Effects of Genotype, Environment and Management on Yields and Quality of Black Tea

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Abstract The tea beverages processed from the young tender shoots of *Camellia sinensis* (L.) O. Kuntze, are claimed to be the most widely consumed fluids after water. The tea plant originates from the point of confluence of Northeast India, North Burma, Southwest China and Tibet. Its production has spread and economic production has been reported in between 49°N in Outer Carpathians to 33°S in Natal, South Africa, at altitudes ranging from sea level to 2,700 m above mean sea level. The adaptability of the plant to areas with large variations in geographical, climatic and environmental factors can cause changes in growth patterns in different genotypes leading to variations in yields and black tea quality. Tea producers usually import genotypes, management and production techniques suitable for optimal production in one region in the hope that beneficial attributes observed at source shall be maintained in the new areas. But the tea plant responses in new environments have not always yielded the desired results. Here we review the effects of genotypes, environment and management on the yields and quality of black tea.

Previous investigations demonstrated that black tea yields and quality changes are due to environmental factors like soil type, altitude, seasons, weather factors,

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geographical areas of production, agronomic inputs, processing technologies and management. Black tea quality and yields of similar genotypes grown on different soils vary. The extent and patterns of the variations change with varieties. High altitude grown teas are more aromatic than low altitude grown black teas, implying that the low grown teas are plain in character. Thus producers at high altitudes should aim at producing aromatic black teas, although yields will be lower than same genotypes at lower altitudes. Producers growing teas at low altitudes should focus on high output and ensure optimal conditions for production of plain black teas. There are seasonal black tea quality and yield variations. Cold seasons lead to slow growth resulting in low yields, but high black tea quality. Provided soil moisture and temperatures are adequate, warm temperatures lead to fast growth, leading in turn to high yields, but low black tea quality. It is therefore not possible to have uniform production or to produce the same black tea quality throughout the year. The situation is adverse further away from the equator with no production in winter as the labour management can be critical during the long cold seasons, necessitating long labour layoffs. Many genotypes have been developed, some with very high yields and quality. As a result, producers continuously try to access the good varieties into new geographical areas in the hope the genotypes would retain their economic advantages. While some genotypes are stable to locational changes, most show wide variations due to planting in the new areas.

Management policies induce yield and black tea quality differences. Imported management policies should be domesticated and modified to suit the new environments. Harvesting, by hand plucking, the young tender shoots is done when they are of the right size. Delayed harvesting leads to shoot overgrowth and crop loss. Whereas plucking two leaves and a bud is a compromise between yields and black tea quality, some growers practice coarser plucking standards. Black tea quality declines with coarse plucking standards. Short plucking rounds lead to high production and high quality black teas. When a plucking standard is preset, growers in a location need to establish the shortest harvesting interval for realization of good yields and quality. Fertilizers are essential for establishment and growth. Varying results have been recorded on yield and quality responses to NPK application. For potassium and phosphorus, evaluations are necessary in different regions because where there is no beneficial effects their application can be reduced to decrease costs. High rates of nitrogen reduce black tea quality and do not increase yields. Nitrogen fertilizers need to be applied at rates that are a compromise between yields and black tea quality. Such rates vary with regions and genotypes. To reach high production and quality, region- and genotype-specific fertilizer rates are needed.

In regions producing relatively inferior black teas producers try to import processing technologies from other areas. These efforts may not improve quality due to variations of environmental conditions. Indeed, for the same genotype grown in different regions and processed under identical conditions, differences in quality and chemical composition have been reported. This was due to variations in the leaf biochemical constituents composition caused by the environment in which the plant was grown. Different regions must therefore optimize their processing conditions to realize high quality.

Keywords Black tea • *Camellia sinensis* • Environment • Genotypes • Cultural and agronomic practices • Yields • Quality

1 Introduction

Tea (*Camellia sinensis* (L.) O. Kuntze) is believed to have originated in Southeast Asia around the intersection of altitude 29°N and longitude 98°E, the point of confluence of the lands of Northeast India, North Burma, Southwest China and Tibet (Mondal 2007). The perennial tree crop is now grown in many parts of the world for production of various tea beverages which are the most widely consumed fluids after water. Commercially, three varieties of tea: – the China type (*Camellia sinensis* var. *sinensis*), the Assam type (*Camellia sinensis* var. *assamica*) and the hybrid (*Camellia sinensis* var. *assamica* ssp *lasiocalyx*) are extensively exploited (Banerjee 1992). However recently, two new varieties, *Camellia sinensis* var. *pubilimba*, and *Camellia sinensis* var. *Kucha* have been recognized to have commercial potential in China (Yao et al. 2008). The China type consists of small semi-erect leaves, while, the Assam types has relatively larger horizontally held leaves and the hybrid type has characteristics in between the China and Assam types (Banerjee 1992). If left to grow freely, the plant can grow to over 30 m (Fig. 1). The classification of tea beverages is based on the processing methods. Black tea is prepared by biochemical oxidation (or fermentation) of crushed fresh tender leaves, involving multi-step enzyme-mediated oxidation of polyphenols that is terminated by firing (drying); while green tea is prepared by steaming withered or unwithered leaves to inactivate oxidative enzymes, prior to crushing before drying. Processing conditions for oolong are intermediate between black and green teas, whereby, in oolong tea macerated leaves undergo short fermentation durations.

Tea is an important economic crop grown in many countries for production of various tea beverages. As at the year 2008, the ten leading world tea producers were India, China, Kenya, Sri Lanka, Turkey, Indonesia, Japan, Iran and Argentina (Anon 2008). In Africa, tea is mainly grown in Kenya, Malawi, Uganda, Tanzania, Zimbabwe, Rwanda, South Africa, Burundi and Mauritius, although some tea is also grown in Ethiopia, Nigeria and Cameroon. Tea is a major economic crop for some developing countries. In Kenya, for example, tea is a key player within the agro-industrial crops and is the single commodity leading foreign exchange earner accounting for about 26% of the total export earnings and 4% of the gross domestic product (GDP), and is a source of livelihood to over 3 million people (Mbadi and Owuor 2008). Over 62% of the Kenya tea is produced by the smallholder growers, living in the rural set ups where industrialisation is low and economic activities are rare. The crop is viewed as a source of rural development in many developing countries.

Being an antioxidant, tea has been reported to have ability to manage several diseases including colon, oesophageal, and lung cancer, urinary stone, dental caries, etc (Sharma et al. 2007). For black tea, there is clear evidence that intake of ≥3 cups per day reduces the risk of coronary heart disease (Gardner et al. 2007). It has been

Fig. 1 Tea plants left to grow in a seed barie

claimed that tea beverages are the most widely consumed fluids after water (Agarwal 1989; Sharma et al. 2007). World tea production has grown rapidly, causing over supply of the commodity, resulting in stagnation or reduction in prices (Anon 2008). As a result tea growers strive to improve productivity and profits through optimising agronomic in-puts and cultural practices to realise highest production per unit area and best quality at the lowest cost of production. Tea yields are controlled by yield components which include; harvestable shoot size, number of shoots per unit area and rate of shoot growth (Odhiambo 1989; Mathews and Stephens 1998a). The expressions of these components are controlled by environments, management practices and the genotype. Similarly, black tea quality is influenced by agronomic in puts (Ravichandran 2004) and cultural practices (Cloughley 1983; Owuor and Othieno 1991).

As a results of high demand, commercial production has been reported under diverse environments from as 49°N, Outer Carpathians, to 33°S, Natal, South Africa (Shoubo 1989), and from altitudes ranging from sea level in Japan and Sri Lanka (Anandacoomaraswamy et al. 2000) to 2,700 m above mean sea level (amsl) in Kenya and Rwanda (Owuor et al. 2008b) and under varying topographies (See Fig. 2). The plant is adaptable to environments with large climatic variations. The variations in the environment and growing conditions can cause large differences in yields and black tea quality. But despite the variations, tea farmers usually import genetic materials and production technologies across the borders. In countries where tea plant growth parameters are different, usually experimental testing for genetic materials or production technologies are centralised. It is usually assumed the genotype with good yield and/or quality attributes or a successful pro-

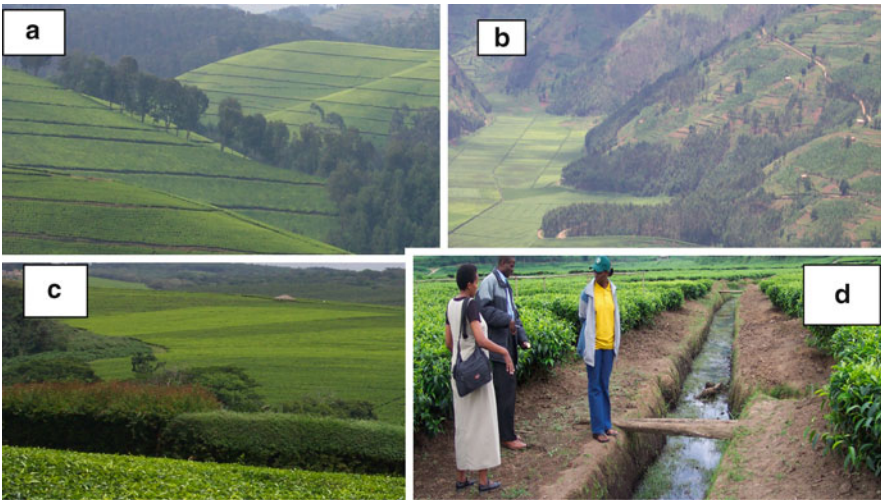

Fig. 2 Some geographical features of areas where tea grows (**a**) tea on hill topography, (**b**) tea in a valley, (**c**) tea in plain field, (**d**) tea on water logged flat land

duction/manufacturing technology developed in one location maintains the status irrespective of where the plant is grown or technology used. Similarly, tea planters tend to import production technologies and management systems, sometimes even without re-evaluating the technologies in the new environments. The assumption is that proven technology in one region works in all regions. However, tea growers have not managed to replicate yields or black tea quality using production technologies imported from different regions. The lack of replication of the results can be due to many factors including, but not limited to low genetic stability of the genotype over wide localities, climatic changes, agronomic/cultural practices and processing techniques which can cause differences in growth and chemical composition and hence black tea quality (Owuor et al. 2010a,b, 2009, 2008a).

Use of suitable genotypes under optimal management in different environments can lead to most economic yields and realisation of best black tea quality. Despite the large variations in the environmental conditions under which tea is grown, leading to differences in yields and quality, uniform/standard agronomic recommendations/practices are used (Anon 2002; Ranganathan and Natesan 1987) over wide regions. In this review, the variations in black tea yields and/or quality due to growing the plant in different locations, changing management system and use of same production technologies in several locations are reported.

2 Effect of Soil Types on Yields and Black Tea Quality

Environment is a major factor that affects tea yields (Carr and Stephens 1992) and black tea quality (Babu et al. 2007; Owuor et al. 2008a). In particular, soil is an essential environmental factor affecting growth of plants. Soil characteristics in different parts of the world vary (Wallis 1997). However, tea plant prefers deep acidic soils with pH below 5.6 (Othieno 1992). The variation in other soil characteristics in different parts of the world where tea is grown is large. As a result, tea productivity and quality of similar genotypes grown in different soil types vary (Fung et al. 2003; Jin et al. 2008; Li et al. 2007). Caffeine and polyphenol contents of tea vary with geographical origin of the leaf and type of soil (Baptista et al. 1998, 1999). The variations in tea responses, particularly yields due to general agro ecological conditions, and farm-specific soil characteristics have been reported in China (Han et al. 2007), India (Venkatesan et al. 2004) and Uganda (Carter 2007), although within Kericho in Kenya, soil characteristics did not affect productivity (Kamau 2008). This lack of response in Kericho, Kenya could in part be as result of uniformity of soils characteristics within a small region. However, even within some small regions, where tea has been grown for a long time, soil quality deteriorates, especially when the soil nutrients content become depleted (Dang 2002; Kamau et al. 2008a). This stagnates and/or reduces yields (Kamau 2008; Kamau et al. 2008a,b; Zeiss and denBraber 2001). The variations in black tea quality due to soil deterioration after long term tea plantation are not documented. However, the reported effects of soil type on tea quality and yields are normally confounded by non uniformity of tea genotypes and management in the studies.

These results suggest that studies should be conducted to evaluate the effects of soil deterioration due to long term tea plantation on black tea quality. The noted variations in tea yields and black tea quality due to soil types indicate that to maximise yields and quality, it is necessary to evaluate new genotypes on the soils of intended growth, so that only cultivars that produce potential optimal yields and black tea quality in a particular soil type are cultivated. Again cultivars should be tested in different soil types to establish stable varieties that are widely adaptable and those with limited stability that perform well only on specific soil types.

3 Altitudes

Successful economic production of tea has been reported from sea level to over 2,700 m amsl (Anandacoomaraswamy et al. 2000; Owuor et al. 2008b). The variations in the altitude cause large differences in temperatures resulting in changes in growth rates and patterns (Burgess and Carr 1997; Obaga et al. 1989; Squire et al. 1993). An increase in mean air temperature with decrease in altitude lowers the shoot population density (SPD) but increases the mean dry weight of the harvested shoot in same clones (Balasuriya 1999; Squire et al. 1993) (Table 1). Consequently, tea yields decrease with rise in altitude (Anandacoomaraswamy et al. 2000; Balasuriya 1999; Obaga and Ng'etich 1989; Obaga et al. 1989; Squire et al. 1993). Decreased tea yields at rate of 1 kg per 100m rise in altitude have been reported in Kericho, Kenya (Othieno et al. 1992). Tea suffers less from water deficit at higher altitudes since 65% of available soil water has to be depleted before a significant decrease of transpiration occurs (Anandacoomaraswamy et al. 2000). However,

Table 1 Effect of altitude on shoot population density measured in the centre of the bush (SPD), density of shoots harvested from the centre of the bush [HSD(centre)], and density of shoots harvested from the entire plot [HSD(plot)] of clones TRI 2023 and TRI 2025

		Number of shoots per m^2								
		SPD			HSD (centre)			HSD (plot)		
Site	Altitude (m)	TRI 2023	TRI 2025	Mean	TRI 2023	TRI 2025	Mean	TRI 2023	TRI 2025	Mean
Glassaugh	1,859	5,115	4,603	4,859	1,063	2,613	1,838	783	1,078	931
Talawakele	1,382	4,867	3,974	4,421	1,424	2,258	1,741	814	965	890
Vellai-oya	1,300	4,711	3,747	4,229	1,859	1,917	1,888	824	656	740
Strathdon	914	3,854	3,601	3,728	2,086	2,173	2,130	784	708	746
Kottawa	30	3,877	2,794	3,336	2,428	1,821	2,125	788	704	746
Mean		4,485	3,744		1,772	2,116		799	822	
CV		4.4%			1.3%			3.1%		
Clone		***			***			*		
Altitude		***			***			***		
Clone × altitude		**			***			***		

Source: Balasuriya (1999)
*, **, *** LSD values significantly different at P = 0.05, 0.01 and 0.001, respectively

the response to environment can be variable in different genotypes (Ng'etich and Stephens 2001a). In young clonal teas, whereas clone, EPK TN14-3, produced the highest matter at the low altitude, clone AHP S15/10 produced the least (Ng'etich and Stephens 2001b). Analysis of genotype and environment interactions showed that clone EPK TN14-3 has above average stability in dry matter production at various altitudes, but below average stability in yield (Ng'etich and Stephens 2001a). Clone AHP S15/10 showed above average stability for tea yield, but was below average stability in dry matter production (Ng'etich and Stephens 2001a). The harvest index of the clones also varied at the different altitudes (Ng'etich and Stephens 2001b), under uniform management. Overall, yields and dry matter production of tea genotypes differed at different sites situated at different altitudes (Ng'etich et al. 2001) despite uniform management. This suggests that different tea genotypes require different management strategies to realise optimal yields and black tea quality.

The composition of volatile compounds of black tea varied with altitude (Mick and Schreier 1984). Black tea quality increased as the altitude increased (Mahanta et al. 1988) more so in the same genotypes under uniform management (Owuor et al. 1990a). Caffeine (Owuor et al. 1990a) and flavour index increase with altitude (Mahanta et al. 1988; Owuor et al. 1990a); verifying the superiority of quality of higher grown over those teas grown in lower altitudes (Table 2). The slow rate of shoot growth due to cool temperatures at high altitudes (Obaga and Ng'etich 1989; Obaga et al. 1989; Squire et al. 1993) is the source of frequently recorded best quality for high grown black teas. These results demonstrate that black tea quality will improve with rise in altitude particularly in the same genotypes when under uniform management. The extent of changes however, vary with genotypes. Thus there are genotypes that are less susceptible to quality changes as altitude rises and *vice versa.* The quality (Moreda-Pineiro et al. 2003) and mineral composition (Street et al. 2006) of tea from diverse sources also vary with altitude. In Turkey, the iron and manganese levels in tea shoot change with altitude (Sahin et al. 1991). However, it was not documented whether the studies used same tea genotypes or received uniform management.

In conclusion, for production of high quality black teas, especially aromatic black teas, growth at high altitude is essential. However production of tea at low attitudes leads to high yields, provided temperatures and soil moisture are adequate and well distributed. Some cultivars show reasonable stabilities across different altitudes. New genotypes should be evaluated for suitability/stability for production of high yields and black tea quality at different altitudes.

4 Geographical Locations and Seasonal Variability

The weather and seasonal fluctuations in variables such as rainfall, temperature and humidity, and soil water deficits influence annual yield distribution, and hence annual yield (Mathews and Stephens 1998a; Uddin et al. 2005) and black tea quality (Owuor 1992, 1994; Owuor et al. 1991a). Performances of most crops,

Table 2 Effects of altitude on chemical quality parameters of CTC black tea

		Clone S15/10				Clone TN 14-3			
Site	Altitude	Theaflavins (μ mol g^{-1})	Caffeine (%)	Flavour index	Sensory evaluation	Theaflavins (μ mol g^{-1})	Caffeine (%)	Flavour index	Sensory evaluation
Timbilil	2,180 m	25.14	3.57	3.56	37.30	28.97	3.93	1.79	
Chepgoiben	2,120 m	21.93	3.41	3.32	34.33	29.84	3.53	1.51	40.67
Cheptabes	1,940 m	21.19	3.27	2.46	32.97	31.14	3.57	1.41	39.33
Kaproret	1,860 m	20.62	3.10	2.13	30.37	31.54	3.63	1.16	38.00
CV (%)		5.96	4.53	6.62	3.85	2.42	7.24	16.17	37.33
LSD, P = 0.05		2.64	0.30	0.38	1.91	1.47	NS	NS	Ns
r^2		0.85	0.97*	0.997*	0.95*	−0.98*	0.53	0.94*	0.98*

Source: Owuor et al. (1990a)

* Significant, P = 0.05, NS = Not significant

Table 3 Mean yields in tons made tea per hectare (x) and stability parameter estimates (bi, S^2d, σ^2i and SE^2i) for tea yields of 20 genotypes tested in 12 (i.e. 6 years in two sites) environments

Genotype	x	bi	Cluster group	SE^2i	S^2d	σ^2i
1. STC 5/3	1.200	0.80	1	1.052	0.414**	0.258
2. 6/8	1.567	0.84**	2	0.830	0.114***	0.036
3. 7/3	1.786	0.99	2	1.179	0.174**	0.045
4. 7/9	1.763	0.88	2	1.032	0.284***	0.112
5. 2X1/4	1.644	1.16	2	2.032	0.426*	0.364
6. 11/26	1.290	0.78***	1	0.723	0.130**	0.064
7. 12/12	1.616	0.91	2	1.014	0.178**	0.058
8. 12/19	1.650	0.96	2	1.061	0.082***	0.009
9. TN 14-3	1.788	1.00	2	1.233	0.219***	0.061
10. S15/10	2.051	1.20**	3	1.665	0.136**	0.056
11. 31/8	2.277	1.25	4	1.972	0.326***	0.186
12. 31/27	1.632	0.93**	2	0.984	0.048**	0.008
13. BB35	1.994	1.11	3	1.448	0.141**	0.039
14. 54/40	1.933	1.09	3	1.412	0.185***	0.049
15. 56/89	1.542	0.94	2	1.140	0.252**	0.089
16. 57/15	1.738	1.06	2	1.312	0.126***	0.023
17. 303/259	1.659	0.96	2	1.069	0.095***	0.015
18. 303/577	1.960	1.06	3	1.389	0.187***	0.048
19. 303/999	1.925	1.02	3	1.255	0.178**	0.049
20. 303/1199	1.882	1.06	3	1.335	0.153**	0.037

Source: Wachira et al. (2002)
*,** ,*** indicate significantly different from 1.0 for the regression coefficients (bi) and from 0.0 for the deviation mean squares (S^2d) at 0.05; 0.01 and 0.001 levels of probability.
Cluster based on non-weighted values of mean yield (x) and regression coefficient (bi).

tea inclusive, vary from locality to locality and season to season (Wachira et al. 2002). These variations arise from differences in growth parameters (Ng'etich and Stephens 2001a,b) leading to changes in economic yields (Wachira et al. 1990, 2002; Wickremaratne 1981) (Table 3), chemical composition and overall black tea quality (Owuor et al. 2008a) (Table 4). Yield is primarily determined by shoot numbers, shoot weight and the rate of shoot growth (Carr and Stephens 1992; Odhiambo 1989). These components vary with environment, management practices and the genotype (Burgess 1992). The variations in tea productivity and quality due to weather factors have been reported in several studies (Carr and Stephens 1992; Ng'etich 1995; Odhiambo 1989; Wachira et al. 2002). In particular, tea yields vary with temperature, the saturation of water vapour pressure of air, rainfall and evapotranspiration (Stephens and Carr 1990) which vary with locations and seasons. The components of tea yield (i.e. number of harvested shoots per unit area, their rate of growth and the average weight of shoots at harvest) are largely influenced by weather factors (Burgess 1992). Yields are usually low during the dry or very cold seasons (Nixon et al. 2001).

Table 4 Impact of geographical area of production on fermentation and quality of cultivar SFS 150

Parameter	Source	Fermentation time (min) 30	50	70	90	110	Mean source
Theaflavins (μ mol/g)	Kenya	12.86	18.86	21.55	23.05	22.20	19.90
	Malawi	15.01	22.11	21.78	21.29	21.20	20.28
	Mean time	13.94	20.49	21.67	22.17	21.70	
	C.V. (%)			8.69			
	LSD, ($P < 0.05$)			1.78			NS
	Interactions			2.52			
Thearubigins (%)	Kenya	9.61	11.47	11.73	13.02	12.98	11.76
	Malawi	6.97	7.83	7.89	8.56	8.87	8.02
	Mean time	8.29	9.65	9.81	10.79	10.92	
	C.V. (%)			5.08			
	LSD, ($P < 0.05$)			0.80			0.51
Total colour (%)	Kenya	2.51	3.48	3.89	4.47	4.53	3.77
	Malawi	3.14	4.21	4.58	5.22	5.34	4.49
	Mean time	2.83	3.84	4.23	4.84	4.93	
	C.V. (%)			13.35			
	LSD, ($P < 0.05$)			0.88			0.56
Brightness (%)	Kenya	34.32	32.91	32.70	31.01	29.64	32.11
	Malawi	30.11	29.74	27.16	22.28	21.67	26.19
	Mean time	32.21	31.32	29.93	26.64	25.66	
	C.V. (%)			21.80			
	LSD, ($P < 0.05$)			NS			NS

Source: Owuor et al. (2008a)

Tea is grown from the equator to sub tropical environments (Owuor et al. 2008b; Shoubo 1989) where seasonal variations can be very large. For example, at the Tea Research Foundation of Kenya (TRFK) (latitude 0° 22′S, longitude 35° 21′E, altitude 2,200 m amsl) in the Kericho District of Kenya mean seasonal temperatures vary from 15–17°C, substantially less than 18–24°C at the Tea Research Foundation of Central Africa (TRFCA), (latitude 16° 05′S, longitude 35° 37′E, altitude 650 m amsl) Mulanje, Southern Malawi (Carr and Stephens 1992). Tea yields also vary with seasons where significant reductions are observed during the cool season (Tanton 1979). For example, in Malawi, more than 70% of the annual crop is harvested during a 5 month wet warm season (Cloughley 1983; Fordham and Palmer-Jones 1977). Within-season yield variability is directly related to base temperature for shoot extension and shoots population density, which affect management in terms of labour planning, transport requirements and factory capacity (Carr and Stephens 1992; Gulati and Ravindranath 1996; Nixon et al. 2001). Near the Equator, the seasonal changes in temperature are minimal, and the monthly crop distribution can be relatively smooth (Carr and Stephens 1992), but at high latitudes, it can be very uneven as low temperatures and/or droughts restrict shoot extension for part of the year (Burgess and Carr 1997; Stephens and Carr 1990). Away from the equator, large yield peaks often occur following a cool or dry season, with subsequent oscillations which may continue throughout the remainder of the season (Matthews and Stephens 1998b). The yield variations in a single clone can range from about 18% during the rainy season to 30% during the cool, dry weather (Burgess et al. 2006). However, there are genotypic differences in the shoot base temperatures and extension rates resulting in differences in the seasonal distributions of yield in different cultivars with some tea clones undergoing less seasonal variations than the others (Burgess and Carr 1997).

The adverse effects of drought can be partially mitigated by use of shade trees (McCulloch et al. 1965), or irrigation (Kigalu et al. 2008). However, shade trees reduce tea yields (Obaga and Othieno 1987; Othieno and Ng'etich 1992) and nutrient availability (Othieno 1983) but improve black tea quality (Owuor et al. 1989a). The tea yield response to irrigation can be large during dry weather (De Costa et al. 2007). Different tea genotypes differ in responses to irrigation even when they are grown at a single site under uniform management (Kigalu 2007; Kigalu et al. 2008).

The quality of tea is a polygenically controlled trait and is directly or indirectly influenced by various traits (Kamunya et al. 2010) and environments (Babu et al. 2007; Owuor et al. 2008a). Commercial tea of variable genotypes, including seedling and clonal teas show seasonal quality variations even close to the equator (Owuor 1994). Volatile aroma compounds levels and compositions also vary with location of production (Owuor et al. 2008a) and seasons (Cloughley et al. 1982). The variation is more noticeable under temperate or sub-tropical condition (Cloughley et al. 1982; Robinson and Owuor 1992). Dry and cool seasons cause slower shoot growth rate leading to high black tea quality; while, wet season especially rainy period leads to fast tea flush (growth) which reduces black tea quality (Odhiambo et al. 1988). Provided there is adequate moisture in the soil, high temperatures favour fast shoot growth thus increasing yield but lowering the black tea quality. On the contrary, low temperatures in cold seasons cause slow shoot growth rates leading to reduced yields with improved black tea quality. Growth under dry weather with cooler nights and desiccating winds favour the biogenesis of flavour compounds leading to production of flavoury black teas (Rawat and Gulati 2008). Thus, better quality and higher valuation are obtained from teas manufactured from shoots plucked during slow growth conditions (Hilton et al. 1973; Rawat and Gulati 2008).

Seasonal responses to some tea quality parameters with agro-inputs such as fertilizers have been reported in several studies (Mahanta 1988; Mahanta et al. 1995; Ozdemir et al. 1993; Ravichandran and Parthiban 2000; Turkmen and Velioglu 2007; Yao et al. 2005). These occur in different genotypes like in seedling (Sud and Baru 2000) and clonal (Owuor 1994, 2001; Rawat and Gulati 2008) teas due to nitrogenous fertilizer rates; indicating that regardless of season, the use of high nitrogen fertiliser rates reduces black tea quality. The extent of the variations may vary with tea genotypes. Other nutrients of tea also influence the seasonal quality (Ruan et al. 1998, 1999) and extent of seasonal variations in black tea quality vary with location of production.

Locality and seasons affect crop performance. In Malawi, the size of harvested shoots and number of shoots harvested, accounts for 11% and 89%, respectively of the total seasonal yield variations (Tanton 1981). Reduced rate of shoot extension is evident during period of water stress (Ng'etich 1995) and low temperatures (Burgess and Carr 1997). High rate of shoot growth is recorded in warmer conditions at lower altitude (Anandacoomaraswamy et al. 2000; Balasuriya 1999; Obaga and Ng'etich 1989; Obaga et al. 1989; Squire et al. 1993) provided water and temperatures are not limiting. Such fluctuations in harvestable yields due to seasonal variations affect the optimal efficiency of both tea growers and the processors.

Seasonal variations in length of shoot replacement cycle cause variability in yield distribution during the year (Tanton 1982). The shoot replacement cycles vary with geographical region. In the Kenya highlands, along the equator shoot regeneration takes from 80 to 120 days (Odhiambo et al. 1993) unlike further away from the equator in Malawi where shoot regeneration can be as short as 42 days during the favourable growing seasons (Smith et al. 1993; Tanton 1982). Such large differences in growth patterns cause differences in crop distribution, total yields and black tea quality even in the same genotype leading to the need for different management strategies. For example, harvesting intervals vary from 6 to 8 days and 10 to 19 days under warm wet and dry cool seasons in southern Tanzania (Burgess and Carr 1998), respectively.

In conclusion, the seasonal variations in yields and black tea quality dictate that management must make seasonal adjustments. The cool seasons characterised by slow growth usually translate into low production but high quality black teas. There should therefore be efforts to emphasise management to produce high quality black teas. When crop is low due to dry and cool seasons, farm in puts like plucking labour deployment, should change to reflect the low production. Warm wet seasons are characterised by fast growth, high production and low quality black teas. Management should ensure availability of labour or ability to remove all the crop and adequate factory processing capacity to handle all the leaf. These seasonal changes will affect growers further away from the equator much more than those close to the equator where seasonal variations are minimal.

5 Genotypes

Many tea genotypes have been developed in the various tea producing countries. Remarkable achievements have been demonstrated and yields up to 10,995 kg made tea ha^{-1} year^{-1} have been realised under commercial production from selected genotype (Oyamo 1992). This arguably is the highest recorded tea yield per unit area under commercial production. To realise maximum benefits from tea growing, farmers are continuously looking for such high yielding and good quality

Table 5 Comparison of the variations in the theaflavins levels of Cultivar 6/8 grown in Kenya and Malawi due to fermentation duration

Location	Fermentation time (min)	Total TF (Flavognost)	TF	TF-3-G	TF-3'-G	TFDG	TFDG equiv.
Malawi	30	18.18	8.45	4.29	3.11	2.33	6.22
	50	17.30	8.09	4.48	2.75	1.98	5.74
	70	17.30	7.79	4.51	2.79	2.21	5.97
	90	15.10	5.96	4.10	2.56	2.49	5.73
	110	15.28	5.87	4.19	2.64	2.59	5.88
Kenya	30	11.38	7.51	1.79	1.65	0.42	2.21
	50	13.78	8.41	2.51	2.03	0.83	3.72
	70	18.91	9.90	4.56	2.80	1.65	5.75
	90	17.75	9.16	4.53	2.52	1.56	5.44
	110	17.82	8.70	5.11	2.41	1.60	5.57

Source: Owuor et al. (2008b), Total TF = Total theaflavins, TF = Theaflavin, TF-3-G = Theaflavin-3-monogallate, TF-3'-G = Theaflavin-3'-monogallate, TFDG = Theaflavin-3,3'-digallate, TFDG equiv. = Theaflavin-3,3'-digallate equivalent

genotypes. Although tea growers believe that such high yielding cultivars retain their yield potentials wherever they are planted, several studies have demonstrated wide response ranges in yield (Ng'etich et al. 2001; Wachira et al. 1990; Wickremaratne 1981), yield partitioning (Ng'etich et al. 2001), growth (Ng'etich and Stephens 2001a,b), shoot population density (Balasuriya 1999) and dry matter partitioning (Ng'etich and Stephens 2001b) of tea genotypes to different environments (Carr and Stephens 1992; Wachira et al. 1990, 2002; Wickremaratne 1981). The noted variations are due to several factors including water stress (Carr and Stephens 1992), temperatures (Tanton 1982) and altitudes (Obaga et al. 1989; Squire et al. 1993). Such variations are observed even in same genotype planted in various regions (Wachira et al. 1990, 2002; Wickremaratne 1981), although there are also genotypes which are more adaptable in several regions (Wachira et al. 2002) (Table 3).

In terms of black tea quality, variations in chemical composition and quality of same tea genotypes due to geographical influence have been documented (Owuor et al. 2008a) (Table 5). But the management of the cultivars might have been different making comparison difficult. Limited data exist on use of same genotype in different geographical areas due to restricted exchange of genotypes. Where such data exist, management practices are not uniform making comparison difficult. When same genotypes were subjected to same management in different locations, there were variations in yields (Ng'etich and Stephens 2001a,b; Ng'etich et al. 2001; Obaga et al. 1989; Squire et al. 1993; Wachira et al. 2002) and black tea quality (Tables 6 and 7) (Owuor et al. 2010a) even within a radius of only 10 km (Owuor et al. 1990a; Ng'etich and Stephens 2001a,b; Ng'etich et al. 2001; Obaga et al. 1989; Squire et al. 1993). These results demonstrate that the variations in the yields and quality of genotypes can be large when environmental conditions vary widely. However, there are genotypes that are very adaptable over wide regions

Table 6 Response of clonal black tea total theaflavins (μ mol/g) and relative ranking based on theaflavins levels to growing environment

Site	Timbilil		Kipkebe		Kangaita		Mean clones	
Clone	Theaflavins (μ mol/g)	Rank	Theaflavins (μ mol/g)	Rank	Theaflavins (μ mol/g)	Rank	Theaflavins (μ mol/g)	Rank
TRFK 6/8	24.03	7	26.33	4	30.14	1	26.83	4
TRFK 31/8	21.75	14	25.71	7	23.44	16	23.64	12
AHP S15/10	18.06	19	22.48	16	21.19	18	20.58	18
EPK TN 14-3	28.02	1	25.46	9	29.32	4	27.60	1
BBK 35	24.49	5	25.14	10	27.34	8	25.66	9
TRFK 54/40	24.15	6	27.15	2	29.37	3	26.85	3
TRFK 12/12	23.77	8	24.97	11	29.89	2	26.21	5
TRFK 12/19	19.58	16	20.89	18	23.50	15	21.32	17
TRFK 31/27	18.50	17	19.01	20	21.17	19	19.56	19
TRFK 11/26	23.05	10	25.48	8	28.97	6	25.84	8
TRFK 57/15	25.62	2	26.17	5	25.92	10	25.90	7
TRFK 7/3	22.97	11	22.78	15	23.06	17	22.94	14
TRFK 7/9	21.96	13	24.64	13	24.69	11	23.76	11
TRFK 56/89	17.58	20	20.52	19	18.63	20	18.91	20
STCK 5/3	19.76	15	22.98	14	23.58	13	22.10	16
TRFK 303/259	18.48	18	27.30	1	24.15	12	23.31	13
TRFK 303/577	25.29	3	24.97	11	28.23	7	26.16	6
TRFK 303/999	24.86	4	26.84	3	29.05	5	26.92	2
TRFK 303/1199	23.49	8	25.80	6	26.74	9	25.34	10
TRFK 2XI/4	22.07	12	22.20	17	23.54	14	22.60	15
Mean site	22.38		24.34		25.59			
CV (%)			13.27					
LSD, ($P \leq 0.05$)			1.16				2.99	

Source: Owuor et al. (2010a)

(Wachira et al. 2002; Owuor et al. 2010a).Thus new genotype imported into an area may need to be re-evaluated for the yields and quality potentials in the new regions.

The conclusions derived from the observations are that there are cultivars which produce superior yields and black tea. To maximise profits from tea cultivation, growers need to invest in the search for high yielding and black tea quality genotypes. The black tea yields and quality of different genotypes in one location vary suggesting a need for proper cultivar selections and evaluation before wide spread cultivation. Responses of selected cultivars in an area vary when grown in new environments/locations. Thus superior cultivar in one location may not maintain the superior attributes in new locations. But there are genotypes which are suitable for particular geographical areas while some genotypes perform poorly when cultivated away from the locations they were developed. Genotypes should be re-evaluated in new areas before they are availed for wide spread production in areas where they were not developed.

Table 7 Regression coefficients (R^2) of linear regression analyses between same parameters in different regions

Item		Timbilil	Kipkebe	Kangaita
	Timbilil	–		
Theaflavins	Kipkebe	0.3149	–	
	Kangaita	0.5250	0.5665	–
	Mean	0.6864	0.7261	0.9180
Thearubigins	Timbilil	–		
	Kipkebe	0.4340	–	
	Kangaita	0.2329	0.1303	–
	Mean	0.7537	0.7074	0.5383
Total colour	Timbilil	–		
	Kipkebe	0.3768	–	
	Kangaita	0.3996	0.5863	–
	Mean	0.6928	0.8292	0.8203
Chemical Brightness	Timbilil	–		
	Kipkebe	0.2126	–	
	Kangaita	0.4668	0.0562	–
	Mean	0.7760	0.5281	0.6247
Tasters B evaluations	Timbilil	–		
	Kipkebe	0.3425	–	
	Kangaita	0.2563	0.4886	–
	Mean	0.6272	0.7341	0.5905
Tasters A evaluations	Timbilil	–		
	Kipkebe	0.0120	–	
	Kangaita	0.3002	0.0009	–
	Mean	0.6964	0.1234	0.7001

Source: Owuor et al. (2010a)

6 Management

Tea genotypes vary widely in their growth and nutrients uptake responses even in the same environment. This implies that the management and agronomic inputs need to be adjusted with the changes in genotypes and environments to ensure production of optimised tea yields and quality. However, in many regions tea agronomic practices such as fertilizer rates and plucking intervals are similar. In Eastern Africa, for, example, most of the agronomic recommendations originated from the Tea Research Foundation of Kenya, in Kericho (Anon 2002) that was originally part of the Tea Research Institute of East Africa (1951–1980) prior to its dissolution after the break-up of the East Africa Community in 1977. Up to this period, most tea plantations in East Africa were of seedling plants. Such plants have variable yields and quality as individual plants are unique. Usually the yields and black tea quality from seedling plantations are low. Most tea plantations are now planted with clonal materials which have been selected for high yields and/or black tea quality. These plants are sensitive to changes in environmental and management factors. In eastern Africa, there has been lack of research body in Uganda, Rwanda, and Burundi and only recently did Tanzania initiate the Tea Research Institute of Tanzania. It is doubtful whether the recommendations then or those developed in Kenya (Anon 2002) suit all environments in the region for the production of high yields and black tea quality from the clonal teas. Indeed, even, within Kenya yields (Wachira et al. 1990, 2002) and quality (Owuor et al. 2010a) of tea genotypes change with region of production suggesting it is necessary to apply different management practices that would promote realisation of high yields and quality in different regions. The optimal plucking interval (Owuor et al. 2009) and nitrogenous fertiliser rates (Owuor et al. 2010b) for realisation of high quality in same genotype vary with geographical area of production further emphasising the need to fine tune agronomic recommendations for different regions. The optimal fermentation durations to realise high quality black tea also change in the same genotype with geographical area of production. The optimal fermentation duration is attained much faster at TRFCA (altitude 650 m amsl, latitude 16° 05′S, longitude 35° 37′E) than at TRFK (altitude 2,200 m amsl, latitude 0° 22′S, longitude 35° 21′E) (Owuor et al. 2008a). These results suggest that it is necessary to adjust cultural practices and agronomic inputs to suit different geographical areas of tea production for realisation of high yields and quality of black tea.

In conclusion, different regions need to develop region specific production technologies suitable for the particular region. In single locations different genotypes grow at different rates leading to variations in yields and black tea quality. Each genotype should have unique management technologies to enhance their values. The different growth patterns in different cultivars suggest that planting mixed cultivars should be discouraged to ease management. Genotypes should be planted in pure stands or blocks to ease management.

7 Plucking

Tea yields and black tea quality are influenced by agronomic practices. One such agronomic practice is harvesting or plucking (Owuor 1996). Tea plucking costs amount to up to 80% of the total field production costs in manual harvesting (hand plucking) based-estates (Sharma 1987; Willson 1992). To reduce costs of harvesting, several methods are used to pluck tea (Fig. 3). In different genotypes black tea quality and yields vary with plucking intervals (Baruah et al. 1986; Owuor et al. 1997, 2000) (Table 8), standards (Table 9) (Asil 2008; Mahanta et al. 1988; Obanda et al. 2002; Owuor et al. 2000) and methods (Burgess et al. 2006; Owuor et al. 1991b; Ravichandran and Parthiban 1998); while tea yields are affected by plucking intensity (Chandra-Mouli et al. 2007). These results demonstrate that uniform plucking policies may not be appropriate for different tea genotypes even when they are grown in same environment. There are also tea genotypes that are more resistant to quality changes due to plucking standard (Obanda et al. 2002).

Fig. 3 (a) A method of mechanical tea harvesting. (b) Hand plucking of tea

Table 8 Effects of plucking intervals and nitrogen fertiliser on yields and black tea quality

Item	Plucking intervals (days)	Rates of nitrogen (kg N ha^{-1} $year^{-1}$) 100	200	300	400	500	600	Mean plucking intervals
Yield (kg black tea/ha)	7	5,076	7,117	6,787	7,432	7,407	7,388	6,868
	14	5,118	6,491	6,766	6,812	7,449	7,206	6,715
	21	4,607	6,383	5,226	6,254	6,464	6,882	6,186
	Mean rates	4,934	6,813	6,693	6,893	7,107	7,158	
	CV (%)			4.15				7.72
	$LSD,_{0.05}$			713				297
Theaflavins (mol/g)	7	12.80	13.32	11.75	11.21	10.84	12.32	12.04
	14	11.67	10.79	10.53	9.74	9.51	9.87	10.35
	21	10.39	10.03	9.26	9.52	8.59	8.69	9.41
	Mean rates	11.62	11.38	10.51	10.16	9.64	10.29	
	CV (%)			5.84				7.95
	$LSD,_{0.05}$			1.62				0.49
Flavour Index	7	1.13	0.99	0.89	0.80	0.77	0.73	0.89
	14	0.91	0.75	0.72	0.67	0.64	0.61	0.72
	21	0.77	0.66	0.66	0.59	0.57	0.53	0.63
	Mean rates	0.94	0.76	0.80	0.69	0.66	0.62	
	CV (%)			4.67				8.42
	$LSD,_{0.05}$			0.11				0.04
Sensory evaluation	7	44	43	42	40	39	38	41
	14	40	38	37	36	35	36	36
	21	37	32	33	31	33	33	33
	Mean rates	40	38	37	36	36	34	
	CV (%)			1.77				8.80
	$LSD,_{0.05}$			2				2

Source: Owuor et al. (1997)

The plucking rounds vary among tea growing countries in the eastern Africa region. In Kenya, plucking rounds range from 7 to 10 days (Anon 2002), while, in Rwanda it ranges from 9 to 14 days (Uwimana, personal communication) and in Southern Tanzania, the practice is to pluck after 13–14 and 27–30 days under normal long rain season and adverse conditions, respectively (Burgess 1992) in clone TRFK 6/8. These plucking policies demonstrate that there may be a strong plucking interval and environment interactions which could affect profits in tea production in the different regions. Where it is warmer, shoot growth is much faster (Anandacoomaraswamy et al. 2000; Balasuriya 1999; Squire et al. 1993), thus requiring shorter plucking intervals to realise optimal yields and quality (Owuor et al. 2009). As in black tea quality (Obanda et al. 2002), there are differences in the extent of yield variations from region to region in different genotypes. It is necessary to use different plucking management practices to optimise both yield and black tea quality in different cultivars and environments.

Table 9 The influence of plucking standard on quality

Plucking standard	Clone 6/8 Theaflavins (μ mol/g)	Clone 6/8 Thearubigins (%)	Clone 6/8 Theaflavin digallate equivalent	Clone 6/8 Sensory evaluation	S15/10 Theaflavins (μ mol/g)	S15/10 Thearubigins (%)	S15/10 Theaflavin digallate equivalent	S15/10 Sensory evaluation
1 + bud	25.01	14.47	4.28	11.0	17.70	13.09	4.16	11.0
2 + bud	29.28	18.04	3.10	9.7	19.16	14.37	3.21	9.7
3 + bud	23.52	18.25	1.44	7.7	16.58	13.67	1.84	8.3
4 + bud	21.86	17.39	0.93	5.7	14.51	13.66	1.33	7.0
5 + bud	19.10	16.29	0.70	5.7	13.40	13.28	0.95	7.0

Source: Obanda et al. (2002)

In conclusion, plucking younger shoots (fine plucking) ensures production of high yields and black tea quality, and this can be realised through short plucking intervals. However, yield response to plucking intervals varied with locations and possibly duration of the trials or genotypes being evaluated. There is need to develop region specific plucking management technologies to enhance yields and black tea quality.

8 Fertilisers and Nutrients Management

Although fertilizer is one of most expensive agronomic inputs in tea plantations (Bonheure and Willson 1992), it is essential for economic tea production. Fertilizers increase yields (Bonheure and Willson 1992; Kamau et al. 2008a; Owuor et al. 2008b; Venkatesan et al. 2003, 2004) through increased growth rate and density of harvested shoots (Odhiambo 1989) (Fig. 4). The recommended agro-inputs and management on tea such as rates of nitrogen fertilizer in the eastern Africa region are widely adopted from Kenya (Anon 2002). But in practice, the rates, and sources vary from country to country (Bonheure and Willson 1992) and the popular formulation is NPK 25:5:5 or NPK 20:10:10 (Bonheure and Willson 1992). In recent years, there

Fig. 4 Typical fertiliser field trials

have been efforts to use other NPK formulations as tea growers have realised that yield responses vary widely. For example, in Kenya, nitrogen rate between 100 and 250 kg N ha^{-1} $year^{-1}$ is used under rain-fed conditions (Anon 2002); and rates up to 300 kg N ha^{-1} $year^{-1}$ is considered a normal practice for high yielding clones (Owuor et al. 2008b). In Tanzania, 150–250 kg N ha^{-1} $year^{-1}$ rates are applied under rain-fed regime (Anonymous 2004). Similarly, in Rwanda between 100 and 150 kg N ha^{-1} $year^{-1}$ is used (Uwimana, pers. Com). Despite the almost similar nitrogenous fertiliser rates used, the yields in the three east African countries per unit area are very different, even when the genotype is uniform especially for clone TRFK 6/8 that is widely grown in the region. In Iran, Sulphate of Ammonia produced higher yields than Urea in the same genotypes at two locations (Salardini 1978).

There are variations in tea yields (Han et al. 2008) and black tea quality (Venkatesan and Ganapathy 2004; Venkatesan et al. 2003) among tea cultivars with increase in nitrogenous fertilizer. Increasing nitrogen fertilizer rate in combination with rise in tea base temperature increases yield by increasing shoot population (Obaga and Ng'etich 1989). Excessive use of nitrogenous fertilizer reduces the quality of made tea (Cloughley 1983; Owuor and Othieno 1996; Owuor and Wanyoko 1996). There is a decline in black tea total colour with increase in nitrogen rate (Owuor et al. 1997, 2000). Also there is increase of caffeine and decrease of flavour index with higher rates of nitrogenous fertilizers (Owuor et al. 1997, 2000). The extent of these variations were however dependent on the genotypes (Owuor and Othieno 1996; Owuor and Wanyoko 1996) and the environment (Owuor et al. 2010b) (Table 10). But, high rates of nitrogen do not increase tea yields economically when applied beyond 300 kg N ha^{-1} $year^{-1}$and reduce black tea quality (Table 8) (Owuor et al. 1997, 2000; Venkatesan and Ganapathy 2004; Venkatesan et al. 2004). The yields and quality of black tea show dissimilar response patterns to increased nitrogen fertilizer rate, suggesting the importance to optimize the two parameters (Ravichandran 2002) for economic production.

While tea yield responds to potassium in India (Ranganathan and Natesan 1985; Ranganathan et al. 1988; Verma 1997) and Iran (Salardini 1978), tea does not respond to potash application in Kenya (Wanyoko and Othieno 1987), possibly due to the high levels of potassium in east African soils (Bonheure and Willson 1992). Tea quality responses to potassium fertiliser change with the environment. In Southern India applying potassium at high levels lowers the overall tea quality (Venkatesan and Ganapathy 2004), but in Kenya potassium did not affect tea quality (Owuor et al. 1998). In yet other studies in southern India, potassium improved black tea quality (Venkatesan et al. 2004, 2005, 2006). The conflicting responses recorded in Indian teas could be due to differences in genotypes and/or environments of the trials. While further studies may be necessary to explain the basis of these conflicting results, it is likely the differences arise from the native potassium levels in the soil. In young tea, yields have been reported to increase with phophatic fertiliser application (Othieno 1980), while there was no yields response in replanted tea (Othieno et al. 1997). However, in black tea quality there was no response to phophatic fertilisers (Owuor et al. 1998).

Table 10 Effects of rates on nitrogenous fertilisers on mean (1998–2007) tea yields in different regions

Parameter	Location	Rate of nitrogen (kg N ha^{-1} year^{-1})					Mean location
		0	75	150	225	300	
Mean yield (kg black tea/ha/year) (1998–2007)	Kipkebe	1,947	2,977	3,534	3,657	3,859	3,194
	Sotik Highlands	3,151	4,034	5,112	5,720	5,942	4,792
	Karirana	3,379	3,393	3,693	3,647	3,635	3,549
	Changoi	3,952	4,595	4,757	4,925	4,928	4,632
	Timbilil	2,359	2,982	3,532	3,309	3,451	3,126
	Mean rate	2,957	3,595	4,126	4,252	4,363	
	CV (%)			5.55			
	LSD, ($P \leq 0.05$)			217			217
	Interactions			371			
Theaflavins (μ mol/g)	Kipkebe	26.21	24.09	23.31	22.69	21.65	23.59
	Sotik Highlands	22.47	19.85	21.11	19.97	17.05	20.09
	Karirana	26.41	25.21	24.83	23.63	25.35	25.09
	Changoi	26.71	25.85	24.48	25.56	24.58	25.44
	Timbilil	25.04	24.04	23.68	23.49	22.02	23.66
	Mean rate	25.37	23.81	23.48	23.07	22.13	
	CV (%)			13.50			
	LSD, ($P \leq 0.05$)			3.23			3.23
Thearubigins (%)	Kipkebe	17.86	17.94	16.75	15.00	14.67	16.44
	Sotik Highlands	16.82	17.91	16.67	16.87	15.05	16.67
	Karirana	16.53	16.88	15.82	15.64	15.09	15.99
	Changoi	17.68	17.87	16.41	16.67	15.99	16.93
	Timbilil	18.38	16.23	15.82	15.44	14.46	16.07
	Mean rate	17.46	17.37	16.29	15.93	15.05	
	CV (%)			9.51			
	LSD, ($P \leq 0.05$)			1.58			NS
Sensory evaluations	Kipkebe	78	67	73	73	62	71
	Sotik Highlands	107	110	104	59	55	87
	Karirana	104	90	84	76	78	86
	Changoi	85	74	72	62	55	70
	Timbilil	105	98	94	96	79	94
	Mean rate	96	88	86	73	66	
	CV (%)			24.38			
	LSD, ($P \leq 0.05$)			20			20

Source: Owuor et al. (2010b)

Leaf and chemical soil analysis are two methods routinely used in the determination of nutrients availability to plants (Kamau et al. 2005; Venkatesan et al. 2004). Plant analysis elucidates how much of the available nutrients are taken up by the plant (Nathan and Warmund 2008). Thus, chemical analysis details the potential of plant nutrients in the soil and the ability of plant to extract those nutrients (Anon 2002; Kamau et al. 2008a). However, even when planted in one field, different tea genotypes have varying ability to extract nutrients from the soil resulting in variations in leaf nutrients content of different clones grown at the same site (Nyirenda 1991; Wanyoko and Njuguna 1983). The levels of nutrients in different parts of tea bushes also vary (Dang 2005; Kamau 2008; Ruan et al. 2003). This suggests that nutrients removal from the soil by tea plant is dependent on both genotypes and harvesting management which could lead to variations in amounts of fertiliser needed to optimise yields and quality.

In conclusion, different regions need to adopt use of nitrogenous fertiliser rates that are a compromise between yields and quality for the particular region. Use of high rates of nitrogenous fertilisers reduce black tea quality and do not enhance yields, while low rates of nitrogen give high quality black tea but low production. In eastern Africa, for example, it may not be justifiable to use more than 200 kg N ha^{-1} $year^{-1}$, even for high yielding tea cultivars.

9 Processing

The biochemical processes that occur during black tea processing have impact on the resultant quality (Baptista et al. 1998, 1999). The processes are largely influenced by both processing conditions (management) (Obanda et al. 2004) and growing environment (Owuor et al. 2008a, 2009, 2010b). For same genotypes, grown in different environments, optimal fermentation duration, hence quality changes with geographical area of production (Tables 4 and 6) (Owuor et al. 2008a). Thus to produce similar quality tea at different environments, it is necessary to adjust processing conditions. Similarly, maceration methods (Mahanta 1988; Owuor and Obanda 1994a; Owuor et al. 1989b) or sequence (Owuor and Obanda 1994b) cause conditions which alter the fermentation processes resulting in difference in black tea quality. Indeed, the extent of moisture removal during the withering phase (physical wither) (Obanda et al. 1997; Tomlins and Mashingaidze 1997; Ullah et al. 1986), wither duration (chemical wither) (Owuor et al. 1995b; Tomlins and Mashingaidze 1997; Ullah 1984) and withering temperature (Owuor and Obanda 1996) cause differences in black tea quality. The extent of such variations depend on the genotype (Obanda and Owuor 1994) but generally hard physical wither produce more aromatic black teas with low plain black tea quality parameters, while softer physical wither produce black teas with higher plain tea quality parameters but less aromatic black teas. Chemical withers beyond 20 h (Owuor et al. 1990b) and below 8 h (Owuor and Orchard 1992) impair quality of plain teas. Indeed, different genotypes under the same wither conditions have different optimal fermentation durations (Wright et al. 2002). The extent of these variations depend on clones/genotypes, demonstrating that there is strong genotype x environment x management interactions effects in black tea processing. For different genotypes, it is necessary to develop site specific processing conditions (Wright et al. 2002) to realise high black tea quality.

In general, environmental conditions of growth influence black tea processing such that suitable conditions for producing high quality tea in one environment may not be ideal in different regions. Processing technologies should be developed that are region/location specific.

10 Conclusion

Yields and black tea quality vary largely due to genotypes, environment and management. For realisation of high yields and black tea quality, it is necessary that optimal production technologies are developed that are suitable for different genotypes in various environments. Development of genotype and region specific technologies may be a viable way for tea farmers realising better profits from tea growing. There should be specific attention to the effects of soil type, altitude, weather factors, seasons and cultivars on management of tea enterprises, especially on agronomic practices like plucking and fertiliser use and processing technologies.

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