Minimizing Aflatoxin Contamination in the Field, During Drying, and in Storage in Ghana

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ABSTRACT

Aflatoxin in peanut (*Arachis hypogaea* L.) and other crops can negatively affect human health, especially in countries where regulatory agencies do not have limits on aflatoxin entering the food supply chain. While considerable research has been conducted addressing aflatoxin contamination in peanut at individual steps in the supply chain, studies that quantify aflatoxin contamination following combinations of interventions to crop management, drying, and storage are limited. Research was conducted during 2016 and 2017 in two villages in southern Ghana to follow aflatoxin contamination along the supply chain and to compare improved practices with traditional farmer practices used by smallholders. The farmer practice of only a single weeding was compared with improved practices during the growing season up to harvest that included applying local soaps to suppress aphids (*Aphis gossypii* Golver) that transmit peanut rosette virus disease (*Umbravirus*: *Tombusviridae*e), one additional weeding, and calcium applied at pegging. The improved practice for drying included placing pods removed from plants onto tarps compared with the traditional practice of drying on the ground. Storing peanut for four months in hermetically-sealed bags was the improved practice compared with storing in traditional poly bags. All improved practices individually resulted in lower aflatoxin contamination as compared to the farmer practices. While aflatoxin levels were very low (<1 μg/kg) at harvest, the levels increased significantly during drying and storage, with the improved methods resulting in lower levels. Greater estimated financial returns were noted when at least one improved practice along the supply chain was implemented through either increased yield or maintenance of quality kernels. Results from this research demonstrate progression of aflatoxin contamination at pre- and especially post-harvest in villages in Ghana. Future research needs to consider the effects of improved practices as components of packages that farmers can consider, and not just as individual interventions.

Key Words: aflatoxin contamination, integrated pest management, mycotoxin, peanut drying, peanut storing, plant health.

Peanut (*Arachis hypogaea* L.) is an important component of human diets in Ghana and other countries in West Africa (Craufurd *et al*., 2006; Grosso and Guzman, 1995). Although peanut contributes to food security in Ghana and can serve as a cash crop, presence of *Aspergillus flavus* and *A. parasiticus* in raw products can result in aflatoxin contamination in food. Chronic exposure to aflatoxin contributes to poor health and a compromised immune system in vulnerable populations (Gong *et al*., 2012; Jolly *et al*., 2006; Kew, 2012; Turner *et al*., 2003; Williams *et al*., 2003). The aflatoxins B_1, B_2, G_1, and G_2 are classified as Group 1 human carcinogens (Ioannou-Kakouri *et al*., 1999). Over 25% of the world's food may be contaminated by mycotoxins and peanut is particularly prone to contamination (Eskola *et al*., 2019).

Aflatoxin contamination can occur and increase at all steps of the peanut supply chain including production in the field, drying, storage, and in food products (Awuah *et al*., 2006; Guchi, 2015; Malaker *et al*., 2008; Villers, 2014; Waliyar *et al*., 2015). The warm and humid environmental conditions in some areas of Africa are ideal for the

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growth of *A. flavus,* making aflatoxin contamination of food, including peanut, a consistent challenge (Gordon, 2003; Wagacha and Muthomi, 2008). The majority of smallholder farmers often are not able to prevent or mitigate aflatoxin along the value chain. Emmok (2010) estimated less than 20% of peanut produced in Ghana could be exported because of aflatoxin contamination. Consequently, the majority of peanut is consumed domestically, and is often contaminated with aflatoxin. Export of peanut produced in Africa has been reduced substantially during the past decade compared with the 1960s (Fana, 2010). Estimates are that the African continent loses annually 450–670 million US dollars in potential export revenues due to aflatoxins (IITA, 2013).

Downstream in the supply chain, peanut farmers miss market opportunities because of uncertainty regarding aflatoxin levels and other quality considerations. In addition to lost marketing opportunities, malnutrition and nutritional disorders have been linked to aflatoxin exposure (CDC, 2013). According to Kew (2012), a high percentage of people in sub-Saharan Africa and certain areas in Asia are exposed to chronic levels of aflatoxin.

Current aflatoxin mitigation programs have focused on controlling mold that produces aflatoxin in the field through improved management practices (Jordan *et al*., 2018; Villers, 2014). However, most post-harvest drying and storage conditions often are inadequate to maintain aflatoxin levels safe for consumers (Villers, 2014). Existing literature mostly has focused on aflatoxin mitigation at each step of the peanut value chain (practices in the field, during drying, and in storage). Comparisons of aflatoxin contamination traced from the field through storage using different mitigation approaches are limited. Comprehensive studies that analyze aflatoxin through each of these steps are important, especially for determining the monetary value of improved aflatoxin mitigation practices. The ability to ensure cool soil temperatures, rapid reduction of seed moisture content upon harvest, and minimizing moisture absorption during storage to maintain desirable organoleptic and physicochemical properties for marketing and final use of peanut are critical in developing optimal mitigation protocols (Bulaong and Dharmaputra, 2002; Ellis *et al*., 1991; Ramesh *et al*., 2013; Saleemullah *et al*., 2006). To determine the most vulnerable steps of aflatoxin contamination and compare improved mitigation practices with currently used practices by smallholder farmers, research was conducted in two rural villages in Ghana during 2016 and 2017.

Materials and Methods

The experiments were conducted near Drobonso (-1.121° W, 7.064°N) in the Sekyere Afram Plains District and near Ejura (-1.367° W, 7.383°N) in Ejura-Sekyedumasi district, both in the Ashanti Region of Ghana. Initially, the goal was to conduct the experiment during both the major season (April-July) and minor season (August-October) in both villages. Generally, bimodal rainfall is common in this region of Ghana and farmers often plant two crops of peanut each year. Major and minor seasons would have served as a treatment variable. However, rainfall at Ejura during the major season and at Drobonso during the minor season was inadequate for peanut production during 2016. Therefore, rather than considering major and minor seasons as a treatment variable, each run of the experiment was considered as a separate environment regardless of location or season. This resulted in having six experiments (Table 1). The cultivar Konkoma, grown by most farmers in this region of Ghana, was used in all experiments (Owusu–Akyaw *et al*., 2019).

Treatments consisted of different combinations of traditional farmer practices and the improved practices during the growing cycle up to harvest, after drying peanut pods to 10%, and storing peanut for 4 months. The improved practice included one additional hand weeding than the traditional farmer practice at 6 weeks after planting (WAP), the application of a locally-derived potash soap at 3 WAP (e.g. at initiation of flowering), and the application of ground oyster shells at the base of peanut plants at 180 kg/ha at 4 WAP. The farmer practice included only one hand weeding 3 WAP and no calcium or soap sprays. The improved practice for drying included drying peanut pods on a polyethylene tarp compared with the farmer practice of drying peanut on the soil surface. Farmers stored peanut in traditional poly bags (farmer practice) or in hermetically-sealed plastic bags (GrainPro, Inc., Boston, MA) for the improved practice. Each farmer served as a replication and 10 to 12 farmers were randomly selected in each experiment. Plot size was 20 rows with a length of 20 m and spaced 30 cm apart. Within each farmer's field, a plot with the farmer practice and a plot with the improved practice were included. Pod yield was determined from the center eight rows of each plot and final yield adjusted to 10% moisture. Pods from five plants randomly selected from each of five sections within a plot (total of 25 plants) were used for aflatoxin determination at harvest (Mahuku *et al.,* 2010). Approximately 20 kg of unshelled pods were placed

Table 1. Mean and range of aflatoxin concentration in kernels for the farmer practice in the field within 2 weeks prior to harvest, after drying pods over soil to 10% moisture, and after storage in poly bags for 4 months from six experiments in Ghana.

Village	Year	Season[b]	Mean aflatoxin concentration and range [a]		
			At harvest[c]	After drying	After four months in storage
			μg/kg		
Drobonso	2016	Major	1.9 (0.1-2.7)	430 (280-2680)	1407 (403-5581)
Drobonso	2017	Minor	0 (0)	185 (70-411)	1810 (605-4782)
Drobonso	2017	Major	0 (0)	20 (15-28)	263 (70-862)
Ejura	2016	Minor	0.8 (0.1-3.0)	150 (81-780)	191 (40-432)
Ejura	2017	Major	0 (0)	48 (13-129)	887 (206-3421)
Ejura	2017	Minor	0 (0)	16 (13-21)	381 (78-823)

[a]Mean and range represent 10 to 12 farmers in each village.
[b]Major season was from April through July and the minor season was from August through November.
[c]A value of 0 may represent aflatoxin concentrations below the detection limit of instrumentation.

on tarps (Kotap America LTD, Lawrence, NY) and on soil for drying to 10% or less moisture prior to placing in poly bags or sealed bags for 4 months. Using sampling protocols by Codex Alimentarius Standard (2001), 2 kg of unshelled pods were collected by aggregating incremental weights of 150 g for aflatoxin determination at harvest, after drying, and then again after storage. Samples were transported in plastic zip lock bags on ice until placed in a freezer at -20°C until analysis.

Prior to preparation of samples to determine aflatoxin contamination after 4 months of storage, 100 g of kernels was removed to determine the percentage of kernels considered good for marketing. The inclusion criteria for good kernels were the following: free of shrivel, visible mold, and discoloration. This was achieved by dividing the weight of good kernels by the total weight of the sample (100 g). The final yield of good kernels/ha was then calculated as the product of pod yield and the fraction of good kernels.

Analysis of Aflatoxin Contamination. The entire sample of shelled peanut was used in the aflatoxin extraction procedure regardless of quality. Extraction and quantification of aflatoxin were based on the USDA-GIPSA 2013-041 protocol (USDA-GIPSA, 2015) using RevealQ^{+} aflatoxin lateral flow strips (Neogen Corp., Lansing, MI) for quantitative test with Mobile Diagnostic Reader (mReader™) (Mobile Assay Inc., Boulder, CO). A 2-kg sample of shelled peanut kernels was milled at mid to high speed using a blender (Preethi Mixer-Blender, Sholinganallur, Chennai, India) after which 10 g was weighed into a 50 ml extraction tube. Thirty ml of 65% ethanol was added to the sample and vortexed for 3 min. The mixture was allowed to settle and then filtered using a 0.45 μm micro filter paper. A volume of 500 μl of Reveal Q^{+} sample diluent was pipetted into a dilution cup after which 100 μl of sample extract was added. The resulting solution was mixed by pipetting up and down 5 times. A volume of 100 μl of diluted sample extract was pipetted into a new clear sample cup. The test strip was placed into the sample cup to make contact with the solution and allowed to wick. The strip was removed after 6 min and the level of toxin quantified using the Mobile Detection Reader. Aflatoxin levels greater than 50 μg/kg (threshold determination level for the lateral flow strips) were diluted and re-analyzed. Aflatoxin concentration was also determined using High Performance Liquid Chromatography (HPLC) based on the AOAC (Association of Official Agricultural Chemists Method 2005.08 (AOAC International, 2006). The minimal detection levels for the Mobile Diagnostic Reader and HPLC were 2 μg/kg and 0.5 μg/kg, respectively.

Financial Analysis. Base cost of production was set at $140/ha and included costs for land preparation, seed, planting, and one hand weeding. Additional cost for the improved practice during the growing cycle prior to harvest included the local soap for aphid and rosette suppression, one additional hand weeding, and oyster shells was set at $52/ha. Cost of tarps to dry peanut was set at $8/ha. The cost of a poly bag for the farmer practice storage was $0.5. Cost for a hermetically-sealed bag for the improved storage was $1.6. Total cost of storage was the product of individual bag cost and the number of bags required depending on yield. The two types of bags used on this experiment could hold 18 kg of unshelled peanut. The hermetically-sealed GrainPro bags are not available in Ghana and were provided from the US when the study was initiated. Therefore, the cost of sealed bags was based on locally-available PICS storage bags (Purdue Improved Crop Storage bags, West Lafayette, IN). Ibrahim *et al.* (2013) reported that both GrainPro and PICS bags performed similarly for cowpea (*Vigna unguiculata*). Data are either not available in the literature or experiments comparing effectiveness of these bags have not been conducted with peanut. Additional research is needed to support or refute our assumption of efficacy of these bags. Cost of removing pods from vines was set at \$0.075/kg farmer stock. Shelling cost was set at \$0.075/kg shelled peanut.

Peanut price was set at \$1.2/kg for whole kernels that were not damaged (referred to as good kernels). The percentage of good kernels was determined based on an estimated 65% shell out from yield of unshelled pods. The percentage of good kernels was measured after storage when aflatoxin concentration was determined. Estimated financial returns were determined for each combination of the improved and farmer practices during the growing cycle prior to harvest and following both drying and storing (8 combinations) by subtracting the gross return (product of unshelled yield in the field, a 65% shell out rate, and percentage of kernels classified as good quality) minus costs of each combination of practices.

Peanut pod yield from plots were considerably higher than the national average and may reflect cooperators selected or land resources and site selection compared to constraints and capacities of most smallholder farmers (Mochiah, B., personal communication). Because the improved practices used in this research are considered expensive and generally fixed (tarps and bags), in a second financial analysis, yield potential was adjusted down by 50% to more effectively determine the monetary value of improved practices to the broader audience of farmers with lower yield compared with traditional practices employed by smallholder farmers.

Statistical Analysis. Data for pod yield, percentage of good kernels, aflatoxin concentration, yield of good kernels, and estimated financial return were subjected to the GLIMMIX Procedure in SAS (SAS, Cary, NC) considering the 2 by 2 by 2 factorial treatment arrangement (2 practices in the growing cycle prior to harvest by 2 drying practices by 2 storing practices). Experiment and replication within experiments were considered random effects and treatments at each step in the supply chain were considered fixed effects. Pooled data are presented with least square means separated using Fisher's Protected LSD test ($\alpha = 0.05$). Data for aflatoxin concentration was transformed to natural logs prior to statistical analysis with mean separations based on the transformed data used to separate means for the non-transformed data. Data for the interaction of practices during the growing cycle and drying and the interaction of practices at all three steps in the supply chain are presented. These comparisons allow practitioners to compare and ultimately select various combinations of practices based on availability of inputs and resource constraints. Pearson correlation coefficients were determined for percentage of good kernels, aflatoxin concentration after storage, and estimated financial return.

Results and Discussion

At both Drobonso and Ejura in 2016, low levels of aflatoxin were detected in kernels collected at harvest when peanut was grown using only the farmer practices (Table 1). In 2017, aflatoxin was not detected regardless of location or planting season. Although local weather data were not available from these locations and years, rainfall was generally abundant during 2017 and considered adequate for peanut production in the region (Mochiah, M., personal communication). In contrast, rainfall during both major and minor seasons was much lower in 2016. Rainfall is a major indicator of aflatoxin contamination for peanut at harvest (Craufurd *et al*., 2006). This most likely explains the difference in detection of aflatoxin from samples collected in the field during 2016 compared with no detection in 2017. Specific information related to temperature and rainfall would have been more informative.

A 226-fold (Drobonso) and 188-fold (Ejura) increase in aflatoxin concentration was observed when comparing concentrations in the field to concentrations after drying on the ground in 2016 (Table 1). Although aflatoxin was not detected in the field sampling in the other four experiments, between 16 and 185 μg/kg of aflatoxin was observed after drying on the soil. A further increase in aflatoxin concentration after four months of storage in traditional poly bags was observed at all locations (Table 1). The change in aflatoxin during storage in poly bags was characterized by a 3.3 to 13.2-fold increase. At Ejura, the increase in aflatoxin concentration during storage was 1.3 to 23.8-fold. These data provide an indication of the scope of aflatoxin contamination from the field through storage under typical management practices used by smallholder farmers in the Ashanti region of Ghana during these two years and growing seasons. The levels of aflatoxin contamination following storage were well above concentrations considered acceptable for human consumption without significant health consequences (Knutsen *et al*., 2018). These data provide

Table 2. Mean aflatoxin concentration in kernels for the farmer practice and improved practice when peanut pods were removed at harvest for six experiments in Ghana.

Management practice[a]	Pod yield[b]	Aflatoxin concentration[b]
	kg/ha	μg/kg
Farmer	1,800	0.4
Improved	2,260	0.2
P > F	<0.0001	<0.0001

[a]Improved practice consisted of one additional hand weeding, local soap applied for aphid suppression, and calcium applied at pegging. The farmer practice consisted of only a single hand weeding and no application of local soaps or calcium.

[b]A t-test was used to compare management practices pooled over six villages with 10 to 12 farmers in each village from 2016-2017.

Table 3. Mean aflatoxin concentration in kernels for the improved practice compared to the farmer practice after drying practices immediately prior to storage for six experiments in Ghana.

Management practice[a]		
In-season practice	Drying method	Aflatoxin concentration[b]
		μg/kg
Farmer	Farmer	150 a
Farmer	Improved	33 cd
Improved	Farmer	57 bc
Improved	Improved	9 d
P > F	-	0.1068

[a]Improved field practice included one additional weeding, application of local soaps for aphid suppression, and calcium applied at pegging. The improved drying practice included placing pods on a tarp immediately after removing pods from vines. The farmer practice for field was a single weeding and for drying placing pods on the soil surface.

[b]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $\alpha = 0.05$. Data are pooled over six experiments from 2016-2017.

a baseline for comparing efficacy of improved management practices designed to minimize aflatoxin contamination before and after storage.

Greater peanut pod yield and lower aflatoxin were observed when one additional weeding occurred, calcium was applied at pegging, and local soap was applied to suppress aphids and rosette (Table 2). Previous research (Curkovic 2016; Mochiah *et al*., 2011; Nutsugah *et al*., 2007) demonstrated that local soaps can result in modest reductions of aphid populations and rosette virus. Greater calcium nutrition can also increase yield and decrease aflatoxin contamination (Davidson *et al*., 1983; Helper, 2005; Waliyar *et al*., 2008; White and Broadley, 2003). Weed control can also increase yield (Abudulai *et al*., 2018; Dzomeku *et al*., 2018). This experiment was not designed to determine the most effective component within the improved production package during the growing cycle prior to harvest. These data suggest that combinations of practices that reduce pest damage and improve plant nutrition likely will increase peanut yield and decrease aflatoxin contamination.

When pooled over experiments, the highest concentration of aflatoxin after drying was observed when farmer practices were employed in the field and during drying (Table 3). Including the improved practice during the growing season (e.g., extra weeding, aphid and rosette suppression, and calcium) and drying on tarps rather than on the ground resulted in lower aflatoxin concentrations after drying. The improved field practice alone or the improved drying practice alone had similar levels of aflatoxin, but lower than farmer practice at both steps. Using improved practices at both steps in the supply chain resulted in lower aflatoxin concentrations compared with the improved growing season practice with farmer drying practice. Including the improved practices at both steps resulted in aflatoxin levels that were similar to using a tarp for drying when the farmer practice was used in the field. It is suspected that drying peanut on tarps minimizes movement of spores from the soil surface onto pods, especially if rain occurs during the drying period. Additionally, if rain occurs during drying, farmers can cover peanut with a portion of the tarp or more easily move peanut under shelter if peanut is placed on a tarp for drying.

A limited quantity of peanut is sold immediately after harvest in Ghana and most are stored for household use or sale when prices strengthen later in the season. When comparing all possible combinations of improved and farmer practices, the highest aflatoxin concentration was noted when farmer practices were implemented at all steps in the supply chain (Table 4). When comparing a single improved practice, storing peanut in hermetically-sealed bags was the most effective practice to minimize aflatoxin contamination. Improving peanut production practices prior to harvest and drying on tarps resulted in similar concentrations of aflatoxin after storage. Drying on tarps and storing in hermetically-sealed bags resulted in lower aflatoxin after storage than improving management in the field (e.g., additional weeding and application of calcium and local soap) and either drying peanut on a tarp or storing peanut in sealed bags. The lowest concentration of aflatoxin

Table 4. Mean aflatoxin concentration in kernels, percentage of good kernels, and yield of good kernels for the farmer practice and improved practice in the growing cycle at harvest, after drying practices immediately prior to storage, and storage for 4 months.

Management practice[a]					
In-season practice	Drying method	Storage method (sampled after 4 months storage)	Aflatoxin concentration[b]	Good kernels[b]	Yield of good kernels[b,c]
			μg/kg	%	kg/ha
Farmer	Farmer	Farmer	832 a	59 f	680 e
Farmer	Farmer	Improved	170 c	79 d	1,070 bc
Farmer	Improved	Farmer	258 c	80 d	970 cd
Farmer	Improved	Improved	49 e	89 b	1,170 ab
Improved	Farmer	Farmer	273 b	70 e	950 d
Improved	Farmer	Improved	91 d	84 c	970 cd
Improved	Improved	Farmer	142 d	87 bc	1,150 ab
Improved	Improved	Improved	18 f	95 a	1,180 a
P > F	-	-	0.0069	0.0219	0.0607

[a]Improved field practice included one additional weeding, application of local soaps for aphid suppression, and calcium applied at pegging. The improved drying practice included placing pods on a tarp immediately after removing pods from vines. The farmer practice for field included a single weeding and for drying placing pods on the soil surface. Peanut was stored for 4 months in the shell in traditional poly bags for the farmer practice and hermetically-sealed bags for the improved practice.

[b]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test $\alpha = 0.05$. Data are pooled over six experiments from 2016-2017.

[c]Yield of good kernels (kg/ha) was calculated as the product of pod yield (kg/ha) and the fraction of good kernels after 4 months of storage.

in kernels was noted when improved practices were implemented at all three steps of the supply chain.

These data indicate that implementing improved practices during the growing season, while drying, and when storing peanut will decrease aflatoxin contamination compared with practices currently being implemented by smallholder farmers. The primary goal of this research was to determine the relative importance of practices at each step in the supply chain in minimizing aflatoxin contamination. While smallholder farmers may not be able to implement improved practices at all three steps, it is possible that they could invest in one or two practices that lower the risk of aflatoxin contamination. For example, tarps might be commercially available whereas hermetically-sealed bags may not be an option. While the components (e.g., additional weeding, calcium, and local soaps) of the improved strategy during the growing season were not dissected in a manner that indicates which has the greatest value, implementing one or two of the practices based on labor availability (weeding) or product availability (calcium and local soap and their application) would likely contribute positively to plant health and increase yield and quality of peanut at some level.

Aflatoxin in kernels was negatively correlated with the percentage of good kernels ($p < 0.0001$, $R = -0.79$). For example, when farmer practices were implemented at all three steps in the supply chain, the highest average aflatoxin concentration was noted (828 μg/kg) and the lowest percentage of good kernels (59%) and yield of good kernels (680 kg/ha) (Table 4). In contrast, when all three steps in the supply chain incorporated improved practices the lowest concentration of aflatoxin was observed (12 μg/kg) along with the highest percentage of good kernels (95%) and the highest numerical yield of good kernels (1,180 kg/ha). Aflatoxin contamination is often associated with damaged kernels of poor quality with limited market value (Awuah and Ellis, 2002; Awuah *et al*., 2006; Whitaker *et al*., 1997).

Financial return was derived based on yield, cost of inputs, and quality of kernels that would be marketed after storage. Analyses in Table 5 includes actual farmer stock pod yield (kg/ha) from the experiment and yield from plots adjusted downward to reflect more accurately the financial returns that most smallholder farmers might experience. Yields obtained when farmer practices or improved practices were used were substantially higher than yields estimated to reflect typical smallholder farmer conditions. Because costs for tarps and hermetically-sealed bags are fixed and relatively high, the lower yield scenarios could impact the recommendations on use compared with plot yield that was higher than what most smallholder farmers likely experience.

While some shifts in ranking of financial returns were noted when comparing the two yield structures, differences among combinations of improved

Table 5. Influence of practices during the growing cycle at harvest, drying practices prior to storing, and storage method (sampled after 4 months) on estimated financial return based on harvested weight from research plots and when adjusted to approximate average yield in Ghana.

Management practice[a]			Estimated financial return[b]	
In-season practice	Drying method	Storage method (sampled after 4 months in storage)	Actual plot yield levels	Plot data adjusted to approximate national average
			\$/ha	
Farmer	Farmer	Farmer	439 e	206 f
Farmer	Farmer	Improved	700 c	454 bc
Farmer	Improved	Farmer	752 bc	395 cd
Farmer	Improved	Improved	821 ab	522 a
Improved	Farmer	Farmer	657 cd	318 e
Improved	Farmer	Improved	585 d	353 de
Improved	Improved	Farmer	891 a	459 b
Improved	Improved	Improved	799 ab	484 ab
$P > F$	-	-	0.0773	0.0767

[a]Improved field practice included one additional weeding, application of local soaps for aphid suppression, and calcium applied at pegging. The improved drying practice included placing pods on a tarp immediately after removing pods from vines. The farmer practice for field included a single weeding and for drying placing pods on the soil surface. Peanut was stored for 4 months in the shell in traditional poly bags for the farmer practice and hermetically-sealed bags for the improved practice.

[b]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $\alpha = 0.05$. Data are pooled over six experiments from 2016-2017.

and farmer practices were often similar (Table 5). In both instances the lowest returns were noted when the farmer practice was used at all three steps in the supply chain. When actual plot data were used in the analysis, the greatest returns were observed when improved practices were used at each step or when two improved practices were used at steps including drying and storing or prior to harvest and drying. The least effective combination of two improved practices was the combination of practices during the growing cycle and drying. Even though cost was lower when only one improved practice was used, financial return was generally higher when the more expensive approaches at two steps in the supply chain were implemented. For example, financial return for the more expensive approach of including improved practices at all three steps exceeded financial returns when the improved practice was used during the growing cycle followed farmer practices during drying and storage or including the improved practice during storage but not during drying (Table 5). When yield more closely approximated smallholder yields in Ghana, the greatest return was noted when the improved practice was implemented at drying and storage or when improved practices were implemented at all three steps in the supply chain.

The correlation of aflatoxin concentration after storage with estimated financial return for both yield scenarios was significant ($p < 0.0001$) but not highly correlated ($R = -0.21$ to -0.24). Similarly, the percentage of good kernels and estimated return were weakly correlated ($p < 0.0001$, $R = 0.20$). While kernel quality had an impact, yield in the field also contributed to financial return.

Collectively, the data presented above provide insight into the levels of aflatoxin in peanut in rural villages in Ghana where resources are limited for incorporation of improved practices that could impact yield and quality of peanut and reduce aflatoxin. While there are numerous economic pressures on smallholder farmers, results indicate that the increase in revenue from greater yields and higher quality in the form of non-damaged kernels entering the market more than pay for the costs of improved practices during the growing cycle prior to harvest as well as using tarps for drying and hermetically-sealed bags for storage. However, a major challenge for smallholder farmers is acquiring adequate credit that would enable the purchase of components of the improved practices at each step in the village supply chain (Hong and Hanson, 2016). A further limitation is that even when smallholder farmers have access to credit, they may not have access to inputs or labor that could increase yield and improve quality. None-the-less, these data can be used to assist farmers and their advisors as well as buyers in developing production approaches and post-harvest strategies that could increase the amount and quality of peanut going into the supply chain beyond the village level. This research is the first published information in the peer-reviewed literature that documents aflatoxin contamination prior to harvest through drying and then storage contrasting traditional farmer practices with improved practices at each step along the village supply chain.

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Literature Cited

Abudulai, M., J. Naab, S. S. Seini, I Dzomeku, K. Boote, R. Brandenburg, and D. Jordan. 2018. Peanut (*Arachis hypogaea*) response to weed and disease management in northern Ghana, Int. J. Pest Manag. 64(3): 204–209.

AOAC International [Association of Official Agricultural Chemist International]. 2006. Aflatoxins in corn, raw peanuts and peanut butter: liquid chromatography with post-column photochemical derivatization. Official Method 2005.08, 49.2.18A.

Awuah, R. T., and W. O. Ellis. 2002. Effects of some groundnut packaging methods and protection with *Ocimum* and *Syzygium* powders on kernel infection by fungi. Mycopathologia, 154:29–26.

Awuah, R. T., S. C. Fialor, A. D. Binns, J. Kagochi, and C. M. Jolly. 2006. Factors influencing market participant decision to sort groundnuts along the marketing chain in Ghana. Peanut Sci. 36:68–76.

Bulaong, S. S. P., and O. S. Dharmaputra, 2002. Fungal population, aflatoxin and free fatty acid contents of peanuts packed in different bag types. Biotropia, 19:1–25.

CDC [Centers for Disease Control and Prevention]. 2013. Aflatoxin. Centers for Disease Control and Prevention (updated 13 January 2012). http://www.cdc.gov/nceh/hsb/chemicals/aflatoxin.htm [Accessed July 28, 2017].

CAS [Codex Alimentarius Standards]. 2001. Maximum level and sampling plan for total aflatoxins in peanuts intended for further processing. CODEX STAN 209-1999, Rev. 1-2001. http://www.iss.it/binary/iupa/cont/MaxLevelSamplingAFsPeanut_2001.pdf.

Craufurd, P. Q., P. V. Prasad, F. Waliyar, and A. Taheri. 2006. Drought, pod yield, pre- harvest *Aspergillus* infection and aflatoxin contamination on peanut in Niger. Field Crops Res. 98:20–29.

Curkovic, S. T. 2016. Detergents and soaps as tools for IPM in agriculture. Integrated Pest Management (IPM): Environmentally Sound Pest Management, Harsimran Kaur Gill and Gaurav Goyal, IntechOpen, DOI: 10.5772/64343. Available at: https://www.intechopen.com/books/integrated-pest-management-ipm-environmentally-sound-pest-management/detergents-and-soaps-as-tools-for-ipm-in-agriculture.

Davidson, J. I., Jr, P. D. Blankenship, and T. H. Sanders. 1983. Effect of gypsum and calcium carbonate on plants. http.//www.fao.org/doCrep/t032e/to32e05.htm.

Dzomeku, I. K., S. Baba, M. Abudulai, A. M. Mohammed, and A. L. Abdulai, 2019. Groundnut (*Arachis hypogaea* L.) response to phosphorus and weed management in the Guinea Savannah Zone of Ghana. Tropicultura 37(1). Available at: https://popups.uliege.be:443/2295-8010/index.php?id=253.

Ellis, W. O., J. P. Smith, B. K. Simpson, and J. H. Oldham. 1991. Aflatoxins in food: Occurrence, biosynthesis, effects on organisms, detection, and methods of control. Cri. Rev. Food Sci. Nutri. 30 (4):403–439.

Emmok, C. P. 2010. Procurement for Development Forum: Groundnuts Case Study Chatham House. http://www.chathamhouse.org/publications/papers/view/109368.

Eskola, M., G. Kos, C. Elliott, J. Hajšlová, S. Mayar, and R. Krska. 2019. Wordwide contamination of food-crops with myctoxins: Validity of the widely cited 'FAO estimate' of 25%. Cri. Rev. Food Sci. Nutri. DOI 10.1080/10408398.2019.1658570

Fana, S. 2010. Revitalization of the groundnut sector in West Africa (Gambia, Guinea Bissau, and Senegal. Global Agricultural Information Network Report). Available at: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Revitalization%20of%20the%20Groundnut%20sector%20in%20West%20Africa_Dakar_Senegal_12-3-2010.pdf.

Gong, Y. Y., S. Wilson, J. K. Mwatha, M. N. Routledge, J. M. Castelino, B. Zhao, G. Kimani, H. C. Kariuki, B. J. Vennervald, D. W. Dunne, and C. P. Wild. 2012. Aflatoxin exposure may contribute to chronic hepatomegaly in Kenyan school children. Environ Health Perspect. 120 (6):893–896.

Gordon, S. S. 2003. Aflatoxin and food safety: Recent African perspectives. Promec Unit, Medical Research Council, Tygerberg, South Africa. J. Toxicol. Toxin Rev. 22:264–268.

Grosso, N. R., and C. A. Guzman. 1995. Chemical composition of aboriginal peanut (*A. hypogaea*) seeds from Peru. J. Agric. Food Chem. 43:102–105

Guchi, E. 2015. Implication of aflatoxin contamination in agricultural products. Am. J. Food Nutri. 3(1):12–20.

Helper, P. K. 2005. Calcium: A central regulator of plant growth and development. Plant Cell. 17:2142–2155.

Hong, D., and S. Hanson. 2016. Scaling up agricultural credit in Africa. *In* Frontier Issues Brief submitted to the Brookings Institution's Ending Rural Hunger project. Available at: https://www.endingruralhunger.org/. Accessed January 9, 2020.

Ibrahim, B., L. Amadou, J. Lowenberg-DeBoer, and L. Murdock. 2013. Side by side comparison of GrainPro and PICS bags for postharvest preservation of cowpea grain in Niger. J. Stored Products Res., Vol. 54. DOI:10.1016/j.jspr2013.03.003.

IITA [International Institute of Tropical Agriculture]. 2013. Tackling killer aflatoxins in African food crops. European Initiative on Agriculture Research for Development (EIARD). Available at: https://www.iita.org/news-item/iita-partners-launch-initiative-tackle-killer-aflatoxin-african-crops/.

Ioannou-Kakouri, L., A. Aletrali, E. Christou, A. Hadjioannou-Ralli, A, Koliou and D. Akkelidou, 1999. Surveillance and control of aflatoxins B_1, B_2, G_1, G_2, and M_1 in foodstuffs in the Republic of Cyprus: 1992–1996. J. AOAC. Int. 82:883–892.

Jolly, P., Y. Jianga, W. Ellis, R. Awuah, O. Nnedua, T. Phillips, J. Wange, E. Afriyie-Gyawu, L. Tange, S. Person, J. Williams, and C. Jolly. 2006. Determinants of aflatoxin levels in Ghanaians: Sociodemographic factors, knowledge of aflatoxin and food handling and consumption practices. Int. J. Hyg. Environ. Health. 209:345–358.

Jordan, D., R. Brandenburg, G. Payne, D. Hoisington, N. Magnan, J. Rhoads, M. Abudulai, K. Adhikari, J. Chen, R. Akromah, W.

Appaw, W. Ellis, M. Balota, K. Mallikarjunan, K. Boote, G. MacDonald, K. Bowen, B. Bravo-Ureta, J. Jelliffe, A. Budu, H. Chalwe, A. Mweetwa, M. Ngulube, A. Dankyi, B. Mochia, V. Hoffman, A. Muitia, A. Mwangwela, S. Njoroge, D. Okello, and N. Opoko. 2018. Preventing mycotoxin contamination in groundnut cultivation. Pages 181–214 *in* S. Sivasankar, D. Berguinson, P. Gaur, S. Kumar, S. Beebe, and M. Tamó, eds., Achieving Sustainable Cultivation of Grain Legumes; Improving Cultivation of Particular Grain Legumes. Volume 2. Burleigh Dodds Series in Agricultural Science, Burleigh Dodds Science Publishing, Cambridge, UK.

Kew, M. C. 2012. Hepatocellular carcinoma in developing countries: Prevention, diagnosis and treatment. World J. Hepatol. 4(3):99–104.

Knutsen, H. K., J. Alexander, L. Barregård, M. Bignami, B. Brüschweiler, S. Ceccatelli, B. Cottrill, M. Dinovi, L. Edler, B. Grasl-Kraupp, C. Hogstrand, L. R. Hoogenboom, C. S. Nebbia, I. P. Oswald, M. Rose, A. C. Roudot, T. Schwerdtle, C. Vleminckx, G. Vollmer, H. Wallace, P. Fürst, K. Baert, J. Cortiñas Abrahantes B. Dujardin, K. Ferrini, and A. Petersen. 2018. Statement on the effect on public health of a possible increase of the maximum level for 'aflatoxin total' from 4 to 10 μg/kg in peanuts and processed products thereof, intended for direct human consumption or use as an ingredient in foodstuffs. EFSA Journal. 16 (2):5175.

Mahuku, G., H. S. Nzioki, F. Waliyar, B. Diarra, and O. Kodio. 2010. Aflatoxin prevalence data collection: sampling framework and methodology. Internal Food Policy Research Institute (IFPRI), Working Paper 1. Available at: https://www.ifpri.org/publication/aflatoxin-prevalence-data-collection.

Malaker, P. K., I. H. Mian, K. A. Bhuiyah, A. M. Akanda, and M. M. A. Reza. 2008. Effect of storage containers and time on seed quality of wheat. Bangladesh J. Agri. Res., 33:469–477.

Mochiah M. B., B. Banful, K. N. Fening B. W. Amoabeng, K. Offei Bonsu, S. Ekyem, H. Braimah, and M. Owusu-Akyaw. 2011. Botanicals for the management of insect pests in organic vegetable production. J. Entomol. Nematol. 3(6):85–97.

Nutsugah, S. K., M. Abudulai, C. Oti-Boateng, R. L. Brandenburg, and D. Jordan. 2007. Management of leaf spot diseases of peanut with fungicides and local detergents in Ghana. Plant Pathol. 6:248–253.

Owusu–Akyaw, M., M. B. Mochiah, J. Y. Asibuo, K. Osei, A. Ibrahim, G. Bolfrey Arku, J. N. L. Lamptey, A. A. Danyi, A. Oppong, J. K. Addo, M. K. Boateng, H. K. Adu-Dapaah, S. Addy, S. Amoah, S. Osei-Yeboah, M. Abudulai, N. Denwar, J. Naab, G. Mahama, R. Akroma, R. L. Brandenburg, J. E. Bailey, D. L. Jordan, T. H. Williams, D. Hoisington, and J. Rhoads. 2019. Evaluation and release of two peanut cultivars: a case study of partnerships in Ghana. Peanut Sci. 46:37–41.

Ramesh, J., G. Sarathchandra, and V. Sureshkumar. 2013. Survey of market samples of food grains and grain flour for aflatoxin B1 contamination. Int. J. Curr. Microbiol. Appl. Sci. 2(5):184–188.

Saleemullah, A., I. A. Iqbal, and H. Shah. 2006. Aflatoxin contents of stored and artificially inoculated cereals and nuts. Food Chem. 98(4):699–703.

Turner, P. C., S. E. Moore, A. J. Hall, A. M. Prentice, and C. P. Wild. 2003. Modification of immune function through exposure to dietary aflatoxin in Gambian children. Environ Health Perspect. 111(2):217–20.

USDA-GIPSA [United States Department of Agriculture Grain Inspection, Packers and Stockyards Administration Technology and Science Division]. 2015. Test Kit Instructions: 8085 AS III and Pro. Neogen Reveal Q^+ for aflatoxin using Accusan III and Accuscan Pro Readers. Pages 1-11. Available at: https://www.gipsa.usda.gov/fgis/metheqp/instructions/8085%20AS%20III%20and%20Pro%20Revision%200.pdf.

Villers, P. 2014. Aflatoxins and safe storage. Frontiers Microbiol. 5 (158):1–6.

Wagacha, J. M., and J. T. Muthomi. 2008. Mycotoxin problem in Africa: Current status, implications to food safety and health and possible management strategies. Intl. J. Food Microbiol., 124:1–12.

Waliyar, F., P. L. Kumar, A. Traore, B. R. Ntare, B. Diarra, and O. Kodio. 2008. Pre and post-harvest management of aflatoxin contamination in peanuts. Pages 209–218 *in* J. F. Leslie, R. Bandyopadhyay, and A. Visconti, eds. Mycotoxins: Detection Methods, Management, Public Health and Agricultural Trade. CAB International.

Waliyar, F., V. C. Umeh, A. Traore, M. Osiru, B. R. Ntare, B. Diarra, O. Kodio, K. V. K Kumar, and H. Sudini. 2015. Prevalence and distribution of aflatoxin contamination in groundnut (*Arachis hypogaea* L.) in Mali, West Africa. Crop Prot. 70(1):1–7.

Whitaker T. B., W. M. Hagler, Jr, F. G. Giesbrecht, J. W. Dorner, F. E. Dowell, and R. J Cole. 1997. Estimating aflatoxin in farmers' stock peanut lots by measuring aflatoxin in various peanut-grade components. Journal of AOAC International. 81:61–67.

White, P. J., and M. R. Broadly. 2003. Calcium in plants. Ann. Bot. 92:487–511.

Williams, J., T. D. Phillips, P. E. Jolly, J. K. Stiles, C. M. Jolly, and D. Aggarwal. 2003. Human aflatoxicosis in developing countries: a review of toxicology, exposure, potential health consequences, and interventions. Am. J. Clin. Nutri. 80:1106–1122.