THE QUALITY OF LOCALLY-MANUFACTURED CORN-MILL GRINDING PLATES

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ABSTRACT
Maize was milled either 'wet' or ''dry'' using locally-manufactured milling plates. Samples of milled maize were taken and analyzed for elemental iron (Fe). Results show that iron particles from milling plates contaminates the milled maize and that the level of contamination increases with the quantity of milled maize. This is the case in both 'wet' and 'dry' milling. However, the relationship between the mass of elemental iron (Fe) in milled maize and mass of milled maize in 'wet' milling differed from that of 'dry' milling. That is, in 'dry' milling the rate of metal loss decreases at first and then increases with mass of milled maize, whereas in 'wet' milling, the rate increases monotonically with mass of milled maize. The difference could be explained in terms of the mechanism(s) or mode(s) of metal loss under the different milling conditions. In 'dry' milling, loss of metal is initially controlled by friction wear and later by erosion-corrosion. In the case of 'wet' milling metal loss could be attributed to conjoint action of corrosion and friction wear. The implications of these results are briefly discussed in terms of the possible health effects on consumers of foods prepared from such contaminated milled maize.

Keywords: *maize; cast-iron; wear; contamination; iron-overload*

INTRODUCTION
In an earlier paper (Kwofie and Chandler, 2006), locally-manufactured corn-mill plates (i.e. plates manufactured in Ghana) were analyzed to investigate the cause of their early wear and failure and the results compared with those of foreign/imported plates (i.e. plates manufactured in India and UK). It was found that locally-manufactured plates wear between about 3-10 times faster than the foreign counterparts. Meanwhile unpublished market survey indicates that majority of maize milling shops/operators in Ghana use their locally-manufactured plates and only a few use imported plates. The reasons for the high patronage of the local plates stem from the fact that they are relatively inexpensive and easily available. Even for those operators who use the imported plates they do so because it lasts longer and thus, saves them the trouble of having to replace them.

Maize milling is a major activity in Africa, especially in Ghana since over 95% of all Ghanaians enjoy delicacies prepared from milled maize (MoFA, 2001). Examples of such delicacies include '*banku*', '*kenkey*', '*akple*', '*aprenprensa*' and maize porridge. Milling is achieved by means of a pair of metal plates, one stationary and the other rotating, in a burr mill. Wearing of the plates in service implies that debris of metal particles would contaminate the milled maize, which when consumed could have health implications. Thus, even though iron is essential element in humans (Andrews, 1999; Bhaskaram, 2001; Bothwell, 1979; Corbett, 1995; Dallman, 1986; Haas and Brownlie, 2001; IMFNB, 2001), excess of it could result in toxicity and even death (WHO, 1973).

In general, milling may be done either 'wet' or 'dry' (i.e. level of moisture content of maize before milling) depending on the intended use. The effect of moisture content of maize on wear rate of milling plates as well as the level of metal contamination of milled maize has not been investigated. This information is important for the assessment of the health implications of consuming metal particles with the maize-prepared foods and when necessary for the improvement of quality of the milling plates.

The objective of the paper is to investigate the quality of locally-manufactured corn-mill plates in terms of the level of iron contamination in milled maize during milling. Result of this investigation is expected to enable better assessment of the suitability of the mill plates for the purpose and, when required, to design or develop a suitable material for milling of maize.

MATERIALS AND METHODS

A survey was conducted on the kind of corn-mill plates being used in Ghana. Out of the 105 maize milling shops visited in selected regions in Ghana, 80% used locally-manufactured corn-mill plates only, whilst the remaining 20% used both foreign and local corn-mill plates. An example of a corn-mill plate is shown in Figure 1. In this work only locally-manufactured corn-mill plates were used due to their high patronage and low wear resistance relative to that of the foreign counterpart (Kwofie and Chandler, 2006).

Fig. 1: Locally-manufactured corn-mill plate.

The milling process was carried out using two different milling machines; one for 'wet' milling and the other for 'dry' milling. Here, 'wet' milling implies that the maize was soaked in water for up to three days prior to milling, whereas in 'dry' milling no soaking in water was done. The average moisture content of 'dry' and 'wet' maize prior to milling were determined using a moisture meter to be 10.4% and 24.7%, respectively. Two new pairs of milling plates were used; one pair was used for milling 'dry' maize and the other pair for milling 'wet' maize. The maize used for the work was that which was brought in by individual customers or clients to the milling shop. Wearing of the burrs of the plates occurred during milling and at some point this made further milling almost impossible. In practice, worn-out plates are re-sharpened to create new burrs before further milling operation is continued. In this work no re-sharpening was done but rather both faces of the milling plates were used in order to investigate whether the faces used have any effect on the rate of wear.

For each milling condition, each face-pair was used for 18 days, making a total of 36 days of milling. For each batch-milling operation, the weight of milled product was measured and recorded. Twenty grams of the milled maize was collected or sampled for further test/ analysis. Samples collected in a day were thoroughly mixed to obtain an average daily sample of milled maize making sure that representative samples were obtained and therefore minimizing sampling errors. Samples collected each day were grouped into 3-day period namely; 1-3 days, 4-6 days, 7-9 days, etc., bringing the total samples obtained for further analyses to six from each pair-face of plates.

For the purpose of determining the concentration of elemental iron in the milled maize, two grams of the milled samples were weighed into crucibles and placed in the furnace for two hours at 600^{o}C to allow for ashing. The crucibles were first disinfected by washing in 1 M hydrochloric acid (HCl) followed by washing in distilled water and left in an oven to dry. Ashed samples were digested with 2 ml of the HCl, filtered and distilled water added to make 50 ml solution. For the unmilled maize, samples were first ground into flour using laboratory pestle and mortar after they have been disinfected with HCl and distilled water. The process of ashing and digestion was repeated for all samples. Concentration of iron was then determined using Atomic Absorption Spectrophotometer (Perkin Elmer Analyst 400). The concentrations recorded were converted to mass of iron in the sample using the following equation:

$$m = \frac{1}{A} xD \qquad (1)$$

where *m* is total mass of iron in unit mass of maize (milled or unmilled), *A* is the mass of sample used in digestion, and *D* is the mass of iron in *A*. The difference between the milled and unmilled maize gives the mass of iron contribution from burr mill plates.

RESULTS

Table 1 shows the concentration by mass of iron (Fe) in 1g of sample, determined according to equation (1), for milled (M_m) and un-milled (M_u) 'dry' and 'wet' maize. Also shown in Table 1 is the concentration of iron in milled maize due solely to wearing of milling plates,

Table 1: Mass of unmilled and milled maize samples for 36-day period grouped into 3-day period.

Plate of Face	Day	Mass of Fe in maize (mg in 1g)				Mass of iron in milled maize, M_m-M_u	
		Unmilled, M_u		Milled, M_m			
		Dry	Wet	Dry	Wet	Dry	Wet
1	1-3	0.0108	0.0125	0.1103	0.0934	0.0995	0.0809
	4-6	0.0043	0.0125	0.1509	0.0405	0.1466	0.0280
	7-9	0.0045	0.0124	0.0453	0.0299	0.0410	0.0175
	10-12	0.0070	0.0165	0.0372	0.0587	0.0302	0.0422
	13-15	0.0063	0.0164	0.0263	0.0771	0.0200	0.0607
	16-18	0.0055	0.0080	0.1609	0.0122	0.1555	0.0042
2	19-21	0.0086	0.0104	0.1863	0.0849	0.1777	0.0745
	22-24	0.0056	0.0130	0.0959	0.0540	0.0903	0.0410
	25-27	0.0085	0.0195	0.0791	0.0487	0.0110	0.0292
	28-30	0.0117	0.0096	0.0428	0.0344	0.0311	0.0248
	31-33	0.0069	0.0148	0.0329	0.0903	0.0260	0.0755
	34-36	0.0053	0.0044	0.0314	0.0076	0.0261	0.0032

Table 2: Mass of elemental iron present in milled maize with respect to contribution from burr mill plates.

Face of Plate	Days	Mass of Milled Maize (Kg)		Mass of Elemental Iron (g)	
		Dry	Wet	Dry	Wet
1	1-3	243.65	274.55	24.24	22.21
	4-6	480.40	362.25	94.45	10.15
	7-9	276.00	220.45	11.26	3.86
	10-12	264.40	301.05	8.02	12.70
	13-15	188.52	473.55	3.77	28.74
	16-18	317.13	147.25	30.25	0.62
2	1-3	505.60	243.00	89.86	18.10
	4-6	282.40	282.40	354.50	25.51
	7-9	264.99	192.00	5.82	5.61
	10-12	187.00	133.00	4.97	3.30
	13-15	191.33	753.60	4.84	56.85
	16-18	185.78	107.00	24.24	0.34

determined as the difference between those of the milled and the un-milled maize samples, (M_m-M_u). The calculated values for both pair of faces used are given in the Table 1. The quantity of milled maize for each 3-day period and the corresponding mass of iron content due to the milling plate only is shown in Table 2.

From Table 2, data of cumulative mass of iron from plates in milled maize and the corresponding total mass of milled maize were derived and plotted (Figure 2) for both 'dry' and 'wet' milling. It is observed that, for each milling condition, data obtained from both faces of the milling plates fall on a single curve and could be fitted by a cubic curve. This seems to indicate that for any given pair of milling plates and milling condition the level of iron contamination in the milled maize as a function of quantity of milled maize is more or less independent of the plates faces used for milling. The mass of metal (Fe) from the milling plates into the milled maize increases monotonically with quantity of maize milled (Figure 2). This was the case for both 'wet' and 'dry' milling. It is important to note that for 'dry' condition a

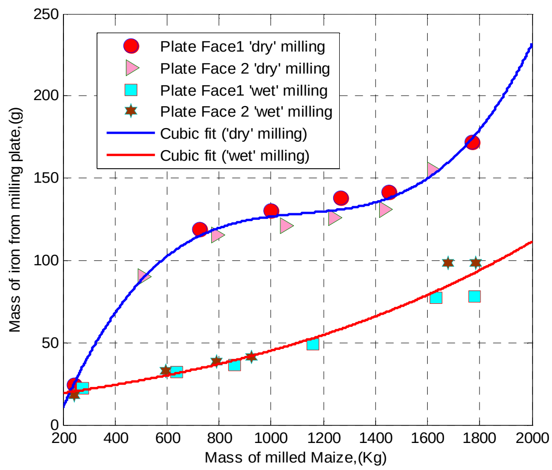

Fig. 2: Mass of iron content from milling plate as a function of milled maize.

specified quantity of maize was milled four (4) times to achieve the desired fineness whereas in 'wet' condition the same quantity was milled only once. Thus, the mass of metal particles in milled maize is higher in 'dry' milling than in 'wet' milling for any given mass of milled maize.

Figure 3 shows the rates R (= dy/dx) of increase of mass of Fe (y) in milled maize as a function of the mass of milled maize (x). Here the rate (dy/dx) for 'dry' condition was determined taken into consideration that milling was carried out 4 times for any given quantity of milled maize. Thus, the x-values were multiplied by four (4) before the rates were determined. Figure 3 shows that for 'dry' condition, the rate of metal loss decreases to a minimum value and then increases with mass of milled maize.

This clearly indicates that there are at least two different mechanisms or modes at which metal particles are lost from the surface of the mill-plates. These include friction-wear and corrosive-wear. It is likely that in the initial stages, loss of metal particles would be controlled by friction wear which rate decreases as cumulative milled maize increased. The decreased rate could be due either to (i) blunting of burrs of plates resulting in increased area of contacting surfaces or (ii) increased resistance of material to wear. The increased rate at later stages may be due to corrosive-wear. It is noted that the 'dry' maize contains an average of 10.4 % moisture which appears insufficient for corrosion to contribute to metal loss in the initial stages. However, after milling an appreciable quantity of maize, the amount of moisture in contact with mill-plates become significant causing corrosion products to form thereby controlling metal loss to the milled maize, especially at stages when substantial blunting has occurred. In the case of 'wet' milling, the rate of metal loss increases monotonically with amount of milled maize. This behaviour could be due to conjoint action of friction-wear and corrosive-wear. Here, the amount of moisture in contact with the mill-plates is significant to initiate corrosion earlier in the life of the mill-plate. This behaviour has been confirmed by Andrews and Kwofie (2010) where it was found that corrosion of cast iron mill plates contribute to its wear behaviour in wet grinding. The corrosion product of iron is non-adherent to the metal surface and is easily eroded by the maize during milling as well as the relative motion of the plates thus, exposing

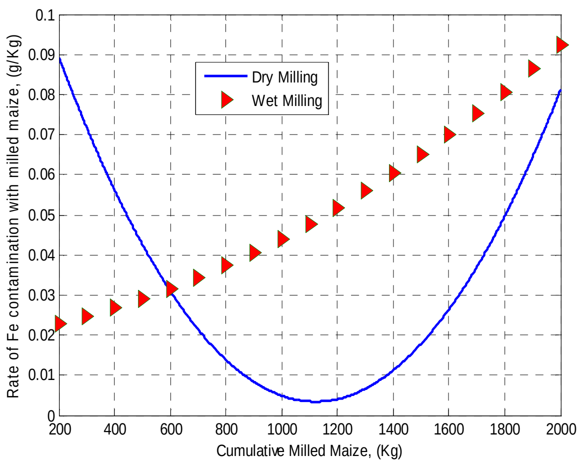

Fig. 3: Rate of metal (Fe) loss from milling plate as function milled maize.

fresh surfaces for further corrosion and wear. It should be expected, however, that due to significant amount of moisture (water), some level of lubrication occurs and reduces the extent of friction wear, relative to that of 'dry' milling.

DISCUSSION

Quality of locally-manufactured corn mill grinding plates was investigated under service conditions. Plates were used in milling maize under 'dry' and 'wet' conditions and the amount of metal debris in the milled maize determined. Results indicated that the amount of Fe particles in milled maize increased with the quantity of maize milled, both for 'dry' and 'wet' milling operations (see Fig.2). For a total mass of 1800 kg of maize milled, the amount of Fe metal particles measured was about 175 kg and 90 kg for 'dry' and 'wet' milling, respectively. Thus, the average concentration of Fe metal particles in milled maize could be estimated as 0.0972 g/kg (0.0972 mg/g) and 0.050 g/kg (0.050 mg/g) for 'dry' and 'wet' milling, respectively. The much higher concentration level of 'dry' milling is due to the fact that quantity of maize was milled four (4) times to attain the required fineness for its intended purpose. Hence, meals or delicacies prepared from maize milled 'dry' are expected to have higher Fe metal debris than those milled 'wet'.

Maize is a staple food in Ghana and can be considered as the main source of food for the average man or household. On the average it can be estimated that the average Ghanaian consumes between 500 g to 1000 g per day of meal prepared from milled maize. This implies that about 48.6 mg to 97.2 mg per day of Fe particles are consumed if meals are of 'dry' milled maize only and about 25 mg to 50 mg per day of Fe particles if meals are prepared from 'wet' milled maize only. Using the average of the lower and upper bounds of the two, it could be estimated that the average Fe particles intake by an individual that consumes between 0.5 kg to 1 kg of meal prepared from milled maize is between 36.8 mg to 73.6 mg. Meanwhile, the recommended iron intake for an individual (see Table 3) is far below the consumed Fe particles (i.e. estimate of between 36.8 mg to 73.6 mg/day). This obviously has health implications and raises lots of concerns about the quality of locally-manufactured mill plates. In the human body, the Fe could exist in soluble or insoluble form. The soluble form may be taken into the blood stream while the insoluble form may undergo corrosion to form rust in the body. Earlier work by Andrews and Kwofie (2010) on the corrosion of mill plates has shown that during corrosion, the pH of the corroding environment increases with time. This implies that corrosion of consumed Fe particles could alter the pH of the body system and could interfere with metabolism and hence have negative impact on human health.

Table 3: National Research Council recommended daily dietary iron allowances

Age group	Age (yrs)	Iron (mg)
Infants	– 0.5	10
	0.5 – 1.0	15
Children	1 – 3	15
	4 – 6	10
	7 – 10	10
Males	11 – 14	18
	15 – 18	18
	19 – 22	10
	23 – 50	10
	50+	10
Females	11 – 14	18
	15 – 18	18
	19 – 22	18
	23 – 50	18
	50+	10

Source: National Research Council (1980)

That notwithstanding, iron is an essential element in humans as it helps in oxygen transport and also regulates cell growth and differentiation (Andrews, 1999; Bothwell, 1979; Dallman, 1986; IMFNB, 2001). Deficiency of iron will therefore limits oxygen delivery to cells resulting in fatigue, poor work performance, and decreased immunity (Bhaskaram, 2001; Haas and Brownlie, 2001; IMFNB, 2001). Nevertheless, excess iron intake can result in iron overload and toxicity since the human body excretes very little iron. The rather high levels of Fe particles in milled maize vis-a-vis the recommended dietary Fe intake obviously indicate that locally-manufactured mill plates are far from being of good quality. The metal (Fe) particles enter into the milled maize by either abrasive wear ('dry' milling) or/and corrosive wear ('wet' milling). Thus, the wear and corrosion resistance property of the mill plates are low.

The wear and corrosion resistance can be improved by carefully controlling the chemical composition and processing it to achieve the right microstructure through heat treatment processes. In general, locally-manufactured corn mill plates are of unalloyed cast iron (i.e. grey cast iron). The carbon in grey cast iron exists in the form of graphite and does not impart adequate resistance to wear. On the other hand, white cast iron has low carbon and silicon content such that the carbon exists in the combined form as Fe_3C which imparts hardness and wear resistance. To impart corrosion resistance, the cast iron must be alloyed with elements such as chromium (Cr) and nickel (Ni) (Rajagopal and Iwasaki, 1992). In addition to improving corrosion resistance, Cr also form complex carbide (M_7C_3) which is harder and resistant to wear compared to Fe_3C (Sailors, 1989). Furthermore, hardness and the resistance to surface cracking can be improved by heat treatment.

As mentioned, chemical composition must be carefully controlled and requires some level of education for batch calculation of the melts. Unfortunately, most artisans involved in the production of local mill plates have little knowledge in science and metallurgy since they have little or no formal education in foundry technology. They have acquired skills only through years of apprenticeship and trial and error. Formal training of these artisans is therefore necessary to assist in producing quality mill plates locally so as to reduce the wearing of plates into milled corn thereby minimizing any health dangers associated with this unorthodox way of consuming iron into the human body.

CONCLUSIONS

Locally-manufactured corn-mill grinding plates were used to mill maize under 'dry' and 'wet' conditions. In each milling condition, both faces of plates were used with the objective of investigating the level of iron contamination of milled products. The following conclusions from the results obtained may be drawn:

1. During milling operation, metal particles contaminate the milled products, with the level of contamination increasing with quantity of milled maize.
2. For any given quantity of milled maize, the mass of iron particles under 'dry' milling is much higher than under 'wet' milling condition.
3. For 'dry' milling, metal loss from mill-plates was initially dominated by friction-wear and later by corrosive-wear. The rate of metal loss with quantity milled decreases in the friction-wear dominated region but increases in the corrosive-wear dominated region.
4. For 'wet' milling, metal loss is by the conjoint action of friction-wear and corrosive-wear. The rate of metal loss in this case increases with quantity of milled maize.
5. Consumption of metal particles via foods prepared from milled maize constitutes an unknown and unorthodox source of iron intake. Hence, it should be expected that this would impact on the health of consumers as far as iron intake is concerned.
6. Further research is recommended to investigate the effect of intake of elemental iron and/or rust from milled plates on human body, especially adult men and post-menopausal women for whom iron deficiency is unlikely or uncommon.

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