaking and cooking, but fermentation and nixtamalization (soaking in alkaline solution) can increase bioavailability of riboflavin and niacin. Carotenoids, found mainly in the kernel endosperm, increase in concentration after degermination, while other vitamins and minerals, found mainly in the germ, are reduced. Mineral bioavailability can be improved by processing methods that reduce phytic acid, such as soaking, fermenting, cooking, and nixtamalization. Losses of micronutrients during processing can be mitigated by changes in methods of processing, in addition to encouraging consumption of whole-grain maize products over degermed, refined products. In some cases, such as niacin, processing is actually necessary for nutrient bioavailability. Due to the high variability in the baseline nutrient contents among maize varieties, combined with additional variability in processing effects, the most accurate data on nutrient content will be obtained through analysis of specific maize products and consideration of *in vivo* bioavailability.

Introduction

Maize is one of the most produced cereal crops in the world, with over 120 million metric tons for human consumption in 2011 (FAO 2011), and it is a staple food for over 1.2 billion people (Lozano-Alejo and others 2007). Maize contributes almost one-third of the calories in the food supply of Central America and Southern Africa (FAO 2011), and even higher in some individual countries, such as Zambia, in which maize contributes over half of the calories in the food supply (FAOSTAT 2013). Such populations may be dependent on maize for micronutrients as well as macronutrients; among a group of Guatemalans, intake of maize tortillas was found to contribute a mean energy intake of 1164 kcal/d, and provided at least half of the daily requirement of calcium, iron, and zinc (Krause and others 1992).

Maize is a crop that develops ears that each contains 300 to 1000 kernels. Types of maize include sweet, popcorn, dent (starchy or floury), and flint, which is also used as animal feed (FAO 1992). Although the most commonly consumed varieties are white or yellow, maize can be found in other colors including red, blue, purple, and orange (FAO 1992; Gannon and others 2014). The kernel is mainly for storage of starch, but it also contains protein, fat, vitamins, and minerals. The major parts of the kernel are shown in Figure 1. Kernel weight is distributed among the endosperm (70% to 90%), germ (10% to 12%), and seed coat [pericarp plus tipcap (5% to 6%)] (FAO 1992; Bressani and others 2002). The minerals in maize are found mainly in the germ, which contains about 78% of that in the whole kernel (FAO 1992), yet many processing methods remove the germ, in part to improve shelf-life. The most abundant minerals in maize are phosphorus, magnesium, and potassium. Vitamins are found in all major parts of the kernel, including the endosperm (provitamin A carotenoids), germ (vitamin E), and aleurone (water-soluble vitamins) (FAO 1992). Maize contains no vitamin D or B_{12}, which must be obtained from animal foods. The vitamin and mineral contents of maize and some common maize products are listed in Table 1 and 2.

Maize is consumed across the world in a variety of whole and processed products. Whole-grain maize is consumed boiled or roasted on the cob, canned or frozen sweetcorn, and as popcorn. Different processing methods result in changes to the nutritional profile of maize products, which vary by nutrient and strain of maize. Types of maize processing methods and examples of maize products from around the world can be found in Table 3. The most common processing method is milling, which grinds the maize into coarse whole-grain pieces or fine flour and removes much of the bran and germ, as in the case of refined maize flour. Alternative types of milling produce different products; products of

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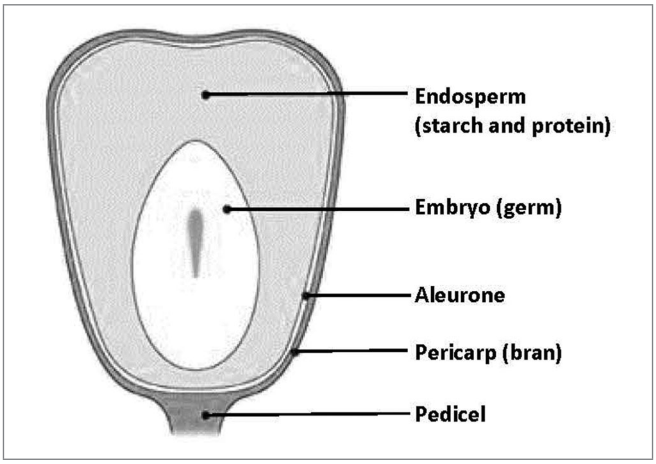

Figure 1–Major components of a maize kernel. Adapted from: Micklos, http://www.carolina.com/teacher-resources/Interactive/using-carolina-corn-ears-to-teach-genetic-imprinting/tr28902.tr.

dry milling include grits, meal, and flour; products of wet milling include starch, syrups, and dextrose, mainly for industrial uses; traditional grinding methods retain some of the maize germ (Slavin and others 2000). Milled maize can be processed by heat into foods such as porridge, polenta, grits, baked goods, and other locally named dishes. Traditional preparation methods often include further processing, such as soaking, fermentation, and nixtamalization (a process used in the production of tortillas in which maize is mixed with alkaline lime solution, heated, and soaked overnight, resulting in a chemically altered dough), which affects the content and bioavailability of several nutrients (Bressani and others 1958). Other maize products include snack foods, such as deep-fried maize chips, and industrially extruded, puffed, or flaked products. Extrusion is a quick, high-temperature technology used for processing maize that results in chemical and nutritional changes in the resulting maize products (Athar and others 2006). Each of these processing methods can affect the nutritional value of the maize.

Nutritional changes during processing are important to consider when assessing nutrient intake in populations who consume a large proportion of their daily intake as maize or maize products. Furthermore, nutrient losses have important implications in the nutritional value of processed maize products targeted toward populations at risk of nutrient deficiencies. The objective of this paper is to review the effects of different processing methods on the nutrient contents of maize products by individual micronutrients (including vitamins and minerals) and some other important phytochemicals. Effects on macronutrients are reviewed separately (Ai and Jane 2016).

Effect of Maize Processing on Vitamin and Mineral Contents

Provitamin A carotenoids: β-carotene, α-carotene, and β-cryptoxanthin

Vitamin A requirements are estimated using the concept of retinol activity equivalent (RAE), which, in addition to preformed retinol and retinyl esters found in animal products, supplements, and fortified foods, describes the amount of provitamin A carotenoids required to be converted to 1 μg retinol from a mixed diet in healthy people. The Inst. of Medicine (IOM) set RAEs at 12 μg for β-carotene, and 24 μg for α-carotene and β-cryptoxanthin (Otten and others 2006), which is based on the structural differences among them. Some studies have shown more efficient conversion factors (Muzhingi and others 2011), likely related to vitamin A status among other factors (Tanumihardjo 2008; Tanumihardjo and others 2010). The Recommended Daily Allowance (RDA) for vitamin A is 900 μg RAE and 700 μg RAE for men and women, respectively (Otten and others 2006).

Carotenoid content of maize is highly variable among different strains; some varieties can contain as much as 80 μg total carotenoids/g dry weight (Pixley and others 2013), while white maize contains little to no retinol activity (Kean and others 2008; USDA 2011; Žilić and others 2012). In the yellow maize kernel, over 90% of carotenoids are found in the endosperm (Lozano-Alejo and others 2007), specifically the horny endosperm, which contains 74% to 81%, and the floury endosperm, which contains 9% to 23%. In contrast, the bran and germ contain only 1% and 2% to 4% of the carotenoids, respectively (Blessin and others 1963). The carotenoid contents of maize and some maize products are shown in Table 4.

Biofortification. Biofortification is the process of improving nutritional profiles of crops through traditional breeding or biotechnology (Nestel and others 2006). Due to the natural variability in carotenoid content of maize, breeding efforts have aimed to increase the provitamin A carotenoids in maize, from less than 2 μg provitamin A carotenoids/g in yellow varieties to a target of 15 μg/g in orange varieties (Pixley and others 2013). One strain of high-β-carotene maize meeting this target contains 10 to 15 times the β-carotene of other strains, as well as increased amounts of α-carotene and β-cryptoxanthin (Li and others 2007; USDA 2011). Another example of provitamin A biofortified maize contains 12.7 μg β-carotene/g, 0.95 μg α-carotene/g and 1.62 μg/g β-cryptoxanthin (Li and others 2007). A randomized controlled study with high-β-carotene maize (about 20 μg β-carotene equivalents at harvest) found that children consuming the orange biofortified maize had similar total body vitamin A increases at the end of the trial compared with children given vitamin A supplements at the level of the RDA, indicating good bioefficacy of the β-carotene from biofortified maize (Gannon and others 2014).

Harvest, drying, and storage. Mugode and others (2014) examined the carotenoid content of biofortified provitamin A maize, harvested both at its "green" stage (60% moisture) and immediately boiled and roasted, and 2 mo later when dried on the stalk (12% moisture). Their analysis data showed that the green maize retained more total carotenoids than the dry maize, due mainly to higher levels of lutein and zeaxanthin, while the dry maize had higher concentrations of provitamin A carotenoids (for the majority of genotypes tested).

A recent review found carotenoid retention in maize during storage to be highly variable (39% to 78%), and in addition to storage time, retention can depend on environmental conditions, such as temperature, light exposure, and humidity, maize genotype, and initial carotenoid content (de Moura and others 2015). Mugode and others examined the effect of storage on dry maize stored shelled or on the ears over a period of 6 mo in a "traditional storage bin at ambient temperature" in Zambia. Provitamin A carotenoid levels dropped to about 50% within the first 30 d, after which the content stabilized, although levels continued to decrease slightly over time. There was little difference between maize kernels stored shelled or on the ear (Mugode and others 2014). Burt and others (2010) found that the carotenoid content of high-carotenoid maize lines stored in the dark at 25 °C remained stable for the first 3 mo but declined significantly by 6 mo

Table 1–Mineral contents of maize and common maize products.

		Nutrient content/100 g[a]									
Maize product	USDA NDB no.	Calcium (mg)	Copper (mg)	Iron (mg)	Magnesium (mg)	Manganese (mg)	Phosphorus (mg)	Potassium (mg)	Selenium (mg)	Sodium (mg)	Zinc (mg)
Whole kernels											
Yellow maize (dent), dry	20014	7	0.314	2.71	127	0.485	210	287	15.5	35	2.21
Yellow maize (sweet), raw	11167	2	0.054	0.52	37	0.163	89	270	0.6	15	0.46
White maize, dry	20314	7	0.314	2.71	127	0.485	210	287	15.5	35	2.21
Milled products											
Flour, whole grain, yellow	20016	7	0.23	2.38	93	0.46	272	315	15.4	5	1.73
Flour, degermed, yellow	20018	2	0.142	0.91	18	0.056	60	90	8	1	0.37
Flour, whole grain, white	20316	7	0.23	2.38	93	0.46	272	315	15.4	5	1.73
Flour, masa, white	20019	138	0.209	1.47	93	0.376	231	262	10.5	5	1.8
Flour, masa, white, enriched	20017	138	0.209	8.5	93	0.376	231	262	10.5	5	1.8
Flour, whole-grain, blue	20315	5	0.154	1.74	110	0.54	263	381	2.2	5	2.24
Cornmeal, degermed, yellow	20422	3	0.076	1.1	32	0.174	99	142	10.5	7	0.66
Corn bran	20015	42	0.248	2.79	64	0.14	72	44	16.5	7	1.56
Processed products											
Grits, yellow	08160	2	0.075	1	27	0.106	73	137	17	1	0.41
Hominy, canned, yellow	20330	10	0.03	0.62	16	0.07	35	9	3	345	1.05
Tortillas	18363	81	0.154	1.23	72	0.326	314	186	6.1	45	1.31
Tortilla chips, yellow	25028	104	0.105	1.32	84	0.357	234	206	8.4	310	1.46
Chips, corn-based, extruded	19003	138	0.101	1.2	72	0.333	194	144	7.6	514	1.29
Popped corn, yellow	19034	7	0.262	3.19	144	1.113	358	329	0	8	3.08
Kellogg's corn flakes	08020	5	0.198	28.9	39	0.168	102	168	8.3	729	1
Recommended daily allowances[b]											
Men		1000	0.90	8	265	2.3	700	4700	55	1500	11
Women[c]		1000	0.90	18	420	1.8	700	4700	55	1500	8

[a]Source: USDA Nutrient Database (USDA 2011).
[b]Recommended daily allowances are for adults 19 to 30 y of age (Otten and others 2006).
[c]Nonpregnant, nonlactating.

Table 2–Vitamin contents of maize and common maize products.

Maize product	USDA NDB no.	Vitamin (μg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)	Pantothenic (mg)	Vitamin B_6 (mg)	Folate (μg)	Vitamin B_{12} (μg)	Vitamin C (mg)	Vitamin D (μg)	Vitamin E (mg)	Vitamin K (μg)
		Nutrient content/100 g[a]											
Whole kernels													
Yellow maize (dent), dry	20014	11	0.39	0.20	3.63	0.42	0.62	19	0	0	0	0.49	0.3
Yellow maize (sweet), raw	11167	9	0.16	0.06	1.77	0.72	0.09	42	0	6.8	0	0.07	0.3
White maize, dry	20314	0	0.39	0.20	3.63	0.42	0.62	N/A	0	0	0	N/A	N/A
Milled products													
Flour, whole grain, yellow	20016	11	0.25	0.08	1.90	0.66	0.37	25	0	0	0	0.42	0.3
Flour, degermed, yellow	20018	11	0.07	0.06	2.66	0.05	0.10	48	0	0	0	0.15	0.3
Flour, whole grain, white	20316	0	0.25	0.08	1.90	0.66	0.37	25	0	0	0	0.42	0.3
Flour, masa, white	20019	0	0.22	0.10	1.63	0.19	0.48	29	0	0	0	0.12	0
Flour, masa, white, enriched	20017	0	1.48	0.81	9.93	0.19	0.48	209	0	0	0	0.12	0
Flour, whole-grain, blue	20315	N/A	0.16	0.23	2.60	0.55	0.47	N/A	N/A	N/A	N/A	N/A	N/A
Cornmeal, degermed, yellow	20422	11	0.14	0.05	1.00	0.24	0.18	30	0	0	0	0.12	0
Corn bran	20015	4	0.01	0.10	2.74	0.64	0.15	4	0	0	0	0.42	0.3
Processed products													
Grits, yellow	08160	11	0.13	0.04	1.20	0.49	0.15	5	0	0	N/A	N/A	0.3
Hominy, canned, yellow	20330	N/A	0.00	0.01	0.03	0.15	0.01	1	0	0	0	N/A	N/A
Tortillas	18363	0	0.09	0.07	1.50	0.11	0.22	5	0	0	0	0.28	0
Tortilla chips, yellow	25028	8	0.13	0.04	1.50	0.41	0.20	22	0	0	0	2.97	0.6
Chips, corn-based, extruded	19003	3	0.05	0.08	0.84	0.19	0.17	8	0	0	0	7.23	6.3
Popped corn, yellow	19034	10	0.10	0.08	2.31	0.51	0.16	31	0	0	0	0.29	1.2
Kellogg's corn flakes	08020	490	1.34	1.52	17.90	0.23	1.79	357	5	21	3.6	0.12	0
Recommended daily allowances[b]													
Men		900	1.2	1.3	16	5	1.3	400	2.4	90	5	15	120
Women[c]		700	1.1	1.1	14	5	1.3	400	2.4	75	5	15	90

[a] *Source:* USDA Nutrient Database (USDA 2011); biotin content not available; N/A, data not available.
[b] The recommended daily allowances listed are for adults 19 to 30 y of age (Otten and others 2006).
[c] Nonpregnant, nonlactating.

Table 3–Types of maize processing methods and examples of food products.

Processing method	Brief description	Example products
Milling		
Dry milling and degermination	Particle size reduction, mechanical separation and removal of bran and germ from endosperm for a highly shelf-stable product	Quick grits, refined flour
Wet milling	Industrial process which separates maize into starch, protein, oil, and fiber constituents; not typically used at the household level	Starch, syrups, dextrose
Traditional stone-grinding	Retains some of the maize germ	Whole maize meal, whole kernel ("speckled") grits
Heat	Boiling, baking, roasting, deep-frying	Porridge, bread, chips, popped corn, whole ears of maize ("corn-on-the-cob"), canned and frozen kernels
Extrusion	Quick, high-temperature/pressure industrial process	Extruded chips and flakes
Nixtamalization	Maize is mixed with alkaline lime solution, heated, soaked, and rinsed, resulting in a chemically altered dough known as *masa*	Tortillas
Other traditional methods: soaking, germination, fermentation	Traditional maize preparation may involve one or more of these methods	*Ogi*, a fermented porridge eaten in Nigeria

Sources: Athar and others (2006), Bressani and others (1958), Gwirtz and Garcia-Casal (2014), Nuss and Tanumihardjo (2010), and Slavin and others (2000).

Table 4–Carotenoid contents of maize and common maize products.

	Nutrient content/100 g [a]								
Maize product	USDA NDB no.	Vitamin A RAE (μg)	Retinol (μg)	β- Carotene (μg)	α-Carotene (μg)	β-Cryptoxanthin (μg)	Vitamin A (IU)	Lycopene (μg)	Lutein + Zeaxanthin (μg)
Whole kernels									
Yellow maize (dent), dry	20014	11	0	97	63	0	214	0	1355
Yellow maize (sweet), raw	11167	9	0	47	16	115	187	0	644
White maize, dry	20314	0	0	N/A	N/A	N/A	0	N/A	N/A
Milled products									
Flour, whole grain, yellow	20016	11	0	97	63	0	214	0	1355
Flour, degermed, yellow	20018	11	0	97	63	0	214	0	1355
Flour, whole grain, white	20316	0	0	1	0	1	3	0	5
Flour, masa, white	20019	0	0	2	0	2	5	0	6
Flour, masa, white, enriched	20017	0	0	2	0	2	5	0	6
Flour, whole-grain, blue	20315	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cornmeal, degermed, yellow	20422	11	0	97	63	0	214	0	1628
Corn bran	20015	4	0	32	21	0	71	0	1355
Processed products									
Grits, yellow	08160	11	0	97	63	0	214	0	1355
Hominy, canned, yellow	20330	N/A	0	N/A	N/A	N/A	110	N/A	N/A
Tortillas	18363	0	0	1	0	1	2	0	3
Tortilla chips, yellow	25028	8	0	39	56	57	158	0	1198
Chips, corn-based, extruded	19003	3	0	20	2	41	69	0	527
Popped corn, yellow	19034	10	0	89	58	0	196	0	1450
Kellogg's corn flakes	08020	490	481	83	54	0	1786	0	339

[a] *Source*: USDA Nutrient Database (USDA 2011). N/A, data not available.
RAE, retinol activity equivalents, which is 12 μg β-carotene or 24 μg α-carotene and β-cryptoxanthin estimated to yield 1 μg retinol for healthy, vitamin A-adequate individuals.

of storage, with a total carotenoid loss of 35% to 40%, but then remained stable up to 18 mo. Burt and others (2010) also compared drying 6 high-carotenoid maize lines at −80 (freeze-drying), 25, or 90 °C; among all but one of the lines, freeze-drying retained the most carotenoids initially, while maize dried at 25 or 90 °C exhibited similar initial losses. During 4 mo of dark storage, there was no further loss in the freeze-dried samples stored at −80 °C. The maize lines originally dried at 25 or 90 °C were stored at 25 °C in the dark, and after 4 mo showed losses ranging from 24% to 61%, with an inverse relationship between losses due to drying and storage for each genotype; those strains that lost more carotenoids during the drying process tended to lose less during storage, and vice versa. The carotenoid profiles (that is, relative amounts of each) of these lines were maintained throughout, while total carotenoid losses occurred during drying and storage (Burt and others 2010). In summary, unless maize was freeze-dried, it lost substantial quantities of carotenoids during long-term storage.

Milling and soaking. As the majority of carotenoids in maize are found in the endosperm, degermination has very little impact on the quantity and, thus, maize meal and flour contain more carotenoids than the bran and germ. Pillay and others (2014) found a higher retention of provitamin A carotenoids in biofortified maize meal (106% to 137%) compared with *samp* (broken maize grain, 95% to 118%), but both had values similar to un-milled maize or slightly higher, perhaps due to the breakdown of the maize kernel matrix. Li and others (2007) found soaking and wet milling of high-β-carotene maize kernels resulted in 7% to 9.5% losses in α-carotene, β-carotene, and β-cryptoxanthin.

Boiling, baking, and extrusion. Pillay and others (2014) examined carotenoid retention among cooked porridges made from provitamin A-biofortified maize. *Phutu* (a very thick porridge made from boiling maize meal) and cooked *samp* retained 78% to 118% provitamin A carotenoids (89% to 129% of the unprocessed maize), while a thin porridge retained only 63% to 71% β-cryptoxanthin during cooking (76% to 92% that of unprocessed maize) and 72% to 78% of the β-carotene (78% to 97% that of unprocessed maize). Muzhingi and others (2008) found that both thick and thin yellow maize porridges retained, or even increased, their carotenoid contents, with the exception of β-cryptoxanthin, which decreased about 20% in the thin porridge. Li and others (2007) examined the effects of fermentation on carotenoid retention in high β-carotene maize porridge, and they found that while fermentation prior to cooking reduced losses during cooking, losses during fermentation made up for this resulting in similar total carotenoid losses of about 25% from cooking alone or fermenting and then cooking. Kean and others (2008), on the other hand, found that maize meal porridge retained only 52% to 60% of total carotenoids. Overall, maize porridge preparations retain 50% to over 100% of initial carotenoids. Values greater than 100% may be due to processing and cooking which increase bioaccessibility during extraction procedures (Tanumihardjo and others 2010).

There are different estimates of carotenoid retention for baked maize products, with Muzhingi and others (2008) reporting 25% to 50% retention of provitamin A carotenoids in baked corn muffins. Kean and others (2008), on the other hand, found that baked corn bread retained 65% to 75% of initial carotenoids. Kean and others (2008) analyzed extruded puffs made from maize meal and found carotenoid retention between 56% and 65%. Lozano-Alejo and others (2007) found that a little more than a third of provitamin A carotenoids was lost from deep-fried maize snacks. De La Parra and others (2007) found that deep-fried maize chips made from white or yellow maize had very low retention of provitamin A carotenoids (0% to 6%), while chips made from high-carotenoid maize retained about 20%. Thus, while maize porridge retains half to all its carotenoids, other heat treatments, such as baking, frying, and extrusion, have wide variation and, depending on the method used, may result in almost 0% to 75% retention.

Scott and Eldridge (2005) examined losses of carotenoids from canned and frozen maize. Canned yellow maize heated to 126.7 °C for 12 min suffered 62% losses of α-carotene, but changes to the contents of other provitamin A carotenoids were not significant. Maize processed to be sold frozen is also subjected to heat treatment. In the same study, yellow maize kernels were steam-blanched at 87.8 to 93.3 °C for about 3 min and then quickly frozen at temperatures of −17.8 to −23.3 °C. The resulting provitamin A content was similar to fresh maize, with the exception of α-carotene content which decreased by about 42% (Scott and Eldridge 2005).

Nixtamalization. Nixtamalization is often employed in Latin America for the preparation of tortillas. During this process, maize (including germ and endosperm) is cooked and then soaked in an alkaline lime solution (usually calcium hydroxide), thereby breaking down the pericarp (Serna-Saldivar and others 1993). The resulting mixture, "nixtamal," is then washed and ground into a dough called "masa" (Bressani and others 1958). The effect of nixtamalization on carotenoid content varies and may depend on what methods are used during processing. De La Parra and others (2007) found that the nixtamalization process significantly reduced levels of β-cryptoxanthin (84%) and β-carotene (38%), and further decreases occurred during additional processing into tortillas. Fried tortilla chips had effectively no provitamin A carotenoids remaining. Gutiérrez-Uribe and others (2014), on the other hand, found that the nixtamalization process released carotenoids from the kernels, yielding 100-fold higher β-carotene levels in the resulting masa; however, the subsequent processing of masa into tortillas brought carotenoid levels back down to the same level as the whole kernel content.

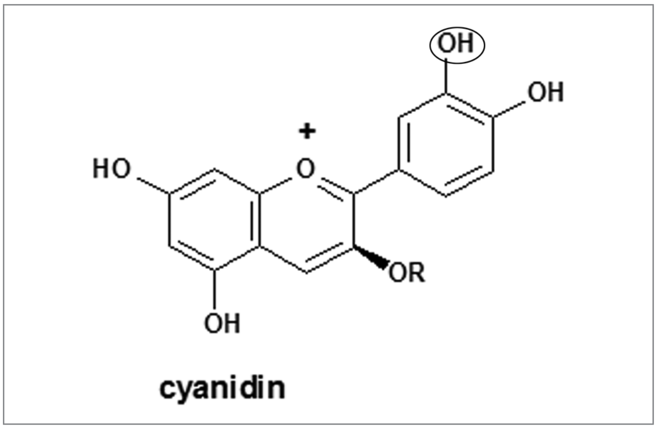

Figure 2–Polyphenols that are commonly quantified in purple, blue, or red maize include 7 anthocyanins (Collison and others 2015). The basic anthocyanin backbone is called cyanidin that contains the circled hydroxyl group. The circled functional group is not present in pelargonidin or it is methylated in peonidin. The R group can be various glycosides and include cyanidin-3-glucoside, pelargonidin-3-glucoside, cyanidin-3-(3-malonylglucoside), peonidin-3-glucoside, cyanidin-3-(6-malonylglucoside), pelargonidin-3-malonylglucoside, and peonidin-3-malonylglucoside.

Anthocyanins and other polyphenols

Different strains of maize contain varying amounts of antioxidant polyphenols. For example, colored maize strains contain high quantities of anthocyanins which confer deep pigmentation, such as blue, purple, and red, compared with white or yellow maize that has minimal quantities (De La Parra and others 2007; Žilić and others 2012). The most common anthocyanins in colored maize are cyanidins, perlargonidins, and peonidins (Figure 2) (Abdel-Aal and others 2006), which are found in the pericarp and aleurone layer of the maize endosperm (Escalante-Aburto and others 2013). Antioxidant capacity is not always directly related to total anthocyanin and polyphenol contents. For example, varieties of Mexican blue maize and American blue maize were found to contain similar amounts of anthocyanins, but the American strain contained higher levels of other polyphenols; however, despite this, the Mexican blue maize exhibited a higher antioxidant capacity (Del Pozo-Insfran and others 2006).

Total polyphenol and anthocyanin contents of whole and processed maize are shown in Table 5. Generally, thermal processing decreases phenolic content of foods; however, that decline may be due to leaching of water-soluble polyphenols into brine or syrup. Canned sweetcorn was found to have only 5% loss of phenolic content (Dewanto and others 2002). During processing of maize into tortillas and chips, often nixtamalization is employed that causes changes to the structure, chemical composition, and nutritional value of the resulting product (Bressani and others 1958).

Table 5–Polyphenol and anthocyanin contents of whole and processed blue maize.

Blue maize product	Polyphenols mg gallic acid/100 g Mean ± SD	Anthocyanins mg cyanidin 3-glucoside/100 g Mean ± SD
Whole kernels	266.2 ± 0.7[a]	36.87 ± 0.71[a]
Dry flour	343 ± 8.6[b]	99.5 ± 1.8[b]
		27.2[c]
	343.2 ± 6.8[d]	63.1 ± 1.4[d]
Masa	158.5 ± 1.2[a]	2.63 ± 0.12[a]
	195.4 ± 4.5[d]	27.9 ± 1.7[d]
Tortillas	161.8 ± 2.1[a]	3.81 ± 0.11[a]
	201.4 ± 5.8[d]	18.9 ± 2.9[d]
Chips	136.9 ± 1.2[a]	3.29 ± 0.10[a]

Sources:
[a]De La Parra and others (2007).
[b]Lopez-Martinez and others (2009).
[c]Cortés and others (2006).
[d]Lopez-Martinez and others (2011).

Preparation of tortillas and chips from blue maize results in overall polyphenol losses, with the nixtamalization process having the most detrimental effect. Masa made through traditional nixtamalization can lose 54% to 66% of polyphenols (Del Pozo-Insfran and others 2006).

Blue maize contains bound and free polyphenols. Bound phenolics are the primary contributors to antioxidant activity in blue maize (>80%); however, these decrease by about 75% after nixtamalization, while free phenolic antioxidant activity increases after lime-cooking and processing into tortillas and chips (De La Parra and others 2007). Further processing can decrease polyphenol content, but nixtamalization has the largest impact on losses. One study found that processing blue maize into tortillas and chips resulted in 75% and 81% losses of polyphenols, respectively (Del Pozo-Insfran and others 2006). However, the effects of traditional nixtamalization can be mitigated through an acidification treatment. Adding 0.2 g fumaric acid/100 g dry maize (reducing pH to 5.2) resulted in a 10% reduction in polyphenol losses in masa made by traditional nixtamalization (Del Pozo-Insfran and others 2006).

Up to 100% of anthocyanins in blue maize can be lost during nixtamalization, mainly by leaching into the lime solution, but different methods of nixtamalization can lead to higher retention of anthocyanins (Del Pozo-Insfran and others 2006; De La Parra and others 2007; Escalante-Aburto and others 2013). The pH is an important factor because it influences structural changes of anthocyanins during nixtamalization. One study found that nixtamalization of blue maize reduced anthocyanin content by 82%; however, when cooked without calcium hydroxide, anthocyanin loss was half of traditional nixtamalization, with 42% loss compared with dry maize flour (Cortés and others 2006). While nixtamalization causes most of the anthocyanin losses, additional processing steps can further reduce their content. Del Pozo-Insfran and others (2006) found anthocyanin losses were 37%, 54%, and 75% from nixtamal, tortillas, and chips, respectively; however, with acidification treatment, these losses were reduced to 9%, 11%, and 17%, respectively. In addition to nixtamalization, extrusion and heat treatment can reduce anthocyanin content of maize. Extrusion lowers anthocyanin content of blue maize by about 57% (Mora-Rochin and others 2010). Extracts of purple maize heated to 98 °C showed high degradation of anthocyanin content (Cevallos-Casals and Cisneros-Zevallos 2004).

B vitamins

Maize contains the B vitamins thiamin, riboflavin, niacin, pantothenic acid, B_6, folate, and biotin, but not B_{12} which is typically obtained from animal foods. These water-soluble vitamins are found in the maize endosperm and germ, with the highest concentration in the aleurone layer (Nuss and Tanumihardjo 2010). Differing amounts are present depending on the type of maize. The amounts of these nutrients found in maize and common maize products and the RDAs for adults are shown in Table 2. However, many of the B vitamins are present in a bound form in maize, therefore resulting in limited bioavailability (Hegedüs and others 1985). Processing may increase or decrease quantity and bioavailability of the B vitamins in maize.

Vitamin B_1 (thiamin). Whole grain yellow and white maize varieties contain 0.39 mg thiamin/100 g. The RDA for thiamin set by the IOM is 1.2 mg/d for adult men and 1.1 mg/d for women. Processed maize products contain less than whole grains; however, bioavailability of thiamin increases with processing. Utilization of thiamin from maize bran seems to increase with dry milling, but not wet milling, and fine particle size compared with coarse particle size, with size being more of a factor for wet-milled than dry-milled maize bran (Yu and Kies 1993). Extrusion reduces thiamin content of degermed maize grits by over 50% (Athar and others 2006). A study in Guatemala found that the nixtamalization process used in preparation of tortillas resulted in a loss of 60% and 65% of thiamin in white and yellow maize masa, respectively, compared with dry maize (Bressani and others 1958). Most of these losses were from the maize germ.

Vitamin B_2 (riboflavin). Whole yellow and white maize varieties contain 0.2 mg riboflavin/100 g, which is 15% of the RDA for adult men (1.3 mg) and 18% for women (1.1 mg). Processed maize tends to have less riboflavin, with non-enriched maize flours containing between 0.08 and 0.1 mg. Blue maize flour, however, has more riboflavin (that is, 0.23 mg/100 g) than whole yellow and white maize. Riboflavin is fairly evenly distributed in the maize kernel; thus milling results in lower loss of riboflavin compared with other B vitamins. Degermed maize loses a little over 50% of riboflavin content during processing (Hegedüs and others 1985). The production of maize masa was found to reduce levels of riboflavin 52% and 32% in white and yellow maize, respectively (Bressani and others 1958). Fermentation and germination (sprouting) of maize can increase its nutritive value. One study showed that maize fermented after germination had significantly higher levels of riboflavin (Lay and Fields 1981). Extrusion reduces riboflavin content of degermed maize grits by about 16% (Athar and others 2006).

Vitamin B_3 (niacin). Dry maize contains about 3.6 mg niacin/100 g. The RDA is 16 mg for men and 14 mg for women. Most of the niacin in maize is found in the aleurone, germ, and endosperm (Heathcote and others 1952). However, niacin is bound in maize, making it less available for absorption during digestion, that is, only about 0.4 μg niacin/g maize is found as free nicotinic acid or nicotinamide (Wall and Carpenter 1988). Processing of maize may reduce total niacin but can also release bound niacin, making it more bioavailable. One study showed that maize fermented after germination had significantly higher levels of niacin (Lay and Fields 1981). Roasting maize can release bound niacin (Kodicek and others 1974). Nixtamalization reduces total levels of niacin by about 30% in white and yellow varieties (Bressani and others 1958), but the remaining niacin becomes more bioavailable (Kodicek and others 1956). Extrusion reduces niacin content of degermed maize grits by 25% (Athar and others 2006).

Dry-milling of maize increases bioavailability of niacin, while wet-milling decreases it (Yu and Kies 1993).

Pellagra is a deficiency disease resulting from inadequate dietary niacin and/or tryptophan (Prinzo 2000). Maize is low in both of these nutrients, putting populations dependent on maize for the majority of their calories at high risk of pellagra. Pellagra as related to maize was first documented over 250 y ago in Europe after maize was introduced from the Americas; however, there was very little pellagra documented in the populations of Central America despite high consumption of maize (Prinzo 2000). It was hypothesized, and subsequently confirmed, that this was due to the increased niacin bioavailability from traditional nixtamalization (Laguna and Carpenter 1951; Kodicek and others 1956; Harper and others 1958). Furthermore, typical maize is also deficient in tryptophan, which can spare niacin deficiency due to conversion of tryptophan to niacin, which is why other cereals low in niacin do not have the same pellagragenic effect as maize (Goldsmith and others 1961; Prinzo 2000).

Vitamin B_5 (pantothenic acid). Dry maize contains 0.42 mg pantothenic acid/100 g, about 8% of the adult RDA (5 mg/d) (Otten and others 2006; USDA 2011). The amount of pantothenic acid increases in whole-grain maize flour to 0.66 mg/100 g, and grits and popcorn contain slightly more than dry maize at approximately 0.5 mg/100 g, while other forms of processed maize contain less pantothenic acid than dry maize. Pantothenic acid utilization is higher in dry-milled or finely ground maize compared with wet-milled or coarse-ground maize (Yu and Kies 1993).

Vitamin B_6. Vitamin B_6 is present in food in free or bound forms of pyridoxine, pyridoxal, and pyridoxamine. In maize, more than half of its B_6 content occurs as pyridoxal (Roth-Maier and others 2002). Dry maize contains 0.62 mg vitamin B_6/100 g, almost half of the RDA for adults (1.3 mg). This amount decreases in processed maize. Prececal digestibility of B_6 from maize was found to be 67% in pigs (Roth-Maier and others 2002); however, B_6 in maize bran may be unavailable to humans (Kies and others 1984). Extrusion has little effect on pyridoxine content of degermed maize grits (Athar and others 2006).

Vitamin B_7 (biotin). Biotin content is not available from the USDA nutrient database. Animal studies have found that the biotin content of finely ground maize is 0.04 to 0.11 mg/kg (Anderson and others 1978), with high bioavailability estimated at 100% (Frigg 1976). Furthermore, microbiological assays determined the contents to be 7.3 μg/100 g in whole-grain maize flour and 1.4 μg/100 g in degermed maize flour. Accordingly, 100 g whole-grain flour provides about 4.1 to 10.8 μg of biotin, or 14% to 36% of the RDA (30 μg), with degermed flour providing only 1.4 μg/100 g, about 5% of the RDA.

Vitamin B_9 (folate). Dry maize contains little folate, about 19 μg/100 g. The RDA for folate is 400 μg for nonpregnant, nonlactating females, and for male adults. Whole grain maize flour contains 28 μg/100 g, which is reduced by 64% to 10 μg/100 g after degerming (Hegedüs and others 1985). Populations consuming maize as a staple may have higher rates of neural tube defect. This may explain, in part, why Hispanic populations in the United States have a higher rate of neural tube defects because they are not consuming as much folic acid from fortified wheat products (CDC 2010). Fortification of maize flour masa is a potential solution. One study modeled the effects of folic acid fortification on maize masa flour consumption, and this would increase Mexican Americans' folic acid intake by 22% from the fortificant (Hamner and Tinker 2014). There is little research on the effect of processing on folate content of maize, but in a study of spinach and broccoli, boiling resulted in folate retention of 49% and 44%, respectively, but steaming resulted in no significant decreases (McKillop and others 2002).

Calcium

The RDA for calcium is 1000 mg/d for adults aged 19 to 50 y (Otten and others 2006). Whole, dry maize is very low in calcium, containing only 7 mg/100 g (USDA 2011), with a higher concentration in the germ compared with the endosperm (Bressani and others 2004). Therefore, maize itself is not a good source of calcium. However, the nixtamalization process actually increases calcium content of maize (Mendoza and others 1998); one study found an average increased calcium content of several maize varieties to 170 mg/100 g, about an 18-fold increase from dry maize (Bressani and others 2002). Another study found a highly significant increase in calcium content associated with cooking, soaking, and soaking time of maize in lime water (calcium hydroxide solution). Furthermore, lime-soaking increased calcium concomitant with alkalinity increases (Bressani and others 2004). Thus, nixtamalized maize products can be a major source of calcium in populations consuming high amounts of these products, such as in Mexican and Central American diets (Bressani and others 2004; Hambidge and others 2005), meeting up to 78% of daily calcium requirements in Guatemalan women (Krause and others 1992).

Vitamin C

The RDA for vitamin C is 75 and 90 mg/d for women and men, respectively. Most sources indicate that processed maize does not contain detectable amounts of vitamin C (Saldana and Brown 1984; USDA 2011). However, raw sweetcorn has a content of 6.8 mg/100 g according to USDA (2011), and Dewanto and others (2002) found that raw sweet corn had a vitamin C content of 0.24 $\pm$ 0.02 μmol vitamin C/g corn; duration of heating and increased temperature had negative associations with vitamin C content. Canned sweetcorn is normally processed at 115 °C for 25 min, conditions which Dewanto and others (2002) found decreased vitamin C content by 25%. Interestingly, while vitamin C content decreased, total antioxidant activity increased with longer heating and higher temperatures, likely due to freeing of bound phenolics and ferulic acid.

Copper

The RDA for copper is 900 μg/d for adults 19 to 30 y of age (Otten and others 2006). Whole, dry maize contains 314 μg/100 g (USDA 2011). Maize is an important source of dietary copper in some populations; for example, one study found that Guatemalan women consumed an average of 880 μg copper from maize tortillas (Krause and others 1992). The effects of processing on copper content of maize have not been well-studied. Whole-grain maize products, such as popcorn and whole-grain flour, seem to retain between 60% and 80% of copper, while hominy, grits, and degermed cornmeal may retain only 10% to 24% (USDA 2011). Interestingly, phytic acid may not affect copper bioavailability to the same extent as it does iron, zinc, and other metals found in maize (Lonnerdal 2002).

Vitamin E

Vitamin E describes 8 fat-soluble compounds with α-tocopherol activity, grouped as tocopherols and tocotrienols, which serve as antioxidants (Rocheford and others 2002). The RDA for vitamin E (d-α-tocopherol) is 15 mg/d for adult men and women (nonpregnant, nonlactating) (Otten and others 2006).

Dry maize contains about 0.5 to 1.5 mg d-α-tocopherol/100 g (Herting and Drury 1969; USDA 2011). Presence of tocopherols can vary by genotype, but the majority of the tocopherols in the maize kernel are found in the germ along with most of the stored oil which contains 70% to 86%, while the endosperm contains 11% to 27% (Rocheford and others 2002).

Tocopherols include α, β, δ, and γ, with α and γ as the predominant forms in maize (Kurilich and Juvik 1999). Kurilich and others (1999) found that total tocopherol content averaged 30.1 μg/g dry weight among 44 maize varieties, with γ-tocopherol most predominant at two-thirds of total tocopherol, α-tocopherol making up 27%, and δ-tocopherol only 4%. α-Tocotrienol and γ-tocotrienol are also found in maize, but in smaller quantities; γ-tocotrienol ranges from 2% to 28% of total tocol concentration and α-tocotrienol ranges from 4% to 21% (Weber 1984; Rocheford and others 2002).

Generally, processing of maize decreases vitamin E content, in part due to reduction in lipid content. Herting and Drury (1969) found α-tocopherol losses among processed maize products was very high, ranging from 35% loss for white maize meal to 73% to 98% for yellow maize in the form of meal, grits, and flakes or when puffed or shredded. Extrusion led to decreases in tocopherols and tocotrienols of 63% to 94% among other grains (including wheat, barley, rye, and oats) (Zielinski and others 2001). Crude maize oil contains about 210 mg vitamin E/100 g, which is decreased by more than half during the refining process (Ferrari and others 1996). During storage, about a third of vitamin E can be lost (Herting and Drury 1969), but, interestingly, the phytic acid in maize provides protection to the kernel from the pro-oxidant effects of the metals present, and it may also prevent damage to DNA and loss of lipids, particularly γ-tocopherol (Doria and others 2009).

Iron

The RDA for iron is 8 mg/d for men and 18 mg/d for nonpregnant, nonlactating women. Dry maize contains about 2.7 mg nonheme iron/100 g. The endosperm contains the majority of the iron in the kernel; Bressani and others (2002), for example, found that the endosperm contains 76% of kernel iron while the germ contains about 18%.

Nixtamalization may slightly decrease levels of iron in whole maize; however, these decreases were found mainly to be in the endosperm, while germ iron content actually increased, although these differences were not significant (Bressani and others 2002). Bressani and others (2004) showed that iron content of whole maize kernels was not affected by alkalinity of lime solution during nixtamalization, cooking, or cooking time. Furthermore, cooking maize in lime solution or water did not affect levels; however, steeping time was associated with a significant decrease in iron (Bressani and others 2004). Relatively high amounts of calcium may also inhibit iron bioavailability (Platt and Clydesdale 1987); therefore, soaking cooked maize in water may be preferred if iron absorption is the priority, because calcium levels are lower in water-soaked maize compared with alkaline-soaked maize (Bressani and others 2004). Extruded maize products can have higher iron levels with about one-third loss, which could be due, in part, to iron "contamination" added from extrusion machines during processing (Hazell and Johnson 1989).

Iron is bound by phytic acid, a known inhibitor of iron absorption, which highly reduces bioavailability from maize (Gillooly and others 1983; Hallberg and others 1987). Methods that reduce phytic acid will improve iron bioavailability in processed maize products (Mendoza and others 1998; Hambidge and others 2005). Removal of bran and germ results in about equal losses of phytic acid and iron, that is, about one-third to quarters (Hazell and Johnson 1989; Proulx and Reddy 2007). Soaking alone may not decrease phytic acid levels enough to improve iron absorption (Egli and others 2002). However, addition of lactic acid to unfermented maize products (that is, tortillas, arepa, and porridge) was found to increase iron bioavailability (*in vitro*), perhaps due to the improved solubility in the increased acidity (Proulx and Reddy 2007). Fermentation can reduce phytic acid levels more than cooking (66% compared to 16 to 17%) (Marfo and others 1990). Furthermore, Svanberg and others (1991) found that soaking maize flour for 24 to 48 h prior to fermentation resulted in almost a 96% reduction in phytic acid. When the researchers examined the percent of soluble iron in maize gruel, fermenting and soaking increased soluble iron from about 4% to 6%; fermentation with germinated flour or fermentation plus 10 mg phytase resulted in about 9% soluble iron, but fermentation in combination with the addition of 50 mg phytase resulted in a 99% reduction of phytic acid and a 43% increase in soluble iron. The nixtamalization process reduces phytic acid by about 20%, enough to potentially improve iron absorption (Bressani and others 2004).

Vitamin K

The RDA for vitamin K_1 (phylloquinone) is 120 μg/d for men and 90 μg/d for nonpregnant, nonlactating women (Otten and others 2006). Maize contains little phylloquinone, about 0.3 μg/100 g (USDA 2011). As a fat-soluble vitamin, the vitamin K content of maize oil is higher, at about 2.9 μg/100 g; this amount is low when compared with other oils such as rapeseed and soybean oils that contain $>$140 μg/100 g (Ferland and Sadowski 1992).

Vitamin K in maize oil is stable during processing; although it decreases by about 15% with heat and can be rapidly destroyed by light exposure (Ferland and Sadowski 1992). Processed maize foods, such as corn bread, grits, tortillas, and tamales, show no detectable quantities of phylloquinone, with the exception of popcorn, which has 1 to 4 μg/100 g (Ferreira and others 2006; USDA 2011; Centi and others 2015). Fried maize snacks, such as corn and tortillas chips, have 6.3 to 20.9 μg vitamin K/100 g, but this content is mainly due to the oil in which they are fried (Weizmann and others 2004). Taco shells were found to have 8.6 μg vitamin K/100 g, but this was due to the addition of hydrogenated oils during processing (Ferreira and others 2006). Hydrogenation of plant oils containing vitamin K causes the transformation of phylloquinone to dihydrophylloquinone (Davidson and others 1996), which does not occur naturally. Decreasing use of hydrogenated oils in the U.S. since 2006, when the Food and Drug Association began to require *trans*-fat labeling, has generally resulted in slight decreases in dihydrophylloquinone in processed maize foods, but no increases in phylloquinine content (Centi and others 2015).

Magnesium

Maize contains about 127 mg magnesium/100 g whole kernels (USDA 2011). The RDAs for magnesium are 265 and 420 mg for men and women, respectively (Otten and others 2006). Magnesium content of maize tends to decrease with milling when the germ is removed. Degermed flour contains 18 mg magnesium/100 g, while whole-grain maize flour retains 93 mg/100 g.

Magnesium has been studied less than iron and zinc in the context of phytic acid, but it does form phytate complexes that inhibit absorption (Bohn and others 2004). One study showed magnesium content increased slightly, but significantly, after nixtamalization and preparation into dough and tortillas, from 165 mg/100 g unprocessed maize to 180 mg/100 g in dough and tortillas (Mendoza and others 1998). The authors offered other reasons for the increase in magnesium in the dough and tortillas as contamination from the soaking solution or transfer from grinding equipment and cooking pans.

Manganese

Manganese content of whole dry maize is about 0.49 mg/ 100 g. The RDAs for manganese are 2.3 and 1.8 mg/d for men and women, respectively (Otten and others 2006). Manganese content decreases with maize processing, especially with removal of the germ. Degermed maize flour contains only 0.06 mg manganese/100 g, whereas whole-grain maize flour contains 0.46 mg (USDA 2011). As with other metal minerals, reduction in phytic acid may also modestly improve absorption of manganese (Davidsson and others 1995; Lonnerdal 2002) as observed with soy formula, but this has not been well-studied in the context of maize and maize products.

Phosphorus

The adult RDA is 700 mg/d for phosphorus (Otten and others 2006). The phosphorus content of maize is around 210 mg/100 g, found mainly as phytic acid (FAO 1992). About 90% of the phytic acid in maize is found in the germ, while the remaining 10% occurs in the aleurone layer (Raboy and others 1990). Phytic acid chelates and reduces the bioavailability of iron and other nutrients (Gillooly and others 1983; Nävert and others 1985; Hallberg and others 1987). Thus, processing methods that reduce phytic acid will improve bioavailability of these nutrients in maize products (Mendoza and others 1998; Hambidge and others 2005).

Phytic acid can be reduced by one-quarter to one-third by physical removal of the maize bran and germ (Proulx and Reddy 2007). Different heat treatments of fresh and dried maize reduce phytic acid content; for example, one study found that boiling maize reduced phytic acid by 18%, while roasting maize decreased it by 24% to 53% (Khan and others 1991). The nixtamalization process reduces phytic acid by about 20% (Bressani and others 2004).

Soaking can activate endogenous phytase activity in many cereals, which decreases phytic acid; however, maize has low phytase activity and one study found that soaking whole maize for 16 h did not have an appreciable effect on phytic acid content (Egli and others 2002). On the other hand, soaking of unrefined white maize flour for at least 2 h did decrease phytic acid in another study, with a resulting 71% and 43% retention of zinc and phytic acid, respectively, with no further reduction for longer soaking times (Hotz and Gibson 2001).

During germination or fermentation of maize, phytase activity increases considerably. After 72 h of germination, phytase activity increased almost 6-fold and phytic acid levels decreased to 65% of the initial content (Egli and others 2002). Lactic acid fermentation of maize flour resulted in reduction of phytic acid to 88%, and even lower levels of phytic acid remained when using a starter culture (61%) or germinated flour (71%) (Hotz and Gibson 2001). These strategies can be combined for greater phytic acid reduction. For example, soaking maize flour with germinated flour for 24 to 48 h and adding a starter culture to facilitate fermentation or adding phytase can replace soaking and further reduce phytic acid (Svanberg and others 1991; Gibson and Ferguson 1998). Another study also found that soaking for 24 to 48 h prior to fermentation resulted in almost 96% reduction in phytic acid (Svanberg and others 1991).

Although phytic acid reduces the bioavailability of some nutrients, it also serves as an antioxidant (Graf and Eaton 1990). The phytic acid in maize provides protection to the kernel from the pro-oxidant effects of the metals present, and may also prevent damage to DNA and loss of lipids, particularly γ-tocopherol, during storage (Doria and others 2009). A low-phytic acid strain of maize was found to have double the level of free radicals compared with a wild-type strain after aging (Doria and others 2009). Thus, if lower levels of phytic acid are desired for the purpose of enhanced nutritive metal absorption, it may be important to consider the impact of low-phytic acid strains versus methods to reduce phytic acid in normal maize during processing.

Potassium

White and yellow maize contains 287 mg potassium/100 g, or about 6% of the RDA, which is 4700 mg/d for adults (Otten and others 2006). There is limited research on the effects of processing on potassium content in maize. According to the USDA Nutrient Database, whole-grain maize flour contains slightly higher amounts, at 315 mg potassium/100 g, while degermed flour contains only 90 mg/100g (USDA 2011). Further-processed maize products, such as tortillas, extruded chips, and flakes, contain 186, 144, and 168 g/100 g, respectively (USDA 2011).

Selenium

Whole-grain maize is a good source of selenium, containing about 15.5 μg/100 g (USDA 2011), which provides almost a third of the adult RDA for selenium at 55 μg/d (Otten and others 2006). Yellow maize has slightly higher quantities of selenium than white maize (Ferretti and Levander 1974). However, blue maize contains much less selenium compared with yellow or white maize, at 2.2 μg/100 g whole-grain flour (USDA 2011).

While whole-grain maize flour retains most of the selenium content, processing of maize into degermed flour or cornmeal reduces selenium content by 10% to 32% (Ferretti and Levander 1974; USDA 2011). Selenium content is further reduced by processing maize into tortillas or extruded corn chips, with losses of 51% to 61% (USDA 2011). In the case of sugared corn flake cereal, selenium losses of 40% to 46% occur, with some of the loss due to dilution of nutrient content by the added sugar (Ferretti and Levander 1974). However, due to the high content of selenium in whole yellow and white maize, processed products, such as degermed flour, chips, and flakes, still retain 15% of the RDA for selenium in 100 g.

Sodium

The RDA for sodium is 1500 mg/d for adults (Otten and others 2006). Maize is naturally very low in sodium, containing 35 mg/100 g. The sodium content of maize flour and grits is slightly lower per 100 g. However, many maize food products acquire sodium during processing, such as sodium hydroxide added to tortillas and hominy. Salt is often added for palatability reasons such that the sodium content is increased considerably especially in snack foods. Hominy, tortilla chips, and corn flakes contain between 310 and 729 mg sodium/100 g (USDA 2011).

Xanthophyll carotenoids: Lutein and zeaxanthin

Two additional carotenoids common in typical maize, lutein and zeaxanthin, have no vitamin A activity, but they have been associated with other health benefits including lowered risk of

Table 6–A summary of maize processing effects on retention of vitamin and mineral contents

Nutrient	Major location in kernel	Percent retention of nutrients after processing			
		Milling, degermination	Soaking, fermentation, germination	Nixtamalization	Heat (boiling, baking, frying, extrusion)
Provitamin A carotenoids	Endosperm	85% to 118% (Pillay and others, 2014)	Soaking: 90% to 93% (Li and others, 2007)	16% to 63% (De La Parra and others, 2007)	Porridge: 76% to 129% (Pillay and others, 2014) Tortillas: 9% to 33% Fried chips: ∼0% (De La Parra and others, 2007)
Anthocyanins and polyphenols	Endosperm			34% to 63% (Del Pozo-Insfran and others, 2006)	Tortillas: 25% to 46% Fried chips: 19% to 25% (Del Pozo-Insfran and others, 2006) Extrusion: 43% (Mora-Rochin and others, 2010)
B vitamins	Aleurone, germ	28% (thiamin) 43% (riboflavin) 60% (niacin) 35% (B_6) 14% (biotin) 36% (folate) (Hegedüs and others, 1985)	Fermentation+ germination: 250% (niacin) 450% (riboflavin) (Lay and Fields, 1981)	35% to 40% (thiamin) 48% to 68% (riboflavin) 70% (niacin) (Bressani and others, 1958) Increased niacin bioavailability (Kodicek and others, 1955)	Extrusion: 50% (thiamin) 100% (B_6) 84% (riboflavin) 75% (niacin) (Athar and others, 2006)
Calcium	Endosperm			18-fold increase[a] (Bressani and others, 2002)	
Copper	Germ	10% to 24% (USDA, 2011)			
Vitamin E	Germ	2% to 65% (Herting and Drury, 1969)			6% to 37% (among other grains) (Zielinski and others, 2001)
Iron	Endosperm	28% to 69% (Hazell and Johnson 1989; Proulx and Reddy 2007)	Improved bioavailability (43% increase) due to reduced phytic acid (Svanberg and others, 1991)	70% to 100% (Bressani et al., 2002, 2004)	Extrusion: 67% (Hazell and Johnson, 1989)
Vitamin K	Germ				85% (Ferland and Sadowski, 1992) Fried snacks: > 20-fold[a] (Weizmann and others, 2004)
Magnesium	Germ	14% (USDA, 2011)		109%[a] (Mendoza and others, 1998)	
Manganese	Germ	12% (USDA, 2011)			
Phosphorus (phytic acid)	Germ	65% to 75% (Proulx and Reddy, 2007)	Soaking + fermentation: 4% (Svanberg and others, 1991) Fermentation: 42% to 75% (Marfo and others, 1990; Proulx and Reddy, 2007)	80% (Bressani and others, 2004)	Boiling: 82% Roasting: 47% to 76% (Khan and others, 1991) Dry heat (tortillas): 82% (Proulx and Reddy, 2007)
Selenium	Germ	68% to 90% (Ferretti and Levander, 1974; USDA, 2011)			39% to 49% (USDA, 2011)
Xanthophyll carotenoids	Endosperm	91% to 136% (Pillay and others, 2014)	100% (Li and others, 2007)	33% to 14-fold increase (Gutiérrez-Uribe and others, 2014; De La Parra and others, 2007)	78% to 118% (porridge) (Pillay and others, 2014) 50% to 71% (bread, extruded puffs) (Kean and others, 2008) 27% to 116% (tortilla) (Gutiérrez-Uribe and others, 2014; De La Parra and others, 2007) 18% to 20% (fried chips) (De La Parra and others, 2007)
Zinc	Germ	20% to 30% (Gannon and others, 2014.; Pedersen and Eggum, 1983)	Soaking: 71% (Hotz and Gibson, 2001)	90% to 100% (Bressani and others, 2002; Bressani and others, 2004)	

[a]Increases may be from exogenous sources, such as machinery, cooking oils, or processing substrates.

macular degeneration and cataracts; there is no RDA but intakes of 10 to 20 mg/d of lutein have been recommended (Vishwanathan and Johnson 2013). In yellow maize, lutein and zeaxanthin make up 70% or more of the total carotenoid content (Kean and others 2008). Yellow maize is likely the highest source of zeaxanthin in the human diet.

The effects of processing on the xanthophylls can differ from that of the provitamin A carotenoids. Unlike provitamin A carotenoids, soaking and wet-milling do not result in significant losses of lutein or zeaxanthin (Li and others 2007). While heat treatment of maize will isomerize some lutein and zeaxanthin from all-*trans* into *cis* isomers, the total xanthophyll content may increase slightly; for example, canned maize had a 5% increase in lutein compared with fresh maize (Updike and Schwartz 2003). Pillay and others (2014) found a higher retention of zeaxanthin in maize meal (116% to 136%) compared with raw *samp* (91% to 112%) among varieties of provitamin A biofortified maize, and preparation of *phutu* or *samp* porridges from these products resulted in overall retention of zeaxanthin close to or slightly higher than that of the unprocessed maize (102% to 118%). A thin porridge contained only 78% to 88% that of the initial zeaxanthin content (Pillay and others 2014). Kean and others (2008) found that yellow maize meal into bread, porridge, or extruded puffs had lutein and zeaxanthin losses of 29% to 50%. Canned yellow maize heated to 126.7 °C for 12 min had slight, nonsignificant increases in lutein and zeaxanthin (2% to 3%) (Scott and Eldridge 2005). In preparation for commercial freezing, yellow maize kernels were steam-blanched at 87.8 to 93.3 °C for about 3 min and then quickly frozen at temperatures of −17.8 °C to −23.3 °C. Lutein content increased by about 9% while zeaxanthin content increased by 2% (Scott and Eldridge 2005).

The effect of nixtamalization on the xanthophylls varies depending on the methods used. De La Parra and others (2007) found that only about one-third of initial lutein and zeaxanthin content remained in masa, with further decreases in tortillas and chips. Conversely, Gutiérrez-Uribe and others (2014) found that the nixtamalization process yielded 10-fold higher lutein and zeaxanthin in the masa; however, the levels in the tortillas made from this masa were very similar to those of the original whole kernel.

Zinc

The RDA for zinc is 8 mg/d for nonpregnant, nonlactating adult women and 11 mg/d for men (Otten and others 2006). Dry yellow and white maize contain a little over 2 mg zinc/100 g (USDA 2011), the majority of which is found in the germ (Bressani and others 2002). The zinc content of whole maize and common maize products is shown in Table 1. However, maize also contains about 1 g phytic acid/100 g, concentrated in the germ, which forms insoluble complexes with zinc, reducing its bioavailability (Nävert and others 1985; Hídvégi and Lásztity 2002). One approach to enhance zinc absorption is the reduction of phytic acid content (Kivistö and others 1989), which can be accomplished through a variety of methods (described in section on phosphorus). Zinc absorption is also influenced by other nutrients found in maize and the rest of the diet.

Milling. Refined milling of maize removes the germ leaving mainly the starchy endosperm. This process removes many nutrients including zinc; thus, degermed maize contains only about 20% of the zinc content of whole maize (Pedersen and Eggum 1983). Gannon and others (2014) found that the zinc content of refined (germ and pericarp removed) white and orange maize had 21% and 30% of the zinc as that in the whole grain. On the other hand, removal of the germ reduces phytic acid, decreasing the phytate:zinc molar ratio, which enhances the bioavailability of the remaining zinc (Pedersen and Eggum 1983).

Thermal processing and extrusion. Heat-treated corn products can be subject to the Maillard reaction, evidenced by "browning," which can bind zinc, making it less bioavailable. Lykken and others (1986) compared the absorption of zinc from cornflakes (browned) and corn grits, finding higher zinc absorption from the grits, which they attributed to the Maillard reaction occurring in the cornflakes. The high heat and pressure of extrusion processing are unlikely to affect the content of zinc in maize, but they may reduce phytic acid and thus improve zinc availability (Singh and others 2007); however, Kivisto and others (1989) found that the extrusion process actually caused a decrease in zinc absorption in an extruded wheat bran product, but was ameliorated when phytate was removed before extrusion. Further work is needed to determine the effect of extrusion on phytic acid and zinc availability in maize products.

Soaking, germination, and fermentation. These methods can be used to reduce phytic acid and enhance zinc bioavailability. For example, soaking of unrefined maize flour for at least 2 h resulted in a 29% loss of zinc and 57% loss of phytic acid (Hotz and Gibson 2001). Germination and fermentation can increase phytase activity further than soaking alone (Svanberg and others 1991; Gibson and Ferguson 1998; Egli and others 2002). Combining these strategies may reduce phytic acid and further enhance zinc bioavailability.

Nixtamalization. Phytic acid is decreased during the nixtamalization process, which may improve the bioavailability of zinc, but there is no considerable increase in zinc itself in nixtamalized maize (Bressani and others 2002). Altering the amount of lime and length of cooking time can affect phytic acid levels. Bressani and others (2004) found the highest losses of phytic acid using 1.2% lime and 75 min cooking time, while zinc content was unchanged. Changes to the steeping time and the solution (alkaline cooking liquid versus water) also affected phytic acid; after cooking in lime, phytic acid was reduced 22%, and steeping for up to 8 h in either an alkaline or water medium reduced phytic acid further to a total of 28% to 29% losses from dry maize. Steeping for over 5 h resulted in small but statistically significant losses of zinc.

Nutrients that influence zinc absorption. Fiber, protein, calcium, and iron are all known to influence zinc absorption. Fiber has been implicated in poor zinc absorption, but this may be due more to the concomitant occurrence of phytic acid in high-fiber foods, and studies have shown that fiber actually has little independent effect on zinc absorption (Lonnerdal 2000). Generally, higher protein intakes modestly augment zinc absorption (Miller and others 2013), and animal protein, even in small quantities, can improve zinc absorption during a meal by inhibiting the negative effect of phytic acid (Sandström and others 1989). Individual amino acids enhance zinc absorption, including lysine, which is found in higher amounts in opaque or quality protein maize (Bänziger and Long 2000; Graham and others 2001). The potential impact of quality protein maize on lysine and tryptophan intake in Africa has been predicted by Nuss and Tanumihardjo (2011).

Previous studies have shown a decrease in the bioavailability of zinc in the presence of calcium and phytic acid due to the formation of zinc-calcium-phytate complexes in the intestine (Fordyce and others 1987). However, more recent research suggests that phytic acid will preferentially bind to calcium and iron and, thus, may actually increase the bioavailability of zinc (Miller and others 2013; Moretti and others 2014). This is particularly pertinent in the case of nixtamalized maize, which has enhanced levels of calcium due to the lime (Bressani and others 2002). More research is needed in this area to determine the effect of interactions between zinc, calcium, and phytate on zinc absorption.

Summary and Conclusions

Maize is a good source of some micronutrients, but amounts can vary by genotype, and different processing methods can have substantial effects on the nutrient content of the resulting products (summarized in Table 6). The majority of B vitamins are lost during long-term storage and milling (degermination), and additionally in soaking and cooking. Other processing methods, however, such as fermentation and nixtamalization, can increase bioavailability of riboflavin and niacin. Carotenoid content may increase through degermination because they are mostly found in the endosperm. A large proportion of the minerals in maize are lost during degermination, while mineral bioavailability can be improved by processing methods that reduce phytic acid, such as soaking, fermenting, cooking, and nixtamalization.

Losses to micronutrients during processing can be mitigated by changes in processing methods or reduction in processing, and also by encouraging consumption of whole-grain maize products over degermed, refined products. When losses cannot be mitigated and populations consuming the product are at risk of specific micronutrient deficiencies, these can be potentially reduced through fortification (Peña-Rosas and others 2014) or biofortification strategies (Tanumihardjo and others 2010).

The effects of different processing methods on nutrient content in maize, from field to plate, indicate that, generally, the fresher and less processed the maize is, the more nutrients it retains. However, this is nutrient-specific, and this trend is reversed in the case of nutrients such as niacin, which has very low bioavailability from unprocessed maize, but can be released during processing. As such, the general trends in the effects of processing on the micronutrient content of maize products can be used to guide food producers, food analysis and dietary nutrient evaluations. However, due to the high variability in baseline nutrient content among maize varieties, combined with additional variability in processing effects, for the most accurate data it will be necessary to analyze the actual nutrient content of the maize product. Furthermore, attention should be placed on not only the nutrient content but also the potential *in vivo* bioavailability.

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Author Contributions

D. Suri prepared the manuscript. S. Tanumihardjo conceptualized, reviewed, and edited the manuscript.

References

Abdel-Aal ESM, Young JC, Rabalski I. 2006. Anthocyanin composition in black, blue, pink, purple, and red cereal grains. J Agric Food Chem 54:4696–704.

Ai Y, Jane J-L. 2016. Macronutrients in corn and human nutrition. Compr Rev Food Sci Food Safety 15:581–98.

Anderson PA, Baker DH, Mistry SP. 1978. Bioassay determination of the biotin content of corn, barley, sorghum and wheat. J Animal Sci 47:654–9.

Athar N, Hardacre A, Taylor G, Clark S, Harding R, McLaughlin J. 2006. Vitamin retention in extruded food products. J Food Comp Anal 19:379–83.

Ball GFM. 2006. Vitamins in foods: analysis, bioavailability, and stability. Boca Raton, Fla.: Taylor and Francis Group.

Bänziger M, Long J. 2000. The potential for increasing the iron and zinc density of maize through plant-breeding. Food Nutr Bull 21:397–400.

Blessin C, Brecher J, Dimler R. 1963. Carotenoids of corn and sorghum: V. Distribution of xanthophylls and carotenes in hand-dissected and dry-milled fractions of yellow dent corn. Cereal Chem 40:582–5.

Bohn T, Davidsson L, Walczyk T, Hurrell RF. 2004. Phytic acid added to white-wheat bread inhibits fractional apparent magnesium absorption in humans. Am J Clin Nutr 79:418–23.

Bressani R, Paz y Paz R, Scrimshaw NS. 1958. Chemical changes in corn during preparation of tortillas. J Agric Food Chem 6:770–4.

Bressani R, Turcios JC, Ruiz ASC. 2002. Nixtamalization effects on the contents of phytic acid, calcium, iron and zinc in the whole grain, endosperm and germ of maize. Food Sci Technol Intern 8:81–6.

Bressani R, Turcios JC, Colmenares de Ruiz AS, de Palomo PP. 2004. Effect of processing conditions on phytic acid, calcium, iron, and zinc contents of lime-cooked maize. J Agric Food Chem 52:1157–62.

Burt AJ, Grainger CM, Young JC, Shelp BJ, Lee EA. 2010. Impact of postharvest handling on carotenoid concentration and composition in high-carotenoid maize (*Zea mays* L.) kernels. J Agric Food Chem 58:8286–92.

CDC. 2010. CDC Grand Rounds: additional opportunities to prevent neural tube defects with folic acid fortification. Morb Mortal Wkly Rep 59: 980–4.

Centi AJ, Brown-Ramos M, Haytowitz DB, Booth SL. 2015. Changes in the content and forms of vitamin K in processed foods. J Food Comp Anal 41:42–4.

Cevallos-Casals BA, Cisneros-Zevallos L. 2004. Stability of anthocyanin-based aqueous extracts of Andean purple corn and red-fleshed sweet potato compared to synthetic and natural colorants. Food Chem 86:69–77.

Collison A, Yang L, Dykes L, Murray S, Awika J. 2015. Influence of genetic background on anthocyanin and copigment composition and behavior during thermoalkaline processing of maize. J Agric Food Chem 10:5528–38.

Cortés GA, Salinas MY, Martín-Martinez ES, Martínez-Bustos F. 2006. Stability of anthocyanins of blue maize (*Zea mays* L.) after nixtamalization of separated pericarp-germ tip cap and endosperm fractions. J Cereal Sci 43:57–62.

Davidson KW, Booth SL, Dolnikowski GG, Sadowski JA. 1996. Conversion of vitamin K1 to 2′,3′-dihydrovitamin K1 during the hydrogenation of vegetable oils. J Agric Food Chem 44:980–3.

Davidsson L, Almgren A, Juillerat MA, Hurrell RF. 1995. Manganese absorption in humans: the effect of phytic acid and ascorbic acid in soy formula. Am J Clin Nutr 62:984–7.

De La Parra C, Serna Saldivar SO, Liu RH. 2007. Effect of processing on the phytochemical profiles and antioxidant activity of corn for production of masa, tortillas, and tortilla chips. J Agric Food Chem 55:4177–83.

Del Pozo-Insfran D, Brenes CH, Serna Saldivar SO, Talcott ST. 2006. Polyphenolic and antioxidant content of white and blue corn (*Zea mays* L) products. Food Res Intl 39:696–703.

de Moura FF, Miloff A, Boy E. 2015. Retention of provitamin A carotenoids in staple crops targeted for biofortification in Africa: cassava, maize and sweet potato. Crit Rev Food Sci Nutr 55:1246–69.

Dewanto V, Wu X, Liu RH. 2002. Processed sweet corn has higher antioxidant activity. J Agric Food Chem 50:4959–4964.

Doria E, Galleschi L, Calucci L, Pinzino C, Pilu R, Cassani E, Nielsen E. 2009. Phytic acid prevents oxidative stress in seeds: evidence from a maize (*Zea mays* L.) low phytic acid mutant. J Exp Bot 60:967–78.

Egli I, Davidsson L, Juillerat MA, Barclay D, Hurrell RF. 2002. The influence of soaking and germination on the phytase activity and phytic acid content of grains and seeds potentially useful for complementary feeding. J Food Sci 67:3484–8.

Escalante-Aburto A, Ramírez-Wong B, Torres-Chávez PI, Manuel Barrón-Hoyos J, de Dios Figueroa-Cárdenas J, López-Cervantes J. 2013. La nixtamalización y su efecto en el contenido de antocianinas de maíces pigmentados, una revisión. Revista Fitotecnia Mexicana 36:429–37.

FAO. 1992. Maize in human nutrition. Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO. 2011. FAOSTAT Food Balance/Food Supply - Crops Primary Equivalent at maize and products, food supply quantity. Available from: http://faostat3.fao.org/browse/FB/CC/E. Accessed 2015 July 12.

FAOSTAT. 2013. Food Balance Sheets/Bulk Downloads, Available from: http://faostat3.fao.org/download/FB/FBS/E. Accessed 2015 December 17.

Ferland G, Sadowski JA. 1992. Vitamin-K1 (phylloquinone) content of edible oils—effects of heating and light exposure. J Agric Food Chem 40:1869–73.

Ferrari RAA, Schulte E, Esteves W, Brühl L, Mukherjee KD. 1996. Minor constituents of vegetable oils during industrial processing. J Am Oil Chem Soc 73:587–92.

Ferreira D, Haytowitz D, Tassinari MA, Peterson JW, Booth SL. 2006. Vitamin K contents of grains, cereals, fast-food breakfasts, and baked goods. J Food Sci 71:66–70.

Ferretti RJ, Levander OA. 1974. Effect of milling and processing on the selenium content of grains and cereal products. J Agric Food Chem 22:1049–51.

Fordyce EJ, Forbes RM, Robbins KR, Erdman JW. 1987. Phytate × calcium/zinc molar ratios: are they predictive of zinc bioavailability? J Food Sci 52:440–4.

Frigg M. 1976. Bio-availability of biotin in cereals. Poul Sci 55:2310–8.

Gannon B, Kaliwile C, Arscott SA, Schmaelzle S, Chileshe J, Kalungwana N, Mosonda M, Pixley K, Masi C, Tanumihardjo SA. 2014. Biofortified orange maize is as efficacious as a vitamin A supplement in Zambian children even on the background of high liver reserves of vitamin A: a community-based, randomized placebo-controlled trial. Am J Clin Nutr 100: 1541–50.

Gannon B, Tanumihardjo S. 2014. Milling method affects zinc content of maize and health status of *Mongolian gerbils*. FASEB J 28:646–5.

Gibson R, Ferguson E. 1998. Food processing methods for improving zinc content and bioavailability of home-based and commercially available complementary foods. In: Micronutrient interactions impact on child health and nutrition. Washington DC: ILSI Press. p 50–7.

Gillooly M, Bothwell TH, Torrance JD, MacPhail AP, Derman DP, Bezwoda WR, Mills W, Charlton RW, Mayet F. 1983. The effects of organic acids, phytates and polyphenols on the absorption of iron from vegetables. Br J Nutr 49:331–42.

Goldsmith G, Miller O, Unglaub W. 1961. Efficiency of tryptophan as a niacin precursor in man. J Nutr 73:172–6.

Graf E, Eaton JW. 1990. Antioxidant functions of phytic acid. Free Rad Biol Med 8:61–9.

Graham RD, Welch RM, Bouis HE. 2001. Addressing micronutrient malnutrition through enhancing the nutritional quality of staple foods: principles, perspectives and knowledge gaps. Adv Agron 70:77–142.

Gutiérrez-Uribe JA, Rojas-García C, García-Lara S, Serna-Saldivar SO. 2014. Effects of lime-cooking on carotenoids present in masa and tortillas produced from different types of maize. Cereal Chem 91:508–12.

Gwirtz JA, Garcia-Casal MN. 2014. Processing maize flour and corn meal food products. Ann NY Acad Sci 1312:66–75.

Hallberg L, Rossander L, Skånberg A-B. 1987. Phytates and the inhibitory effect of bran on iron absorption in man. Am J Clin Nutr 45:988–96.

Hambidge KM, Krebs NF, Westcott JL, Sian L, Miller LV, Peterson KL, Raboy V. 2005. Absorption of calcium from tortilla meals prepared from low-phytate maize. Am J Clin Nutr 82:84–7.

Hamner HC, Tinker SC. 2014. Fortification of corn masa flour with folic acid in the United States: an overview of the evidence. Annals NY Acad Sci 1312:8–14.

Harper AE, Punekar BD, Elvehjem CA. 1958. Effect of alkali treatment on the availability of niacin and amino acids in maize. J Nutr 66:163–72.

Hazell T, Johnson IT. 1989. Influence of food processing on iron availability in vitro from extruded maize-based snack foods. J Sci Food Agric 46:365–74.

Heathcote J, Hinton J, Shaw B. 1952. The distribution of nicotinic acid in wheat and maize. Proc Roy Soc Lond 139:276–87.

Hegedüs M, Pedersen B, Eggum BO. 1985. The influence of milling on the nutritive value of flour from cereal grains. 7. Vitamins and tryptophan. Plant Foods Hum Nutr 35:175–80.

Herting DC, Drury EJE. 1969. Alpha-tocopherol content of cereal grains and processed cereals. J Agric Food Chem 17:785–90.

Hídvégi M, Lásztity R. 2002. Phytic acid content of cereals and legumes and interaction with proteins. Periodica Polytechnica: Chem Eng 46:59–64.

Hotz C, Gibson RS. 2001. Assessment of home-based processing methods to reduce the phytate content and phytate/zinc molar ratio of white maize (*Zea mays*). J Agric Food Chem 49:692–8.

Kean EG, Hamaker BR, Ferruzzi MG. 2008. Carotenoid bioaccessibility from whole grain and degermed maize meal products. J Agric Food Chem 56:9918–26.

Khan N, Zaman R, Elahi M. 1991. Effect of heat-treatments on the phytic acid content of maize products. J Sci Food Agric 54:153–6.

Kies C, Kan S, Fox HM. 1984. Vitamin B6 availability from wheat, rice and corn brans for humans. Nutr Reports Intl 30:483–91.

Kivistö B, Cederblad Å, Davidsson L, Sandberg A-S, Sandström B. 1989. Effect of meal composition and phytate content on zinc absorption in humans from an extruded bran product. J Cereal Sci 10:189–97.

Kodicek E, Braude R, Kon SK, Mitchell KG. 1956. The effect of alkaline hydrolysis of maize on the availability of its nicotinic acid to the pig. Br J Nutr 10:51–67

Kodicek E, Ashby D, Muller M, Carpenter KJ. 1974. The conversion of bound nicotinic acid to free nicotinamide on roasting sweet corn. Proc Nutr Soc 33:105A–6A.

Krause VM, Solomons NW, Tucker KL, Lopez CY, Palacios MR, Kuhnlein HV. 1992. Rural-urban variation in the calcium, iron, zinc and copper content of tortillas and intake of these minerals from tortillas by women in Guatemala. Ecology Food Nutr 28:289–97. http://www.tandfonline.com/doi/abs/10.1080/03670244.1992.9991282.

Kurilich AC, Juvik JA. 1999. Quantification of carotenoid and tocopherol antioxidants in *Zea mays*. J Agric Food Chem 47:1948–55.

Laguna J, Carpenter KJ. 1951. Raw versus processed corn in niacin-deficient diets. J Nutr 45:21–8.

Lay MM, Fields ML. 1981. Nutritive value of germinated corn and corn fermented after germination sample preparation. J Food Sci 46: 1069–73.

Li S, Tayie FAK, Young MF, Rocheford T, White WS. 2007. Retention of provitamin A carotenoids in high beta-carotene maize (*Zea mays*) during traditional African household processing. J Agric Food Chem 55:10744–50.

Lonnerdal B. 2000. Dietary factors influencing zinc absorption. J Nutr 130:1378S–83S.

Lonnerdal B. 2002. Phytic acid—trace element (Zn, Cu, Mn) interactions. Intl J Food Sci Technol 37:749–58.

Lopez-Martinez LX, Oliart-Ros RM, Valerio-Alfaro G, Lee CH, Parkin KL, Garcia HS. 2009. Antioxidant activity, phenolic compounds and anthocyanins content of eighteen strains of Mexican maize. LWT - Food Sci Technol 42:1187–92.

Lopez-Martinez LX, Parkin KL, Garcia HS. 2011. Phase II-inducing, polyphenols content and antioxidant capacity of corn (*Zea mays* L.) from phenotypes of white, blue, red and purple colors processed into masa and tortillas. Plant Foods for Human Nutr 66:41–7.

Lozano-Alejo N, Carrillo GV, Pixley K, Palacios-Rojas N. 2007. Physical properties and carotenoid content of maize kernels and its nixtamalized snacks. Innov Food Sci Emerging Technol 8:385–9.

Lykken GI, Mahalko J, Johnson PE, Milne D, Sandstead HH, Garcia WJ, Dintzis FR, Inglett GE. 1986. Effect of browned and unbrowned corn products intrinsically labeled with ^{65}Zn on absorption of ^{65}Zn in humans. J Nutr 116:795–801.

Marfo EK, Simpson BK, Johnson JSI, Oke OL. 1990. Effect of local food processing. J Agric Food Chem 38:1580–5.

McKillop DJ, Pentieva K, Daly D, McPartlin JM, Hughes J, Strain JJ, Scott JM, McNulty H. 2002. The effect of different cooking methods on folate retention in various foods that are amongst the major contributors to folate intake in the UK diet. Br J Nutr 88:681–8.

Mendoza C, Viteri FE, Lönnerdal B, Young KA, Raboy V, Brown KH. 1998. Effect of genetically modified, low-phytic acid maize on absorption of iron from tortillas. Am J Clin Nutr 68:1123–7.

Micklos D. Epigenetics I: Using Carolina Corn Ears to Teach Genetic Imprinting. DNA Learning Center, Cold Spring Harbor Laboratory. Available from: http://www.carolina.com/teacher-resources/Interactive/using-carolina-corn-ears-to-teach-genetic-imprinting/tr28902.tr. Accessed 2016 March 30.

Miller LV, Krebs NF, Hambidge KM. 2013. Mathematical model of zinc absorption. Effects of dietary calcium, protein and iron on zinc absorption. Br J Nutr 109:695–700.

Mora-Rochin S, Gutiérrez-Uribe JA, Serna-Saldivar SO, Sanchez-Pena P, Reyes-Moreno C, Milan-Carrillo J. 2010. Phenolic content and antioxidant activity of tortillas produced from pigmented maize processed by conventional nixtamalization or extrusion cooking. J Cereal Sci 52:502–8.

Moretti D, Biebinger R, Bruins MJ, Hoeft B, Kraemer K. 2014. Bioavailability of iron, zinc, folic acid, and vitamin A from fortified maize. Ann NY Acad Sci 1312:54–65.

Mugode L, Ha B, Kaunda A, Sikombe T, Phiri S, Mutale R, Davis C, Tanumihardjo S, de Moura FF. 2014. Carotenoid retention of biofortified provitamin A maize (*Zea mays* L.) after Zambian traditional methods of milling, cooking and storage. J Agric Food Chem 62:6317–25.

Muzhingi T, Yeum K-J, Russell RM, Johnson EJ, Qin J, Tang G. 2008. Determination of carotenoids in yellow maize, the effects of saponification and food preparations. Intl J Vitam Nutr Res 78:112–20.

Muzhingi T, Gadaga TH, Siwela AH, Grusak MA, Russell RM, Tang G. 2011. Yellow maize with high β-carotene is an effective source of vitamin A in healthy Zimbabwean men. Am J Clin Nutr 94:510–9.

Nävert B, Sandström B, Cederblad A. 1985. Reduction of the phytate content of bran by leavening in bread and its effect on zinc absorption in man. Br J Nutr 53:47–53.

Nestel P, Bouis HE, Meenakshi JV, Pfeiffer W. 2006. Biofortification of staple food crops. J Nutr 136:1064–7.

Nuss ET, Tanumihardjo SA. 2010. Maize: a paramount staple crop in the context of global nutrition. Compr Rev Food Sci Food Safety 9:417–36.

Nuss ET, Tanumihardjo SA. 2011. Quality protein maize for Africa: closing the protein inadequacy gap in vulnerable populations. Adv Nutr 2:217–24.

Otten JJ, Hellwig JP, Meyers LD (Editors). 2006. Dietary reference intakes. The essential guide to nutrient requirements. Washington, DC: The National Academies Press. 560 p.

Pedersen B, Eggum BO. 1983. The influence of milling on the nutritive value of flour from cereal grains. 5. Maize. Plant Foods Human Nutr 32:299–311.

Peña-Rosas JP, Garcia-Casal MN, Pachón H, Mclean MS, Arabi M. 2014. Technical considerations for maize flour and corn meal fortification in public health. Consultation rationale and summary. Ann N Y Acad Sci 1312:1–7.

Pillay K, Siwela M, Derera J, Veldman FJ. 2014. Provitamin A carotenoids in biofortified maize and their retention during processing and preparation of South African maize foods. J Food Sci Technol 51:634–44.

Pixley K, Palacios-Rojas N, Babu R, Mutale R, Surles R, Simpungwe E. 2013. Biofortification of maize with provitamin A carotenoids. In Tanumihardjo SA, editor. Carotenoids and human health. New York: Springer Science and Business Media. p 271–92.

Platt S, Clydesdale F. 1987. Interactions of iron alone and in combination with Ca, Zn, and Cu with a phytate-rich, fiber-rich fraction of wheat bran under gastrointestinal pH conditions. Cereal Chem 64:102–5.

Prinzo ZW. 2000. Pellagra and its prevention and control in major emergencies. World Health Organization: WHO/NHD/00.10.

Proulx AK, Reddy MB. 2007. Fermentation and lactic acid addition enhance iron bioavailability of maize. J Agric Food Chem 55:2749–54.

Raboy V, Dickinson DB, Neuffer MG. 1990. A survey of maize kernel mutants for variation in phytic acid. Maydica 35:383–90.

Rocheford TR, Wong JC, Egesel CO, Lambert RJ. 2002. Enhancement of vitamin E levels in corn. J Am College Nutr 21:191S–8S.

Roth-Maier DA, Kettler SI, Kirchgessner M. 2002. Availability of vitamin B6 from different food sources. Intl J Food Sci Nutr 53:171–9.

Saldana G, Brown HE. 1984. Nutritional composition of corn and flour tortillas. J Food Sci 49:1202–3.

Sandström B, Almgren A, Kivistö B, Cederblad A. 1989. Effect of protein level and protein source on zinc absorption in humans. J Nutr 119:48–53.

Scott CE, Eldridge AL. 2005. Comparison of carotenoid content in fresh, frozen and canned corn. J Food Compos Anal 18:551–9.

Serna-Saldivar SO, Gomez MH, Almeida-Dominguez HD, Islas-Rubio A, Rooney LW. 1993. A method to evaluate the lime-cooking properties of corn (*Zea mays*). Cereal Chem 70:762–4.

Singh S, Gamlath S, Wakeling L. 2007. Nutritional aspects of food extrusion: a review. Intl J Food Sci Technol 42:916–29.

Slavin JL, Jacobs D, Marquart L. 2000. Grain processing and nutrition. Crit Rev Food Sci Nutr 40:309–26.

Svanberg U, Lorri W, Sandberg A-S. 1991. Phytate hydrolysis by phytase in cereals: effects on *in vitro* estimation of iron availability. J Food Sci 56:1330–3.

Tanumihardjo SA. 2008. Food-based approaches for ensuring adequate vitamin A nutrition. Compr Rev Food Sci Food Safety 7:373–81.

Tanumihardjo SA, Palacios N, Pixley KV. 2010. Provitamin A carotenoid bioavailability: what really matters? Intl J Vitam Nutr Res 80:336–50.

Updike AA, Schwartz SJ. 2003. Thermal processing of vegetables increases cis isomers of lutein and zeaxanthin. J Agric Food Chem 51:6184–90.

USDA. 2011. USDA National Nutrient Database for Standard Reference, Release 24. Accessed at Database.

Vishwanathan RJ, Johnson EJ. 2013. Lutein and zeaxanthin and eye disease. In: Tanumihardjo SA, editor. Carotenoids and human health. New York, N.Y.: Springer Science and Business Media. p 215–36.

Wall J, Carpenter KJ. 1988. Variation in availability of niacin in grain products: changes in chemical composition during grain development and processing affect the nutritional availability of niacin. Food Technol 42:198–203.

Weber E. 1984. High-performance liquid chromatography of gibberellins. J Am Oil Chem Soc 61:1231–4.

Weizmann N, Peterson JW, Haytowitz D, Pehrsson PR, de Jesus VP, Booth SL. 2004. Vitamin K content of fast foods and snack foods in the US diet. J Food Comp Anal 17:379–84.

Yu BH, Kies C. 1993. Niacin, thiamin, and pantothenic acid bioavailability to humans from maize bran as affected by milling and particle size. Plant Foods Hum Nutr 43:87–95.

Zielinski H, Kozlowska H, Lewczuk B. 2001. Bioactive compounds in the cereal grains before and after hydrothermal processing. Innov Food Sci Emerging Technol 2:159–69.

Žilić S, Serpen A, Akillioğlu G, Gökmen V, Vančetović J. 2012. Phenolic compounds, carotenoids, anthocyanins, and antioxidant capacity of colored maize (*Zea mays* L.) kernels. J Agric Food Chem 60:1224–31.

