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Physical rice grain quality as affected by biophysical factors and pre-harvest practices

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Abstract

Varietal purity and proportions of grains with brown spots, fissured grains, chalky grains and whole grains in a rice sample are important grain quality attributes influencing consumers' preference and price but little information exist on how these grain quality attributes are affected by biophysical factors and pre-harvest practices. Several authors have studied in isolation the effect of biophysical factors and pre-harvest practices on rice grain quality but most of these studies neither looked at these within the context of agro-ecological zones nor production systems. The effects of agro-ecological zone (AEZ) (highlands, sub-humid, humid and semi-arid), production system (irrigated lowland, rain-fed lowland and rain-fed upland) and pre-harvest practices on grain quality attributes were investigated in 5 African countries using data collected through on-farm survey. The rice samples were generally characterized by low varietal purity, high proportion of brown spots, fissured and chalky grains and a low proportion of whole grains. Also, they had large variations across and within AEZs and production systems. AEZs and crop establishment method affected varietal purity. AEZ, production system affected chalkiness. AEZ and type of variety influenced percentage of grains with fissures. Percentage of whole grains were affected by AEZ, production system and weeding frequency. While grain quality attributes were strongly affected by biophysical factors, there is also room for improving grain quality through good pre-harvest practices.

Keywords: Agro-ecological zone; *Oryza spp*; Production systems; Varietal purity; Brown spot; Chalkiness; Fissures; Whole grains; Africa.

Abbreviation

AEZ: Agro-ecological zone
CEM: Crop establishment method
NGO: non-governmental organization
PS: Production system
REN: Research institute, Extension or Non-governmental organization
SS: Source of seed
SSA: sub-Sahara Africa
VT: Type of variety
WF: Weeding frequency

Introduction

Rice (*Oryza spp*) is a staple food crop worldwide and of strategic importance to sub-Sahara Africa (SSA) countries (Hodges et al., 2011; Seck et al., 2013). Due to changing eating habit and high population growth rate, consumption of rice has increased in West and Central Africa, resulting in increased importation as local production has not caught up with increasing demand (Seck et al., 2010; Otsuka and Kijima, 2010; Food and Agricultural Organization [FAO], 2015). Furthermore, most of the rice produced locally is insufficient in quality for most urban consumers who prefer imported rice to locally produced rice (Demont, 2013; Akoa-Etoa et al., 2016). Consequently, imported rice has gained grounds in markets in urban cities in SSA especially those close to the port (Demont and Ndour, 2015). Sub-optimal production and processing practices are major reasons for the low production and quality of rice in Africa. Rice with a high proportion of impurities, chalky and/or diseased grains and a low proportion of whole grains is not preferred and records a low market value especially in urban centers (Demont, 2013; Lapitan et al., 2007; Ndindeng et al., 2015).

Grain quality attributes such as varietal purity, grains with brown spots, grains with fissures, chalky and whole grains may be affected by several factors along the pre- and post-harvest interventions. Mixtures of varieties with different shape and sizes increase breakages during milling since a mill can only be calibrated to accept grains with uniform shape and size (Attaviroj et al., 2011). Varietal purity also affects the appearance of milled rice especially parboiled milled rice when varieties are mixed especially the mixture of pigmented and non-pigmented grains. Brown spot in rice caused by *Bipolaris oryzae* is common worldwide and known to cause substantial quantitative and qualitative losses in grain yield (Pannu et al., 2002; Joshi et al., 2007; Sunder et al., 2014). Grain chalkiness is an undesirable quality criterion in the world market except for the production of special products, notably Japanese sake and risotto rice in Italy (Zhou et al., 2009). Low chalky value generally indicates better sensory quality both for non-parboiled and parboiled rice (Kim et al., 2000). Fissures in grains occur when grains are left to dry and re-absorb moisture in the field (Desikachar and Subrahmanyan, 1961; Kunze, 1979; Ndindeng et al., 2014) or due to rapid and/or over drying of grain after harvest. Chalky centers and fissures are points of weaknesses on the grain and these tend to increase breakages during milling. Many studies have demonstrated the effect of post-harvest practices on these attributes (Bonazzil et al., 1997; Chouw and Noomhorm, 2001; Balasubramanian et al., 2007; Debabandya and Bal, 2007; Rickman et al., 2013; Ndindeng et al., 2015; Baoua et al., 2016; Amponsah et al., 2017). Also, climatic factors such as heat (temperature and humidity) and drought before harvest have been shown to affect rice grain quality attributes (Osada et al., 1973; Yoshida et al., 1977; Barnabas et al., 2008; Zhang et al., 2008; Wassmann et al., 2009; Abbasi and Sepaskhah, 2011). Studies in Asia show that higher application rate of nitrogen (N), phosphorus (P) and potassium (K) increased percent milling recovery and whole grains (Adhikari et al., 2005; Murthy et al., 2015). Although paddy rice yields have been associated with biophysical factors and pre-harvest practices in SSA (Saito et al., 2013; Tanaka et al., 2015; Tanaka et al., 2017), little information exists on how biophysical factors and different pre-harvest practices affect rice grain quality attributes in the region. This information is necessary for modeling qualitative losses and development of site-specific recommendations to enhance rice grain quality. The objective of this study was thus to investigate and characterize the quality of rice produced in some sites across SSA and study the effect of biophysical factors [(agro-ecological zone (AEZ) and production system (PS)] and pre-harvest practices [(weeding frequency (WF), type of variety (VT), source of seed (SS) and crop establishment method (CEM) on some grain quality attributes.

Materials and Methods

Brief description of study site

Six sites located in four contrasting tropical agro-ecological zones (AEZs) (HarvestChoice, 2009) were selected for this study. These sites were selected by national partners of Africa Rice Centre (AfricaRice) based on the importance of rice production and value chain in their countries (AfricaRice, 2011). HarvestChoice (2009) has classified AEZs in sub-Saharan Africa as either tropic warm or cold. The tropic warm zone which are < 1200 m above sea level is further sub-divided into 4 humidity zones by length of the growing period; arid (<70 days), semi-arid (70–180 days), sub-humid (180–270 days) and humid (>270 days). The tropic cold zones which are areas > 1200m above sea level are aggregated to form the highland zone. The arid z one is characterized by higher solar radiation, lower relative humidity and larger temperature fluctuations compared with other zones. Along the tropic warm agro-ecological gradient from arid to humid, solar radiation decreases, relative humidity is higher and temperature fluctuates less (HarvestChoice, 2009). In this study, Malanville (Benin) and Tandjilé-Est (Chad) were classified as semi-arid zones, Haute Guinée (Guinea) and Lagdo (Cameroon) were classified as sub-humid zones, Gagnoa (Cote d'Ivoire) was classified as humid zone and Ndop (Cameroon) was classified as highland zone (Table 1). There were three production systems (PS) in the study sites: irrigated lowland rice in Malanville, Lagdo and Gagnoa; rain-fed lowland rice in Tandjilé Est and Ndop; and rain-fed upland rice in Haute Guinée.

Table 1. Agro-ecological zone, production system and geographical coordinates of some rice production sites in sub-Sahara Africa.

Agro-ecological zone	Production system	Country	Site	Geographical location
Semi-arid	Irrigated lowland	Benin	Malanville	11° 52' N, 3° 23' E
	Rain-fed lowland	Chad	Tandjilé Est	9° 24' N, 16° 18' E
Sub humid	Irrigated lowland	Cameroon	Lagdo	9° 36' N, 13° 44' E
	Rain-fed upland	Guinea	Haute Guinée	11° 00' N, 10° 00' W
Humid	Irrigated lowland	Côte d'Ivoire	Gagnoa	6° 7' N, 5° 57' W
Highland	Rain-fed lowland	Cameroon	Ndop	5° 59' N, 10° 69' E

Field survey and data collection

Villages and farmers were randomly selected to participate in the study. A total of 163 farmers were selected for the study with 55 from irrigated lowland [(Gagnoa (25) and Malanville (30)], 88 from rainfed lowland [(Ndop (20), Lagdo (19) and Tandjilé-Est (49)] and 20 from rainfed upland (Haute Guinée).

In each farmer's field, a 200 m^2 survey area was selected and three 12 m^2 (3m × 4 m) plots within each survey area were randomly identified during crop establishment phase. Data on pre-harvest practices were collected for each farmer's survey area through interview during several field visits and at maturity, rice grain samples were collected near the three plots. Table 2 shows variables used in this study. A composite rice sample composed of 8 randomly harvested hills or plants per survey area was hand-threshed and used for grain quality analysis.

Table 2. Grain quality attributes and qualitative and quantitative variables on pre-harvest practices considered as potential factors affecting rice grain quality attributes.

Pre-harvest practices	Description or unit
Type of variety	Improved or traditional*
Source of seed	Other farmers, farmer own (last cropping season), or research, extension or NGO
Crop establishment method	Broadcasting or transplanting
Weeding frequency	0 time, 1-2 times, or 3-4 times
Nitrogen application rate**	kg/ha
Phosphorus application rate**	kg/ha
Potassium application rate**	kg/ha
Grain quality attribute	
Grains with brown spots	%
Grains with fissures	%
Whole grains	%
Chalky grains	%
Varietal purity	%

NGO: non-governmental organization.
* This identification was based on farmers' answer.
** Quantitative variables.

Grain quality analysis

Grain quality analysis was done on paddy, brown and milled rice. Milling was done with a THU-34A Satake testing rice husker (Satake, Hiroshima, Japan). Brown rice was polished in a Recipal 32 rice whitener (Yamamoto Co., Higashine, Japan). The following grain quality parameters were analyzed.

Varietal purity

Varietal purity was evaluated on 50 g de-husked rice grains by visually identifying and removing kernels that were different based on size, shape and color. Varietal purity was the number of grains with same size, shape and color expressed as a percentage of total number of grains analyzed.

Grains with brown spots

Fifty (50) grams of brown rice was placed on a flat surface to visually identify under a loop and white light grains with brown spots (spotted grains). The weight of grains with brown spots was expressed as a percentage of the weight of the sample used.

Grains with fissures

Twenty (20) grams of paddy was hand de-husked and viewed under a Grainscope TX-200 (Kett Co., Ltd., Seoul, Korea) for presence of fissures (cracks). The weight of fissured or cracked grains was expressed as a percentage of weight of grains used.

Whole grains (kernels)

The whole grain, which is an indication of the milling potential of the sample, was evaluated using 100 g of brown rice. A grain or kernel was considered whole if the grain was 75% to 100% whole (intact) after de-husking. Whole grains in the sample were manually separated from broken grains and the weight of whole grains was expressed as a percentage of the weight of sample used.

Chalky grains

The percentage of chalky grains was evaluated following Ndindeng et al. (2015) and Graham-Acquaah et al. (2015). 50 g of polished rice was run in the S21 rice statistical analyzer (LKL Technologia, Santa Cruz do Rio Pardo, Brazil).

Statistical analysis

The distribution of each grain quality attribute was subjected to descriptive statistical analysis at 95% level of confidence. The mean, standard deviation, skewness and coefficient of variation were noted. Chi's square test of independence was used to test the relationship between biophysical factors and pre-harvest practices. Pearson's correlation was used to determine relationships between inorganic fertilizer application rate and grain quality attributes. Multiple regression analysis with nested effect was used to study the effects of biophysical factors (AEZs and PS) and pre-harvest practices (WF, SS, VT and CEM) on grain quality attributes (varietal purity, grains with brown spots, chalky grains, grains with fissures and whole grains). The tolerance level of 0.00001 was used to prevent the ordinary least square (OLS) regression calculation algorithm considering variables which might be either constant or closely correlated with other variables already used in the model. The following categories were used as references for each factor; AEZ: Semi-arid, PS: Rain-fed upland, WF: 3-4 times, VT: Traditional, SS: Research, extension or NGO and CEM: Transplanting. The statistical program used for the analysis was XLSTAT™ software for Windows® Version 18.6 (2017) (Addinsoft SARL, Paris, France). All analysis was done at 5% significance level.

Results

Some key facts about factors and grain quality attributes in study sites.

A distribution of percentage of varietal purity, grains with brown spots, grains with fissures, whole grains and chalky grains from the six study sites is shown in Table 3. Samples across study sites show a high degree of variability for all grain quality attributes studied. Grains with fissures had the largest difference between maximum and minimum values, followed by whole grains, whereas varietal purity had the smallest difference. Mean percentage of varietal purity was 87% with coefficient of variation (CV) of 16% and skewness (Pearson) of -1.49. Forty-two (42) percent of samples from study sites had varietal purity equal to or below 88%, which is considered as threshold standard value (International Standards ISO 7301, 2011). Varietal purity was mainly due to the presence of red rice as opposed to difference due to shape and size. Mean percentage of grains with brown spots was 28% with CV of 67% and skewness of 1.3. Only 0.65% of samples from study sites had damaged grains due to brown spots in rice ≤ 4%. The percentage of damaged grains in a de-husked sample is expected to be ≤ 4%. Mean percentage of chalky grain was 25% with CV of 80% and skewness of 1.3. Sixty-nine- (69) percent of samples from the study sites had percentage chalky grains > 11% which is considered the threshold. Mean percentage of grains with fissures was 45% with CV of 57% and skewness of 0.18 and more than 88% of samples from sites had percent fissured grains greater than 10%. Mean percentage of whole grain was 56% with CV of 34% and skewness of -0.28. Only 9.5% of samples from study sites recorded percent whole grains after de-husking > 80%.

Table 3. Distribution of five selected grain quality attributes in six sub-Sahara African countries.

Percentile	VP	GWBS	CG	GWF	WG
100	100	92	85	100	93
99	100	90	84	95	89
95	100	66	70	90	81
90	99	51	59	80	79
75	97	36	33	65	72
50	89	24	18	45	56
25	79	14	11	20	41
10	65	8	6	11	30
5	56	6	5	5	23
1	34	3	2	0	10
0	32	2	1	0	7
Mean (Std. dev.)	86 (13.9)	27.7 (18.9)	25.0 (20.1)	44.5 (25.6)	55.8 (19.2)
skewness	-1.49	1.3	1.3	1.8	0.28
Coefficient of variation (%)	16	67	80	57	34

VP: Varietal purity; GWBP: Grains with brown spots; CG: Chalky grains, GWF: Grains with fissures; WG: Whole grains.

Biophysical factors and pre-harvest practices studied were associated with each other (P<0.05) except for type of variety and weeding frequency that showed no association (Table 4a). About 79% of farmers weed their rice fields 1-2 times during rice growing season, whereas 4.4% did not weed (Table 4b). Eighty-seven- (87) percent of farmers used improved varieties and the percentage of farmers using improved varieties did not differ across sites, AEZs and PS except for Haute Guinee a rain-fed upland system located in the sub-humid zone where farmers used mostly traditional varieties. About half of the farmers (54.7%) used their own rice grains preserved from the last cropping season as seeds. Fifty-seven- (57) percent of them used broadcasting method for crop establishment. In addition, fifty-one (51) percent of farmers applied fertilizers at different rates that ranged from 38 to183 kg/ha, 15 to 4 kg/ha and 15 to 43 kg/ha, for N, P and K, respectively. It was observed that in the irrigated lowland, rice farmers tended to have higher WF than rain-fed lowland and upland rice farmers (Table 4b), while upland farmers tended to use more traditional varieties, grains from last cropping season as seed and broadcasting method for crop establishment. Farmers who used improved varieties also tended to use transplanting for crop establishment, while those who used traditional varieties used broadcasting method. Farmers who used last cropping season grains as seed also tended to use broadcasting method for crop establishment while those who got seed from research, extension or non-governmental organization (NGO) established their field by transplanting and the seeds were of the improved type (Table 4c).

Table 4a. Association between biophysical and pre-harvest parameters used to study their effects on grain quality attributes in six contrasting sites in sub-Sahara Africa.

Variables	AEZ	PS	WF	VT	SS
AEZ	1.00				
PS	138.9**	1.00			
WF	38.6**	22.3**	1.00		
VT	55.4**	91.1**	5.8	1.00	
SS	21.5**	48.1**	15.1*	10.2*	1.00
CEM	68.0**	77.7**	15.0*	22.5**	62.8**

AEZ: Agro-ecological zone; PS: Production system; WF: Weeding frequency; SS: Source of seed; VT: Type of variety; CEM: Crop establishment method.
* Denotes P<0.05
** Denotes P<0.001

Table 4b. Proportion of farmers based on biophysical factors and pre-harvest practices in six contrasting sites in sub-Saharan Africa.

Factors		Hignland	Humid	Sub-humid		Semi-arid		Total
		Rainfed lowland	Irrigated lowland	Rainfed lowland	Rainfed upland	Irrigated lowland	Rainfed lowland	
WF	0 time	3.1	0.6	0.0	0.6	0.0	0.0	4.4
	1-2 times	9.4	10.1	11.3	11.9	10.1	25.8	78.6
	3-4 times	0.0	5.0	0.6	0.0	6.9	4.4	17.0
VT	Improved	18.5	17.6	6.5	0.9	27.8	15.7	87.0
	Traditional	0.0	0.0	0.0	12.0	0.0	0.9	13.0
SS	Other farmers	0.6	0.6	3.7	2.5	1.2	8.1	16.8
	LCS	6.8	11.2	5.6	9.9	0.0	21.1	54.7
	REN	5.0	3.7	1.2	0.0	17.4	1.2	28.6
CEM	Broadcasting	0.0	3.7	11.7	12.3	0.0	30.1	57.7
	Transplanting	12.3	11.7	0.0	0.0	18.4	0.0	42.3

WF: Weeding frequency; SS: Source of seed; VT: Type of variety; CEM: Crop establishment method; LCS: Last cropping season; REN: Research institute, extension service or NGO.

Table 4c. Proportion of farmers based on type of variety used per pre-harvest practices in six contrasting sites in sub-Saharan Africa.

Factors	Categories	Type of variety		
		Improved	Traditional	Total
WF	0 time	5.7	0.0	5.7
	1-2 times	60.0	13.3	73.3
	3-4 times	21.0	0.0	21.0
SS	Other farmers	10.2	2.8	13.0
	LCS	38.0	10.2	48.1
	REN	38.9	0.0	38.9
CEM	Broadcasting	28.7	13.0	41.7
	Transplanting	58.3	0.0	58.3

WF: Weeding frequency; SS: Source of seed; CEM: Crop establishment method; LCS: Last cropping season; REN: Research institute, extension service or NGO.

Effects of biophysical factors and pre-harvest practices on grain quality attributes

Multivariate regression model showed that varietal purity was affected by AEZ and CEM (F=3.3, P=0.001) but not by PS, WF, VT and SS (Table 5a). Samples from highland zone recorded 34% lower varietal purities than those from semi-arid zones (P<0.0001). The percentage of varietal purity of samples from semi-arid zones was comparable with that of humid and sub-humid zones. Samples from field where farmers used broadcasting recorded 20% reduced varietal purity than where transplanting was used (P<0.003). None of the biophysical factors and pre-harvest practices used in this study affected the percentage of grains with brown spots (F=1.09, P=0.37) in study sites. AEZ and PS were the main factors affecting the amount of chalky grains in study sites while WF, VT, SS and CEM had no effect (F=6.56, P<0.0001). Samples from highland zone recorded 29% less chalky grains than those from semi-arid zones (P<0.011). The percentage of chalky grains from humid and sub-humid zones was slightly lower and comparable with that of semi-arid zones (Table 5a). Samples from rain-fed and irrigated lowlands recorded respectively 39% and 60% reduced chalky grains than those from rain-fed upland (P<0.01).

Table 5a. Model parameters demonstrating the effect of biophysical and pre-harvest practices and their interactions on grain quality attributes in six contrasting sites in sub-Sahara Africa.

Factors	Varietal purity	Standard error	Grains with brown spots	Standard error	Chalky grains	Standard error	Grains with fissures	Standard error	Whole grains	Standard error
Intercept	104.00**	10.55	23.91	14.53	67.01**	13.75	90.73**	18.64	14.19	13.76
AEZ-Highlands	-33.86**	8.33	10.91	11.67	-28.64*	11.04	-22.85	14.96	35.45**	11.05
AEZ-Humid	-1.67	5.05	-0.27	6.94	-7.11	6.57	-20.08*	8.91	13.41*	6.57
AEZ-Sub humid	-4.74	6.71	-3.09	9.24	-13.50	8.74	-27.30*	11.85	18.47*	8.75
PS-Irrigated lowland	-26.57	14.23	7.27	19.52	-60.22**	18.48	-8.68	25.04	27.37	18.49
PS-Rain-fed lowland	-0.10	11.00	0.65	14.98	-38.77**	14.17	19.65	19.21	-0.99	14.18
WF-0 time	-7.00	6.90	15.08	9.61	1.41	9.10	11.54	12.33	8.73	9.10
WF-1-2 times	-0.98	3.43	5.04	4.77	0.21	4.51	-3.95	6.11	9.18*	4.51
VT-Improved	10.64	9.37	-10.46	12.76	12.72	12.07	-38.05*	16.36	7.54	12.08
SS-Other farmers	3.90	4.86	-3.95	6.67	4.96	6.32	7.64	8.56	1.70	6.32
SS-Last cropping season	1.10	4.25	1.47	6.01	0.90	5.69	2.89	7.71	-1.85	5.69
CEM-Broadcasting	-20.41**	6.68	3.58	9.09	-4.04	8.61	-7.10	11.66	8.57	8.61
Number of observations	105.00		100.00		100.00		100.00		100.00	
F-statistic	3.30**		1.09		6.56**		4.58**		5.08**	
R^2	0.28		0.12		0.45		0.36		0.38	
df1	11.00		11.00		11.00		11.00		11.00	
df2	93.00		88.00		88.00		88.00		88.00	

AEZ: Agro-ecological zone; PS: Production system; WF: Weeding frequency; SS: Source of seed; VT: Type of variety; CEM: Crop establishment method.
* Denotes statistical significance at the 5% level.
** Denotes statistical significance at the 1% level.
df: Denotes degree of freedom.
References used in the model: AEZ=Semi-arid; PS=Rain-fed upland; WF=3-4 times; VT=Traditional; SS=Research, extension or NGO; CEM=Transplanting.

The percentage of grains with fissures was influenced by the AEZ and VT in the proposed model while PS, WF, SS and CEM had no effect (F=4.58, P<0.0001). Samples from sub-humid and humid zones recorded respectively 27% and 20% reduced number of grains with fissures than those from semi-arid zone (P<0.02). Samples from fields where farmers planted improved varieties recorded 38% reduced number of grains with fissures than in fields were traditional varieties were planted (P=0.022). Percentage of whole grains was affected by AEZ and WF while PS, VT, SS and CEM did not (F=5.08, P<0.0001). Samples from highland, sub-humid and humid zones had respectively 35.4% (P=0.003), 18.7% (P=0.038) and 13.4% (P=0.044) more whole grains than those from semi-arid zone. Farmers who weeded their fields 1-2 times had about 9.2% more whole grains than farmers who weeded 3-4 times (P=0.045).

In the studied samples, varietal purity was observed to be negatively correlated with whole grains (R= -0.27; P=0.001). There was a weak and positive correlation between grains with brown spots and chalky grains (R=0.17, P=0.03) (Table 5b). Percent chalky grains and grains with fissures were positively correlated with each other (R=0.23, P=0.004) but negatively correlated with percent whole grains (R= -0.27, P=0.001) and (R= -0.69, P<0.0001) respectively. Percent chalky grains weakly and negatively correlated with application rates of nitrogen (N) (R= -0.18, P=0.025), phosphorus (P) (R=0.17, P=0.033) and potassium (K) (R=0.17, P=0.033), respectively.

Table 5b. Correlations between inorganic fertilizer application rate and some grain quality attributes in six contrasting sites in sub-Sahara Africa.

Variables	Nitrogen	Phosphorus	Potassium	Varietal purity	Brown spot	Whole grains	Chalky grains
Nitrogen	1.00						
Phosphorus	0.59**	1.00					
Potassium	0.59**	0.98**	1.00				
Varietal purity	0.05	0.11	0.10	1.00			
Grains with brown spot	-0.09	0.01	0.04	-0.11	1.00		
Whole grains	-0.04	-0.02	0.00	-0.27**	-0.03	1.00	
Chalky grains	-0.18*	-0.17*	-0.17*	0.04	0.17*	-0.27**	1.00
Grains with fissures	0.08	0.02	0.01	0.11	0.02	-0.69**	0.23**

* Denotes statistical significance at the 5% level.
** Denotes statistical significance at the 1% level.

Discussion

SSA rice quality and losses

As step towards the development of models for qualitative loss assessment and site-specific recommendations to reduce qualitative losses along the rice value-chain in SSA, it was imperative to study the effects of biophysical factors and pre-harvest practices on some grain quality attributes (varietal purity, grains with brown spot, grains with fissures, whole grains and chalky grains). Samples collected from six contrasting sites across SSA representing four AEZs and three rice PS demonstrated that paddy rice produced in those sites was of low physical quality and the samples from each site was characterized by a high degree of non-uniformity. The rice samples were characterized by low varietal purity, high proportions of disease damaged grains (brown spots in rice), chalky grains and a low proportion of whole grains. The rice samples did not meet international standards for paddy, brown and milled rice production (International Standards ISO 7301, 2011). The above results are in line with market studies in the region that indicated that the quality of locally produced rice was poor (Demont et al., 2012; Demont et al., 2013a; Fiamohe et al., 2014; Akoa-Etoa et al., 2016) with consumers showing higher preference for imported rice due to better quality.

High number of grains with brown spots in samples from all study sites is indicative of a serious problem affecting rice production in the region. Brown spot in rice caused by *Bipolaris oryzae* induces substantial quantitative and qualitative losses in grain yield (Pannu et al., 2002; Joshi et al., 2007; Sunder et al., 2014). Brown spot of rice becomes more prominent after parboiling due to enzymatic browning resulting in 100% quantitative loss since most of the spotted grains are sorted in the parboiled sample and discarded (Ndindeng et al., 2015). However, in the non-parboiled milled sample that experienced low severity of brown spots, the spots are not so prominent but the grains appear chalky (loss in value). It should also be noted that when the severity of brown spots is high, non-parboiled grains will be completely lost.

The low percent whole grain recorded in the samples were expected since the proportion of grains with fissures and chalky grains was high. Mixture of rice with different shape and size will result in low percent whole grains (Attaviroj et al., 2011). However, in this study, a negative correlation was observed between varietal purity and whole grain and this was mainly because varietal purity was mainly due to the presence of red rice as opposed to differences in shape and size. Percent whole grain was negatively correlated with percent grain with fissures ($R = -0.69$, $P<0.05$) and chalky grains ($R = -0.24$, $P<0.05$). Grains with fissures or chalky centers increase breakages during milling since fissures and chalky centers are points of weakness on the grain. Fissures in rice grains may have been caused by moisture re-absorption of dried grains in the field (Desikachar and Subrahmanyan, 1961; Kunze, 1979; Ndindeng et al., 2014) while chalky centers represent points of poor starch formation during the grain filling process (Yamakawa et al., 2007).

Rice quality, biophysical factors and pre-harvest practices

Several authors have studied in isolation the effect of biophysical factors and pre-harvest practices on rice grain quality but most of these studies neither looked at these within the context of agro-ecological zones nor production systems. The grain quality attributes studied were mostly influenced by biophysical factors although some were also influenced by pre-harvest practices. AEZ influenced all grain quality attributes studied except brown spots in rice while PS influenced only proportion of chalky grains. Weeding frequency, type of variety and crop establishment method which are pre-harvest practices each influenced at least one grain quality attribute.

The variations in varietal purity across AEZs was probably related to the quality of seeds at study sites at the time of the study. Varietal purity varied with CEM as samples from fields where farmers used transplanting were 20.4% purer than where broadcasting was used. In this study, farmers who used transplanting were more inclined to plant improved varieties (Table 4c) which also showed higher percentage of purity than traditional variety. In addition, off-types can be observed in the nursery and removed, allowing for purer varieties to be transplanted. In addition, transplanting can somehow reduce contamination with seeds that dropped during previous harvest. If broadcasting is used, it become very difficult to remove off types.

The severity of brown spots in rice was high across AEZs, production systems and neither varied with AEZ nor with production system. Like biophysical factors, pre-harvest practices did not also influence the percentage of grains with brown spots in the studied sites. Biophysical factor such as high humidity, temperature of 25 ^{o}C, limited rainfall, heavy dew and dry soils have been shown to favor disease establishment and progression (Sherf et al., 1947; Ou, 1985; Pannu et al., 2005; Singh et al., 2005). Pre-harvest practices that favor the disease are nutrient deficient soils, the use of broadcasting and manual transplanting (Ou, 1985; Hegde et al., 2000; Sunder et al., 2005). One or several of these factors were common in each study site and these factors were contributing favorably to the establishment and progression of brown spot in rice. For example, broadcasting was common in rain-fed upland while manual transplanting was common in irrigated lowland (Table 4b). However, more detailed studies need to be conducted at each site for a better understanding of brown spot in rice disease establishment and progression.

Percentage of chalky grains varied with AEZ with highland zone recording the lowest proportion of chalky grains compared to the other three zones. It is important to recall that HarvestChoice (2009) classified SSA AEZs either as tropic cool or warm zones. The warm zones are further sub-divided into 4 humidity zones (humid, sub-humid, semi-arid and arid). In this study, one tropic cool (highland) and three tropic warm (semi-arid, sub-humid and humid) sites were selected. Along the tropic cool-warm gradient, chalky grains were lower in the tropic cool zone compared to tropic warm zones but no difference was observed amongst the tropic warm zones. These results are supported by earlier studies that showed that high temperature at the milky stage of grain filling had the greatest influence on rice grain chalkiness (Tashiro and Wardlaw, 1991; Yamakawa et al., 2007; Ndindeng et al., 2014). Percentage of chalky grains varied with production system with lowest proportions in irrigated lowlands, followed by rain-fed lowland and highest in rain-fed upland. The low percentage of chalky grains in irrigated and rain-fed lowlands suggested that areas with high surface water regimes (Saito et al., 2013) enhance starch formation process during grain-filling stage in rice. In addition, upland breeding did not consider chalkiness as important trait; as upland rice, would not target market.

Percentage of grains with fissures varied with AEZ with sub-humid and humid zones recording lower number of grains with fissures compared with arid and highland. Along the humidity gradient (humid-semi-arid), number of grains with fissures was low in high humidity (humid and sub-humid) zones and high and low humidity (semi-arid) zone. Unlike with humidity gradient, no difference was observed along the cool/warm gradient with respect to percentage of grains with fissures. Fissure in grains is caused by moisture re-absorption of dried grains in the field due to high differences in day and night temperatures and humidity (Desikachar and Subrahmanyan, 1961; Kunze, 1979; Ndindeng et al., 2014). VT influenced the number of grains with fissures with improved varieties recording 38% lower number of grains with fissures than traditional varieties. Unlike traditional varieties, improved varieties are usually developed and released in environments where they are most adapted (Tobita, 2000; Futakuchi, 2001; Saito et al., 2014; Diagne et al., 2014). Most of the traditional varieties in this study were grown in rain-fed upland production systems located in sub-humid AEZ which are warm with moderately high humidity. Varieties grown under such conditions recorded lower number of grains with fissures compared to irrigated and rain-fed lowland production systems located in semi-arid zones. This result suggested that the AEZ was more important in determining the development of fissures in grains than the production system.

Percentage of whole grains varied with AEZ but not with PS. Percentage of whole grains was affected both by the cool/warm gradient and the humidity gradient. The proportion of whole grains was higher in highland (cool zone) compared to irrigated and rain-fed lowland (warm zones). In addition, the percentage of whole grains was higher in the humid and sub-humid zones compared to the semi-arid zone demonstrating differences in the percentage of whole grains along the humidity gradient. In this study, cool-warm gradient influenced chalkiness while humidity gradient influenced fissures in grains. Both cool-warm and humidity gradients influenced percentage of whole grains. Although other factors such as moisture content of grain, type of mill and variety influence grain breakage during milling, the synergistic role of chalkiness and fissures on grain breakages is confirmed in this study using biophysical data.

The percentage of whole grains varied with WF but weeding 3-4 times did not seem to have any added value in terms of percentage of whole grains. Although samples where farmers got seeds from research institutes, extension services or NGO tended to show slightly better grain quality traits compared to other sources, however, the difference was not important as expected. There is thus a need to analyze the quality of certified seeds distributed to farmers and their distribution channels to know if standards are respected.

Conclusion

Several authors have studied in isolation the effect of biophysical factors and pre-harvest practices on rice grain quality but most of these studies neither looked at these within the context of agro-ecological zones (AEZ) nor production systems (PS). This study is the first of its kind to demonstrate the effect of biophysical factors (AEZ and PS) and pre-harvest practices on rice grain quality attributes in some sites in SSA. This is significant because the information generated in this study will be useful in modeling qualitative loss at each site and the development of site-specific recommendations to increase rice productivity in the region. Samples collected from six contrasting sites across SSA representing four AEZs and three rice PS demonstrated that paddy rice produced in those sites was of low physical quality and the samples from each site were characterized by a high degree of non-uniformity that could potentially lead to high quality losses.

AEZ influenced percentage varietal purity, chalky grains, grains with fissures and whole grains but did not affect percentage of grains with brown spots. Along the agro-ecological gradient, the tropic cool-warm gradient was the main factor affecting percentage of chalky grains while the humidity (humid-arid) gradient was the main factor affecting the percentage of grains with fissures. Both tropic warm-cold and humidity gradients affected the percentage of whole grains. PS had an effect only on the percentage of chalky grains indicating that the surface water regime and water source are important factors affecting chalkiness. Highland (tropic cool) AEZ was suitable for rice production especially during grain filling compared to the warm sites. In addition, areas with high surface water regimes or stable water supply are also favorable for the grain-filling.

A few pre-harvest practices had effect on grain quality attribute in the study sites indicating that biophysical factors have a dominant effect on grain quality attributes. This was the case for percentage varietal purity that was affected by CEM with purer varieties recorded when transplanting was used as opposed to broadcasting. In addition, there is a need to carry out more work to understand the reasons behind the high severity of brown spots in rice recorded in the region and how to eradicate the disease.

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