# Estimation of tea quality by infusion colour difference analysis

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**Abstract: The colour differences in terms of $\Delta L$, $\Delta a$, $\Delta b$ and $\Delta E$ between distilled water and infusions of 29 green teas, 16 black teas and 13 oolong teas and their correlation with sensory quality attributes of tea were investigated. The results showed that the $\Delta L$ value decreased but the $\Delta a$, $\Delta b$ and $\Delta E$ increased with the degree of fermentation of the three kinds of tea. The $\Delta L$ was positively correlated to quality attributes of green tea and oolong tea but negatively correlated to those of black tea. The $\Delta a$ of tea infusions is a reliable descriptor to differentiate among green and black teas. The regression of total quality score of green tea (TQSg) upon the $\Delta a$ was TQSg $= -2.26\Delta a + 77.2$ ($R^2 = 0.22$, $p < 0.01$), that of total quality score of black tea (TQSb) upon $\Delta b$ was TQSb $= 0.70\Delta b + 44.6$ ($R^2 = 0.31$, $p < 0.05$) and that of total quality score of oolong tea (TQSo) upon $\Delta L$ was TQSo $= 1.09\Delta L + 94.5$ ($R^2 = 0.75$, $p < 0.01$). Because the infusion colour difference indicators of $\Delta a$, $\Delta b$ and $\Delta L$ can be done rapidly, it could be very useful for on-site or on-line quality monitoring during tea manufacture and storage.**
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**Keywords:** *Camellis sinensis*; green tea; oolong tea; black tea; infusion; color difference; quality estimation; linear correlation

## INTRODUCTION

Tea is one of the most consumed beverages across the world. Usually tea is classified as green, black, oolong, yellow, white and dark compressed tea. Green tea is an unfermented tea and black tea a fermented one. If the fermentation is partially carried out, oolong tea is obtained. The quality of tea largely depends on the components in the leaves. Prices of various teas are quite variable and are dependent on the quality, which traditionally has been assessed by a tea taster. The tea taster and trade have developed a language to describe various quality attributes of a tea infusion, which sometimes is difficult to understand for consumers. It is therefore important to develop precise chemical or physical methods for the objective estimation of the quality of tea.

Many attempts have been made by various researchers to explain quality and various infusion characteristics of teas. Black tea quality is influenced by the concentration of theaflavins (TFs) and thearubigins (TRs).[1,2] Black tea cream formation is influenced by the concentration of TFs.[3] Roberts and Smith[1] confirmed that TF content is an important factor in determining black tea quality. A very close relationship was found between TF content and broker's valuation of black tea.[2,4,5] Flavanol composition and caffeine content were also used as quality potential indicators of black tea.[6,7] Contents of amino acids and catechins were found to be correlated to green tea quality assessed by professional tea tasters[8–10] and infusion colour difference parameter $\Delta a$ was negatively correlated to Chinese famous green tea.[11] Capillary electrophoresis, electronic tongue and lipid membrane taste sensors have been applied to tea quality estimation.[12–15] However, these techniques have yet to prove useful in commercial tea production and marketing. It is still necessary to search for some other techniques to solve the problem of estimating tea quality.

While assessing the cash valuation of a tea, the tea taster takes into consideration mainly the infusion characteristics.[16] During the process of fermentation in black and oolong tea manufacture, enzymatic oxidation of tea polyphenols, especially tea catechins, takes place, leading to formation of a series of colored chemical compounds, ie TFs and TRs, which are responsible for the characteristics of black tea infusions. Thus, depending on the extent of fermentation, the colour of the tea infusions will vary accordingly, leading to the colour difference between different samples of tea types. Such colour difference could be used to differentiate between various teas, irrespective of the type of processing. The tea infusion colour difference analysis might be used to characterize the three kinds of tea and to investigate the relationship between the infusion colour difference and the tea quality.

According to the concept of the *L*, *a*, *b* in three-dimensional colour space, the *L* represents the lightness, with 100 for white and 0 for black. The *a* shows the redness when positive and the greenness when negative. Similarly, the *b* shows yellowness when positive and blueness when negative. Comparisons between a tea infusion and distilled water can be easily expressed as a colour difference in terms of $\Delta L$, $\Delta a$, $\Delta b$, $\Delta E$, which describe both the size of difference (large or small values) and direction of color difference ($+$ or $-$). Because distilled water is used as control, $-\Delta L$ shows that the tea sample infusion is darker than water, $+\Delta a$ shows that the tea sample infusion is redder and $-\Delta a$ greener than water and $+\Delta b$ shows that the tea sample infusion is yellower and $-\Delta b$ bluer than water. The $\Delta E$ is a total color difference between the tea infusion and the water with a $+\Delta E$ showing total lightness and hue changes.

## MATERIALS AND METHODS
### Materials
Samples of green tea, oolong tea and black tea were collected from major estates of each kind of tea in China (Table 1). TFs for HPLC references were provided by Dr Takeda from National Research Institute of Tea Science of Japan. The other chemical reagents used were of HPLC grade (Tianjin Shild Biometric Technical Co Ltd, China), except where stated otherwise.

### Methods
*Infusion colour difference analysis*
The above tea sample (5 g) was extracted in 240 ml of freshly boiled distilled water for 5 min. The tea infusion was allowed to cool to room temperature before it was filtered on Double-ring No 102 filter paper (Xinhua Paper Industry Co Ltd, Hangzhou, China). The filtrate obtained was then diluted to 250 ml with distilled water. The infusion colour difference analysis was carried out on TC-PIIG automatic colour difference meter (Beijing Optical Instrument Factory, Beijing, China). The white plate supplied by the TC-PIIG automatic colour difference meter was used as background. To reduce the errors arising from different determination conditions, such as equipment and temperature differences, distilled water was used as control and the infusion colour difference parameters of $\Delta L$, $\Delta a$, $\Delta b$ and $\Delta E$, representing the light–dark, red–green, yellow–blue

**Table 1.** Sources and numbering of tea samples

| Green tea | Black tea | Oolong tea | Estate |
|---|---|---|---|
| G1 | | | Lujiang Ketan Tea Factory, Anhui Province |
| G2 | | | Shanwo tea factory, Chongqing City |
| G3 | | | Wufeng Caihua Town Tea Farm, Hubei Province |
| G4 | | | Yichang Dengcun Tea Company, Hubei Province |
| G5 | | | Hefeng Agricultural Produces Bureau, Hubei Province |
| G6 | B1 | | Mingjia Tea Farm, Chongqing City |
| G7 | | | Liping Guihuatai Tea Farm, Guizhou Province |
| G8 | | | Kaihua Ruilong Tea Co Ltd, Zhejiang Province |
| G9 | | | Jingcheng Tea Co Ltd, Zhejiang Province |
| G10 | | | Third Tea Factory of Anji Nanhu Forestry Farm, Zhejiang Province |
| G11, G12 | | | Shilifeng Tea Farm, Zhejiang Province |
| G13 | | | Longquan Agricultural Produces Industry Co Ltd, Zhejiang Province |
| G14 | | | Douyun Jiajia Yishou Health Tea Factory, Guizhou Province |
| G15, G16 | | | Xinsheng Tea Factory, Chongqing City |
| G17 | | | Lujiang Ketan Tea Factory, Anhui Province |
| G18 | | | Wuyuan Green Food Co Ltd, Jiangxi Province |
| G19, G20 | | | Changsha Tea Factory, Hunan Province |
| G21 | | | Xianju Xianlong Tea Co Ltd, Zhejiang Province |
| G22, G23 | B2 | | Longbei Farm Tea Factory, Guangxi Province |
| G24 | | | Shucheng Tea Co Ltd, Anhui Province |
| G25 | B3, B4, B5, B6, B7 | | Menghai Tea Factory, Yunnan Province |
| G26, G27 | | | Lishui Experimental Tea Farm, Jiangsu Province |
| G28 | | | Jinglong Tea Company, Guizhou Province |
| G29 | | | Jiaonan Zhufeng Green Tea Factory, Shangdong Province |
| | B8 | | Lingyun Shalixiang Tea Farm, Guangxi Province |
| | B9, B10 | | Huzhou Tea Factory, Zhejiang Province |
| | B11, B12 | | Fengqing Tea Factory, Yunan Province |
| | B13, B14, B15, B16 | | Jiangming Tea Co Ltd, Zhejiang Province |
| | | O1, O2, O3, O4, O5 | Chaozhou Tea Import and Export Company, Guangdong Province |
| | | O6, O7 | Quanzhou Ruilong Tea Co Ltd, Fujiang Province |
| | | O8, O9, O10 | Anxi Tea and Fruits Bureau, Fujian Province |
| | | O11 | ,Dabutong Tea Co Ltd, Shanghai City |
| | | O12, O13 | Fujian Tea Import and Export Co, Ltd, Fujian Province |

and total colour difference, respectively, in the three-dimensional colour coordinate system between the tea sample infusion and distilled water, were read and printed out directly by the TC-PIIG automatic colour difference meter.

*Organoleptic examination of tea quality*
The tea samples were examined and scored by professional tea tasters from the Department of Tea Science, Zhejiang University, China. The grading system was based on a maximum total score of 100 of which 10% was awarded for dry tea appearance, 30% for aroma, 15% for liquor colour, 35% for taste and 10% for infused leaf.

The tests in the present paper were duplicated and the mean values of the duplicate tests are presented in the paper.

## RESULTS AND DISCUSSION
### Colour difference of various tea infusions
The $\Delta L$ the results showed that infusions of the black teas were the darkest and those of green teas the lightest, with that of oolong teas intermediate (Tables 2–4). According to the $\Delta a$, all the black tea infusions were red while the green tea infusions were green, except for sample G8 (Tables 2 and 3). The $\Delta a$ could easily differentiate between green and black teas. However, oolong tea infusions were different, with 38% of samples showing red and 62% green (Table 4). The $\Delta b$ showed that the infusions of the three kinds of tea were yellow, although the deepness of the yellow colour changed with various kinds of tea. The total colour difference, $\Delta E$, was the largest for the fully fermented black tea and the smallest for the non-fermented green tea, with oolong tea intermediate (Tables 2–4).

### Relationship between the infusion colour difference and the quality attributes of tea
The average sensory quality score given by the tea tasters was $81.0 \pm 4.5$ for green tea (Table 5), $78.5 \pm 5.1$ for black tea (Table 6) and $79.9 \pm 6.8$ for oolong tea (Table 7). Linear correlation analysis confirmed that the $\Delta L$ was negatively correlated to various quality attributes of black tea but positively correlated to quality attributes of green tea and oolong tea (Table 8). It suggests that, the deeper the infusion colour, the better for black tea but the worse for green tea and oolong tea. The $\Delta a$, $\Delta b$ and $\Delta E$ were negatively correlated to quality attributes of green tea and oolong tea but

**Table 2.** Colour difference parameters of green tea infusions (mean ± SD[a])

| Sample no | $\Delta L$ | $\Delta a$ | $\Delta b$ | $\Delta E$ |
|---|---|---|---|---|
| G1 | −9.54 ± 0.16 | −3.03 ± 0.02 | 22.16 ± 0.25 | 24.31 ± 0.33 |
| G2 | −8.15 ± 0.13 | −1.25 ± 0.01 | 17.56 ± 0.33 | 19.40 ± 0.24 |
| G3 | −9.46 ± 0.18 | −1.96 ± 0.02 | 18.02 ± 0.22 | 20.45 ± 0.51 |
| G4 | −8.96 ± 0.20 | −1.35 ± 0.03 | 18.83 ± 0.39 | 20.86 ± 0.36 |
| G5 | −8.05 ± 0.16 | −2.59 ± 0.01 | 17.36 ± 0.37 | 19.31 ± 0.42 |
| G6 | −9.53 ± 0.09 | −0.13 ± 0.01 | 19.27 ± 0.39 | 21.50 ± 0.44 |
| G7 | −8.02 ± 0.16 | −0.42 ± 0.02 | 14.09 ± 0.21 | 16.22 ± 0.68 |
| G8 | −11.32 ± 0.23 | 0.22 ± 0.01 | 20.03 ± 0.23 | 23.01 ± 0.46 |
| G9 | −12.03 ± 0.21 | −1.31 ± 0.02 | 18.81 ± 0.46 | 22.37 ± 0.18 |
| G10 | −8.47 ± 0.23 | −1.61 ± 0.01 | 16.85 ± 0.08 | 18.93 ± 0.33 |
| G11 | −9.94 ± 0.15 | −1.13 ± 0.02 | 19.51 ± 0.39 | 21.93 ± 0.19 |
| G12 | −12.56 ± 0.24 | −2.44 ± 0.03 | 19.89 ± 0.32 | 23.66 ± 0.24 |
| G13 | −9.79 ± 0.18 | −3.35 ± 0.02 | 18.28 ± 0.56 | 21.01 ± 0.16 |
| G14 | −11.90 ± 0.22 | −2.06 ± 0.03 | 24.48 ± 0.29 | 27.29 ± 0.24 |
| G15 | −10.57 ± 0.11 | −1.18 ± 0.01 | 18.77 ± 0.31 | 21.57 ± 0.33 |
| G16 | −10.74 ± 0.09 | −1.30 ± 0.01 | 18.75 ± 0.38 | 21.65 ± 0.21 |
| G17 | −11.91 ± 0.20 | −2.80 ± 0.03 | 21.29 ± 0.81 | 24.55 ± 0.22 |
| G18 | −13.77 ± 0.23 | −0.84 ± 0.01 | 22.08 ± 0.43 | 26.04 ± 0.39 |
| G19 | −10.86 ± 0.06 | −1.14 ± 0.03 | 25.24 ± 0.62 | 27.50 ± 0.34 |
| G20 | −12.09 ± 0.08 | −1.22 ± 0.03 | 28.31 ± 0.33 | 30.81 ± 0.26 |
| G21 | −7.64 ± 0.11 | −3.12 ± 0.05 | 19.19 ± 0.34 | 20.89 ± 0.52 |
| G22 | −9.95 ± 0.14 | −1.54 ± 0.02 | 15.31 ± 0.72 | 18.33 ± 0.25 |
| G23 | −8.39 ± 0.11 | −2.19 ± 0.06 | 18.33 ± 0.43 | 20.28 ± 0.31 |
| G24 | −13.97 ± 0.06 | −1.27 ± 0.01 | 22.95 ± 0.17 | 26.90 ± 0.62 |
| G25 | −17.22 ± 0.21 | −0.08 ± 0.01 | 30.44 ± 0.32 | 34.98 ± 0.13 |
| G26 | −14.08 ± 0.18 | −2.33 ± 0.6 | 20.11 ± 0.22 | 24.66 ± 0.46 |
| G27 | −10.44 ± 0.07 | −2.98 ± 0.05 | 20.12 ± 0.31 | 22.86 ± 0.53 |
| G28 | −8.42 ± 0.10 | −2.40 ± 0.10 | 18.28 ± 0.42 | 20.27 ± 0.12 |
| G29 | −6.86 ± 0.05 | −2.07 ± 0.03 | 14.27 ± 0.11 | 15.97 ± 0.18 |
| Average | −10.50 ± 1.82 | −1.69 ± 0.79 | 19.95 ± 2.60 | 22.67 ± 3.07 |

[a] SD, standard deviation.

**Table 3.** Colour difference parameters of black tea infusions (mean ± SD[a])

| Sample no | $\Delta L$ | $\Delta a$ | $\Delta b$ | $\Delta E$ |
|---|---|---|---|---|
| B1 | −27.17 ± 0.31 | 13.67 ± 0.11 | 44.58 ± 0.52 | 53.97 ± 0.22 |
| B2 | −75.62 ± 0.81 | 44.03 ± 0.21 | 58.88 ± 0.32 | 105.47 ± 0.32 |
| B3 | −27.08 ± 0.21 | 12.61 ± 0.09 | 47.39 ± 0.24 | 56.02 ± 0.42 |
| B4 | −25.49 ± 0.33 | 11.26 ± 0.04 | 46.89 ± 0.21 | 54.55 ± 0.41 |
| B5 | −44.10 ± 0.13 | 30.43 ± 0.06 | 51.04 ± 0.33 | 74.01 ± 0.21 |
| B6 | −38.30 ± 0.32 | 27.38 ± 0.05 | 50.89 ± 0.25 | 69.33 ± 0.40 |
| B7 | −39.77 ± 0.41 | 30.39 ± 0.31 | 52.38 ± 0.60 | 72.88 ± 0.41 |
| B8 | −39.51 ± 0.62 | 19.08 ± 0.22 | 49.69 ± 0.26 | 66.29 ± 0.46 |
| B9 | −25.40 ± 0.31 | 10.26 ± 0.21 | 42.95 ± 0.24 | 50.94 ± 0.33 |
| B10 | −28.54 ± 0.11 | 11.12 ± 0.13 | 44.45 ± 0.33 | 53.98 ± 0.38 |
| B11 | −33.06 ± 0.24 | 19.46 ± 0.11 | 51.01 ± 0.52 | 63.82 ± 0.34 |
| B12 | −47.01 ± 0.48 | 33.87 ± 0.21 | 51.49 ± 0.08 | 77.51 ± 0.67 |
| B13 | −37.26 ± 0.63 | 27.70 ± 0.31 | 51.32 ± 0.63 | 69.21 ± 0.66 |
| B14 | −21.90 ± 0.42 | 8.34 ± 0.10 | 42.27 ± 0.22 | 48.33 ± 0.55 |
| B15 | −38.23 ± 0.41 | 18.00 ± 0.13 | 46.50 ± 0.18 | 62.83 ± 0.64 |
| B16 | −34.44 ± 0.33 | 19.18 ± 0.14 | 47.38 ± 0.62 | 61.64 ± 0.42 |
| Average | −36.43 ± 12.75 | 21.05 ± 10.23 | 48.69 ± 4.24 | 65.05 ± 13.91 |

[a] SD, standard deviation.

**Table 4.** Colour difference parameters of oolong tea infusions (mean ± SD[a])

| Sample no | $\Delta L$ | $\Delta a$ | $\Delta b$ | $\Delta E$ |
|---|---|---|---|---|
| O1 | −23.32 ± 0.32 | 5.39 ± 0.09 | 35.43 ± 0.36 | 42.76 ± 0.33 |
| O2 | −13.31 ± 0.21 | 0.15 ± 0.01 | 24.58 ± 0.26 | 27.87 ± 0.31 |
| O3 | −11.87 ± 0.62 | −0.20 ± 0.03 | 22.24 ± 0.24 | 25.21 ± 0.25 |
| O4 | −12.56 ± 0.42 | −0.36 ± 0.05 | 23.79 ± 0.33 | 26.91 ± 0.42 |
| O5 | −13.32 ± 0.12 | −0.26 ± 0.05 | 23.78 ± 0.16 | 27.26 ± 0.16 |
| O6 | −9.79 ± 0.13 | −0.72 ± 0.02 | 27.18 ± 0.14 | 28.90 ± 0.62 |
| O7 | −9.93 ± 0.21 | −1.30 ± 0.06 | 28.16 ± 0.41 | 29.88 ± 0.42 |
| O8 | −5.63 ± 0.31 | −1.75 ± 0.07 | 16.22 ± 0.02 | 17.26 ± 0.27 |
| O9 | −10.28 ± 0.52 | −3.69 ± 0.09 | 30.42 ± 0.44 | 32.32 ± 0.67 |
| O10 | −6.71 ± 0.24 | −2.73 ± 0.12 | 19.26 ± 0.51 | 20.58 ± 0.55 |
| O11 | −21.08 ± 0.22 | 2.02 ± 0.47 | 33.44 ± 0.87 | 39.58 ± 0.21 |
| O12 | −19.94 ± 0.33 | 4.90 ± 0.51 | 39.08 ± 0.91 | 44.15 ± 0.22 |
| O13 | −17.23 ± 0.31 | 2.53 ± 0.12 | 36.89 ± 0.66 | 40.80 ± 0.42 |
| Average | −13.46 ± 5.46 | 0.31 ± 2.72 | 27.73 ± 7.00 | 31.04 ± 8.46 |

[a] SD, standard deviation.

positively correlated to quality attributes of black tea (Table 8).

Correlation analysis showed that total quality score of green tea (TQSg) was negatively associated with $\Delta a$, with the linear regression coefficient $r = -0.472$ ($p < 0.01$). Regression of TQSg on $\Delta a$ produced the following highly significant relationship ($R^2 = 0.22$, $p < 0.01$):

$$\text{TQSg} = -2.26\Delta a + 77.2$$

This equation predicted TQSg within a standard error of 4.1 points.

The result was consistent with the greenness of tea leaves (including dry tea leaf and infused leaf) and infusion being very important for green tea.[11] To preserve the green colour of green tea leaf and its infusion during green tea manufacture, freshly picked tea shoots are steamed in a steamer or roasted in a hot drum to inactivate various enzymes

of the tea shoots so as to inhibit the enzymatic oxidation of tea polyphenols and the degradation of chlorophyll.

Correlation analysis showed that total quality score of black tea (TQSb) was positively correlated to $\Delta b$, with the linear regression coefficient $r = 0.564$ ($p < 0.05$), while $\Delta L$ and $\Delta a$ were not significantly correlated to TQSb (Table 8). Regression of TQSb on $\Delta b$ gave the following significant relationship ($R^2 = 0.318$, $p < 0.05$):

$$\text{TQSb} = 0.70\Delta b + 44.6$$

This equation predicted the TQSb with a standard error of 4.5 points.

The $\Delta b$ is a parameter of yellowness when its value is positive. TFs are a group of major pigments giving yellow-orange colour in black tea.[1] HPLC results showed that the mean concentration of total TFs in the 16 black tea samples was 9.002 mg g$^{-1}$, ranging

**Table 5.** Sensory quality scores of green tea samples (mean ± SD[a])

| Sample no | Appearance | Aroma | Liquor colour | Taste | Infused leaf | TQSg[b] |
|---|---|---|---|---|---|---|
| G1 | 7.9 ± 0.2 | 23.1 ± 0.1 | 12.2 ± 0.4 | 27.0 ± 0.1 | 7.6 ± 0.3 | 77.7 ± 1.2 |
| G2 | 8.1 ± 0.1 | 23.4 ± 0.1 | 12.3 ± 0.2 | 27.3 ± 0.8 | 8.4 ± 0.2 | 79.5 ± 1.6 |
| G3 | 8.3 ± 0.3 | 24.0 ± 0.3 | 12.9 ± 0.1 | 27.7 ± 0.3 | 8.3 ± 0.1 | 81.2 ± 1.1 |
| G4 | 8.2 ± 0.1 | 26.4 ± 0.5 | 12.8 ± 0.5 | 28.7 ± 0.2 | 8.3 ± 0.2 | 84.4 ± 1.5 |
| G5 | 8.1 ± 0.4 | 27.0 ± 0.2 | 13.1 ± 0.1 | 28.7 ± 0.1 | 8.4 ± 0.2 | 85.3 ± 1.2 |
| G6 | 8.2 ± 0.1 | 23.1 ± 0.3 | 11.0 ± 0.3 | 27.3 ± 0.2 | 8.5 ± 0.2 | 78.1 ± 1.1 |
| G7 | 8.4 ± 0.2 | 24.9 ± 0.2 | 12.6 ± 0.2 | 29.4 ± 0.1 | 8.9 ± 0.3 | 84.2 ± 1.2 |
| G8 | 7.8 ± 0.5 | 22.8 ± 0.3 | 11.3 ± 0.1 | 26.3 ± 0.5 | 7.8 ± 0.1 | 75.9 ± 1.8 |
| G9 | 8.1 ± 0.3 | 25.8 ± 0.2 | 12.8 ± 0.1 | 30.1 ± 0.1 | 8.8 ± 0.3 | 85.6 ± 1.1 |
| G10 | 7.9 ± 0.2 | 22.8 ± 0.1 | 12.9 ± 0.2 | 27.0 ± 0.2 | 8.1 ± 0.2 | 78.7 ± 1.0 |
| G11 | 7.9 ± 0.5 | 22.5 ± 0.2 | 11.7 ± 0.3 | 26.3 ± 0.1 | 8.3 ± 1.0 | 76.7 ± 1.3 |
| G12 | 7.8 ± 0.4 | 22.5 ± 0.2 | 12.0 ± 0.1 | 25.9 ± 0.3 | 8.2 ± 0.6 | 76.4 ± 2.1 |
| G13 | 8.1 ± 0.4 | 26.1 ± 0.1 | 13.4 ± 0.2 | 28.4 ± 0.2 | 8.3 ± 0.2 | 84.2 ± 1.2 |
| G14 | 7.3 ± 0.2 | 22.2 ± 0.1 | 12.2 ± 0.3 | 27.0 ± 0.6 | 8.0 ± 0.1 | 76.6 ± 1.7 |
| G15 | 7.8 ± 0.2 | 22.5 ± 0.1 | 12.5 ± 0.2 | 26.6 ± 0.2 | 8.2 ± 0.3 | 77.6 ± 1.2 |
| G16 | 7.6 ± 0.4 | 22.5 ± 0.3 | 12.3 ± 0.1 | 26.6 ± 0.1 | 8.3 ± 0.3 | 77.3 ± 1.4 |
| G17 | 8.1 ± 0.2 | 24.9 ± 0.1 | 12.5 ± 0.3 | 30.1 ± 0.3 | 8.2 ± 0.2 | 83.8 ± 1.2 |
| G18 | 7.9 ± 0.2 | 23.7 ± 0.2 | 11.7 ± 0.1 | 28.0 ± 0.2 | 8.2 ± 0.5 | 79.5 ± 1.2 |
| G19 | 7.6 ± 0.3 | 23.7 ± 0.1 | 11.6 ± 0.2 | 27.3 ± 0.2 | 8.0 ± 0.2 | 78.2 ± 1.0 |
| G20 | 6.8 ± 0.2 | 22.8 ± 0.3 | 11.6 ± 0.2 | 25.9 ± 0.1 | 7.5 ± 0.3 | 74.6 ± 1.3 |
| G21 | 8.8 ± 0.3 | 25.8 ± 0.2 | 12.6 ± 0.1 | 31.2 ± 0.3 | 8.9 ± 0.3 | 87.3 ± 1.4 |
| G22 | 8.0 ± 0.3 | 26.7 ± 0.2 | 13.4 ± 0.3 | 31.5 ± 0.3 | 8.8 ± 0.4 | 88.4 ± 1.6 |
| G23 | 7.9 ± 0.2 | 24.9 ± 0.1 | 12.5 ± 0.2 | 27.7 ± 0.4 | 7.9 ± 0.4 | 80.8 ± 1.7 |
| G24 | 7.8 ± 0.1 | 23.7 ± 0.3 | 11.4 ± 0.1 | 27.7 ± 0.1 | 7.9 ± 0.3 | 78.5 ± 1.2 |
| G25 | 7.1 ± 0.2 | 22.2 ± 0.4 | 11.0 ± 0.3 | 26.3 ± 0.3 | 7.4 ± 0.1 | 73.9 ± 1.5 |
| G26 | 8.5 ± 0.2 | 27.6 ± 0.2 | 13.4 ± 0.4 | 32.2 ± 0.1 | 8.7 ± 0.2 | 90.4 ± 1.2 |
| G27 | 8.3 ± 0.4 | 26.1 ± 0.1 | 13.2 ± 0.1 | 29.8 ± 0.2 | 8.6 ± 0.3 | 86.0 ± 1.3 |
| G28 | 7.7 ± 0.1 | 24.3 ± 0.1 | 12.6 ± 0.3 | 27.7 ± 0.5 | 7.9 ± 0.4 | 80.2 ± 1.8 |
| G29 | 8.0 ± 0.2 | 26.7 ± 0.5 | 13.5 ± 0.1 | 31.2 ± 0.2 | 8.5 ± 0.3 | 87.9 ± 1.6 |
| Average | 7.9 ± 0.4 | 24.3 ± 1.7 | 12.4 ± 0.7 | 28.1 ± 1.8 | 8.2 ± 0.4 | 81.0 ± 4.5 |

[a] SD, standard deviation.
[b] TQSg, total quality score of green tea.

**Table 6.** Sensory quality scores of black tea samples (mean ± SD[a])

| Sample no | Appearance | Aroma | Liquor color | Taste | Infused leaf | TQSb[b] |
|---|---|---|---|---|---|---|
| B1 | 8.3 ± 0.3 | 24.3 ± 0.5 | 11.3 ± 0.2 | 28.7 ± 0.6 | 8.0 ± 0.2 | 80.6 ± 2.0 |
| B2 | 8.6 ± 0.2 | 24.9 ± 0.6 | 13.1 ± 0.1 | 28.4 ± 0.5 | 8.5 ± 0.3 | 83.4 ± 1.6 |
| B3 | 6.6 ± 0.1 | 23.1 ± 0.7 | 12.9 ± 0.3 | 27.0 ± 0.4 | 6.8 ± 0.3 | 76.4 ± 1.9 |
| B4 | 6.8 ± 0.2 | 23.4 ± 0.5 | 12.6 ± 0.2 | 27.3 ± 0.5 | 7.1 ± 0.4 | 77.2 ± 2.0 |
| B5 | 8.0 ± 0.2 | 21.0 ± 0.4 | 11.3 ± 0.2 | 25.6 ± 0.3 | 7.8 ± 0.3 | 73.6 ± 1.7 |
| B6 | 8.3 ± 0.1 | 20.4 ± 0.3 | 11.7 ± 0.3 | 26.3 ± 0.3 | 8.1 ± 0.2 | 74.8 ± 1.5 |
| B7 | 7.8 ± 0.2 | 23.4 ± 0.3 | 12.0 ± 0.2 | 27.7 ± 0.4 | 7.7 ± 0.3 | 78.6 ± 1.5 |
| B8 | 9.2 ± 0.2 | 23.7 ± 0.3 | 13.8 ± 0.2 | 28.7 ± 0.4 | 9.2 ± 0.3 | 84.6 ± 1.6 |
| B9 | 6.4 ± 0.1 | 20.4 ± 0.2 | 11.4 ± 0.2 | 26.6 ± 0.3 | 6.5 ± 0.1 | 71.3 ± 1.2 |
| B10 | 6.2 ± 0.2 | 19.8 ± 0.3 | 11.0 ± 0.2 | 25.9 ± 0.4 | 6.4 ± 0.2 | 69.3 ± 1.5 |
| B11 | 8.0 ± 0.3 | 25.8 ± 0.5 | 12.8 ± 0.2 | 30.5 ± 0.5 | 8.2 ± 0.2 | 85.2 ± 1.8 |
| B12 | 8.8 ± 0.2 | 26.4 ± 0.6 | 12.8 ± 0.3 | 29.8 ± 0.6 | 8.6 ± 0.3 | 86.3 ± 2.1 |
| B13 | 8.2 ± 0.2 | 24.0 ± 0.4 | 12.3 ± 0.3 | 27.3 ± 0.4 | 8.2 ± 0.2 | 80.0 ± 1.6 |
| B14 | 6.6 ± 0.1 | 22.2 ± 0.2 | 10.8 ± 0.2 | 25.9 ± 0.3 | 6.8 ± 0.1 | 72.3 ± 1.1 |
| B15 | 8.1 ± 0.2 | 22.8 ± 0.3 | 12.3 ± 0.3 | 28.4 ± 0.5 | 7.8 ± 0.3 | 79.4 ± 1.8 |
| B16 | 8.3 ± 0.2 | 24.6 ± 0.3 | 12.6 ± 0.2 | 29.1 ± 0.7 | 8.0 ± 0.2 | 82.6 ± 1.7 |
| Average | 7.8 ± 0.90 | 23.1 ± 1.89 | 12.2 ± 0.83 | 27.7 ± 1.41 | 7.7 ± 0.78 | 78.5 ± 5.07 |

[a] SD, standard deviation.
[b] TQSb, total quality score of black tea.

from 1.472 to 25.108 mg g$^{-1}$ (Table 9). The average concentration of theaflavin-3′-gallate (TF3′G) was highest and theaflavin-3-gallate (TF3G) the lowest

among the four detected TF compounds. Linear correlation analysis showed that the concentration of individual TF compounds except for TF3D

**Table 7.** Sensory quality scores of oolong tea samples (mean ± SD[a])

| Sample no | Appearance | Aroma | Liquor colour | Taste | Infused leaf | TQSo[b] |
|---|---|---|---|---|---|---|
| O1 | 6.5 ± 0.2 | 22.2 ± 0.4 | 10.5 ± 0.3 | 27.3 ± 0.6 | 7.0 ± 0.3 | 73.5 ± 1.9 |
| O2 | 7.9 ± 0.2 | 24.9 ± 0.3 | 13.4 ± 0.2 | 28.7 ± 0.4 | 8.5 ± 0.3 | 83.4 ± 1.5 |
| O3 | 7.8 ± 0.2 | 24.3 ± 0.2 | 13.2 ± 0.3 | 27.7 ± 0.6 | 8.3 ± 0.3 | 81.3 ± 2.0 |
| O4 | 7.9 ± 0.1 | 21.6 ± 0.5 | 13.2 ± 0.3 | 24.5 ± 0.5 | 8.4 ± 0.3 | 75.6 ± 1.9 |
| O5 | 7.6 ± 0.1 | 21.0 ± 0.3 | 12.9 ± 0.2 | 23.8 ± 0.4 | 8.2 ± 0.3 | 73.5 ± 1.5 |
| O6 | 8.4 ± 0.2 | 24.9 ± 0.3 | 13.4 ± 0.2 | 28.7 ± 0.5 | 8.2 ± 0.4 | 83.6 ± 1.7 |
| O7 | 8.3 ± 0.2 | 24.6 ± 0.2 | 13.2 ± 0.2 | 29.1 ± 0.4 | 8.1 ± 0.3 | 83.3 ± 1.4 |
| O8 | 9.0 ± 0.3 | 27.3 ± 0.3 | 13.5 ± 0.1 | 31.9 ± 0.4 | 8.5 ± 0.3 | 90.2 ± 1.5 |
| O9 | 8.8 ± 0.3 | 27.0 ± 0.4 | 12.9 ± 0.2 | 31.5 ± 0.3 | 8.2 ± 0.3 | 88.4 ± 1.7 |
| O10 | 8.8 ± 0.2 | 26.7 ± 0.3 | 13.4 ± 0.2 | 30.5 ± 0.3 | 8.3 ± 0.2 | 87.6 ± 1.3 |
| O11 | 7.7 ± 0.2 | 19.5 ± 0.3 | 11.1 ± 0.2 | 22.8 ± 0.2 | 7.4 ± 0.2 | 68.5 ± 1.2 |
| O12 | 7.3 ± 0.2 | 22.2 ± 0.3 | 11.1 ± 0.2 | 26.3 ± 0.3 | 7.0 ± 0.2 | 73.9 ± 1.4 |
| O13 | 7.5 ± 0.3 | 22.8 ± 0.4 | 11.3 ± 0.3 | 27.0 ± 0.4 | 7.2 ± 0.3 | 75.7 ± 1.9 |
| Average | 8.0 ± 0.70 | 23.8 ± 2.44 | 12.5 ± 1.10 | 27.7 ± 2.83 | 7.9 ± 0.57 | 79.9 ± 6.83 |

[a] SD, standard deviation.
[b] TQSb, total quality score of oolong tea.

**Table 8.** Linear correlation coefficient between infusion colour differences and quality score of various teas

| Tea types | Infusion colour difference | Quality attributes | | | | | |
|---|---|---|---|---|---|---|---|
| | | Appearance | Aroma | Liquor colour | Taste | Infused leaf | TQS[a] |
| Green tea (n = 29) | $\Delta L$ | 0.459** | 0.306 | 0.490** | 0.201 | 0.396* | 0.348 |
| | $\Delta a$ | −0.336 | −0.462* | −0.644** | −0.383* | −0.173 | −0.472** |
| | $\Delta b$ | −0.685** | −0.476** | −0.665** | −0.447* | −0.704** | −0.584** |
| | $\Delta E$ | −0.654** | −0.445* | −0.643** | −0.395* | −0.656** | −0.541** |
| Black tea (n = 16) | $\Delta L$ | −0.622* | −0.347 | −0.427 | −0.267 | −0.613* | −0.479 |
| | $\Delta a$ | 0.674** | 0.367 | 0.338 | 0.239 | 0.655** | 0.479 |
| | $\Delta b$ | 0.640** | 0.447 | 0.547* | 0.326 | 0.673** | 0.564* |
| | $\Delta E$ | 0.631** | 0.382 | 0.436 | 0.269 | 0.632** | 0.498* |
| Oolong tea (n = 13) | $\Delta L$ | 0.906** | 0.783** | 0.926** | 0.660* | 0.867** | 0.866** |
| | $\Delta a$ | −0.908** | −0.673* | −0.871** | −0.541 | −0.866** | −0.768** |
| | $\Delta b$ | −0.661* | −0.523 | −0.862** | −0.381 | −0.899** | −0.625* |
| | $\Delta E$ | −0.752** | −0.608* | −0.915** | −0.463 | −0.926** | −0.710** |

* $p < 0.05$; ** $p < 0.01$.
[a] TQS, total quality score.

**Table 9.** TF concentrations of various tea black samples[a] (mg g$^{-1}$)

| Sample no | TF | TF3G | TF3′G | TF3,3′DG | Total TFs |
|---|---|---|---|---|---|
| B1 | 5.022 | 1.073 | 6.141 | 4.717 | 16.953 |
| B2 | 4.493 | 0.426 | 5.418 | 5.879 | 16.216 |
| B3 | 0.740 | 0.029 | 0.787 | 0.974 | 2.530 |
| B4 | 1.271 | 2.006 | 2.151 | 0.990 | 6.418 |
| B5 | 3.248 | 0.845 | 3.041 | 3.146 | 10.279 |
| B6 | 2.475 | 0.401 | 3.286 | 4.209 | 10.371 |
| B7 | 5.845 | 6.503 | 8.756 | 4.004 | 25.108 |
| B8 | 1.302 | 0.131 | 2.216 | 3.806 | 7.454 |
| B9 | 0.559 | 0.046 | 0.911 | 0.814 | 2.330 |
| B10 | 0.600 | 0.058 | 0.826 | 0.781 | 2.265 |
| B11 | 3.156 | 0.685 | 2.276 | 1.100 | 7.216 |
| B12 | 5.216 | 1.682 | 5.992 | 3.480 | 16.370 |
| B13 | 4.019 | 0.819 | 4.881 | 1.856 | 11.575 |
| B14 | 0.563 | 0.030 | 0.786 | 0.946 | 2.325 |
| B15 | 1.096 | 0.031 | 1.730 | 2.298 | 5.155 |
| B16 | 0.159 | 0.248 | 1.009 | 0.057 | 1.472 |
| Mean | 2.485 | 0.938 | 3.138 | 2.441 | 9.002 |

[a] TF, theaflavin; TF3G, theflavin-3-gallate; TF3′G, theaflavin-3′-gallate; TF3,3′DG, theaflavin-3,3′-digallate.

and total TFs was significantly correlated to TQSb (Table 10).

Black tea quality is strongly influenced by the concentration of TFs, which are a group of yellow-orange pigments produced as a result of enzymatic oxidation of tea polyphenols in the fresh leaf. Thearubigins (TRs), a group of red pigments converted from TFs under the action of peroxidase,[2] contribute to the colour and strength of black tea infusions.[1] However, because TFs are extremely

**Table 10.** Linear correlation coefficients between TF concentration and colour difference parameters of black tea

| | $\Delta L$ | $\Delta a$ | $\Delta b$ | $\Delta E$ |
|---|---|---|---|---|
| TF | −0.517* | 0.708** | 0.632** | 0.601* |
| TF3G | −0.092 | 0.313 | 0.300 | 0.195 |
| TF3′G | −0.483 | 0.672** | 0.585* | 0.563* |
| TF3,3′DG | −0.700** | 0.702** | 0.635** | 0.705** |
| Total TFs | −0.519* | 0.692** | 0.620* | 0.597* |

* $p < 0.05$; ** $p < 0.01$.

important for black tea quality,[1] the conversion from TFs to TRs should be inhibited by controlling fermentation temperature and pH so that the ratio of TRs to TFs remains at a low level.[2,4] The darkness of black tea infusions is influenced by many factors, such as pH.[3] It explains why the yellowness indicator, $\Delta b$, was significantly correlated to total quality score of black tea (TQSb) while $\Delta L$ and $\Delta a$ were not significantly correlated with TQSb (Table 8).

There is no special fermentation stage during oolong tea manufacture, although it is called a semi-fermented tea. The partial oxidation of tea polyphenols takes place during the withering and leaf handling stages of oolong tea manufacture, in which the tea shoots are partially bruised by mechanical handling, leading to the enzymatic oxidation of tea polyphenols. The major purpose of the withering and leaf handling is to promote the enzymatic hydrolysis of the glycoside aroma precursors to release volatile flavour compounds, but not to accelerate the oxidation of tea polyphenols as in black tea. High-quality oolong tea is always lighter in colour and stronger in aroma (such as samples $G_6$, $G_7$, $G_8$, $G_9$ and $G_{10}$ in Tables 4 and 7). Regression of the total quality score of oolong tea (TQSo) upon the darkness indicator, $\Delta L$, gave a highly significant relationship with $R^2 = 0.75$, $p < 0.01$ and standard error of 0.35 points:

$$TQSo = 1.09\Delta L + 94.5$$

From the above results, it can be seen that the $\Delta a$ of tea infusions is a reliable descriptor to differentiate between green and black teas. It is of great importance for quality estimation that the $\Delta a$, $\Delta b$ and $\Delta L$ are significantly correlated to TQSg, TQSb and TQSo, respectively. Because the analysis of the colour difference indicators of $\Delta a$, $\Delta b$ and $\Delta L$ can be done rapidly (in about 15 min), it could be very useful for on-site or on-line quality monitoring during tea manufacture and storage.

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