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RESEARCH ARTICLE

Reduction in rancidity development in fortified whole-grain maize meal by hot-air drying of the grain

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Abstract

Background and Objective: Maize is the major staple in sub-Saharan Africa. Whole-grain maize meal (WGMM) is highly susceptible to rancidity development. This work investigated whether rancidity development in micronutrient-fortified WGMM is retarded by drying the grain of safe moisture content to below this level using a commercial hot-air grain dryer before milling.

Findings: Fat acidity (hydrolytic rancidity measure) of WGMM from maize dried to 11.6% moisture and stored for 47 days at 40°C was only 61% of meal from the undried grain control (13.3% moisture). Peroxide value (oxidative rancidity measure) was only 53%. With the exception of riboflavin, there was no reduction in fortificant micronutrients during meal storage. Descriptive sensory evaluation indicated greater similarity to the control for stored maize meal and its stiff porridge from dried maize than for meal and porridge from undried maize.

Conclusions: Drying maize grain to 11.6% moisture substantially retards rancidity development in fortified WGMM development, probably by inactivating the grain's lipase and oxidative enzymes, providing a shelf life of at least 20 weeks at 25°C.

Significance and Novelty: This simple process to extend the shelf life of whole-grain maize meal is implementable by any mill with access to a hot-air grain dryer.

KEYWORDS

heat treatment, lipase, lipoxygenase, maize porridge, micronutrient fortification, whole grains

1 | INTRODUCTION

Whole grains and whole-grain foods are increasingly and rightly a focus of attention by the grains and nutrition communities on account of their better nutrient quality and health-promoting attributes when compared to their refined grain counterparts (Milani et al., 2022). However, the majority of scientific and technological research to optimize the quality of whole-grain food products has focused on wheat and bread, see for example, Dapčević-Hadnađev et al. (2022), Gómez et al. (2020), and Parenti et al. (2020), whereas other cereal grains and their food staples have received considerably less attention.

Maize is the major cereal staple in sub-Saharan Africa and is generally consumed in the form of various types of doughs and porridges (Ekpa et al., 2019). The sensory acceptability of whole-grain maize porridge presents several challenges, including stronger flavors, darker color, and coarser texture, when compared to refined grain maize porridge (Taylor et al., 2022). Flour/meal fat rancidity is a major cause of the stronger flavors of whole-grain products, including maize meal (Mestres et al., 2003). The fat rancidity is primarily caused by endogenous lipid-degrading enzymes (lipases, lipoxygenases, and other oxidases) released from the aleurone and germ during milling acting on the free oil released from germ and aleurone oil bodies (Doblado-Maldonado et al., 2012; Gonzalez-Thuillier et al., 2015). Thermal treatment of the intact or milled cereal grain can retard the development of rancidity in milled whole grain food products by inactivating the lipid-degrading enzymes. See, for example, Vinutha et al. (2022) who investigated the effect of different thermal treatments on the activity of the various enzymes responsible for fat rancidity in pearl millet. With oats, wet or dry heat treatments are routinely applied during grain processing to stabilize the oat flakes and flour products because of their high fat content (Heiniö et al., 2002).

Despite the importance of maize meals and flours for porridge making in sub-Saharan Africa and across the world in applications such as snack foods and brewing adjuncts, there have been very few published studies on stabilization of maize milling products. This is possibly because industrially produced meals/flours are invariably refined and have relatively low fat contents, between 0.8% and 2.7% compared to the approximately 4.5% in whole-grain maize (Gwirtz & Garcia-Casal, 2014).

Deepa and Hebbar (2014, 2017) studied the effect of micronization (infrared heat treatment) on rancidity development in stored maize flour. When maize grains conditioned to 25% moisture were micronized at an air temperature of 200°C, lipase activity was reduced by 84% and peroxidase was completely inactivated. Furthermore, there was no increase in free fatty acids over the periods of the shelf-life tests. Under the accelerated condition (38°C, 90% relative humidity), flour shelf life, as quantified by very low lipase and lipoxygenase activity, was increased from 15 to 60 days without significant change, and at 27°C from 30 to 120 days.

In tropical Africa, micronutrient fortified whole-grain maize meal (WGMM), which is used in nutrition schemes and increasingly in packaged products (Fortified Whole Grain Alliance, 2023), needs to have a similarly long storage life because of challenges in distribution to rural areas. The requirement is for a thermal treatment process to retard rancidity development in micronutrient fortified WGMM that does not necessitate local grain storage facilities or medium-scale millers in Africa purchasing costly additional drying equipment. Many of these facilities have access to commercial hot-air grain driers to dry the maize to a safe moisture content directly after harvest, as harvested maize moisture contents are often as high as 20%. Hence, in this research, we investigated the effects of drying maize grain of safe normal storage moisture content (approximately 13% moisture) to below this level using a commercial grain dryer, before milling, on the storage life of fortified WGMM, its micronutrient content and sensory quality of stiff porridge (ugali) made from it.

2 | MATERIALS AND METHODS

2.1 | Maize hot-air drying and milling

Hot-air drying and milling of the maize was performed by Minimex Ltd., Kigali, Rwanda. White maize (800 kg) of moisture content of 13.3% (as is basis) was further dried using a commercial diesel-fueled, furnace-heated hot-air, tower-type grain dryer to two moisture contents, 11.6% and 9.9% (as is basis). The general drying parameters used were similar to those described by Çelik et al. (2021) for this type of dryer with maize. The actual conditions were a hot-air inlet temperature of 125°C and the time of hot-air drying was 55 min. At the end of which, the maize grain temperature was 60°C. The relatively high inlet temperature was used because the grain was being further dried from an already safe moisture content and hence was not readily prone to thermal damage, as would have been the case with damp grain (Lewandowski, 2019). Once the temperature of the grain had reached 60°C, the grain was then dried to the required moisture contents (11.6% and 9.9% moisture) by blowing ambient-temperature air into the grain mass in the dryer, in accordance with the grain dryer manufacturer's instructions. During this time, grain moisture content was monitored at 5-min intervals using an off-line grain moisture meter.

Within 2 weeks of drying, the three batches of maize grain were cleaned and then milled into fine particle size WGMM using a pilot-scale industrial hammer milling system (design production capacity of 1 ton/h) incorporating a 500 μm mesh opening screen. The maize meal was fortified using a micronutrient premix (DSM) in accordance with the East African Standard specification (Kenya Bureau of Standards, 2019). The vitamin and mineral fortificants were vitamin A (retinol palmitate), vitamins B1, B2, B3, B6, and B12, folic acid, iron (sodium iron EDTA), and zinc (zinc oxide). After milling, the maize meals had moisture contents of 12.9% as is basis (control—maize undried), 10.7% and 9.5% as is basis (hot-air dried).

The batches of the maize meals were then air-freighted to South Africa and Tanzania for analysis. On receipt, 10 days after milling, multiple 500 g samples were packaged in woven polypropylene bags with polyethylene liners, in accordance with World Food Programme (WFP) specifications for maize storage bags (WFP, 2020a). The bags were stored at −20°C until shelf-life testing.

2.2 | Accelerated shelf-life testing

The bags of fortified WGMM were held at 40°C, equivalent to 25°C, assuming a Q_{10} factor of 2 (WFP, 2020b), in a thermostatically controlled incubator under low light conditions. Bags were removed at 24 and 47 days, equivalent to 10.3 and 20.1 weeks at 25°C, respectively, and stored at −20°C until analysis.

2.3 | Analyzes

2.3.1 | Fat acidity and peroxide value

Samples of the maize meal were analyzed at 0, 24, and 47 days for fat acidity according to AACC Method 02-02 and for peroxide value according to AACC Method 58-16 (Cereal and Grains Association, n.d.), with minor modifications.

2.3.2 | Micronutrients

These were determined by the Southern Africa Grain Laboratories (Pretoria, South Africa), a nationally certified laboratory for analysis of micronutrient fortificants in cereal products. Iron and zinc were determined by microwave digestion of the samples, followed by analysis using flame atomic absorption spectrometry (Doner & Ege, 2004). The content of the vitamin A fortificant was determined by saponifying the meals with 5.7 M alcoholic KOH, followed by extraction with diethyl ether and petroleum ether (Qian & Sheng, 1998). Vitamin A as retinol was analyzed by reversed-phase high-performance liquid chromatography and detected at 327 nm (Ashoor & Knox, 1987). The contents of vitamin B fortificants were determined by extraction with 0.1 M HCl (Ndaw, 2000), followed by separation using reversed-phase UPLC and detection with a photodiode array detector (Li & Chen, 2001). Detection was at two wavelengths, 265 and 280 nm. Vitamin B12 is not determined by this method.

2.3.3 | Sensory evaluation of fortified WGMM and ugali (stiff maize porridge)

Ethical approval for the study was obtained from the National Institute for Medical Research of Tanzania, approval number NIMR/HR/R.8a/Vol.IX/3895.

Sensory evaluation of maize meal samples and ugali prepared from the meals was performed by a panel of 10 assessors, screened for normal sensory acuity and receiving 4 h of training on the evaluation method and to identify small product differences. For training, the panel evaluated maize meal and compared the sensory properties of ugali porridge from freshly milled WGMM versus stored WGMM.

The panel evaluated uncooked maize meal samples (5 g in small zip lock-type polyethylene bags) at ambient temperature. Ugali was prepared for evaluation by adding maize meal (250 g) to 400 mL water (40–50°C) in a plastic container. The contents were thoroughly stirred using a wooden spoon until all particles had completely dispersed in the water to form a pourable slurry. In parallel, 500 mL water was heated to boiling in an aluminum pan. On boiling, the maize meal slurry was poured into the pan while stirring. The plastic container was rinsed with 100 mL room temperature water and then added to the pan. The suspension was stirred continuously until it boiled. Thereafter, intermittent stirring was performed until the mixture had thickened uniformly. The ugali was cooked for approximately 8 min from the time that the suspension was boiling until a slightly baked ugali aroma developed. The ugali was then removed from the heat source for serving. Ugali samples (20 g) were scooped into disposable plastic cups for each panelist and served within 10 min.

The maize meal and ugali samples were evaluated using the "difference-from-control" sensory method (Muñoz et al., 1992). The identified control sample was the freshly milled Day 0 WGMM of 13.3% moisture grain (or ugali made from it). The control sample was evaluated first. Thereafter, three or four blind-coded with random three-digit numbers samples (including a blind-coded version of the freshly milled Day 0 WGMM) were evaluated. The panelists recorded whether each of the blind-coded samples was the same or different compared to the control using a category scale: *No difference* (0), *very slight difference* (1), *slight difference* (2), *moderate difference* (3), *large difference* (4), and *very large difference* (5). If a sample was rated as different (>0), the panelists recorded in what way the sample was different compared to the control by selecting one or more of the following options: Color/Appearance, Aroma, Texture/Feel, Flavor, Aftertaste, and Other (describe). Data were collected online using Compusense20 (Compusense). The order of serving the blind-coded samples to the panelists was balanced, following a Williams' design. The samples were evaluated in duplicate during four evaluation sessions on different days. Additionally, the panelists recorded comments to explain the nature of differences in sensory properties compared to the identified control sample (Supporting Information S1: Table S1).

Sensory evaluation was performed in a room where the panelists sat at separate tables and were able to concentrate on the task without external influences. Provisions for coronavirus disease 2019 social distancing and hygiene protocols were adhered to.

2.4 | Statistical analysis

The effect of storage time and moisture content of the meal on the fat acidity and peroxide values were determined by separate one-way analyses of variance (ANOVA) and for sensory analyses using two-way ANOVA with panelists as the secondary independent variable. The means were separated with Fisher's least significant difference test.

3 | RESULTS AND DISCUSSION

From photographs received from the Minimex company in Rwanda, hot air-drying the maize grain down to 11.6% and 9.9% moisture had no evident effect on the color of the grain or on the integrity of the grains (Figure 1a). This was confirmed by a later trial, where the authors were able to photograph the grains (Figure 1b).

3.1 | Rancidity chemical parameter development

The fat acidity (measure of hydrolytic rancidity) and peroxide values (measure of fatty acid primarily oxidation products) of the fortified WGMMs from both the hot-air dried and undried maize grain increased steadily over the 47-day storage period at 40°C (equivalent to storage for 141 days at 25°C) (Table 1).

Concerning fat acidity, with fortified WGMM from grain that had not been hot-air dried (13.3% moisture), its fat acidity of almost 200 mg KOH/100 g at 0 days storage (Table 1) already greatly exceeded the East African Standard (Kenya Bureau of Standards, 2019) specification of maximum 80 mg KOH/100 g. Its very high fat acidity was related to the fact that there were 10 days between milling the grain and receipt of the meals in South Africa and Tanzania (see Materials and methods section). After storage for 47 days at 40°C, the fat acidity of this maize meal was 412.4 mg KOH/100 g. This was rather higher than the values reported by Mestres et al. (2003) for milled whole-grain maize, in the range 100–300 mg KOH/100 g after storage at 35°C for 70 days, and by Szafrańska (2015) for maize, which were in excess of 200 mg KOH/100 g after storage at room temperature for 196 days. In contrast, the fat acidity values of the maize meals from grain that had been hot-air dried were considerably lower at both the start and end of storage when compared to meal from grain that had not been hot-air dried ($p < .05$). For example, drying the grain to 11.6% moisture resulted in the meal having fat acidities of 33% at Day 0 storage and 61% at Day 47 of the values of meal from grain at 13.3% moisture. Furthermore, drying the grain to 9.9% moisture was more effective at retarding the development of fat acidity than drying to 11.6% moisture.

Concerning peroxide value, meal from grain that had not been hot-air dried had a much higher peroxide value at 0-day storage than the meals from the maize that had been hot-air dried, ≥40% higher (Table 1). As with fat acidity, this was because of the 10-day interval between milling and receipt of the meals in South Africa and Tanzania. The meal that had not been hot-air dried also exceeded the WFP (2021) peroxide value specification of a maximum 10 milli equivalents O_2/1 kg fat after 47 days of storage at 40°C. In contrast, the peroxide values of the meals from grain that had been hot-air dried were at most only 50% of the WFP (2021) peroxide value specification after 47 days of storage at 40°C. Furthermore, as with fat acidity, the maize meal peroxide values were consistently lower for grain that had been dried to 9.9% moisture than for grain dried to 11.6% moisture ($p < .05$) (Table 1).

From these results, it is evident that drying unconditioned maize grain with hot air at a temperature of 125°C only partially inactivated the grain lipase enzymes, as consequence maize meal hydrolytic rancidity development was only reduced by up to approximately 50% (Table 1). This is in contrast to the more severe treatment used by Deepa & Hebbar (2014, 2017) involving conditioning the maize grain followed by micronization at an air temperature of 200°C, which resulted in no increase in fatty acids. Retardation of oxidative rancidity by hot-air drying of the grain was, however, more effective, with the peroxide value in the stored maize meal being reduced by up to 69%. This is likely because the oxidative enzymes in cereals, lipoxygenase, peroxidase and polyphenol oxidase, which are

(a)

(b)

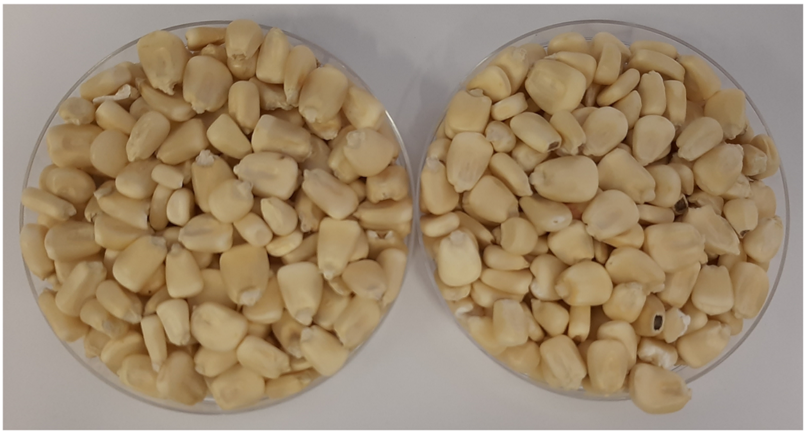

FIGURE 1 Photographs of maize grain that had not been dried and grain that had been hot-air dried. (a) L to R—Undried (13.3% moisture), dried to 11.6% moisture, dried to 9.5% moisture (photographs courtesy of Minimex, Rwanda). (b) L to R—Undried (13.8% moisture, dried to 10.9% moisture (authors' photograph). [Color figure can be viewed at wileyonlinelibrary.com]

mainly responsible for oxidative rancidity, can be more thermolabile than lipases, which are responsible for hydrolytic rancidity. Vinutha et al. (2022) found that hydrothermal treatment followed by micronization of conditioned whole-grain pearl millet meal resulted in complete or almost complete inactivation of these oxidative enzymes, whereas the lipase activity was only reduced by approximately 50%.

3.2 | Sensory evaluation

Concerning the effects of maize grain hot-air drying and storage time on the sensory quality of the fortified WGMMs, as expected, there was little difference detected between freshly milled WGMM from 13.3% moisture grain and its blind-coded control (the same meal) (Table 2). The panel also could not detect differences in the sensory characteristics (appearance, aroma, taste/flavor, texture, and aftertaste) of meal from 9.9% and 11.6% moisture grain and meal from the grain that had not been hot-air dried (13.3% moisture maize) 0 days storage, notwithstanding their significantly different fat acidities (Table 1). This was possibly because whole-grain cereal products contain substantial amounts of phenolics that contribute to bitter taste (Heiniö et al., 2016). This could have masked the contribution from the free fatty acids. The panel, however, could detect differences in the sensory characteristics of the day 47 stored meals, with the 13.3% grain moisture meal stored for 47 days differing significantly ($p < .05$) from the Day 0 control (Table 2). Panelist comments were that this meal had a rancid aroma and tasted more bitter (Supporting Information S1: Table S1). These comments are in agreement with the meal's high peroxide value and very high fat acidity (Table 1). Rancid aroma is a characteristic of the volatile

TABLE 1 Effects of grain drying and storage at 40°C on the fat acidity and peroxide value of fortified whole-grain maize meal.

Grain moisture content after drying (%)	Meal moisture content after milling (%) (WFP spec.[a] and East African standard,[b] max. 14.0%)	Fat acidity (mg KOH/100 g meal) (WFP spec. and East African standard, max. 80 mg/100 g meal)			Peroxide value (milli equiv./1 kg fat) (WFP spec., max. 10 milli equiv. O_2/1 kg fat)		
		Storage days at 40°C					
		0	24	47	0	24	47
		Approximately equiv. days at 25°C					
		0	72	141	0	72	141
9.9	9.5	43.6 ± 1.7[c] a	147.9 ± 3.6c	201.3 ± 1.2d	2.43 ± 0.12a	2.97 ± 0.12ab	3.31 ± 0.23b
11.6	10.7	65.0 ± 0.4b	220.5 ± 1.2e	250.5 ± 1.6f	3.13 ± 0.12b	4.13 ± 0.31c	5.12 ± 0.11d
13.3 (undried)	12.9	199.6 ± 2.3d	328.7 ± 4.9g	412.4 ± 0.2h	5.26 ± 0.87d	8.50 ± 0.13e	10.79 ± 0.31f
		$p < .001$			$p < .001$		

Note: a–h means for a specific measurement parameter that does not share a letter are significantly different ($p < .05$).

Abbreviations: equiv., equivalent; max., maximum.

[a]WFP spec., World Food Programme specification (WFP, 2021).

[b]Kenya Bureau of Standards (2019).

[c]Mean ± 1 standard deviation of three replicate analyses.

TABLE 2 Effects of grain drying and storage at 40°C on the evaluation by a trained sensory panel ($n = 9$) of the difference in the overall sensory properties (mean ± 1 standard deviation) of fortified whole-grain maize meal and ugali made from the meal stored for different time periods.

Grain moisture content after drying (%)	Meal moisture content after milling (%) (WFP spec.[a] and East African standard, max. 14.0%)	Degree of sensory difference from a control meal[b] (0 = *no difference*, 5 = *very large difference*)			Degree of sensory difference from a control ugali[b] (0 = *no difference*, 5 = *very large difference*)		
		Storage days at 40°C					
		0	24	47	0	24	47
		Approximately equiv. days at 25°C					
		0	72	141	0	72	141
9.9	9.5	1.0 ± 0.9a	1.1 ± 1.1a	1.8 ± 1.2 ab	2.2 ± 1.1abc	1.9 ± 1.2 ab	1.9 ± 1.0abc
11.6	10.7	1.3 ± 1.2a	1.1 ± 1.0a	1.4 ± 1.0a	2.0 ± 0.9abc	1.2 ± 0.6a	2.4 ± 1.1 bc
13.3 (undried)	12.9	1.0 ± 0.5a	1.2 ± 0.8a	2.6 ± 1.2b	1.4 ± 0.8ab	1.6 ± 1.4ab	2.8 ± 1.0c
		$p = .043$			$p = .073$		

Note: abc means for a product type that do not share a letter are significantly different ($p < .05$).

Abbreviations: equiv., equivalent; max., maximum.

[a]WFP spec., World Food Programme specification (WFP, 2021).

[b]Control meal or ugali 0 stored days 13.3% moisture content.

products of cereal lipid oxidation, notably hexanol (McGorrin, 2019). Rancid bitter taste is a characteristic of oxidized plant oil fatty acids such as linoleic acid (Usuki & Kaneda, 1980). The panelists did not report any differences in the texture of the maize meals from the undried and hot-air dried grains. This indicates that the hot-air drying process did not affect the grain structure to the extent that it changed the milling properties of the grain.

Concerning the sensory evaluation of ugali made from the fortified WGMMs, there was a somewhat greater degree of mean difference between ugali from the freshly milled (Day 0) 13.3% grain moisture meal compared to its blind-coded control (ugali made from freshly milled 0 days stored 13.3% grain moisture meal) than for its meal compared to its blind-coded control (0 days stored 13.3% grain moisture meal) (Table 2). This was also the case for ugali from the freshly milled 11.6% and 9.9% moisture grains compared to their meals and the control. This lower degree of panelist sensory acuity with ugali is likely primarily due to the dilution effect of the added water, 61%, in the product. A further contributory factor to the lower panelist sensory acuity is that the rancidity products of secondary oxidation in flour, such as epoxyaldehydes, ketones, lactones, and furans, are volatile (Doblado-Maldonado et al., 2012). Hence, some would be lost during cooking of the ugali.

Notwithstanding this, ugali from 47-day stored 11.6% and 13.3% grain moisture meals had the highest numerical sensory differences to the control (Table 2). This is in agreement with the very high fat acidity of these two maize meals (Table 1). The panelists commented that the ugali had a bitter aftertaste and that the ugali from the 13.3% grain moisture meal had a bitter taste and rancid flavor (Supporting Information S1: Table S1). In contrast, the sensory quality of ugali made from 9.9% dried grain WGMM and stored for 0, 24, and 47 days did not differ from the control ($p > .05$) (Table 2). Panelists mentioned that 0 days stored WGMM ugali from hot air-dried grain had a different, but not rancid, aroma, and flavor compared to the control (Supporting Information S1: Table S1). It is possible that intrinsic flavor differences due to the drying treatment were recorded rather than differences related to rancidity development. The difference-from-control sensory method is not capable of providing information on the nature of the difference (Costell, 2002).

3.3 | Stability of micronutrients

As the WGMM was fortified with vitamins and minerals to an East African governmental standard (Kenya Bureau of Standards, 2019), micronutrient stability over storage is an equally important concern as rancidity development. At the start of the storage period (Day 0), the

TABLE 3 Effects of grain drying and storage at 40°C on the iron, zinc, and vitamin A content of fortified whole-grain maize meal.

Grain moisture content after drying (%)	Meal moisture content after milling (%) (WFP spec.[a] and East African standard,[b] max. 14.0%)	Iron (mg/kg, as is basis) (WFP spec. and East African standard, min. 21 mg/kg, max. not applicable)		Zinc (mg/kg, as is basis) (WFP spec. and East African standard, min. 3 mg/kg, max. 65 mg/kg)		Vitamin A (mg/kg, as is basis) (WFP spec. and East African standard, min. 0.5 mg/kg, max. 1.4 mg/kg)		
	Storage days at 40°C	0	47	0	47	0	24	47
	Approximately equiv. days at 25°C	0	141	0	141	0	72	141
9.9	9.5	36.6 ± 6.3[c]	41.5 ± 7.1	60.3 ± 10.6[c]	62.0 ± 10.9	0.84 ± 0.15[c]	0.94 ± 0.17	1.00 ± 0.18
11.6	10.7	46.7 ± 8.1	56.5 ± 9.8	46.7 ± 8.1	79.9 ± 14.0	1.49 ± 0.26	1.26 ± 0.22	1.73 ± 0.30
13.3 (undried)	12.9	42.8 ± 7.4	50.4 ± 8.7	60.1 ± 10.5	62.4 ± 11.0	1.02 ± 0.18	1.08 ± 0.19	1.06 ± 0.19

Abbreviations: equiv., equivalent; max., maximum; min., minimum.

[a]WFP spec., World Food Programme specification (WFP, 2021).

[b]Kenya Bureau of Standards (2019).

[c]Expanded uncertainty of measurement at the 95% confidence level: iron ±17.3%, zinc ±17.6%, vitamin A ±17.6%.

TABLE 4 Effects of grain drying and storage at 40°C on the B vitamin fortificant content of fortified whole-grain maize meal.

Grain moisture content after drying (%)	Meal moisture content after milling (%) (WFP spec.[a] and East African standard,[b] max. 14.0%)	Vitamin B1 (thiamine) (mg/kg, as is basis) (WFP spec. and East African standard min. 3.0 mg/kg, max. not applicable)			Vitamin B2 (riboflavin) (mg/kg, as is basis) (WFP spec. and East African standard, min. 2.0 mg/kg, max. not applicable)			Vitamin B3 (niacin) (mg/kg, as is basis) (WFP spec. and East African standard, min. 14.9 mg/kg, max. not applicable)			Vitamin B6 (pyridoxine) (mg/kg, as is basis) (WFP spec. and East African standard, min. 2.0 mg/kg, max. not applicable)			Folate (mg/kg, as is basis) (WFP spec. and East African standard, min. 0.6 mg/kg, max. 1.7 mg/kg)	
		Storage days at 40°C													
		0	24	47	0	24	47	0	24	47	0	24	47	0	47
		Approximately equiv. days at 25°C													
		0	72	141	0	72	141	0	72	141	0	72	141	0	141
9.9	9.5	9.3 ± 2.8[c]	9.4 ± 2.9	9.2 ± 2.8	3.6 ± 1.4[c]	2.4 ± 0.9	1.1 ± 0.4	33.6 ± 4.5[c]	30.7 ± 4.2	29.8 ± 4.1	11.0 ± 2.8[c]	11.1 ± 2.9	11.0 ± 2.8	0.9 ± 0.2[c]	1.1 ± 0.2
11.6	10.7	12.4 ± 3.8	11.2 ± 3.41	11.1 ± 3.4	2.9 ± 1.2	3.0 ± 1.2	1.5 ± 0.6	46.4 ± 6.4	46.2 ± 5.8	42.5 ± 5.7	10.7 ± 2.7	9.3 ± 2.4	10.2 ± 2.6	1.2 ± 0.2	1.2 ± 0.2
13.3 (undried)	12.9	8.9 ± 2.7	7.7 ± 2.3	8.3 ± 2.5	1.9 ± 0.8	2.2 ± 0.9	1.2 ± 0.5	28.2 ± 3.9	28.2 ± 3.9	29.9 ± 4.1	7.0 ± 1.8	7.6 ± 2.0	8.3 ± 2.1	0.9 ± 0.2	1.0 ± 0.2

Abbreviations: equiv., equivalent; max., maximum.

[a]WFP spec., World Food Programme specification (WFP, 2021).

[b]Kenya Bureau of Standards (2019).

[c]Expanded uncertainty of measurement at the 95% confidence level: vitamin B1 ±30.5%, vitamin B2 ±39.4%, vitamin B3 ±13.7%, vitamin B6 25.7%, folate ±19.1%.

contents of all the fortificant minerals and vitamins in all three moisture content maize meals met the East African Standard (Kenya Bureau of Standards, 2019) and WFP specification (WFP, 2021) (Tables 3 and 4), with the possible exception of vitamin B2 (riboflavin) in the meal from maize that had not been hot-air dried. Its measured content was 1.9 mg/kg against the standard and specification of 2.0 mg/kg (Table 4). As expected, there was no change in the contents of iron and zinc over storage in the maize meals of differing moisture contents (Table 3), as they are inorganic elements. There was also no change in the content of vitamin A. Vitamin A is very prone to photodegradation when exposed to ultraviolet light and air (Allwood & Martin, 2000; Allen et al., 2006). As a cereal fortificant, it is normally in the form of retinol palmitate to make it readily available and is protected with antioxidants (Allen et at., 2006). These treatments probably account for its stability during storage.

With the exception of vitamin B2, there was no loss in fortificant B vitamins (thiamine, niacin pyridoxine, and folate) during storage of the maize meal and no effect of meal moisture content (Table 4). After 47 days storage at 40°C (equivalent to storage for 20.1 weeks at 25°C), the contents of all these vitamins still met the East African Standard for fortified WGMM (Kenya Bureau of Standards, 2019). The higher contents of vitamin B1 and vitamin B2 in the 11.6% grain moisture content meal throughout the storage period compared to the undried and 9.9% grain moisture meal suggests that it was dosed with a higher proportion of these two vitamins. This was possibly caused by these vitamins separating somewhat in the micronutrient premix.

Concerning vitamin B2 (riboflavin), however, after 47 days storage at 40°C, there was a substantial reduction in its content in the maize meals irrespective of their moisture content, to the extent that none met the standard. Riboflavin is highly susceptible to destruction and can be degraded by several mechanisms, the most common being photodegradation, which can also involve oxidation of its ribityl side chain (Sheraz et al., 2014). In view of the increase in fatty acid peroxides during storage (Table 1), this would be a likely mechanism for the loss in riboflavin.

4 | CONCLUSIONS

Hot-air drying of maize grain to 11.6% moisture or below somewhat retards the development of hydrolytic rancidity during storage of fortified WGMM and considerably retards the development of oxidative rancidity. This is probably because the elevated grain drying temperature (exposure to 125°C air and consequent increase in grain temperature to 60°C) partially inactivated the lipase enzymes and more completely inactivated lipoxygenase enzymes. With the exception of vitamin B2, there was no loss in the fortificant micronutrients in the maize meal over 47 days at 40°C. Furthermore, sensory analysis indicated that the stored meal from the hot-air dried maize and ugali stiff porridge made from this meal was similar to the freshly milled control.

Extension of the shelf life of WGMM by hot-air drying of unconditioned grain using commercial grain dryers is a useful technology as it obviates the requirement for additional energy to remove any added conditioning moisture and the requirement to purchase specific equipment for grain heat treatment.

To further evaluate the efficacy of the process, the next step is to perform a real-time trial where the fortified WGMM from hot-air dried grain is stored at ambient conditions in different tropical environments. In the meantime, maize grain hot air-drying before milling has already been implemented by commercial mills in Rwanda and Burundi with encouraging consumer acceptability of fortified WGMM ugali.

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