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Photosynthetically Active Radiation to Total Solar Radiation Top Canopy Ratio in Tea (*Camellia sinensis* [L.] O. Kuntze) Genotypes in the Kenyan Highlands

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ABSTRACT

Kenya's leading cash crop is tea. It engages over 4 million Kenyans (about 10%) in gainful employment. Tea is the single largest export commodity, accounting for 26% of the country's total export. It earned the country US$ 1.23 billion in foreign exchange in 2017. Tea production is, however, affected by photosynthesis. The positive gains made by the tea sector can only be achieved through increased yield facilitated by photosynthetic process. Determination of photosynthetically active radiation (PAR) to total solar radiation (R_S) ratio is essential in evaluating the ability of tea genotypes to efficiently convert solar to chemical energy for enhanced yield output. PAR:R_S has been measured at low altitude and temperate regions only, but none has been reported in the tea growing highlands of Kenya. The current study investigated PAR:R_S ratio on top of tea (Camellia sinensis) canopy over Kenyan highlands using the equation $\mathbf{Q}_p=\varepsilon R_s$. A split-plot layout study was conducted at three sites differing in altitude and climatic conditions in Kenya: Kangaita (0^O30'S and 37^O16'E, 2100 m.a.s.l.), Kipkebe (0^O17'S and 35^O3'E, 1740 m.a.s.l.), and Timbilil reference site (0^O22'S, 35^O21'E, 2200 m.a.s.l.). Four tea genotypes of commercial and scientific interest in Kenya: AHP SC 31/37, EPK TN14-3, TRFK 301/5 and TRFK 31/8, were studied. Statistical analysis was done using two-way ANOVA (P=0.05) for split plot design. The study calculated top canopy constant of PAR:R_S ratio to be 0.45, SED±0.0243, and recommended this constant to be used in tea-growing highland regions of Africa to evaluate genotypes for radiation use efficiency.

***Keywords**: Epsilon (ε), Photosynthetically Active Radiation (PAR), Ratio, Tea (Camellia sinensis), Total solar radiation (R_S)*

1. INTRODUCTION

Tea beverage is manufactured from the tender leaves and buds of the evergreen shrub *Camellia sinensis* (L.) O. Kuntze [1]. Kenya is the third largest producer of tea after China and India, and the world's largest exporter of black tea [2]. Grown in altitudes between 1500 and 3000 m above sea level, tea is the leading cash crop in Kenya, making significant contribution to the economy [3]. As a labour intensive private sector player, tea industry employs over four million Kenyans (about 10% of the country's total population) living in the rural settings where tea is cultivated, by empowering them economically all-year round [4,5,6] and is currently the single largest export commodity, accounting for about 26% of the country's total export earnings [4,7]. In 2017, tea earned the country US$ 1.23 billion in foreign exchange from 439 million kg exported [2], contributing about 4% of Gross Domestic Product [4,6,7]. These positive economic gains are brought about by robust tea production resulting from an efficient process attributed to the process of photosynthesis.

Solar radiation drives almost all physical, chemical and biological processes in the earth's atmospheric system, and is the primary driver of plant photosynthesis [8]. Solar irradiance, R_{si}, includes both direct beam and diffuse shortwave radiation reaching the earth's surface; and is defined as the radiant energy reaching a horizontal plane at the earth's surface [9]. Furthermore, the daily solar irradiance received at the earth's surface (Rs, MJm^{-2}day^{-1}) is a fundamental driving variable of ecosystem carbon, water, and energy flux processes [10]. Photosynthetically active radiation (PAR- visible light spectrum) is the spectral range of global solar radiation at wavebands between 0.4 µm (400nm) and 0.7µm (700nm), a band most efficiently utilized to drive photosynthesis [11,12,13] and may be expressed on the basis of energy (Wm^{-2}) or as a stream of particles called quanta or photons (mol m^{-2}s^{-1}) [14]. This portion of the solar radiation spectrum is important because it is the sole energy source for vegetative photosynthesis that provides food and fibre sources, biofuel carriers and additional material sources that support industrial processes [11]. Plants use PAR as energy source to convert CO_2 and water through photosynthesis into organic compounds (sugars) that are then used to synthesize structural and metabolic energy required for plant growth and respiration, as well as stored vegetative products that result in plant biomass [11,15,16].

Total solar radiation is routinely observed in weather stations [11], while *in situ* measurements of PAR are rare in space and time [17]. This scarcity has led researchers and practitioners to calculate PAR from the global broadband solar irradiance by empirical means [10]. Investigations on the relationship between PAR and total solar radiation in other crops have been done in low altitude areas by [15,18,19,20,21]. Authors acknowledge that the actual ratio depends on sky conditions, atmospheric properties and time [16]. While [19] and [20] estimated PAR to be 45% of total (incident or broadband) solar radiation (denoted R_s), [21] computed the spectral distribution of direct sunlight at sea level and suggested the ratio of PAR:R_S as 0.44. Studies carried out in Central Nigeria by [16] proposed a ratio of 2.079, while [13] gave a ratio of 1.919 in trials conducted in Cyprus. In measurements and modelling PAR studies done by [17] in Lhasa, Tibet Plateau, ratio of PAR to solar global radiation of 0.439 was suggested. The value of the ratio varies from place to place as it is influenced by meteorological factors from site to time [17]. Work by [13] further indicate that daily patterns of PAR are dependent on local weather patterns, including sky clarity, air purity, and solar elevation, justifying why this trial was set up in the highland region of Kenya. The current study investigated PAR (denoted $\boldsymbol{Q}_p$) to R_S ratio on top of tea (*Camellia sinensis*) canopy in the highland region of Kenya to inform on radiation use efficiency by tea plants for the purpose of enhancing plant biomass production. Furthermore, there is a gap to fill as no author has reported on PAR:R_S constant in tea canopy-covered highland regions of Kenya.

2. MATERIALS AND METHODS

2.1. Location and Treatments

The study was conducted in three sites differing in altitude and climatic conditions in Kenya: Kipkebe (0^O 17' S, 35^O 3' E and 1740 masl), Kangaita (0^O 30' S, 37^O 16' E and 2100 masl), and Timbilil (0^O22'S, 35^O21'E, 2200 masl), which acted as a reference site. A split-plot arrangement for sites was set out in an existing experiment, established in 1998. This trial investigated the ratio between PAR and direct solar radiation (R_S) on top of the four tea clones, using measured direct radiation. This experiment had two factors: R_S (environment) (whole or main-plot factor) and genotypes (G) (split-plot factor). The treatments were 4 tea genotypes of scientific and commercial interest to the country: EPK TN 14-3, TRFK 301/5, AHP SC 31/37 and TRFK 31/8. Clone TRFK 31/8

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was chosen as a standard/ control since it is grown by the majority of smallholder farmers in the region. R_S measurements were done between 2007 and 2013.

2.2. R_S (Wm^{-2}) and PAR (mol $m^{-2}s^{-1}$)

R_S experiment was set up at Timbilil. PAR and R_S were taken thrice daily, i.e. 1000 hours, 1200 hours and 1400 hours, using tube ceptometer and tube solarimeter (R_S). Readings on these two radiation measurement apparatus were taken concurrently on top and beneath tea canopy to obtain ceptometer versus solarimeter ratios, hence determine PAR, as shown in Figure 2.1.

(a) R_S measurement on top of tea canopy **(b) R_S measurement beneath tea canopy**

Figure 2.1. R_S (a) top canopy and (b) beneath canopy measurements using ceptometer and solarimeter tubes

The KIPP & Zonen was used to calibrate tube solarimeter where a conversion factor (*cf*) of 0.706 was obtained. Direct solar radiation (E_{dir}) (Wm^{-2}) was then determined using (1);

$$Edir = \left[\frac{(r \times cf)mV \times 1{,}000}{11.7\text{mV}}\right]\text{Wm}^{-2} \qquad \text{-------------------} \qquad (1);$$

Where: *r*= Broadband direct radiation measurement (solarimeter); *cf* = Conversion factor (Kangaita =1.0; Kipkebe = 0.706; Timbilil = 0.986); *1000* = used to convert Kwm^{-2} energy units to Wm^{-2}; *11.7* = KIPP calibration factor; and *mV* – millivolts.

Fraction of solar energy intercepted by the canopy (***Si***), direct and PAR is given by (2):

$$Si = \frac{Ti - Bi}{Ti} \qquad \text{-------------------} \qquad (2);$$

Where ***Ti*** (Wm^{-2}) is irradiance captured on **top** of tea canopy, while ***Bi*** (Wm^{-2}) is that energy reaching **beneath** the tea bush, i.e. maintenance layer. Leaves on the bottom layer play an equally important role as those located at the top in that food reserves are stored here, and are used to maintain crop growth and production.

2.3. Determination of '*ε*' in Tea

Concurrent photosynthetic photon flux density (PPFD) readings (mol $m^{-2}s^{-1}$, i.e. PAR quantum units) were recorded for use to calculate the site-specific '*ε*' (epsilon) value, where mol (moles) refers to the number of photons (1 mol of light = 6.02×10^{23} photons, Avogadro's number). The quantity of PAR intensity is given is given the symbol Q_p.

Reference [18] defines photosynthetic photon flux density (PPFD) or $\boldsymbol{Q}_p$, as a measure of photosynthetically active radiation (PAR) that can be related to solar broadband irradiance $\boldsymbol{R}_s$ using the ratio as given by (3):

$$Q_p = \varepsilon R_s \quad \text{-------------------} \qquad (3);$$

which can be applied either to global, direct or diffuse radiation. The ratio '$\boldsymbol{\varepsilon}$' (epsilon) can be considered as a product of two ratios: (i) the fraction of the broadband energy that lies in the PAR wave-band (400-700 nm), whose published values global irradiance are around 0.45, and (ii) the photon or quantum efficiency of this band [18].

2.4. Statistical Model and Analysis

The statistical analysis was done using the split plot design following the model:

Xjklm = ì + xj + ßk +åjk + ôij + ëil + åjklm; Where: *Xjklm* = plot observation; *ì* = mean of observation; *xj* = main treatment effect (genotypes); *ßk* = block/ replication effect (A, B, C); *åjk* = error (1); *ôij* = sub-treatment effect (environmental factors - E, including R_S, PAR and seasons); *ëil* = interaction main treatment (G) and the sub-treatment (E); and *åjklm* = error (2).

A two-way ANOVA (p=0.05) for split plot design [22,23] was used to determine significance of direct radiation and PAR between and within seasons and genotypes, and across locations and years. Correlation ANOVA (Pearson) was used to compare the relative strength of parameters and determine interrelationships [24,25].

3. RESULTS AND DISCUSSION

3.1. Incident Solar Radiation (R_S) at Timbilil Agromet Station

Radiation measurements (MJm^{-2}) were taken at the Timbilil Agromet Station from January 2007 to December 2009. Summary of monthly means and the average number of sunshine hours are presented in Table 3.1.

Table 3.1. Mean monthly radiation (MJ m^{-2}) and daily sunshine hours, 2007-2009 at Timbilil

Year	2007	2008	2009	*(x)*	SED
Mean daily sunshine hours (No.)	6.2	7.0	7.1	6.8	±0.493
Monthly radiation *(x)* (MJ m^{-2})	20.3	21.5	21.7	21.2	±0.757

Key: (x) denotes mean, and is used hereafter in subsequent tables.

Reference [26] noted that tea requires at least 5 sunshine hours per day for a worthwhile production, as tea yields drops drastically under cloudy conditions. Data in Table 3.1 indicate that *mean (x)* daily sunshine hours, *(x)* = 6.8, which is > 5.

The 2007 indicate mean daily sunshine hours (measuring 6.2 hours) was lower compared to 7.0 hours in 2008, and 7.1 hours in 2009) with standard error of deviation (differences) of means (SED) of ±0.493. The SED outcome implies no significant variance in sky conditions from clear to overcast. Monthly direct solar radiation measurements for 3 years (2007-2009) showed no significant difference, with radiation mean monthly output of 21.2 MJm^{-2}, SED = ±0.757.

Steady rise in both daily sunshine hours and radiation in 3 years is attributed to temperature increase. Since temperature is driven by solar radiation (R_S), its long-term effect leads to climate change. The low number of mean daily sunshine hours in 2007 (6.2 hours; 20.3 MJm^{-2}) as compared to 2008 and 2009 is attributed to higher cloud cover experienced in 2007 compared to 2008 and 2009, resulting in reduced incident solar radiation.

3.2. Kangaita Direct Radiation (E_{dir} Wm^{-2})

The smallest quantity of energy was recorded on top of the canopy in 2007 (502 Wm^{-2}) compared to 2008 (793 Wm^{-2}) and 2009 (716 Wm^{-2}) (Table 3.2). This result agrees with Timbilil's $\boldsymbol{E}_{dir}$ findings (Table 3.1) whose radiation measurement was also lowest during the 2007 period (20.3 MJm^{-2}). The same low *Edir* figures were also recorded in Kipkebe in 2007 (Table 3.4), denoting higher cloud cover during first year of this study in the three sites, resulting in reduced radiation capture by tea crop canopy.

Table 3.2. Kangaita daily *(x)* E_{dir} (Wm^{-2}) for top and beneath canopy of tea bushes measured from 2007 to 2009.

Parametre	Year	Position	Treatment (tea genotypes)				
			301/5	31/37	31/8	TN 14-3	Annual *(x)*
E_{dir} in Wm^{-2} [Daily *(x)*]	2007	Top	533	465	518	493	502
		Base	90	83	96	88	89
	2008	Top	800	791	831	751	793
		Base	137	139	145	136	139
	2009	Top	699	713	728	724	716
		Base	147	150	161	155	153
		Top *(x)*	677	656	692	656	670
		Base *(x)*	125	124	134	126	127

It was noted that the maintenance layer of clone 31/8 captured the largest E_{dir} (134 Wm^{-2}) on average a 3-year period, while clone 31/37 captured the least irradiance (124 Wm^{-2}).

3.3. Kangaita Computed Intercepted Energy (*Si*) Ratio Results

The fractions of intercepted E_{dir} (Wm^{-2}) by the canopy of the clones (***Si***) computed between 2007 and 2009 using (2) are depicted in Table 3.3.

Table 3.3. Fraction of E_{dir} (Wm^{-2}) intercepted by tea canopy of the clones cumulatively (∑*RSi*) at Kangaita, 2007-2009.

Year	∑*RSi* (unitless) on the tea clones					No. of rain days
	301/5	31/37	31/8	TN 14-3	Annual *(x)*	
2007	0.83	0.82	0.81	0.82	0.82	163
2008	0.83	0.82	0.83	0.82	0.82↔	152↓
2009	0.79*	0.79*	0.78*	0.79*	0.79*↓	134↓
(x)	*0.82*	*0.81*	*0.81*	*0.81*	0.81	
SED	*±0.023*	*±0.017*	*±0.025*	*±0.017*		

Key: 1. * Less radiation intercepted by tea clones at Kangaita in 2009 due to leaf fall occasioned by drought; 2. ↔ = Figure remained constant (unchanged); 3. ↓ = Figure decreased.

Cumulative radiation interception ratio (∑*RSi*) by all clones in 2007 and 2008 was in the range of 78-83% for all the clones, allowing only 17-22% irradiance to the maintenance layer (Table 3.3). In 2009, however, radiation capture by canopy showed a reversed cycle/ deviation, with all the clones recording a uniform ∑***RSi*** of 79% from mean of 82% intercepted in 2008. It was expected that progressive canopy formation should have hindered more light penetration to maintenance layer in 2009, raising the ∑***RSi*** ratio. The canopy allowed the highest intensity of R_S (21%) to penetrate into the lower layers of the leaves compared to the first 2 years of the trial. The question is, what could have caused this deviation? No hail incidence(s) was reported at Kangaita in 2009. Neither was skiffing (light pruning) done to the clones during this period. Only one probable reason then could have led to reduced interception of light: water stress. Precipitation is critical in tea canopy establishment, contributing to maximum R_S interception. Low mean monthly rainfall at Kangaita in 2009 (134 mm) compared to the first 2 years (183 mm in 2007 and 147 mm in 2008) of this trial, coupled with fewer number of rainy days recorded the same year (134 days) compared to the preceding 2 years led to moisture content deficit in the soil, causing senescent leaves to fall off. Hence, limited number of young leaves was unable to shield the lower layers and allowed more light to penetrate to the base of the plant (maintenance layer).

3.4. Kipkebe Radiation (E_{dir} Wm^{-2})

E_{dir} energy intercepted by top part of tea bushes across the clones was lowest in 2007 across the sites, with Kipkebe realizing 513 Wm^{-2} (Table 3.4) when Kangaita had 502 Wm^{-2} (Table 3.2). The 2008 (669 Wm^{-2}) and 2009 (692 Wm^{-2}) (Table 3.4) measurements were equally higher than that of 2007, as was the case with Kangaita (Table 3.2). This agrees with Timbilil's E_{dir} trial (Table 3.1) where radiation measurements were lowest in 2007 (20.3 MJm^{-2}). It shows Kangaita radiation intensity was highest in 2008 (793 Wm^{-2}) (Table 3.2) while the highest peak of 692 Wm^{-2} was realized at Kipkebe in 2009 (Table 3.4). Cloudless skies contributed to higher E_{dir} in 2008 as opposed to 2007 where more cloudy days were recorded.

Table 3.4. Kipkebe daily mean E_{dir} (Wm^{-2}) for top and beneath the canopy of tea bushes computed between 2007 and 2009.

Parameter	Year	Position	Treatment (tea clones)				
			301/5	**31/37**	**31/8**	**TN 14-3**	**Annual *(x)***
Edir in	**2007**	**Top**	513	501	519	518	513
Wm^{-2}		**Base**	198	209	221	185	203
[Daily *(x)*]	**2008**	**Top**	670	675	666	665	669
		Base	162	148	145	139	149
	2009	**Top**	686	695	690	696	692
		Base	144	123	118	88	118
		***(x)* for Top**	623	624	625	627	625
		***(x)* for Base**	168	160	161	138	157

3.5. Kipkebe Computed *Si* Ratio Results

Table 3.5 depicts the ratio of the intercepted irradiance (*Si*) by the top canopy, explained in (2);

Table 3.5. Fraction of E_{dir} (Wm^{-2}) cumulatively intercepted by tea canopy of the clones (∑*RSi*) at Kipkebe, 2007-2009.

Year	∑*RSi* on the tea clones				
	301/5	**31/37**	**31/8**	**TN 14-3**	**Annual *(x)***
2007	0.61	0.58	0.57	0.64	0.60
2008	0.78	0.78	0.78	0.79	0.78↑
2009	0.79	0.82	0.83	0.87	0.83↑
(x)	0.73	0.73	0.73	0.77	0.74
SED	±0.101	±0.129	±0.138	±0.117	

Key: ↑ = Interception increased

At Kipkebe trial site, irradiance penetration to the maintenance layer was higher in 2007, where 40% of it reached the maintenance layer, leaving 60% on average across the treatments to top canopy, compared to the subsequent years- 78% in 2008 and 83% in 2009 (Table 3.5). Two reasons may have led to less radiation in 2007, hence less dense canopy: (i) Water is critical in tea crop canopy establishment. Mean monthly rainfall of 112 mm in 2007 was insufficient, hence may have led to less dense canopy, resulting in poor ground cover formation as was the case with the Kangaita case; (ii) The main reason was the slow recovery of the clones following pruning carried out in February 2007. Faster recovery was impeded as a result of less rainfall received in 2007.

Unlike the Kangaita trial where more light energy penetrated into the maintenance layer (reduced light interception) in the third year (2009) of trial due to leaf fall (Table 3.3), the Kipkebe experiment followed the expected solar interception cycle. Solar radiation interception indicated a progressive canopy development so that by 2009, a more dense canopy had been formed, resulting in more interception of light than in the 2 preceding years (Table 3.5), in which more light was intercepted with time as a result of build-up of denser canopy. TN 14-3 was the most effective in irradiation interception (77%), while clone 301/5 allowed most of E_{dir} to the maintenance layer (73%).

3.6. E_{dir} (Wm^{-2}) Across Locations

Higher E_{dir} energy values was intercepted on top of tea bushes at Kangaita (670 Wm^{-2}) compared to Kipkebe (625 Wm^{-2}) (Table 3.6). Conversely, measurements at the base of tea plants shows that Kipkebe tea plants allowed more light at the base as a result of inadequate canopy cover that arose from pruning that took place in February 2007, a few months prior to commencement of this study. The clones had slow recovery, explaining why there was less irradiance at the base of the plants in Kangaita (bigger canopy cover - 127 Wm^{-2}) compared to Kipkebe (157 Wm^{-2}).

Table 3.6. Summary of Kangaita and Kipkebe daily mean E_{dir} (Wm^{-2}) measurements, 2007-2009

Parametre	Site	Position	Treatment (tea clones)				
			301/5	31/37	31/8	TN 14-3	Annual (*x*)
Direct radiation (Wm^{-1})	**Kipkebe**	Top (*x*)	623	624	625	627	625
		Base (*x*)	168	160	161	138	157
	Kangaita	Top (*x*)	677	656	692	656	670
		Base (*x*)	125	124	134	126	127

The upper surface of the tea bush participates more actively in the photosynthetic process compared to lower maintenance layer, hence requiring more *Edir*. The growth habit (erectness) of a clone determines efficiency in ***Si*** interception to a large extent. The larger the crop canopy size, the higher the solar rays intercepted as more photosynthesizing leaves have access to direct solar irradiance that translates to higher outputs of photosynthates, hence more harvestable yield. A clone with a good frame and hard branches like TRFK 12/12, having horizontal spread and semi-erect leaves realizes higher harvest of solar irradiance than a clone that exhibits vertical growth habits [27].

3.7. PAR Timbilil Measurements

(a) 'ε' Results

The measurements were converted from ceptometer R_S readings in $mol\ m^{-2}s^{-1}$ (PAR) to direct radiation - Wm^{-2} for the purpose of determining the Q_P:R_S ratio from the relationship $Q_p = \varepsilon R_s$, hence 'ε' by use of (3) as given in Table 3.7.

Table 3.7. Mean daily radiation results (Wm^{-2} for E_{dir} & $mol\ m^{-2}s^{-1}$ for PAR) for top tea canopy, and determination of the value 'ε' in an experiment set at Timbilil, 2012.

Time (hours)	PAR (Ceptometer) ($mol\ m^{-2}s^{-1}$)	PAR converted to E_{dir} (Wm^{-2}):Q_P (3)	Conversion: Tube solarimeter (*mV*) to (Wm^{-2}) *cf=0.706*): R_S	Q_P:R_S (ε) on top of canopy
1000	1,268	276	609	0.4532
1200	1,435	312	725	0.4303
1400	1,095	238	497	0.4789
(*x*)	1,266	275	610	0.4541; SED ±0.0243

Solar radiation reaching the earth's surface differ in intensity at different times of the day as shown data captured by ceptometer (PAR) findings (Table 3.7, column 2). In some of the days, the skies were cloudy at 1400 hours, partly explaining why radiation values recorded at 1400 hours were lowest (1,095 mol $m^{-2}s^{-1}$). The highest irradiance was captured at 1200 hours (1435 mol $m^{-2}s^{-1}$), owing to high heat intensity and clearer skies at noon compared to morning and afternoon hours. It was further noted that the lowest Q_P:R_S ratio was at 1200 hours (ε = 43.03%), while radiation measurement on top of tea bushes at 1400 hours gave the highest ε of 47.89%. Upon completion of all measurements, final mean *(x)* was computed at the top canopy of tea bushes using ratio of PAR to R_S, given as ε, where a figure of 0.4541 (45%), with standard error of deviation (SED) of ±0.0243, was obtained.

(b) ∑RSi Results

The proportion of irradiance intercepted by leaves on top canopy of tea plants (∑*RSi*) was higher at 1000 hours (48%) compared to hours later in the day (42%) as illustrated in Figure 3.1.

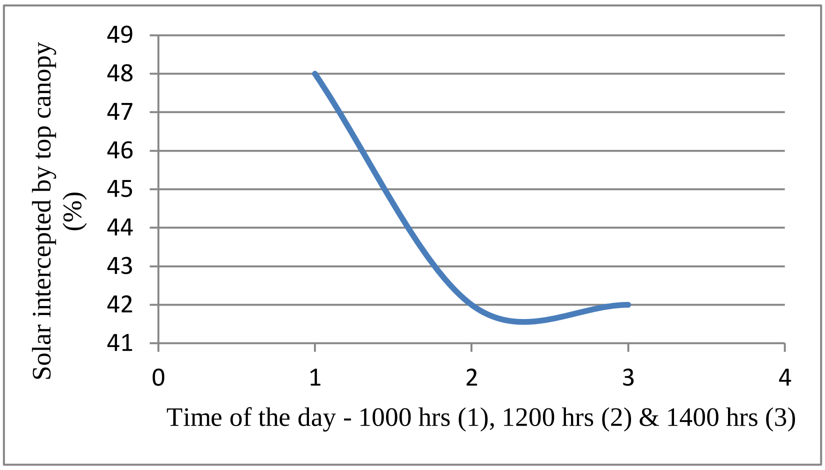

Figure 3.1. The *(x)* of ∑*RSi* values intercepted by the canopy at different times of the day at Timbilil

The ε concept, formalized by [28] on experimental and theoretical grounds, was conceived as a robust and appropriate modelling approach to describe crop growth. This study calculated top canopy ratio between PAR and R_S ('ε') to be 0.4541±0.0243, a figure that is comparable to the global value published by [11,15,18,21]. The calculated factor was used to convert direct radiation measurements (represented here by R_S) for Kangaita and Kipkebe trial sites to PAR (denoted by Q_P) (Table 3.7).

3.8. Conversion of R_S Kangaita and Kipkebe Measurements to *PAR*

Equation (3) states: $\boldsymbol{Q_P} = \boldsymbol{\varepsilon R_S}$. Having calculated the value of ε from the Timbilil trial to be 0.45, this figure was used to convert direct radiation data (R_S *in* Wm^{-2}) taken at Kipkebe and Kangaita to PAR (in mol $m^{-2}s^{-1}$), since these two sites (Kangaita and Kipkebe) lie near the equator as is the case with this study's reference point (Table 3.8).

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Table 3.8. The 2007-2009 Kangaita and Kipkebe R_S and Q_P values, with $\varepsilon = 0.45$ (SED ±0.0243).

Genotype	**Canopy**	**Kangaita**			**Kipkebe**		
		R_S (Wm^{-2})	**R_S×4.6, i.e. R_S (Wm^{-2}) to PAR (mol m^{-2}s^{-1})**	**Q_P ($Q_P=\varepsilon R_S$) (PAR in mol m^{-2}s^{-1})**	**R_S (Wm^{-2})**	**R_S×4.6, i.e. R_S (Wm^{-2}) to PAR (mol m^{-2}s^{-1})**	**Q_P ($Q_P=\varepsilon R_S$) (PAR in mol m^{-2}s^{-1})**
301/5	**Top**	677	3114	1401	623	2866	1290
	Base	125	575	259	168	773	348
31/37	**Top**	656	3018	1358	624	2870	1292
	Base	124	570	257	160	736	331
31/8	**Top**	692	3183	1432	625	2875	1294
	Base	134	616	277	161	741	333
TN 14-3	**Top**	656	3018	1358	627	2884	1298
	Base	126	580	261	261	635	286

From Table 3.8, the largest PAR (Q_P) at Kangaita was recorded on top of canopy of clone 31/8 (1,432 mol m^{-2}s^{-1}), while the least was in clones 31/37 and TN14-3 where 1,358 mol m^{-2}s^{-1} was recorded. These measurements were higher than Kipkebe's where 1,298 mol m^{-2}s^{-1} was captured on top of clone TN14-3 while 1,290 mol m^{-2}s^{-1} was recorded in clone 301/5. The difference in PAR measurements within clones in a given location was not significant.

3.9. Statistical analysis of Genotype (PAR) versus Environment (G×E) and seasons

Data was subjected to test G×E statistical relationship (ANOVA) [22] and PAR and the 3 seasons (Table 3.9).

Table 3.9. ANOVA for G×E (Variate: PAR)

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Environment (E) stratum	1	812853	812853	3.70	
E×Rep	4	877934	219484	0.39	
E×Rep×Season	12	6679598	556633	0.28	
Genotype (G)	3	93090	31030	0.02	0.997
G×E	3	35716	11905	0.01	0.999
Residual	120	239415650	1995130		
Total	143	247914841			

Irradiance capture in the two separate environments showed no significant difference between G×E. Likewise, no significant difference existed between PAR capture by the genotypes across seasons. That means all genotypes tested are suitably adapted to the sites where the experiments were conducted.

4. CONCLUSION AND RECOMMENDATION

A steady rise in both sunshine and solar radiation is attributed to temperature increase. Since temperature is driven by solar radiation, its long-term effect leads to climate change in the tea growing regions of Kenya.

This study computed PAR:R_S ratio 'ε' constant from (3) ($\boldsymbol{Q_P = \varepsilon R_S}$) on top of the tea canopy over Timbilil in Kericho County, Kenya to be 0.45. This outcome concurred with PAR:*RS* ratios suggested by [11,15,18,21]. This ratio was replicated in Kangaita and Kipkebe sites since they lie near the equator with the reference site, receiving moreorless equal solar radiation intensities.

This finding will not only be used to analyze physiological functioning, growth and gross ecological production of tea clones within the Kenyan highland ecosystems, but also essential in evaluating the conversion efficiency of tea genotypes from solar energy to chemical energy. Specifically, this constant is recommended for use in the larger tea highland regions of Africa to evaluate clones for radiation use efficiency, hence yield estimation.

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