Factors Affecting the Caffeine and Polyphenol Contents of Black and Green Tea Infusions

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The effects of product and preparation variables on the in-cup chemical composition of tea extracts is of interest because the appearance and taste characteristics and the possible health effects of a tea liquor arise from the chemical components extracted from the leaf during tea preparation. A comprehensive study was therefore undertaken to determine the contributions of product and preparation variables on the total soluble solids, caffeine, and polyphenol contents of tea extracts. The results of this study show that the variety, growing environment, manufacturing conditions, and grade (particle size) of the tea leaves each influence the tea leaf and final infusion compositions. In addition, the composition of the tea infusion was shown to be influenced by whether the tea was contained in a teabag and, if so, the size and material of construction of the bag. Finally, the preparation method, including the amounts of tea and water used, infusion time, and amount of agitation, was shown to be a major determinant of the component concentrations of tea beverages as consumed. An illustration of the variation introduced by these product and preparation factors is provided by comparing solids, caffeine, and polyphenol contents of green and black tea infusions when commercial products are prepared according to the instructions given on their packaging.

Keywords: *Camellia sinensis; tea; polyphenols; catechins; caffeine; infusions; Folin–Ciocalteu*

INTRODUCTION

Tea is one of the most widely consumed drinks in the world. In the Far East (particularly in China and Japan), tea is consumed mainly as a hot infusion of "unfermented" fresh green shoots (green tea), whereas in most other countries the beverage is prepared from predominantly "fermented" (black) tea. The different methods of manufacture of these products account for the marked difference in the chemical compositions of green and black teas, and even among green and black tea products the effects of plant variety, growth conditions, and processing method would be expected to produce quite wide variations in the chemical compositions of the resulting products.

In addition, worldwide consumer observations and questionnaire studies on tea preparation habits have shown wide variations among countries, and among individuals within countries, in the way they make their tea (e.g., the weight of tea taken, the amount of water added to the leaves, the amount of agitation used to assist infusion, the length of time the leaf is left in contact with the water, and the use of additional ingredients). In general, Western countries drink black tea, made by infusing a quantity of leaf (usually contained in a teabag) in boiling water in a pot or increasingly in a cup/mug. The infusion time is generally short (<3 min), and the beverage is usually consumed hot (either with or without milk and/or sugar). In India, Pakistan, and some Middle Eastern countries an alternative black tea preparation method is widely adopted. Here the drink is largely prepared by boiling the black leaves in a pan for several minutes prior to consumption (often together with water, milk, and sugar). In the Far East (e.g., China and Japan) the drink is normally prepared from green tea by infusing it in hot (but not boiling) water. Generally the first infusion is discarded and it is the second and subsequent infusions that are consumed. More recently, in the West, green teas (often contained in teabags) have gained in popularity.

The effects of these wide product and preparation differences on the in-cup chemical composition of tea infusions is of interest because the quality and health properties of the consumed drink are associated with the chemical components (in particular the polyphenols and caffeine) extracted from the leaf. The health effects of tea consumption have, for example, been the subject of a number of epidemiological and intervention studies, and evidence is emerging of a relationship between tea consumption and a reduced risk of cardiovascular disease and cancer (*1*–*4*). The primary components under study in this respect are the flavonoid polyphenols, which have been demonstrated to have strong antioxidant effects in vitro (*5*, *6*).

Caffeine, because it is widely consumed in a variety of products including tea, continues to be the subject of an intense level of scrutiny. Generally speaking, the extensive studies of caffeine have shown that it is not a harmful compound (*7*), although some epidemiological studies have suggested a link between a high caffeine intake and the risk of spontaneous abortion (*8*, *9*).

In epidemiological and some intervention studies the amount of tea estimated from the number of cups consumed is frequently used as an indicator of caffeine or polyphenol consumption. However, this may provide a misleading measure of intake because of the large variations introduced by product and tea preparation differences. Some of the factors affecting the rate of infusion of tea solubles into aqueous solution have been

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10.1021/jf010759+ CCC: $20.00
Published on Web 10/31/2001

widely studied. One of the earlier experimental studies (*10*) examined the influence of a range of variables, including the nature of the raw materials, the purity and temperature of the water, the infusion time, and the water-to-leaf ratio, on the brewing behavior of tea. This showed that the rate of extraction of selected soluble constituents increased with decreased particle size, increased brewing temperature, and increased water/leaf ratio. Little research then followed until the extensive studies conducted by Spiro and co-workers. Spiro introduced simple kinetic models (*11*, *12*) to explain the observed rates of extraction of individual constituents into aqueous solution. The experimental studies measured the amount of extracted tea constituents as a function of time, when tea is infused in water at a constant elevated temperature. The results yield so-called *infusion curves* in which the liquor concentrations of polyphenols and caffeine (or any other tea soluble) increase with brew time. The rate of increase of concentration with time gradually falls off until an equilibrium level is reached. At this stage the soluble material is partitioned between the tea brew and the hydrated tea leaves.

The rate-determining step in the loose-leaf infusion was determined as the diffusion of the solute through the leaf matrix to the surface. The influence of leaf size, origin, and manufacture on the rate of infusion of caffeine and theaflavin has been reported (*13*). The rate constants increased as leaf size decreased and varied between the different leaf types (i.e., Kenyan CTC infused more rapidly than Indian orthodox teas). Further studies (*14*, *15*) compared the rates of caffeine infusion from green and black teas. These showed that the rate of infusion of caffeine was greater from green tea than from a similarly sized black tea, confirming a possible effect of manufacturing method upon infusion characteristics. A study of the effects of black and green teas on in vitro lipoprotein oxidation (*16*) also looked at the effect of extraction time on the composition of loose-leaf brews prepared at “drinking strength”. Differences were observed between the extraction kinetics of the polyphenolics (50−60% extraction after 4 min) and the caffeine (80% extraction after 30 s). No significant difference in antioxidant activity was detected between green and black teas.

Most of the research to date has been concerned with the physicochemical aspects of the dissolution process from *loose-leaf tea* over comparatively *long time periods*. Of increasing interest, however, are the factors that affect the amounts of physiologically active components in a “consumer brew” obtained when a *teabag tea* is infused for a relatively *short time period*. Two recent studies have investigated the composition of consumer strength teabag brews. The polyphenol and caffeine contents of four commercial black tea blends were determined and the compositions of their infusions measured for brew times of up to 2 min (*17*). This confirmed the previous findings on loose-leaf infusions (*16*) and showed caffeine to be more efficiently extracted (up to 90% of the total available in the leaf) than the polyphenols (up to 55% of the total available in the leaf). A second recent study (*18*) looked at the effects of a few preparation variables (brew time, temperature, teabags, and milk addition) on the antioxidant content of green and black tea infusions. Green teas brewed for long time periods and at high temperature gave the highest antioxidant content. The effects of two important domestic preparation variables (leaf/water ratio and agitation) were, however, omitted from the latter study, which was conducted on only a limited number of tea products.

The aim of this study is to evaluate a wider range of product and preparation variables and to determine the contributions they make to the composition and strength of an in-home infusion.

MATERIALS AND METHODS

Preparation of Extracts. Aqueous extracts were prepared by infusing the loose tea (or teabags) in a measured volume of boiling deionized water for a fixed time period (either with or without mechanical agitation). The teabag was then removed (or in the case of loose-leaf infusion the liquor filtered under vacuum through a No.1 sintered glass crucible) and the solution allowed to cool to room temperature. This was repeated three times, and the extracts were combined to form the analytical sample.

The leaf composition was determined by the analysis of “total” extracts. These were prepared by extracting milled leaf samples (0.20 g) with aqueous methanol (70:30 methanol/water). The leaf was extracted twice with aqueous methanol (5 mL at 70 °C for 10 min) and centrifuged, and the combined supernatant liquors were readjusted to volume (10 mL) with 70% aqueous methanol to form the analytical sample. This procedure was used because it gave total polyphenol values comparable to those obtained by aqueous extraction (100:1 water to ground leaf refluxed for 60 min) without degrading the flavonols (*19*).

Determination of Soluble Solids. Soluble solids were determined by transferring a measured volume of aqueous extract (50 mL) into a tared beaker and evaporating to dryness. The residue was finally dried, in an oven at 103 °C, to constant weight.

Determination of Total Polyphenols. Total polyphenols were determined on the extract samples according to the Folin−Ciocalteu method (*20*, *21*), using gallic acid as the calibrant.

Determination of Caffeine and Flavanols (Catechins). The caffeine and flavanol contents of the extracts were determined by high-performance liquid chromatography (HPLC) as described by Kuhr and Engelhardt (*22*).

RESULTS AND DISCUSSION

Effect of the Nature of the Product. *Tea Origin.* Tea is made from the fresh green shoots of the plant *Camellia sinensis*. Two variants, *C. sinensis* var. *sinensis* (China) and *C. sinensis* var. *assamica* (Assam), exist, which differ significantly in caffeine and polyphenol contents. It has been shown (*23*) that fresh green leaves from Assam teas (*C. sinensis* var. *assamica*) are generally higher in caffeine (mean = 4.09%) and polyphenols (mean = 19.42%) than Chinese cultivars (*C. sinensis* var. *sinensis*) (caffeine mean = 3.11%; polyphenol mean = 16.24%).

The two major commercial tea products, black and green teas, derive from the *C. sinensis* plant but are produced by different processes. To explore the differences between these two tea products, a survey was conducted on a range of black and green tea originals. Caffeine, total polyphenols, and flavanols (catechins) were determined on 70% methanol extracts of black and green teas. The different processing routes can be seen to result in a significant compositional difference between processed green and black products (Table 1). These compositional differences are due in part to the different leaf varieties used as raw material, but more important determinants of final composition are the

Table 1. Total Polyphenols, Caffeine, and Flavanols (Dry Basis) in Original Green and Black Teas

tea type	no. of samples	% total polyphenols (TPP)		% catechins (flavanols) (HPLC)		% caffeine (HPLC)	
		mean	range	mean	range	mean	range
green	95	17.5	11.9−25.2	13.3	7.1−20.8	2.69	1.18−3.66
black	55	14.4	7.3−21.9	2.1	0.7−8.8	3.23	2.21−3.97

Table 2. Composition (70% Methanol Extract) of Green and Black Tea Products from Different Origins

country of origin	green tea				black tea			
	no. of samples	% catechins	% TPP	% caffeine	no. of samples	% catechins	% TPP	% caffeine
Africa					10	1.75	14.83	3.20
Argentina	1	13.8	17.20	2.33	1	0.70	12.90	2.41
Bangladesh	4	11.9	17.65	2.59				
China	40	11.3	15.68	2.74	3	0.93	9.03	2.53
India (Assam)					16	1.45	14.94	3.69
India (Darjeeling)					5	6.30	16.22	3.06
India (south)	25	16.3	20.05	2.57	2	1.25	14.75	2.80
Indonesia	13	14.7	20.43	2.85	5	1.86	15.10	2.92
Japan	12	11.4	13.75	2.30				
Sri Lanka					10	1.63	14.17	3.06
Vietnam					3	1.50	14.30	3.61

different manufacturing processes used to produce the two tea products.

The raw material and process variables that account for the compositional differences in Table 1 can be summarized as follows:

• Most black teas are made using Assam cultivars, the fresh shoots of which contain on average more caffeine than the China cultivars, which are generally used to manufacture green teas (*23*). Hence, black teas are on average higher in caffeine (3.23%) than green teas (2.69%).

• During green tea production the main polyphenols (the catechins) remain relatively intact during the process. This is because the enzymes, which can catalyze their oxidative polymerization, are deactivated by heat treatment (pan-roasting or steaming) soon after plucking. Black tea production, on the other hand, involves a leaf disruption step to promote the enzymatic oxidation of the flavanols (catechins) present in the fresh green leaf to produce polymeric flavonoids (theaflavins and thearubigins) (*24*). Thus, the prepared green teas contain substantially higher levels of catechins (13.3%) than prepared black teas (2.1%).

• The Assam varieties, used to produce most black teas, contain, on average, a higher level of total polyphenols than the China variety, generally used to manufacture green teas (*23*). The total polyphenols in green (17.5%) teas are, however, higher than in black teas (14.4%). The source of this apparent discrepancy is currently under investigation and is thought to be related to the different molecular properties of the green tea polyphenols (mainly catechins) and black tea polyphenols (mainly polymeric thearubigins), which have an influence on the Folin−Ciocalteu results.

Table 1 also shows the considerable variation of caffeine and polyphenol levels within the green and black tea sample sets. Assam and China cultivars can be grown in different geographical regions, where they may be subjected to widely different field conditions and treatments. Furthermore, manufacturing conditions differ from one tea factory to another. One would therefore expect variations in origin and manufacturing conditions to be reflected in the final product composition. A breakdown of the polyphenol and caffeine contents of the teas in Table 1 according to origin confirms this to be the case (Table 2).

Table 3. Changes in Composition of Leaf during the Manufacture of Black and Green Teas from the Same Fresh Assam (*C. sinensis* Var. *assamica*) Tea

stage in the manufacturing process	% catechins	% TPP	% caffeine
(a) Black Tea Process			
freshly plucked tea shoots (flush)	21.34	23.69	3.18
withered leaf	22.17	25.16	3.57
CTC rolled leaf	22.62	24.85	3.75
leaf after 60 min of fermentation	4.78	19.53	3.65
leaf after 120 min of fermentation	2.08	18.39	3.69
fired leaf (60 min of fermentation)	3.35	18.83	3.58
fired leaf (120 min of fermentation)	1.79	17.13	3.60
(b) Green Tea Process			
fresh flush	21.34	23.69	3.18
short withered leaf	24.20	24.90	3.82
pan-fired green leaf	22.00	24.82	3.77
shaped green leaf	21.63	25.05	3.74
fired green leaf	22.76	24.81	3.77

Tea Manufacture (Black and Green Teas). To further investigate the compositional differences between green and black teas, an experiment was conducted that was controlled for raw material variations. Subsamples of the same batch of freshly plucked green leaves (*C. sinensis* var. *assamica*) were made into green and black tea, and the total polyphenol, flavanol, and caffeine determinations were conducted on samples taken at various stages of manufacture. (see Table 3a,b). These data, which were again obtained on total (70% methanol) extracts and calculated on a dry weight basis, showed the following trends:

• A reduction in the total catechin level during the fermentation stage of black tea production. This would be expected from the known reactions of the catechins with oxygen catalyzed by the polyphenol oxidase (PPO) enzyme present in fresh leaf (*25*). The deactivation of this enzyme by the pan-firing of the fresh leaf in the green tea process halts this "fermentation" process and a much lower loss of catechins is observed.

• An apparent reduction in total polyphenols (Folin−Ciocalteu) occurs during fermentation. The reason for this remains unknown but could be a function of (a) a reduction in the level of total methanol extractables (arising from the formation of polymeric thearubigins (TR), which become irreversibly bound to denatured leaf protein in the firing step) or (b) differences in Folin−Ciocalteu response to the green tea polyphenols (mainly

Table 4. Black Tea Manufacturing Methods and Size Fractions Investigated

manufacturing method	grade[a]	nominal classification	particle size range
orthodox	golden flowery broken orange pekoe (GFBOP)	large	1.7−1.18 mm
orthodox	broken orange pekoe fannings (BOPF)	medium	1.18 mm−500 μm
orthodox	pekoe dust (PD)	small	500−250 μm
CTC	broken pekoe (BP)	large	1.7−1.18 mm
CTC	pekoe fannings (PF)	medium	1.18 mm−500 μm
CTC	pekoe dust (PD)	small	500−250 μm

[a] The tea trade classifies different leaf shapes and sizes as these "grades".

Table 5. Composition (70% Methanol Extract) of Black Teas by Manufacturing Method and Size Fraction

manufacturing method	grade	% caffeine	% catechins
orthodox	GFBOP	2.00	1.44
orthodox	BOPF	2.00	1.01
orthodox	PD	2.04	1.06
CTC	BP	2.12	0.71
CTC	PF	2.20	0.43
CTC	PD	2.17	0.48

catechins) and the black tea polyphenols (mainly thearubigins).

• Changes in caffeine content throughout the various stages of black tea production were observed. The increase in caffeine during the withering stage of black tea production, followed by a decrease during the fermentation and drying stages, has been previously observed (*26*).

• A larger initial increase in caffeine content occurs during the (short) withering stage of green tea manufacture. Little subsequent loss of caffeine is observed during the shaping and firing stages of green tea manufacture. As a result the caffeine content of green tea is marginally higher than that of black tea manufactured from the same starting material.

Tea Manufacture (Black CTC and Orthodox Grades). During the manufacture of *black tea* the physical disruption of the fresh green shoots is generally carried out by one of two methods: rolling (orthodox) or crushing, tearing, and curling (CTC). The orthodox process usually involves less fermentation than does the CTC process. The orthodox and CTC manufactured teas are then dried (fired) and sieved (graded) into different particle size fractions.

To investigate the effect of manufacture method and particle size on the leaf tea composition, samples were obtained from a batch of leaves plucked from the same area of an Assam estate. Half of the freshly plucked leaves were manufactured according to the orthodox process and the remaining half according to the CTC method. Each batch of tea was then graded, and the different size fractions (Table 4) were analyzed for caffeine and flavanol contents.

The effects of the method of black tea manufacture and leaf size on the total (70% methanol extract) flavanol and caffeine content are shown in Table 5.

These data illustrate the following effects of black tea processing method/particle size on leaf composition:

• A lower total catechin content of the CTC-manufactured black teas compared with orthodox-manufactured black teas. This is likely a function of the greater leaf disruption (and hence degree of enzymatic oxidation of the catechins) that occurs during the CTC process.

Table 6. Effect of Brew Time and Leaf Water Ratio (LWR) on the Soluble Solids Extracted from a Typical Teabag

LWR (g/L)	brew time 30 s	60 s	180 s
6	1200 (20.0%)[a]	1900 (31.7%)	2800 (46.7%)
9	1700 (18.9%)	2400 (26.7%)	3500 (38.9%)
12	2500 (20.8%)	3500 (29.2%)	5100 (42.5%)

[a] Extraction efficiencies are given in parentheses.

• The different degrees of leaf disruption also provide an explanation for the comparatively low catechin content of the smaller (CTC and Orthodox) particles.

• The CTC teas contain marginally more caffeine than the orthodox teas. This may be as a result of slightly different withering conditions adopted for CTC and orthodox leaf productions.

We have seen how the origin and manufacture determine the composition of a black or green leaf tea. These variations in leaf composition will in turn be reflected in the composition of an aqueous infusion prepared for consumption. Thus, if we assume maximum aqueous extraction from a teabag containing 2.5 g of black tea [i.e., 90% of the total available caffeine in the leaf and 55% of the total available polyphenols as determined by Lakenbrink (*16*)], then the resulting beverage can contain 50−90 mg of caffeine and 100−300 mg of polyphenols depending on its origin (see Table 1).

The composition of the aqueous infusion will also depend heavily on the method used to prepare the liquor. The next section deals with the preparation variables that affect the solids (and therefore the caffeine and polyphenol) content of tea infusions.

Effect of Tea Preparation. *Brew Time and Leaf/Water Ratio (LWR).* Consumer studies, carried out in Europe, have shown that tea drinkers' brewing habits vary considerably among countries and among individuals within countries. Brew times from less than 30 s to 5 min are commonly observed, with the majority of consumers brewing for <2 min. The LWR used by European consumers also varies considerably as a consequence of (a) the different teabag loading (i.e., 1.5−3.125 g/bag), (b) the number of teabags used, and (c) the different quantities of water added [usually dependent upon whether the brewing vessel is a cup (∼180 cm^3), a mug (∼240 cm^3), or a pot (∼500 cm^3)]. The tea solids intake per cup can thus vary considerably as a result of brew time and initial concentration alone.

The effects of brewing time and initial tea concentration, on the soluble solids extracted from a typical teabag, were investigated, and the findings are shown in Table 6 and illustrated in Figures 1 and 2. These show that

• Within the range of typical consumer drinking strength, the soluble solids content extracted after a given time period is directly proportional to the LWR of tea (Figure 1).

• The soluble solids content extracted as a function of brew time yields typical infusion curves in which the rate of extraction of tea solubles is high during the first minute of infusion but gradually falls off with increasing time.

• The extraction efficiency tends to be generally higher at the lower LWR.

Infusion data for caffeine and polyphenols obtained in this laboratory confirm the previously reported find-

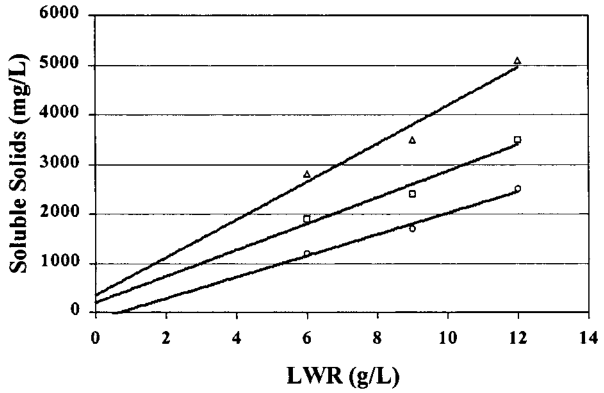

Figure 1. Leaf/water ratio (LWR) effects on extracted solids at different brew times: (○) 30 s brew time; (□) 60 s brew time; (△) 180 s brew time.

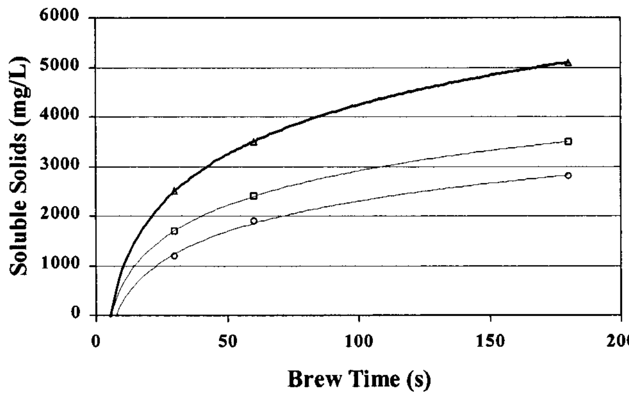

Figure 2. Infusion curves at different leaf water ratios: (○) LWR = 6 g/L; (□) LWR = 9 g/L; (△) LWR = 12 g/L.

Table 7. Effect of Brew Time on the Caffeine and Total Catechins Extracted from a Teabag (3.125 g Bag in 200 mL of Water)

brew time (s)	mg/L in aqueous extract: catechins	mg/L in aqueous extract: caffeine
30	22.1 (19.9%)[a]	108.0 (34.6%)
60	36.5 (32.9%)	159.2 (50.9%)
120	62.9 (56.7%)	227.3 (72.7%)
300	90.5 (81.6%)	285.9 (91.5%)

[a] Extraction efficiencies in parentheses are calculated from leaf content of 2.21% caffeine and 0.71% catechins.

ings (*16*, *17*) that for typical brew times the polyphenol extraction is inefficient compared to that of caffeine (Table 7). These observed differences in the extraction efficiencies of caffeine and polyphenols will affect the relative amounts of these components at different brew times as illustrated in Figure 3.

Teabag Design and Agitation. The kinetics of the loose-leaf infusion system has been thoroughly investigated, and the rate-determining step for a loose-leaf infusion has been determined as the diffusion of the solute through the leaf matrix to the surface. Although many tea drinkers continue to prepare their drink using loose-leaf tea, the more popular way of making tea in the Western world is by using teabags. However, until recently there has been very little published on the effect of teabags on the infusion behavior of tea solubles. The rate of transfer of aqueous caffeine through a membrane of teabag paper has been measured in a model system (*27*), and a negligible resistance to transfer was recorded. Extraction experiments conducted on teabag teas (*28*) did, however, show that differences in

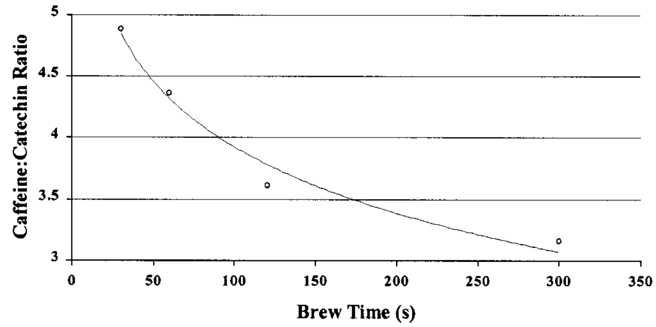

Figure 3. Effect of brew time on caffeine/catechin ratio of an infusion.

the rate of caffeine infusion occur depending on whether the infusion process is carried out on a loose-leaf or a teabag product.

Household studies have revealed a range of tea-making, agitation behaviors among European teabag users. Some add boiling water to the teabag(s) and just leave the bag(s) to float for a given time. Others increase the infusion rate by stirring the water or by moving the teabag up and down (dunking), and both "dunkers" and "stirrers" may or may not squeeze the bag against the side of the tea-making vessel prior to consumption. Furthermore, teabag manufacturers have over the past decade introduced a number of changes to the teabag itself. Bags of different shapes, sizes, and materials of manufacture can now be purchased. The teabag design and the amount of agitation used are both likely to influence the composition of the tea liquor produced during infusion. This was therefore investigated experimentally.

Laboratory studies of the effects of agitation, teabag variables (bag size and paper porosity), and leaf size on infusion performance were conducted on a batch of Assam CTC leaves. The change in the content of liquor soluble solids with time was measured by manipulating the variables below in a full factorial, experimental design. The results are presented as infusion curves

tea particle size	large (1.70−1.18 mm)	small (500−250 μm)
teabag	teabag infusion	loose-leaf infusion
paper type	high porosity	low porosity
bag dimensions	large (51 × 50 mm)	small (44 × 45 mm)
agitation	dynamic (continuous mechanical dunking)	static (none)

(Figures 4−6), which illustrate the following effects of teabag variables on infusion performance:

• Whereas the rate of infusion of tea components has been shown to be independent of the amount of agitation of the loose-leaf tea in solution (*12*), it can be seen (Figures 4−6) that this is not the case for teabag products. These infusion curves illustrate that the agitation to which the teabag is subjected is a major determinant of extraction efficiency; that is, the extraction efficiency is significantly greater for a continuously dunked teabag (dynamic infusion) than it is for a teabag that is left to float in the water, with no external agitation (static infusion).

• Regardless of bag design or brewing method, loose-leaf infusion extracts tea solids into the liquor more efficiently than does teabag infusion. During loose-leaf infusion, soluble components are transported from the tea leaves directly into the bulk liquor. When the tea is contained in a bag, however, the flow resistance, caused by the packed bed of leaves and by the bag material,

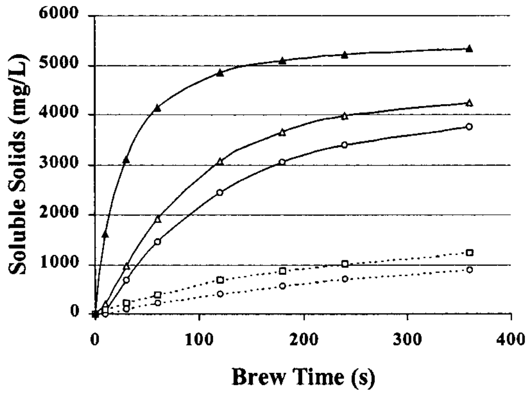

Figure 4. Teabag effects on infusion performance—paper porosity: (−○−) dynamic, low porosity; (··○··) static, low porosity; (−△−) dynamic, high porosity; (··□··) static, high porosity; (▲) loose leaf.

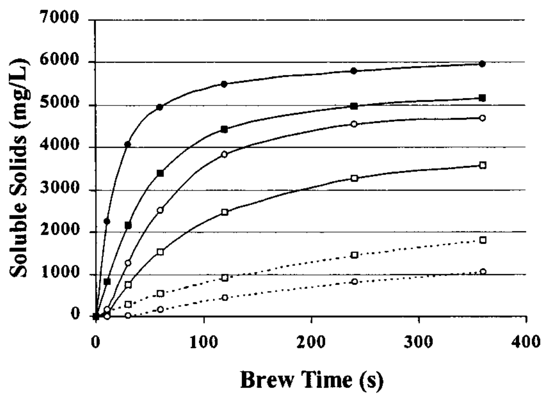

Figure 5. Teabag effects on infusion performance—leaf size effects: (−○−) dynamic, large leaf; (··□··) static, large leaf; (−○−) dynamic, small leaf; (□) static, small leaf; (−■−) loose, large leaf; (−●−) loose, small leaf.

results in a slower transport of the soluble components from inside the bag into the bulk liquid.

• The resistance against flow of tea solubles through the bag increases with decreasing bag material porosity (Figure 4).

• Although the rate of extraction from loose-leaf tea is more rapid with smaller leaves, for teabag teas the effect of leaf size depends on whether the solution is agitated (Figure 5). Under dynamic infusion conditions (continuous mechanical dunking) the small leaf infuses more quickly than the large leaf, whereas with no agitation (static infusion) the reverse is true (large leaf infuses more quickly than small leaf). This has been explained (*29*) in terms of the different driving forces for fluid flow between dynamic and static infusion conditions. Static fluid flow is driven, almost exclusively, by weak forces of convection. Under these conditions the greater porosity of the packed bed of large leaves ensures a more efficient infusion performance than with a more tightly packed (less porous) bed of small leaves. When the liquor is forced through the packed bed of leaves, by external agitation, it is the total surface area of the tea leaves rather than the packing porosity that becomes the controlling factor. Thus, the small leaves infuse more efficiently under “dynamic” infusion conditions.

• The effects of increasing the bag size are to (a) increase the surface area of the bag through which the solution flows and (b) increase the volume and hence the porosity of the leaf bed. As a result the infusion rate

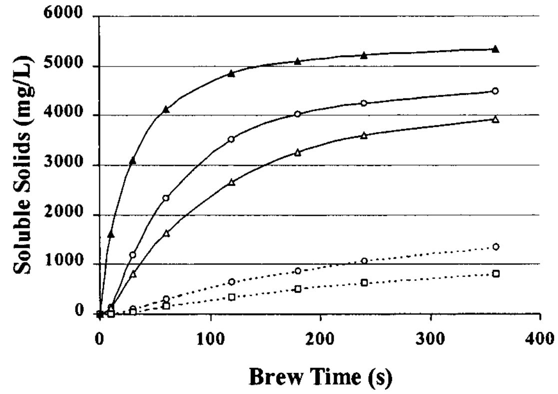

Figure 6. Teabag effects on infusion performance—bag size effect: (−○−) dynamic, large bag; (··○··) static, large bag; (−△−) dynamic, small bag; (··□··) static, small bag; (−▲−) loose leaf.

of tea solids into solution increases with increasing bag size under both dynamic and static conditions (Figure 6).

Composition of Infusions Prepared from Commercial Black and Green Teas. Black teas are usually made from Assam varieties, which are generally higher in polyphenols and caffeine than the China varieties used to produce green teas, but this will be partially offset by the greater rate of infusion of green tea caffeine and polyphenols. In general, therefore, one would expect aqueous infusions of green and black teas, of similar particle size and prepared under identical brewing conditions, to contain similar levels of polyphenols and caffeine.

We have seen, however, that preparation variables have a marked effect on the in-cup composition. Green teas, unlike black teas, are traditionally prepared with water at temperatures lower than the boiling point. This is because green tea infusions are thought to be bitter when infused at too high a temperature, and it is usually recommended that a brewing temperature between 70 and 80 °C be used. To avoid bitterness, the recommended initial concentration and steeping (brewing) time for green tea are usually lower than those for black tea. In addition, the Chinese believe that the second infusion tastes better than the first. This has led some green tea manufacturers to recommend that the first infusion be discarded and the second infusion consumed.

All of these preparation variables are likely to affect the composition of the drink as consumed. A lower infusion temperature, initial concentration, and brew time are factors that will reduce the amount of polyphenols and caffeine extracted into a tea infusion. To investigate the combined effects of product and preparation variables on “consumer” brews of black and green teas, a number of European commercial products were *infused according to the instructions given on their packaging*. The soluble solids, total polyphenols, and caffeine contents of the resultant liquors were measured.

The results (Table 8) show that on average the measured soluble solids (2997 mg/L), total polyphenols (992 mg/L), and caffeine (241 mg/L) concentrations of the black tea infusions are higher than for green tea infusions (1790, 591, and 114 mg/L, respectively). This outcome can be explained in terms of a number of factors that affect the composition of an infusion:

Table 8. Composition of Green and Black Teas Prepared According to Package Instructions

product	teabag/ loose leaf	wt of tea (g)	water vol (cm^3)/ brew time	soluble solids (mg/L)	total polyphenols (mg/L)	caffeine (mg/L)
			Black Tea			
Lipton Yellow Label (France)	teabag	2.00	200/3 min	2810 (28.1%)[a]	810	224
PG Tips (PG Tips (U.K.)	teabag	3.12	235/3 min	3933 (29.6%)	1299	303
Tetley (U.K.)	teabag	3.12	235/3 min	3583 (27.0%)	1120	276
Typhoo (U.K.)	teabag	3.12	235/3 min	3051 (23.0%)	1087	232
Yorkshire (U.K.)	teabag	3.12	235/3 min	2803 (21.1%)	872	215
Twinings Darjeeling (U.K.)	teabag	2.50	235/3 min	2656 (25.0%)	1066	253
Twinings Assam (U.K.)	teabag	2.50	235/3 min	2637 (24.8%)	880	247
Co-op 99 (U.K.)	teabag	3.12	235/3 min	2499 (18.8%)	801	177
mean				2997 (24.7%)	992	241
			Green Tea			
The Pamplemouse (France)	loose leaf	2.00	200/3 min	2485 (24.9%)	677	118
Tchae Grapefruit (France)	teabag	1.75	200/3 min	2263 (25.9%)	624	141
Tetley The Vert (France)	teabag	1.80	200/3 min	2739 (30.4%)	755	144
Twining The Vert Naturele (France)	teabag	2.00	200/3 min	2061 (20.6%)	662	211
Tchae Mint (France)	teabag	2.00	200/3 min	1884 (18.8%)	433	124
Tchae Jasmin (UK)	teabag	2.00	235/3 min	2050 (24.1%)	825	182
Tchae Mint (U.K.)	teabag	2.00	235/3 min	2280 (26.8%)	727	160
Messmer Gruener Tea Munze (Germany)	teabag	1.75	200/3 min	2143 (24.5%)	785	101
Messmer China Gruener Tea (Germany)	teabag	1.75	200/1 min discard, then 200/3 min	1191 (13.6%)	596	56
Ronnefeld China Gruener Tea (Germany)	teabag	1.50	200 (75 °C)/3 min	1346 (17.9%)	387	56
Teekane Teefix	teabag	1.75	200/1 min discard, then 200/3 min	1075 (12.3%)	462	75
Excellent Sencha (Germany)	loose leaf	2.00	200 (90 °C)/3 min	937 (9.4%)	287	40
Messmer (Germany)	loose leaf	2.00	200/1 min discard, then 200/3 min	1477 (14.8%)	607	98
Teekane Green Tea (Germany)	loose leaf	2.00	200/3 min	1518 (15.2%)	631	107
Windsor Castle Green China Tea (Germany)	loose leaf	2.00	200/3 min	1406 (14.1%)	410	102
mean				1790 (19.5%)	591	114

[a] Percent of total solids is given in parentheses.

• The black tea infusions were prepared at a higher LWR (10−13.3 g/L) than the green tea infusions (7.5−10 g/L).

• Both the black and green tea infusions were infused for 3 min, although for some of the green teas the first 1-min's infusion was discarded. The soluble solids (caffeine and total polyphenols) levels in the second infusion were measured and are among the lowest recorded.

• All black teas were steeped in boiling water, whereas the recommended temperatures for two of the German green teas were sub-boiling (90 and 75 °C). The solids and caffeine extracted from these lower temperature infusions were also among the lowest recorded.

• The different compositions of the green and black tea polyphenols will invariably result in a difference in water solubility (availability from the leaf).

• Differences in leaf size/form between the (small) black tea fannings and the (generally larger leaf) green teas will have an influence on the extraction efficiency of the tea components.

• The extraction of polyphenols and caffeine will differ between loose-leaf tea and the teabag teas tested; also, teabags of different sizes and geometries (bags tested varied between two-dimensional round, double-chamber, and pyramid) will differ.

In general the significant differences between the compositions of green and black tea infusions are due mainly to the differences in recommended brewing procedures. Other determining factors include differences in leaf variety/size/form between green tea and standard black fannings, the generally lower green bag loading, and bag size/geometry between green (e.g., Tchae, two-dimensional round) and black (LYL double-chamber, PG pyramid) tea products.

SUMMARY

The results of these studies show that, although the product itself can have a significant effect, the preparation variables also greatly influence the composition of the infusion. The variety, growing environment, and manufacturing conditions have been shown to have a pronounced impact on the fresh leaf composition and upon the biochemical transformations that occur during leaf processing. Other factors inherent in commercial tea products were also shown to affect the in-cup concentrations of tea components. These included the grade (particle size) of the tea leaves, whether they are contained in a teabag, and, if so, the size of the bag and the material used in its construction.

The composition of a tea infusion was also shown to be strongly dependent on the way the consumer prepares it. The amounts of tea and water used, the brewing time, and the amount of agitation were all shown to significantly affect the tea component concentrations in the final brew. The combination of product and preparation factors that determines the in-cup composition help to explain (a) the substantial variations in tea component concentrations that have been found to occur in home-prepared tea infusions (*30*) and (b) the lower solids (and hence caffeine and polyphenol) content observed in green tea infusions when compared with black tea infusions (obtained when commercial products are prepared according to instructions given on their packaging).

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Received for review June 11, 2001. Revised manuscript received September 6, 2001. Accepted September 6, 2001.

JF010759+