Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 120 No. 1 (2019) 45–54

https://doi.org/10.17170/kobra-20190613556 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

Open field screening of the productive parameters, protein content, phenolic compounds, and antioxidant capacity of maize (*Zea mays* L.) in the marginal uplands of southern Madagascar

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Abstract

Madagascar is recognised as having both a high level of poverty and a food shortage. The contribution of the agricultural sector to the national income is higher than for any other sector, though this sector remains insufficiently developed to sustain national food demand. In order to increase food production, the diversification of staple food in conjunction with the detection of best-yield genotypes may be considered the simplest and least expensive alternative approach. For this reason, the response of productive parameters, protein content, phenolic compounds, and antioxidant capacity of maize (*Zea mays* L.) were tested in two different marginal uplands of southern Madagascar using 24 different genotypes. The length of the growing cycle and soil properties were shown to be key aspects for attaining optimal maize performances when cropped in the virgin soils of southern Madagascar. The results also indicated that maize may be considered a reliable alternative to the local staple food currently represented by rice, with sufficient protein and functional compounds for human health. The highest yields, protein content, total polyphenols, and antiradical power (ARP) were observed in the varieties Gasti, Local, Clariti, and Korimbos, respectively. To achieve a good compromise between yield and functional compounds, the varieties Maggi and Gasti are recommended for cultivation. The present results emphasise the effectiveness of maize cultivation in increasing food production in an undernourished country such as Madagascar. Further experiments are required to test maize performances under different soil, cultural and management conditions.

Keywords: maize, Madagascar, genotypes, yield, polyphenols, proteins, antiradical power

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1 Introduction

In a global poverty ranking of countries between 1 and 187, with 187 representing the highest poverty rate, Madagascar (19° 45′ 27″ S; 46° 16′ 28″ E) is ranked in 151st position (UNDP, 2011). Moreover, approximately two-thirds of the Malagasy population are malnourished (Dostie *et al.*, 2002; FAO, IFAD & WFP, 2014). In Madagascar, over 80 % of the Malagasy population are employed in the agricultural sector (FAOSTAT, 2014). However, the agricultural sector remains insufficiently developed to sustain the food demands of the entire population. Whilst the majority of the farmers are smallholders cultivating crops primarily for their own subsistence, large-scale agriculture is practically non-existent (Zeller *et al.*, 1999; Minten & Barret, 2008).

In order to improve the agricultural sector, some specific projects have been proposed. For instance, the "Emergency Food Security and Reconstruction Project for Madagascar"

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Published online: 14 October 2019 – Received: 16 May 2018 – Accepted: 3 June 2019

(World Bank, 2008) was aimed at increasing access by the local population to short-term employment in targeted food-insecure areas. The project was also aimed at restoring access to social and economic services following natural disasters in target communities. However, the financing of projects, as well as their implementation, within the country is still problematic (e.g. funding from national to local level, corruption, lack of knowledge, etc.) (Heidhues *et al.*, 2004).

To overcome the malnutrition issues, one potentially reliable approach may be the diversification of the principle staple food in Madagascar, introducing maize crop. This approach has many potential benefits, including the cultivation of rainfed crops in a water-limited environment and the increase of agronomic experiences of farmers. Additionally, introducing diversification would avoid the problems linked with the Malagasy system of rice' collectors that lead to the resultant negative consequence of selling crops at reduced food prices. This method was tested in Madagascar in an eight-year program focused on maize production (National Maize Project; ADF, 2004), and the results indicated an increase in maize cultivation in the following years. Consequently, maize has become the second principle crop grown in Madagascar. Between 2011 and 2015, average annual production was approximately 400,000 tonnes (FAO, 2016), with a yield increase of 2 % per year (Ray *et al.*, 2013). Moreover, this maize production increase has led to a change in the Malagasy diet, providing a staple food with not only nutritional benefits, but also functional benefits. Functional components in maize include inulin, beta-glucan, resistant starch, carotenoids, proteins, phenolic compounds, tocotrienols, and tocopherols (Borneo & León, 2012), widely recognised as essential for human health (Liu, 2007; Lopez-Martinez *et al.*, 2008; Zilić *et al.* 2012; Doria *et al.*, 2015).

Despite the observed growth in maize production, further increases are imperative in order to meet national food demand. This is potentially achievable by improving the key agronomic drivers: soil, climate, and management (Calviño *et al.*, 2003; Vanlauwe *et al.*, 2010). Whilst the first two components cannot be either rapidly changed (e.g. soil properties) or modified (e.g. solar radiation), changes in management can modify final production by partly compensating for the possible lack of nutrients or water supply through practices such as fertilisation, weed removal, and irrigation. However, these management practices are not easily applied in Madagascar, because of the excessive costs for local smallholders (Abadassi, 2013). In addition, the high prices for agricultural inputs, such as fertilisers and plant protection products, also considering their scarcity in the market, lead to the need to develop alternative approaches. To this end, a simple and straightforward approach for increasing the level of production and reducing expensive investments may reside in the detection of best-yield genotypes. This relatively inexpensive approach may permit the identification of genotypes that are better adapted to specific local soil and climate conditions, thereby reducing the risk factors affecting final yield.

Hence, the present study was focused on assessing both the qualitative and productive characteristics of 24 maize genotypes cultivated in marginal and unexploited soils in Madagascar. The objective was to evaluate the advantages and drawbacks in cultivating both high yielding and the only local variety available on the market as well as in providing recommendations to farmers for the development of future sustainable, low-cost cropping systems.

2 Materials and methods

2.1 Study area

The test sites, namely Andiolava (Lat. 22° 29′ 40.97″ S; Long. 45° 38′ 45.73″ E) and Satrokala (Lat. 22° 19′ 49.24″ S; Long. 45° 43′ 4.23″ E), are located on the Plateaux de l'Horombe in the southern part of Madagascar.

This area has a sub-arid climate characterised by two well-distinguished seasons: the wet season from November to March and the dry season from April to October. Total annual rainfall during the maize growing season (October 2012–April 2013) was 798.7 mm, highly representative of the annual average (856 mm) during the growing season over a long-term period (1997–2012), as calculated by the local weather station (Ranohira village). No rainfall was observed during the remainder of the year.

Monthly maximum and minimum air temperatures were recorded as 30.4 °C (December) and 12.9 °C (July) for summer and winter, respectively. Air humidity was approximately 80 % throughout the year. Solar radiation followed rainfall and temperature patterns, with maximum and minimum values occurring during winter and summer, respectively.

Soil characteristics exhibited marked differences between sites (Table 1). Soils in Andiolava were of a sandy-clay-loamy texture with a pH of 5.8, organic matter content of 1.33 %, and a cation exchangeable capacity of 3.40 meq/100 g. In contrast, Satrokala was characterised by soils of a sandy-clay texture with a pH of 4.8, organic matter content of 0.89 %, and a cation exchangeable capacity of 3.34 meq/100 g. The principal chemical soil properties (i.e. pH, electrical conductivity (EC), soil organic matter (SOM), available-P, cation exchange capacity (CEC), and basic saturation) were obtained using the method proposed by Jackson (1958) while the physical properties of soils were determined following the methodology proposed by Wilke (2005). All these analyses were performed at the University of Florence (Italy).

Table 1: *Soil characterisation of the two experimental sites.*

Data	*Satrokala*	*Andiolava*
Sand (2–0.05 mm) (%)	45.2	62.4
Loam (0.05–0.002 mm) (%)	9.8	9.0
Clay (< 0.002 mm) (%)	45.0	28.6
Fine sand (0.05–0.10 mm) (%)	3.1	3.8
USDA class *	SC	SCL
pH	4.8	5.8
EC (Aqueous extraction 2:1) (dS/m)	0.023	0.027
Organic matter (%)	0.89	1.33
P Olsen (P_2O_5) (ppm)	7	1
Cation exchange capacity pH 7 (meq/100 g)	3.34	3.40
Ca exchangeable (ppm)	140	260
Mg exchangeable (ppm)	28	68
Na exchangeable (ppm)	21	23
K exchangeable (ppm)	31	106
Basic saturation (%)	32.9	65.9

* SC = Sandy Clay, SCL = Sandy Clay Loam.

2.2 *Experimental design and data collection*

Quantitative and qualitative measurements were conducted on 24 maize genotypes (one local variety and 23 hybrids) with different physiological characteristics (i.e. length of cycle, plant height, plant earliness, and seed quality). Some of these characteristics are presented in column 1, 2, 3 and 4 of Table 2. The chosen crop parameters reflected those reported previously in similar experiments (Bosede *et al.*, 2014; Calamai *et al.*, 2018), with the objective of identifying ‘easy-to-measure’ parameters suitable for screening adaptability between cultivars. Existing knowledge was available regarding the physiological differences among commercial varieties, whilst no information was available for the local variety. For the hybrids, maize seeds were provided by KWS Italia Spa and Caussade Semences Italia Srl. The variety used by locals has not yet been registered, and will be referred to as the local variety from here onward.

The maize genotypes were selected mostly on the bases of the FAO classes to have a wide panorama in terms of cycle length and once they were selected, the experimental design was implemented in the form of a completely randomised block design with 4 replicates (96 plots) in each site (192 total plots). Each plot was 24 m^2 (6 × 4 m) with a planting density of 7.1 plant m^{-2} (70 cm × 20 cm). During the study period, sites were ploughed twice at different depths. The first ploughing took place at the beginning of the rainy season (November 2012) using a spike-tooth harrow (30–35 cm depth), and the second occurred prior to sowing (i.e. the first week of December) using a disc harrow (10 cm depth). Fertiliser was applied at two points during the growing cycle. The first application was at sowing and the second in January, in which 500 kg ha^{-1} of NPK (12 : 18 : 20) and 100 kg ha^{-1} of urea (46 %) were applied, respectively. Using the unique locally available fertilisers, the fertilisation rate was considered sufficient for preventing nutrient limitation during the growing season. Two types of data (morphological and productive) were obtained during the entire growing cycle. Data were collected at two times during crop growth from five plants per plot and included plant height (cm), plant fresh weight (g), plant dry weight (g), number of leaves per plant (*n*), and leaf chlorophyll concentration (SPAD). Harvest time was identified when the grain water content in 10 harvested selected plants per plot was lower than 13 % (corresponding to 126 and 143 days after sowing in Satrokala and Andiolava study sites, respectively). Additionally, on the 10 selected plants the following data was collected: ear diameter (mm), ear length (mm), ear rows (*n*), number of kernels per ear (*n*), and kernel weight per spike (g). Finally, the total grain yield and total biomass for each plot were calculated adding to the final harvest data to the previous grain harvested along the experiment.

2.3 *Grain quality parameters assessment*

The analysis of secondary metabolite content and antioxidant activity were performed in the laboratory. The extraction of soluble (free) and insoluble (bound) phenolic compounds followed the methodology as reported in Sofi *et al.* (2013). Total polyphenol content in the free and bound fractions was measured using a modification of the spectrophotometric Folin-Ciocalteu method (Singleton *et al.*, 1999) using Folin-Denis reagent. The radical scavenging activity of antioxidant active substances in the extract was determined according to the spectrophotometric method of Brand-Williams *et al.* (1995). The objective of the present experiment was to assess the concentration of sample required to reduce the efficient concentration (EC) of the stable radical (0,005 % radical 2,2-diphenyl-1-picrylhydrazyl [DPPH]) used in the survey by half (EC50). For each sample, the EC was calculated using a calibration curve using linear regression. The higher the EC50, the less efficient the antioxidant activity of the sample (Sofi *et al.*, 2013). Finally, antiradical power (ARP) was calculated as the reciprocal of EC50 (ARP = 1/EC50), with higher ARP values representing a higher antiradical activity of the respective samples. Grain protein was determined using the Kjeldahl procedure (N * 6.25) (American Association of Cereal Chemists, method 46-12) (AACC, 1995).

Table 2: *Principle vegetative and productive parameters of the 24 maize genotypes. Columns 3 and 4 present the breeding and FAO classes of maize (i.e. the number of days characterising the length of the growing cycle of each maize variety. Depending on the length of growing cycle, each variety was assigned to a class indicated by a number which ranged from 100 (i.e. the shortest growing cycle varieties) to 800 (i.e. the longest growing cycle varieties).*

Genotype	*Company*	*Breeding class*	*FAO class*	*Plant height (cm)*	*Ear diameter (mm)*
Yogi	Caussade	Hybrid	200	65^{g}	34^{bc}
Venici	Caussade	Hybrid	600	101^{cf}	37^{bc}
Joliet	Caussade	Hybrid	300	102^{cf}	29^{bc}
Frontal	Caussade	Hybrid	700	112^{bd}	34^{bc}
Coretta	Caussade	Hybrid	600	125^{ab}	39^{b}
Luigi	Caussade	Hybrid	200	87^{eg}	32^{bc}
Korneli	Caussade	Hybrid	200	80^{fg}	32^{bc}
Gerzi	Caussade	Hybrid	400	108^{be}	31^{bc}
Puccini	Caussade	Hybrid	400	107^{be}	37^{bc}
Gasti	Caussade	Hybrid	500	114^{bd}	25^{c}
Biriati	Caussade	Hybrid	200	91^{df}	29^{bc}
Clariti	Caussade	Hybrid	300	95^{df}	27^{bc}
Drasti	Caussade	Hybrid	400	119^{ac}	31^{bc}
Maggi	Caussade	Hybrid	400	115^{bd}	38^{b}
Eufori	Caussade	Hybrid	400	98^{cf}	34^{bc}
Vivani	Caussade	Hybrid	600	103^{bf}	35^{bc}
Krebs	KWS	Hybrid	400	96^{cf}	39^{bc}
Kalumet	KWS	Hybrid	700	103^{be}	33^{bc}
Korreos	KWS	Hybrid	500	104^{be}	34^{bc}
Kursus	KWS	Hybrid	400	102^{cf}	36^{bc}
Korimbos	KWS	Hybrid	500	105^{be}	33^{bc}
Konsens	KWS	Hybrid	600	113^{bd}	38^{bc}
Alabastro	KWS	Hybrid	300	104^{be}	28^{bc}
local	Ihosy Market	Variety	unknown	143^{a}	55^{a}
Average	–	–	–	103.8	34
sd	–	–	–	4.7	2.6

Means followed by a different letter within the same column are significantly different ($p < 0.05$).

2.4 Statistical analysis

Differences in plant biomass, production, and grain quality parameters were assessed through analysis of variance (ANOVA). Prior to being subjected to ANOVA, the data were tested for normality and homoscedasticity according to the complete randomised block experimental design. Multiple comparisons were performed using a post-hoc Tukey test. All statistical analyses were performed using IBM SPSS Statistics 25 software.

3 Results

3.1 Environmental and genetic effects on plant biomass and production data

When considering the effects attributable to the genetic component, significant differences were observed between the 24 cultivars investigated (i.e. both plant biomass and production data). This was particularly evident for the three most important and representative data, namely: plant height (cm), ear diameter and length (mm), and final yield (Table 2). The local variety exhibited the highest plant height (143 cm) and ear diameter (55.3 mm), but the lowest yield (0.9 t ha^{-1}). The most productive hybrids were Gasti (3.35 t ha^{-1}), followed by Maggi (3.10 t ha^{-1}), Joliet (3.06 t ha^{-1}), and Drasti (3.1 t ha^{-1}). After the local variety the lowest yields were recorded for Biriati (1.58 t ha^{-1}), Yogi (1.74 t ha^{-1}), Kalumet (1.82 t ha^{-1}), and Clariti (1.87 t ha^{-1}). All remaining yields ranged between 2 to 3 t ha^{-1}. The effects attributable to the cultivation site (environment) were significant, with the only exceptions being fresh weight and ear diameter (Table 3). Notably, the morphological and productive variables were significantly lower at Satrokala than at Andiolava.

The combined effect of genotype and environment (genotype-environmental interactions) clearly indicated significant differences between Andiolava and Satrokala (Fig. 1). At Andiolava, the average yield of the 24 varieties was 3.6 t ha^{-1}. Relative to the average production of the site, 12 varieties were found to have an above-average yield, with

Table 3: *Morphological and productive parameters and the relative difference between the Zea mays samples harvested at the two environmentally distinct sites: Andiolava and Satrokala.*

	Site		
Morphological and productive data	*Andiolava*	*Satrokala*	Δ %
Plant height (cm)	125.1 ^{a}	83.5 ^{b}	−33.3
Plant fresh weight (g)	149.2 ^{a}	49.4 ^{a}	0.1
Plant dry weight (g)	122.0 ^{a}	55.4 ^{b}	−54.6
Number of leaves (*n*)	9.8 ^{a}	7.7 ^{b}	−21.4
Soil Plant Analysis Develop. Chlorophyll Meter	50.5 ^{a}	49 ^{b}	−3
Total biomass weight per plot (kg DM)	21.4 ^{a}	18.8 ^{b}	−12.1
Ear diameter (mm)	35.1 ^{a}	34.2 ^{a}	−2.8
Ear length (mm)	128 ^{a}	97.4 ^{b}	−23.9
Kernels/ear (*n*)	299.8 ^{a}	130.9 ^{b}	−56.3
Ears row (*n*)	13.7 ^{a}	10.4 ^{b}	−24.1
Ear weight (g DM)	74.8 ^{a}	30.4 ^{b}	−59.4
Kernel weight/plot (g DM)	8594.2 ^{a}	2985.8 ^{b}	−65.3
Total biomass (t DM ha^{-1})	9.0 ^{a}	7.8 ^{b}	−12.2
Grain yield (t DM ha^{-1})	3.6 ^{a}	1.2 ^{b}	−66.7

Means followed by a different letter within the same column are significantly different ($p < 0.05$).

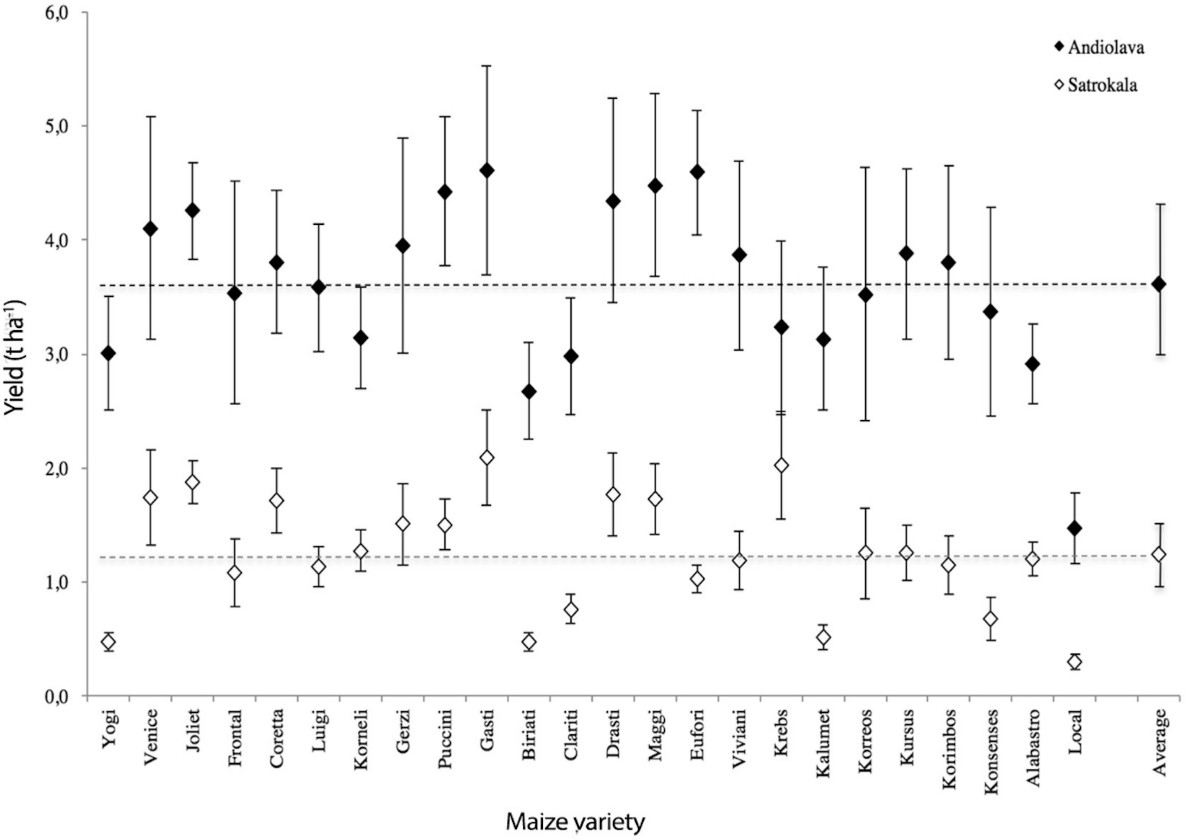

Fig. 1: *Maize grain yield (t ha^{-1}) of the 24 genotypes at Andiolava and Satrokala study sites. Vertical bars represent the mean standard error*

Table 4: *Protein (mg g^{-1} DM), polyphenol content (mg g^{-1} DM), and antiradical power (ARP) according to genotype and location (S. = Satrokala, A. = Andiolava).*

	Proteins			*Free polyphenols*			*Bound polyphenols*			*Total polyphenols*			*Free ARP*			*Bound ARP*			*Total ARP*		
Genotype	*S.*	*A.*	*Average*	*S.*	*A.*	*Average*	*S.*	*A.*	*Average*	*S.*	*A.*	*Average*	*S.*	*A.*	*Average*	*S.*	*A.*	*Average*	*S.*	*A.*	*Average*
Yogi	9.0	9.1	9.0^{ac}	1.4	1.2	1.3^{cc}	3.3	2.2	2.7	4.6	3.4	4.0	6.4	5.5	5.9^{bc}	8.8	13.6	11.2	15.2	19.1	17.2
Venici	6.4	6.6	6.5^{l}	1.5	1.2	1.3^{bc}	4.0	2.5	3.3	5.5	3.7	4.6	6.5	5.7	6.1^{ac}	9.4	15.0	12.2	15.9	20.7	18.3
Joliet	7.2	7.2	7.2^{el}	2.0	1.7	1.8^{ab}	3.6	2.9	3.2	5.5	4.6	5.1	8.2	8.7	8.4^{a}	9.3	17.8	13.5	17.5	26.4	22.0
Frontal	7.1	7.3	7.2^{fl}	1.9	1.7	1.8^{ac}	3.9	2.6	3.2	5.8	4.3	5.0	7.6	6.8	7.2^{ac}	9.7	14.4	12.1	17.4	21.2	19.3
Coretta	6.9	7.0	6.9^{hl}	1.6	1.3	1.5^{ac}	3.9	2.7	3.3	5.5	4.0	4.8	6.7	6.4	6.6^{ac}	10.5	15.6	13.0	17.2	22.0	19.6
Luigi	8.3	8.4	8.3^{af}	1.5	1.5	1.5^{bc}	4.4	2.4	3.4	5.9	3.9	4.9	6.4	5.5	6.0^{bc}	11.1	14.5	12.8	17.5	20.0	18.8
Korneli	7.8	7.9	7.9^{ci}	1.3	1.3	1.3^{c}	3.5	2.5	3.0	4.8	3.8	4.3	6.4	6.2	6.2^{ac}	7.9	15.6	11.7	14.3	21.7	18.0
Gerzi	7.5	7.6	7.5^{el}	1.6	1.4	1.5^{bc}	3.9	2.8	3.3	5.5	4.2	4.8	7.4	7.1	7.2^{ac}	9.1	15.6	12.4	16.5	22.7	19.6
Puccini	7.7	7.8	7.7^{dl}	1.4	1.3	1.3^{bc}	3.7	2.8	3.3	5.1	4.1	4.6	5.9	5.5	5.7^{bc}	11.2	17.4	14.3	17.1	22.9	20.0
Gasti	7.3	7.4	7.3^{el}	1.6	1.2	1.4^{bc}	4.3	2.8	3.6	5.9	4.0	5.0	4.8	5.7	5.27^{c}	10.8	15.0	12.9	15.6	20.7	18.2
Biriati	8.6	9.2	8.9^{ad}	1.3	1.6	1.4^{bc}	4.4	2.4	3.4	5.7	4.0	4.8	5.3	7.6	6.4^{ac}	11.4	14.9	13.1	16.7	22.5	19.6
Clariti	8.4	8.5	8.5^{ae}	2.1	2.0	2.1^{a}	3.9	2.9	3.4	6.1	4.9	5.5	8.8	7.1	8.0^{ab}	10.1	14.4	12.3	19.0	21.5	20.2
Drasti	7.5	7.6	7.6^{el}	1.5	1.4	1.4^{bc}	3.7	2.8	3.2	5.2	4.2	4.7	6.7	6.0	6.4^{ac}	9.8	13.6	11.7	16.5	19.6	18.1
Maggi	9.0	7.2	8.1^{bh}	2.0	1.4	1.7^{ac}	4.0	2.6	3.3	6.0	4.0	5.0	6.8	6.3	6.6^{ac}	8.8	11.8	10.3	15.6	18.1	16.8
Eufori	7.1	7.2	7.2^{fl}	1.4	1.4	1.4^{bc}	3.8	3.1	3.4	5.2	4.5	4.9	6.1	6.9	6.5^{ac}	9.3	17.7	13.5	15.4	24.5	20.0
Vivani	7.0	7.1	7.1^{gl}	1.3	1.5	1.4^{bc}	3.9	3.0	3.5	5.3	4.5	4.9	7.0	6.9	7.0^{ac}	11.7	16.3	14.0	18.7	23.2	21.0
Krebs	6.7	6.8	6.8^{il}	1.6	1.6	1.6^{ac}	2.1	2.3	2.2	3.7	3.9	3.8	6.4	6.5	6.4^{ac}	13.9	13.9	13.9	20.3	20.4	20.3
Kalumet	7.6	7.8	7.7^{dl}	1.6	1.2	1.4^{bc}	2.6	2.4	2.5	4.2	3.6	3.9	5.8	5.2	5.5^{bc}	13.6	12.9	13.3	19.5	18.1	18.8
Korreos	8.1	8.3	8.2^{ag}	1.8	1.7	1.8^{ac}	2.6	3.1	2.8	4.3	4.8	4.6	6.4	6.5	6.4^{ac}	13.8	15.4	14.6	20.2	21.9	21.0
Kursus	7.9	8.0	7.9^{bi}	1.6	1.5	1.5^{ac}	1.9	2.1	2.0	3.5	3.5	3.5	6.2	5.9	6.1^{ac}	12.3	12.7	12.5	18.6	18.6	18.6
Korimbos	6.8	6.9	6.8^{il}	1.7	1.4	1.5^{ac}	2.6	2.7	2.7	4.3	4.1	4.2	6.3	5.7	6.0^{ac}	17.2	15.9	16.5	23.5	21.6	22.5
Konsens	6.8	6.9	6.8^{hl}	1.9	1.6	1.7^{ac}	2.6	2.9	2.8	4.5	4.5	4.5	7.7	6.9	7.3^{ac}	14.7	15.6	15.2	22.4	22.5	22.4
Alabastro	9.1	9.2	9.1^{ab}	1.7	1.6	1.7^{ac}	2.1	2.5	2.3	3.8	4.1	3.9	8.3	6.6	7.5^{ac}	13.1	12.5	12.8	21.5	19.2	20.3
local	9.4	9.3	9.34^{a}	1.4	1.4	1.4^{bc}	2.4	2.5	2.4	3.8	3.9	3.8	5.9	5.0	5.47^{c}	14.2	14.3	14.3	20.1	19.3	19.7
Average	7.7^{a}	7.8^{a}	7.7	1.6^{a}	1.5^{b}	1.5	3.4^{a}	2.6^{b}	3.0	4.9^{a}	4.1^{b}	4.5	6.7^{a}	6.3^{a}	6.5	11.3	14.8	13.1	18.0^{b}	21.2^{a}	19.6
sd	0.8	0.8	0.8	0.2	0.2	0.2	0.8	0.3	0.4	0.8	0.4	0.5	0.9	0.8	0.8	2.3	1.5	1.3	2.3	2.0	1.5

Means followed by different letters within the same column are significantly different ($p < 0.05$).

nine being below average, while the remaining three were consistent with the average value.

At Satrokala, the average yield of the 24 varieties was 1.2 t ha^{-1}. Only nine varieties were observed to have an above-average yield, whilst eight exhibited below-average yield, and the remaining seven were consistent with the average value.

By comparing the varieties per site, Gasti exhibited the highest yield performance at both sites but produced double the yield at Andiolava compared to Satrokala (4.6 t ha^{-1} and 2.1 t ha^{-1}, respectively). The local variety exhibited the lowest yield performance at both sites, with very low yields at Satrokala (0.3 t ha^{-1}), and significantly higher yields at Andiolava (1.5 t ha^{-1}). The Eufori variety exhibited a very contrasting pattern, being the second most productive at Andiolava (4.6 t ha^{-1}) and the least productive at Satrokala (1.0 t ha^{-1}). A similar trend was also reported for the Puccini variety, which exhibited a final yield of 4.4 t ha^{-1} at Andiolava but was much lower (1.5 t ha^{-1}) at Satrokala. The Krebs variety was one of the most productive at Satrokala (2.0 t ha^{-1}), whilst the yield at Andiolava was below average. The varieties Joliet, Venici, Coretta, Yogi, Frontal, Biriati, Clariti, and Kalumet exhibited the same pattern between the two sites, but had higher global yields at Andiolava in comparison to Satrokala.

3.2 Grain quality parameters

Maize quality was assessed by analysing the amount of polyphenols, the related antiradical power (ARP), and the protein content. Polyphenol content and ARP were expressed as free, bound, and total (Table 4).

Total polyphenol content varied between the test sites, with Satrokala exhibiting higher values than Andiolava (Table 4). The Clariti variety exhibited the highest total polyphenol content at both sites. In contrast, the lowest total polyphenol content was observed in both the Kursus and Yogi varieties at Satrokala and Andiolava, respectively. Based on the comparison of total polyphenol content within the KWS hybrids (Krebs, Kalumet, Korreos, Korimbos, Konsens, and Alabastro) cultivated at both sites, average values were not significantly different (i.e. 4.0 mg g^{-1} DM).

Average total ARP values at Satrokala and Andiolava were 18.0 and 21.2, respectively. At Satrokala, the Korimbos variety exhibited the highest value, whilst Korneli exhibited the lowest. At Andiolava, the Joliet and Maggi varieties exhibited the highest and lowest total ARP, at 26.4 and 18.1 mg g^{-1} DM, respectively. Total ARP in the KWS hybrids exhibited the same stability observed for total polyphenolic content, with no significant differences in both areas and average values for approximately 20 mg g^{-1} DM.

The fraction of free ARP was stable in both areas. In contrast, the fraction of bound ARP was lower in Satrokala than in Andiolava.

Moreover, no significant differences were observed for protein content between the sites (Table 4). The highest content was observed for the local variety (8.3 %), followed by Yogi, Biriati, and Alabastro, respectively. All of these varieties attained a protein content corresponding to 8 % of total dry weight; the lowest content was observed in Venici (5.8 %). Maggi showed contrasting results, with a higher protein content in Satrokala (9.0 %) compared to that in Andiolava (7.2 %).

4 Discussion

The attainment of sufficient maize production over the unexploited areas and marginal soils of Madagascar remains a challenge. In the present investigation, a key factor was differences in soil properties between the test sites. The highest yields, found at Andiolava, were shown to reflect the higher soil organic matter content and pH compared to Satrokala. It is widely accepted that the aforementioned soil properties are the most prominent in determining yield (Johnston *et al.*, 2009; Marenya & Barrett, 2009; Matsumoto & Yamano, 2009).

To our knowledge, the present study is one of the first of its kind to be conducted in Madagascar, and raises interesting aspects related to crop yields and food security.

Firstly, the maize hybrids exhibited higher yields compared to the local variety. This suggests that it is necessary to use only the most productive hybrids in order to meet local demand. Indeed, despite hybrids may require higher initial costs for local farmers (i.e. seed costs), their adoption would result at the end more convenient compared to that of local varieties which, by contrast, require more hectares and agronomical inputs to reach the same final production.

In contrast, despite low yield performances, the local variety was found to be close to the national average (i.e. 1.7 t ha^{-1}; FAOSTAT, 2014). This suggests that additional local varieties should be tested in order to find the optimal yield performance variety for cultivation under low-cost farming systems. This may provide beneficial solutions pertaining to cost, since the self-production of seeds would reduce the local market costs for seeds.

Furthermore, the present study also suggests the possibility of transferring the acquired knowledge to improving techniques to enhance not only grain yield but also biomass yield for livestock use. The area where trials were performed is well known for zebù cattle breeding on scarce natural pastures, where maize cultivation is limited to small fields during the rainy season with uncertain and limited production. In this context, due to common harvesting practices performed when the plant is still green, increasing the use of the local variety – which has a high green biomass weight – might represent a source of fodder for local zebù breeders. Although the hybrids produced higher grain yields, it is not advisable to extend these to local farmers. Reasons for this include a minimal level of mechanisation and reduced availability of fertilisers among this group.

From this study, at least three main points emerged that should be carefully addressed. Firstly, the impact of growing cycle length may help local farmers to choose the most appropriate variety. The choice of the most appropriate variety adapted to a specific area may reduce problems related to reduced yields. The yields of hybrids were affected by growing cycle length, as previously reported (Pampana *et al.*, 2009; Opsi *et al.*, 2012; Tesio *et al.* 2014; Oluwaranti *et al.*, 2015). The most productive hybrids at both sites were those characterised by an intermediate growing cycle (Gasti, Maggi, Joliet, and Drasti), whilst those characterised by either shorter or longer growing cycles exhibited the low performance. Hybrids with the shorter growing cycles can more easily avoid problems of drought due to a shorter and faster grain-filling period (Debaeke, 2004; Huang *et al.*, 2006) which, however, does not generally lead to high production On the contrary, late genotypes (i.e. FAO 700) may have encountered abiotic stresses (e.g. reduced water and nutrient supply) during the grain-filling period, which may have reduced their maximum potential production.

Secondly, polyphenol content was observed to be comparable to that found in other staple food such as wheat, barley, oats, and rice (Velioglu *et al.*, 1998; Zielinski & Kozlowska, 2000; Adom & Liu, 2002; Asami *et al.*, 2003). Moreover, ARP (Miller *et al.*, 2000; Adom & Liu, 2002; Bryngelsson *et al.*, 2002) and protein content (7.74 %) (Bressani 1991; Koehler & Wieser, 2013; Enysi *et al.*, 2014; Doria *et al.*, 2015) values were comparable with those found in other staple crops. These trends suggest that maize may represents a suitable alternative staple food crop that can be used to provide sufficient levels of functional compounds in undernourished areas where the water availability for rice cropping is lacking.

Finally, many of the varieties in the present investigation exhibited yields close to the average reported for Southern African regions (Smale *et al.* 2011; Kassie *et al.* 2012). However, the present study highlighted the optimal combination between nutritional/functional aspects and yield. The varieties best suited to Andiolava and Satrokala are Maggi and Alabastro, respectively. Notably, the varieties Luigi and Korreos are suitable for both sites, which represent information relevant both for the extension services and for local farmers.

5 Conclusions

In countries characterised by food shortages, such as Madagascar, the detection and subsequent cultivation of the best-yielding maize genotype may be the most suitable approach to increasing yield under conditions of limited agronomic practices (e.g. reduced mechanisation, narrow fertiliser availability). The results of the present study highlighted several important aspects. Firstly, growing cycle length and soil properties are key factors for attaining optimal maize yields also in unexploited virgin soils. Secondly, in dry areas maize should be considered as a very reliable alternative staple food to rice, as it can guarantee a suitable grain yield and provide a good level of functional compounds for human health. Thirdly, the highest yield, protein content, total polyphenols, and ARP values were observed in the varieties Gasti, Local, Clariti, and Korimbos, respectively. A good compromise between yield and functional compounds can be obtained using the hybrids Maggi and Gasti. Regarding the use of the local variety, despite a limited grain yield compared to other hybrids, the use of this variety is warranted due to its potential use as forage or for seed production to ensure seed security for the following years avoiding to buy expensive seeds from seed companies.

Based on the results obtained in the present study, an expanded cultivation of maize over Madagascar may provide benefits in terms of food security and functional compounds for locals without the risk of land competition with rice due to the lower water demand of maize. As such, these findings may be considered a first step towards improving maize cultivation in the marginal uplands of southern Madagascar as a means to cope with food shortage. However, since the experimental soils exhibited low fertility, the cultivation of the main staple crops, such as maize, could be implemented only within an appropriate crop rotation that should include legumes. Further experiments are thus required to fill the knowledge gap related to maize performance in this area under different soil, cultural and management conditions.

Competing interests

The authors declare that they have no conflict of interest.

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