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ORIGINAL ARTICLE

Swelling and infusion of tea in tea bags

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Abstract The present study deals with swelling and infusion kinetics of tea granules in tea bags. The swelling and infusion kinetics of tea bags differing in tea loading and tea bag shapes were compared with loose tea. Increment in temperature and dipping frequency of tea bag in hot water increased the infusion kinetics of tea bags. Reduction in particle size enhanced the swelling and infusion kinetics of tea in a tea bag. The effects of tea particle size, tea bag dipping rate, loading of tea granules in tea bag and tea bag shapes on infusion kinetics were investigated. Increase in tea loading in tea bags resulted in reduced infusion kinetics. Double chambered tea bag showed the highest swelling (30%) and infusion kinetics (8.30% Gallic acid equivalence) while single chambered tea bags showed the lowest kinetics, amongst the various bags studied. The swelling and infusion kinetics of loose tea was always faster and higher than that of tea bags. It was found that overall effect of percentage filling of tea granules and height of tea bed in a tea bag affects tea infusion kinetics the most. Weibull model was found to be in good agreement with the swelling data.

Keywords Swelling kinetics · Infusion kinetics · Tea bag · Tea loading · Double chambered tea bag

Introduction

In most of countries, the most popular method of preparing a cup of tea is to infuse a certain amount of tea contained in a tea bag (TB) into boiled water. TB has many practical advantages: easier to handle tea particles and simpler to dispose of the remaining infused tea granules. The effect of TB on the final extracts of tea is of great interest to the tea industry since the appearance and taste characteristics will be affected by them (Astill et al. 2001; Chin et al. 2013). There are many variations in the brewing and steeping habits of consumers within different cultures and countries. This is applicable to both, the loose tea (LT) and TB. Infusion time for TB ranging from less than 30 s to 2 min is commonly observed, while majority consumers are steeping the TB for less than 2 min. Various agitation behaviors have been also observed in order to speed-up the infusion process, whereas some tea drinkers do not stir the bulk fluid at all (Lian and Astill 2002). Infusion of tea components is treated analogous to dissolution of solid particle in liquid. Therefore, the steps for infusion kinetics of tea components are (1) diffusion of actives from pores of tea granules to surface, (2) diffusion through swelled granules and clogged tea bed, (3) diffusion through TB paper and (4) and external mass transfer in water affected by turbulent water.

Miyagawa et al. (1995) have measured the heat of green tea swelling with water. The heats of swelling were measured with a twin conductive calorimeter. It was concluded that the heat of swelling of green tea is due to hydration of hydrophilic components and endothermic reactions which occur at the same time. The endothermicity was attributed to the dissolution of water soluble actives from green tea. Jaganyi and Mdletshe (2000) have studied the effect of TB material on the rate and temperature dependence of

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caffeine extraction from black assam tea. Their results suggested that the TB material slows down the infusion process. Therefore there has been much interest in improving the TB infusions by considering the design aspects of TB. Jaganyi and Ndlovu (2001) studied the rate of infusions of caffeine in TB by varying the shape as well as the size of TB. The rate constant of caffeine infusion increased with an increase in size of TB. The shape of TB had no significant effect on the rate of infusion of caffeine. Spiro and Jaganyi (2000) have studied the transport of caffeine across a TB membrane in a modified rotating diffusion cell. It was concluded that any motion which decreases the thickness of the Nernst diffusion layer around the TB enhances the rate of brewing. This explains the different brewing cultures like stirring the brew around TB, vertical movement of the TB in the cup, in an attempt to accelerate the rate of infusion. They also found that the resistance to transfer through the TB membrane is negligible in range of 25–80 °C.

To understand the diffusion of tea from TB, Lian and Astill (2002) developed a computational fluid dynamics (CFD) model to simulate the process under static (no agitation) and dynamic (mechanically agitated) conditions. It was observed that in case of dynamic infusion, the external agitation resulted in a forced fluid flow through the TB which was much greater than the buoyancy driven natural convection. The packing porosity of the TB influenced the recirculation pattern of the fluid which in turn decides the rate of infusion.

Different types of teas were infused at 70, 85 and 100 °C, to study the effects of the number of steeping and varied steeping durations (Yang et al. 2006). The effect of steeping frequency was studied by steeping the same bag tea repeatedly eight times for 30 s each time. The steeping durations were varied experimentally as 0.5–4 min and 0.5–16 h for hot and cold water steeping respectively. It was observed that bag teas steeped in 70 °C water showed the highest contents of caffeine, catechins and gallic acid in second infusion while bag teas steeped in 85 and 100 °C water showed the highest contents in first infusion. Their contents were found to be reduced in later infusions. The tea contents were found to be increasing when steeped at ambient temperature (25 °C) than that of cold water (4 °C). This indicates that swelling and infusion kinetics is dependent on temperature (Jaganyi and Mdletshe 2000; Jaganyi and Ndlovu 2001; Joshi et al. 2016; Lian and Astill 2002). It was observed that tea contents were stable at 4 °C and unstable at 25 °C for 36 h. Another work by Lantano et al. (2015) reports the effect of alternative steeping methods on composition, antioxidant property and liquor color of green, black and oolong tea infusions. Three steeping variation in temperature i.e. hot (75 °C), cold (4 °C), hot + ice (80 °C) were performed for 4, 720, 5 min respectively. The faster infusion kinetics with compound degradation and slower kinetics with higher extraction of tea polyphenols were the characteristics of hot and cold steeping respectively. An innovative method of adding ice to hot water with tea has been found to beneficial for better extraction of tea actives. A conductance method to study the swelling kinetics of the superabsorbent (generally used as special polymeric materials) has been developed by Chen et al. (2007). The swelling was determined by measuring the conductance evolution of the sodium chloride aqueous solution during the superabsorbent swelling. They developed a model for the superabsorbent swelling kinetics, considering the thermodynamic relationship between system and environment. A possible swelling mechanism of superabsorbent was also put forward. A comparative study between conventional and ultrasound assisted extraction of Kenyan black tea was investigated by Both et al. (2014). Differences between conventional and ultrasound assisted maceration were investigated considering particle size distributions and scanning electron microscope (SEM) analyzes. The use of ultrasonic intensification leads to higher quasi-equilibrium concentrations in the liquid phase. The content of polyphenols was enhanced by 15%.

Of the literatures published in past, the swelling kinetics of TB with tea granules has never been studied. The present work deals with the first ever known investigation of swelling kinetics of tea in a TB and its relation with infusion kinetics. Another objective was to understand the infusion and swelling profile of conventional tea bags with respect to LT. Additionally, the correlation of swelling to infusion kinetics for TB shapes, particle size of granules, TB loading has never been studied. In this regard, the swelling and infusion kinetics of these parameters is studied and compared with that of LT. These parameters greatly affect the infusion kinetics of tea and hence the quality of end cup brews. Empirical Weibull model was used to fit the experimental data similar to our previous work (Joshi et al. 2016).

Materials and methods

Materials

Commonly used crush, tear, curl (CTC) tea named S2, procured from the local market has been used in this study. The swelling, infusion kinetics experiments and analyses were performed using de-ionized water (Millipore Inc, USA). Different shapes of the TB like double chambered (DC), single chambered (SC) and circular (Cir) TB were made in-house. Cellulose acetate material was used for making TB and obtained from local market. The swelling experiments involving TB were performed in static conditions. Infusion kinetics experiments were conducted in a baffled reactor.

Volume measurements (measurement of swelling kinetics)

For volume measurements, method used by Joshi et al. (2016) was slightly modified. The tea granules present inside the bag swells in hot water. Hence, the volume of TB changes with time due to swelled tea granules inside the TB. As TBs have 3-D shape, volume change of TB due to swelling cannot be measured from one photograph. Thus change in dimensions of TB during swelling was measured from front and side view using two high resolution cameras (supplementary Fig. 1). Both the cameras were placed perpendicular to each other. One camera was placed at the lateral position of TB whereas the other one was placed in front of the setup. The TB was held in its position using TB string by a rod which was attached to a stand. As soon as the TB was immersed in water in rectangular transparent vessel, a video was recorded for 2 min from both the cameras. Images at 30, 60, 90 and 120 s were extracted from the videos. These images were analyzed using image analysis software (ImageJ2x). An object of known dimensions such as glass side was used for calibration. Length of object was measured in pixels from the image. The ratio of length in mm to that in pixels was used for conversion from pixels to mm. For each time point, two images were obtained i.e. front view and lateral view of the TB. The lateral view of TB was analyzed by image analysis to obtain only the area covered by the tea in TB. The front view of the TB was analyzed to obtain the increase in length of tea bed due to swelling. The product of area obtained from lateral view and the increased length of TB obtained from front view gives the volume of tea bed in TB at each time instant.

To obtain smaller size particles, S2 was ground in a mixer for 15–20 s. The ground tea was then passed through 5 different sieves (1000, 820, 710, 500 and 212 µm) to obtain the fractions of narrow size range. Fraction of tea particles retained on 820, 710 and 212 µm was used for studying the effect of particle size on swelling. To study the effect of different loading in TB on swelling, experiments were performed by changing the amount of tea added to TB. TB with loading of 1, 2 and 3 g of tea particles were considered for swelling studies. All the swelling experiments were performed with conventional DC TB.

Infusion kinetics studies

For mimicking the vertical dipping of TB, a TB dipping set-up was made in-house (Supplementary Fig. 2). A plate was hinged to the circular rotating plate attached to a motor. Other end of the plate was hinged to a dipping rod which was sliding through the guiding cylinder. Thus, rotating motion was converted into simple harmonic motion. A TB was attached to the dipping rod using thread and placed into the water at constant temperature inside the baffled reactor. The TB dipped in and out of water when motor was started. The effect of dipping frequency was evaluated for optimizing the dipping frequency to be used for performing the brewing experiments. For infusion studies of TB, experiments were performed using 5 dips per minute (dpm). Tea brewing was performed over 60–100 °C in a baffled reactor, placed in water bath (Ganesh scientific, Mumbai). The brewing experiments were performed with TB containing 2 g of tea in 100 ml de-ionized water. 1 ml of brew was withdrawn from the reactor at time instants of 0.5, 1, 2, 3, 4, 5, 10 and 15 min. The concentration values were corrected for volume lost due to evaporation and sampling. The analytical method developed earlier was used for the Gallic acid equivalent (GAE) determination (Farakte et al. 2016). The GAE% was calculated with respect to 2 g tea used. In case of experiments with LT, baffled reactor was used with 300 rpm agitation provided by a mechanical stirrer. The tea to water ratio was maintained same as that of the TB infusion studies. Reproducibility in experiments was checked with respect to measured values of experimental GAE. The experiments were repeated thrice and statistical attributes such as standard deviation and % error from average value of GAE for all sample instances of a particular experiment were calculated. The kinetics parameters were estimated as per the expressions given below (Spiro and Siddique 1981; Farakte et al. 2016):

$$\ln\left(\frac{C_\infty}{C_\infty - C}\right) = k_{obs}t \tag{1}$$

where C_∞ (mg/ml) is the concentration of solutes in infusion at equilibrium; C (mg/ml) is the concentration of solutes in infusion at time t (min); K_{obs} (min^{-1}) is the observed rate constant for infusion process. For better fit with experimental data, Eq. (1) can be modified with inclusion of intercept, as shown in Eq. (2):

$$\ln\left(\frac{C_\infty}{C_\infty - C}\right) = K_{obs}t + a \tag{2}$$

where a is the empirical parameter for better fit of kinetic data. Equation (2) was used for estimation of kinetics parameters (K_{obs} and a) using kinetic data of infusion. The value of GAE (mg/ml) at 15 min was used as C_∞ as GAE did not change significantly after 15 min.

The manner of bag dipping is also critical for better infusion profile. The pulse dipping of TB is more practical, as some consumers have a habit of stirring the bag for a very less time. The stirring behavior varies a lot amongst tea drinkers, with majority dipping the bag between 5 and 20 s. Some consumers dip the bag continuously but at low dipping rate, while others dip the bag for few seconds in every 1–2 min at higher dipping rate. Hence, the pulse dipping pattern was varied wherein the dipping was carried out for initial 5 s followed by 55 s of static condition for every min. Similar experiments were conducted with 10 and 15 s of dipping followed by 50 and 45 s of static condition respectively in every min. For these experiments, a dipping frequency of 60 dpm was used for 15 min at 60 °C. The infusion kinetics of pulse dipping studies was compared with that of continuous dipping of TB.

Study of parameters affecting infusion kinetics

Effect of loading in TB

To study the effect of tea loading on swelling and infusion kinetics in TB, experiments were performed with 1–3 g of tea granules in TB. The swelling and infusion kinetics of these loadings were compared in DC TB at 60 °C for 15 min at 5 dpm. Infusion kinetics of TB with loading of 0.25–3 g was also studied at 60 °C at same experimental conditions to optimize the optimum loading in TB which renders least clogging of particles and maximum elution of solutes from TB. The tea to water ratio of 1:50 was maintained constant throughout the experiments.

Different shapes of TB

The effect of different shapes of TB on swelling and infusion kinetics was investigated using DC, SC and circular (5 cm diameter) shaped bags. The swelling kinetics for different shapes of TB was determined on %weight change basis as %volume change determination with respect to time is difficult to measure for different shapes of bags. Circular TB was studied in three different dipping manners for infusion kinetics: circular bag dipped vertically (Cir_vertical), circular bag dipped horizontally (like a disc—Cir_horizontal) and simply steeping the circular bag (Cir_steeping). Slight agitation was provided for sampling uniformity in circular bag steeping study. The swelling kinetics was studied at static condition while infusion kinetics was studied at 50 dpm. These experiments were conducted at 60 °C for 15 min at 50 dpm. The tea to water ratio was maintained 1:50.

For determining %fill of tea granules on volume basis in different shapes of TB, a solid powder of known density was filled in TB along with 2 g S2. The powder was filled in such a way that the sides of the bag were not stretched. Based on the packed density and mass of the powder filled in TB, the %fill of tea granules in different shapes of bag was determined on volume basis. The height of tea bed was measured using Mitutoyo digital vernier calliper. An average of 5 measurements was considered for determining the %fill and height of tea bed. The %fill and height of tea bed for different TB were correlated with their respective infusion kinetics.

Mathematical modeling

Empirical Weibull and Peleg models were used to predict the swelling characteristics of LT granules in previous study (Joshi et al. 2016). Hence in the present paper, Weibull model has been used to predict the swelling kinetics of TB as per the equation presented below:

$$\alpha = 1 - \exp(\lambda t)^{\phi} \tag{3}$$

$$\text{where,} \quad \alpha = \frac{D_t - D_0}{D_f - D_0} \tag{4}$$

α is the dimensionless swelling parameter; D_t is the instantaneous diameter of the granules at any time 't'; D_0 is initial diameter; D_f is final equilibrium diameter of the granules attained after complete swelling (at 120 s); ϕ and λ = Weibull constants. λ is rate parameter which signifies the rate of swelling kinetics which increases with increasing temperature. ϕ is shape parameter. Change in values of ϕ affects the shape of the swelling curve which indicates the nature of the process.

Statistical analysis

The studies concerning effect of brewing temperature, dipping frequency, tea bag loading and tea bag shape for infusion kinetics were subjected to two-way analysis of variance (ANOVA) using MS Excel 2007 (Microsoft Office 2007, USA).

Results and discussion

The reproducibility of experiments lies within ±8.5% for the measured values of GAE. The p value obtained from ANOVA analysis of the measured data is well below 0.0001 for all experiments.

Swelling and infusion kinetics of TB and LT

The swelling and infusion kinetics of tea particles in DC TB and LT are compared in Fig. 1(a, b). Joshi et al. (2016) has investigated the swelling kinetics of LT. From the Fig. 1a, it can be observed that LT showed the highest swelling (42.8%) as compared to DC TB (36.7%) at 90 s. The LT attains maximum swelling in just 40–45 s while

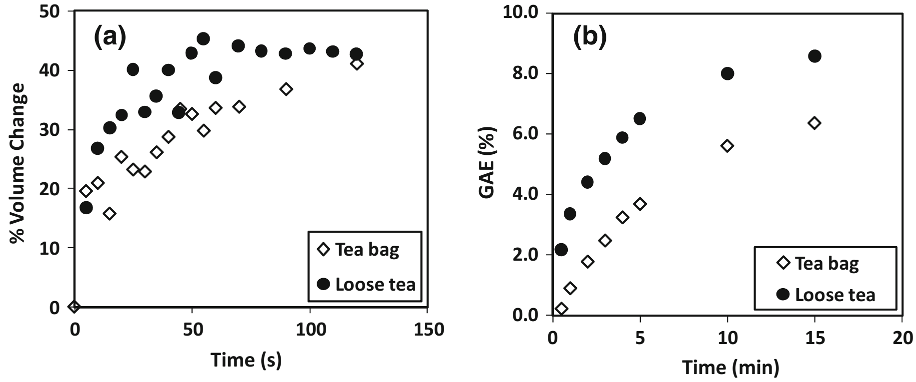


Fig. 1 Comparison of **a** swelling kinetics, **b** infusion profile of 2 g of unground S2 at 60 °C in DC TB (5 dpm) and LT (300 rpm)

TB takes 2 min to achieve the same extent of swelling (41.0%). The difference in percentage swelling of LT and TB at 30 s is 10.1%. The sides of the TB are flexible in nature but still less swelling was observed. This can be attributed to DC TB which does not allow the particles inside to swell freely. In other words, TB hinders the process of swelling. Figure 1b shows the infusion profiles of LT and DC TB with 2 g unground S2 at 60 °C up to 15 min. It is observed that the infusion kinetics of LT is significantly faster than TB. In case of LT, the infusion concentration for initial 30 s is higher than TB (9.8 times of TB). After 30 s, the infusion of LT in terms of GAE % was 2.1–3.7 times that of DC TB. All these observations are well supported by the swelling data obtained, where higher swelling was observed for LT.

Effect of particle size on swelling and infusion kinetics

The effect of particle size on the swelling kinetics of DC TB and LT for S2 at 60 °C is depicted in Fig. 2a. In case of DC TB, a decrease in particle size from 2.21 to 0.36 mm results in enhanced swelling. The final extent of swelling for 2.2, 1.12 and 0.36 mm particles in TB is 41, 63 and 84% respectively. Initially, as the size is reduced by a factor of 1.97, swelling increases 1.53 times. As the particle size is further reduced by a factor of 6 (compared to original size), swelling is doubled when compared with original. Thus, lower sized tea particles are observed to have faster swelling kinetics as well as higher extent of swelling. This behavior is due to larger surface area and more exposure to water for smaller particles as compared to larger ones. Concerning larger sized particles, water may not be able to penetrate tea particle micro porous structure which results in less swelling. This result is in good agreement with the earlier studies for tea particles in a separating funnel, mimicking TB situation (Joshi et al. 2016). For comparison between the swelling kinetics of TB and LT for different particles size, the swelling studies of LT of different particle sizes at 60 °C is reported in our earlier work (Joshi et al. 2016). It can be observed from the figure that as particle size is reducing from 2.21 to 0.64 mm for LT, the final extent of swelling has increased from 43 to 200%. This huge increase in swelling is due to the reduction in particle size by about 5 times. The final extent of swelling for 2.21 mm (unground), 0.91 and 0.64 mm particles as LT is 43, 127 and 200% respectively. The swelling rate of unground LT (2.21 mm) remains fairly same till the end of infusion and is similar to the that of unground S2 in TB. For lower sized LT particles, initial rate of swelling shows a steep increase up to 30 s. Thus, the rate of swelling and final extent of swelling for LT and its

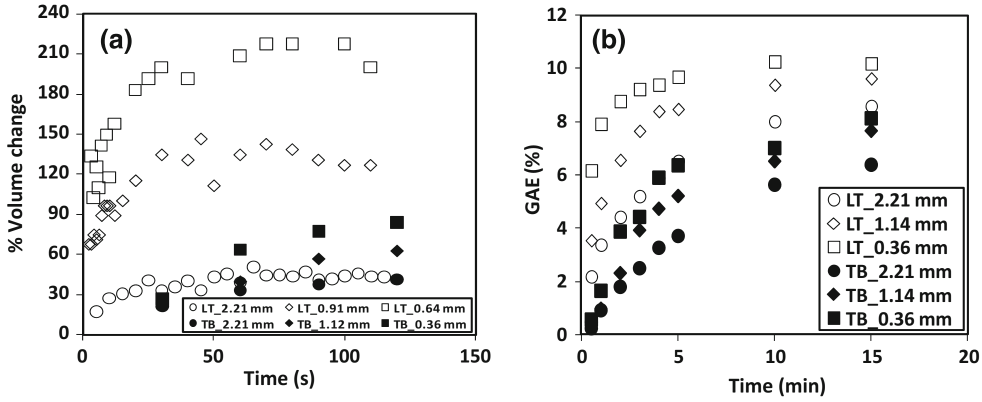


Fig. 2 Effect of particle size on **a** swelling kinetics (static condition), **b** infusion profile for DC TB (5 dpm) and LT (300 rpm) at 60 °C

smaller particle fractions is found to be higher than that of respective particle sizes in DC TB.

Figure 2b depicts the infusion profile of different particle sizes of S2 in LT and TB. In case of DC TB, as the particle size is reduced by a factor of 6 (from 2.21 to 0.36 mm), the GAE% at 15 min is increased by 1.3 times. While for LT, GAE% increases by 1.2 times the original for same particle size. The highest infusion profile was obtained for 0.36 mm particles of LT, followed by its higher sized fractions. The infusion profile of 0.36 mm particles in TB is approaching to that of unground LT at higher particle size with GAE% as 8.11 and 8.58% respectively at 15 min. Therefore, it can be concluded that infusion rate and maximum amount of GAE eluted at the end of infusion for LT is always faster and higher than that of TB for same particle sizes.

Kinetic rate parameters are estimated using Eq. (2) for different particle sizes of LT and DC TB at 60 °C. GAE (mg/ml) value at 15 min was regarded as C_∞ and kinetics data up to 5 min was used. Use of the data after 5 min tend to gives ambiguous results as explained earlier (Price and Spiro 1985). The data showed good linear fit for all particles size. The value of kinetic parameters K_{obs}, a and R^2 estimated from the Eq. (2) is summarized in Table 1. It can be observed from the table that K_{obs} increases as particle size is reduced. This is observed in case of both LT and TB infusion studies. The complex path through which the solute has to travel for diffusion gets shortened in case of smaller particles. Similar trend is observed for intercept as well for LT. This can be attributed to decrease in the diffusion resistance to infusion with decrease in particle size. This results in faster infusion rate for smaller particles. However in case of TB, the intercept is similar (RSD = 0.027) and shows a negative sign. The negative sign of intercept accounts for the initial lag time of 8–10 s, observed during uniform wetting of TB in infusion studies. At the start of TB dipping, TB floats in water and some of the particles present inside bag are not in contact with water. Hence, there is a lag time before the actual infusion starts in case of TB.

Effect of temperature and dipping frequency on infusion kinetics

Effect of temperature

The effect of temperature was studied over 60–100 °C using S2 tea. Figure 3i shows the infusion kinetics in DC TB up to 5 min. It can be observed from the figure that as temperature increases from 60–100 °C, the infusion rate also increases. Higher infusion rate during initial infusion period is observed at higher temperatures. From the kinetics parameter presented in the Table 1, it can be deduced that K_{obs} and a are increasing with increase in temperature. The difference in GAE% at 60–80 °C and 60–100 °C is 3.46 and 4.68% at 15 min. Thus the infusion of tea actives from the TB is highly dependent on the brewing temperature.

Effect of TB dipping frequency

The effect of TB dipping frequency on infusion kinetics was measured in DC TB with S2 at 60 °C up to 15 min and is depicted in Fig. 3ii-a. The dipping frequencies chosen for the study were 2, 5, 8, 10, 15, 20, 30 and 50 dpm. In order to avoid clusters of data in the plot, data of 5, 8, 15, 30 dpm are not included in the figure. It is observed that infusion rates as well as total quantity of GAE eluted at the

Table 1 Kinetic parameters (K_{obs}, a, R^2) for different attributes of TB (*LT* loose tea, *TB* tea bag)

Parameter		K_{obs}	A	R^2
Effect of particle size	LT_2.21 mm	0.240	0.217	0.994
	LT_1.14 mm	0.450	0.246	0.999
	LT_0.36 mm	0.420	0.965	0.953
	TB_2.21 mm	0.184	−0.044	0.997
	TB_1.14 mm	0.253	−0.094	0.990
	TB_0.36 mm	0.326	−0.086	0.985
Effect of temperature	60 °C	0.214	−0.056	0.998
	70 °C	0.19	0.01	0.98
	80 °C	0.179	0.051	0.987
	90 °C	0.206	0.077	0.997
	100 °C	0.261	0.095	0.997
Effect of dipping frequency	2 dpm	0.201	0.036	0.9836
	10 dpm	0.176	0.037	0.992
	20 dpm	0.162	0.066	0.991
	50 dpm	0.179	0.163	0.932

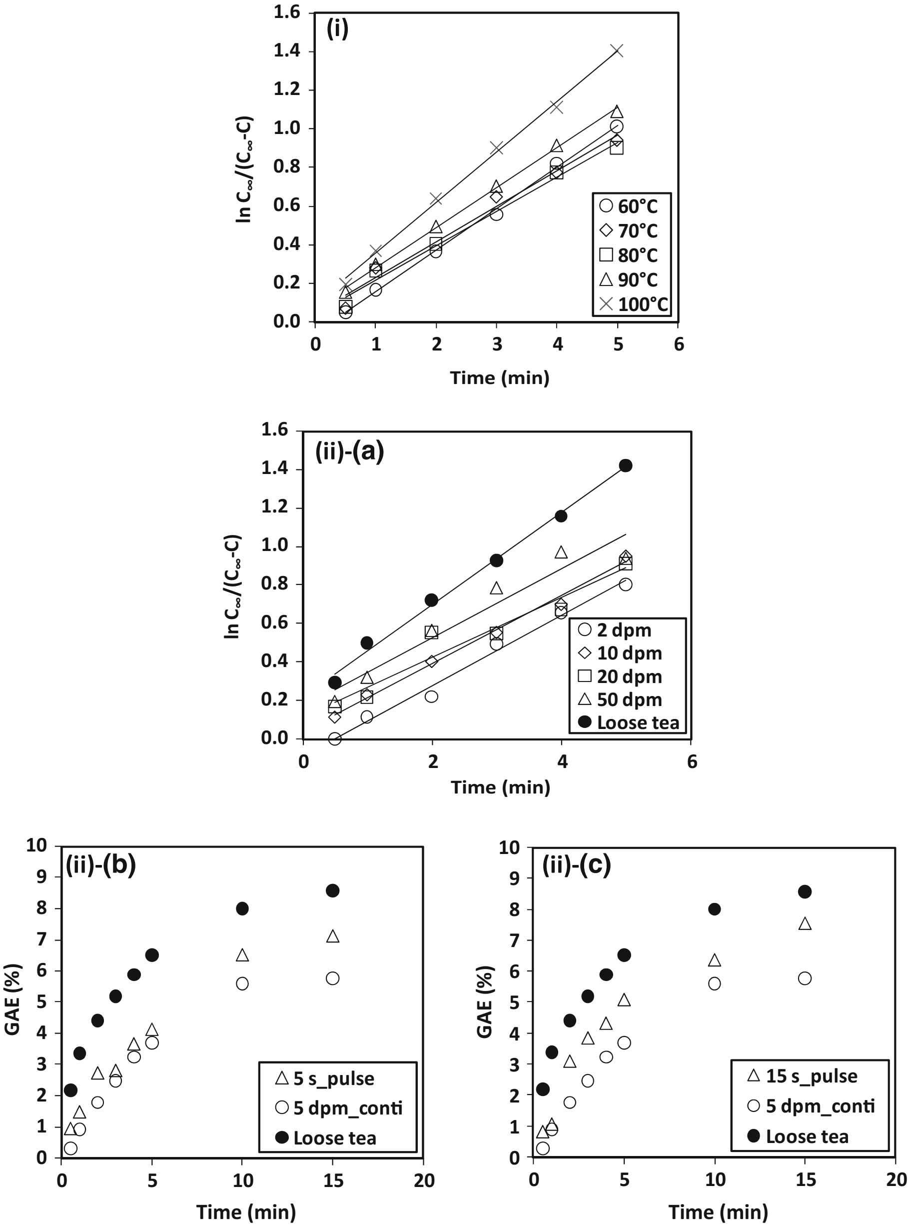


Fig. 3 **i** Infusion kinetics for effect of temperature in DC TB at 5 dpm; **ii** (*a*) infusion kinetics for effect of various dipping frequency (continuous), (*b*) infusion profile for pulse dipping for 5 s, (*c*) 15 s at the rate of 60 dpm in DC TB at 60 °C

end of brewing increases with increments in dipping frequency from 2 to 50 dpm in same order. The infusion kinetics of 10 and 20 dpm are approximately similar from 1 min onwards. The highest infusion concentration is observed for LT with 8.57% GAE at 15 min, followed by TB at 50 dpm (8.43%). All these inferences are well supported by the infusion rate constants as depicted in Table 1. As dipping frequency increases, intercept increases. The change in rate constants with increase is dipping frequency is not significant (RSD = 0.016) and can be considered as similar.

The infusion kinetics of pulse dipping was studied in DC TB at 60 °C. Pulse dipping of 60 dpm for 5, 10 and 15 s was provided in every min. The infusion study was carried out for 15 min at 60 °C. Dipping rate of 60 dpm for 5 s in every min eventually dips the bag 5 times in a min at higher dipping rate. In contrast to this, low dipping rate of 5 dpm dips the bag 5 times in a min but in a continuous mode. Figure 3ii-b, c shows the effect of pulse and continuous dipping for 5 and 15 dips in DC TB at 60 °C for 15 min. From Fig. 3ii-b, it can be observed that the initial infusion profile of 5 dips in pulse mode is marginally higher than that of continuous mode up to 5 min. After 5 min, GAE% of pulse dipping is 7.12% at 15 min. The initial infusion profile of 15 dips in pulse mode is comparatively higher than continuous mode with 7.54% GAE at 5 min (Fig. 3ii-c). Of all the studied pulse modes, the highest infusion kinetics was observed for 15 s, followed by 10 and 5 s. However, the end GAE% eluted from these pulse dipping is similar, ranging from 7.12 to 7.59% at 15 min. Therefore it can be concluded that there is no significant effect of mode of dipping on the end infusion profile. The conventional DC TB shows the lowest infusion profile (5.79%) with 5 dpm continued for 15 min. In case of higher dipping rate for 15 s, higher agitation is provided for disturbing the tea bed which was followed by solubilization of actives at rest for 45 s. In next time interval of 15 s, these solubilized actives elute out of tea matrix. In case of smaller duration of dipping (10 and 5 s), the time is not sufficient enough to disturb the bed completely, resulting in lower infusion profile. LT is always better with end GAE of 8.57%.

Investigation of parameters affecting infusion kinetics

Effect of TB loading

The effect of loading of tea granules on swelling and infusion characteristics in a DC TB has been studied for S2 at 60 °C at 5 dpm and is depicted in Fig. 4i. From Fig. 4i-a, it can be seen that an increase in the loading of TB results in decrease in swelling rate and extent of swelling. TB with 1 g of tea granules swells to about 50%. As the loading increases to 2 g, the swelling decreases to 41% which is about 1.2 times less. As the loading is further increased to 3 g, swelling is reduced substantially to 25% which is half of the 1 g swelling. Hence the swelling observed for 1 g loading is highest compared to 2 and 3 g. This is because 1 g of tea inside DC bag has sufficient space to swell as compared to 2 and 3 g tea particles. As the amount is high, the head space available in a TB is less for 2 and 3 g loading. When the swelling starts, the tea particles do not get enough space to swell which initiates the clogging of the granules.

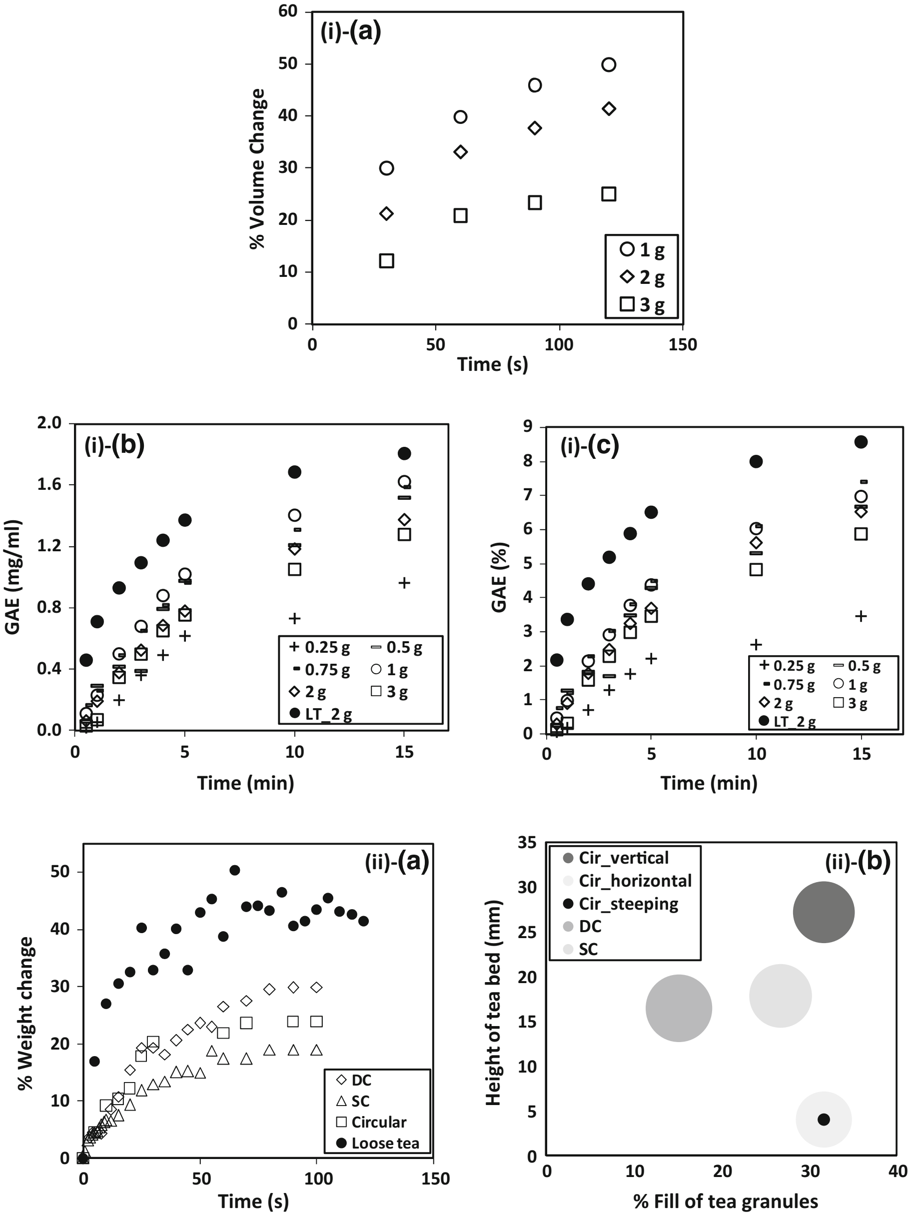
It can be suspected that the loading of tea granules in TB alters the infusion profile substantially and hence there is a need for optimization of quantity of tea to be added in a TB which allows maximum elution of solutes. Figure 4i-b, i-c depicts the infusion profile as mg/ml and GAE% eluted respectively, for TB loaded with 0.25–3 g S2. The tea to water ratio of 1:50 was maintained constant. When compared with conventional TB with 2 g tea, TB with 0.5–1 g of tea shows higher infusion profile. Lowest infusion profile was observed for 0.25 g TB with 0.96 mg/ml (3.46% GAE) at 15 min. The infusion profiles of 0.5, 0.75 and 1 g for initial 4 min are approximately similar but higher than TB. Their initial rates are found to be higher than conventional 2 g TB. A GAE of 0.65 mg/ml and 0.68 mg/ml was achieved in just 3 min with 0.75 and 1 g TB respectively while 2 g bag takes 4 min to achieve the same (0.68 mg/ml). Similar observations were made with 0.5 g TB where 1.24 mg/ml was eluted in just 4 min whereas 2 gm TB takes 5 min to release 0.78 mg/ml only. All these inferences indicate that lesser loading of bag helps in achieving higher infusion profile. From Fig. 4i-c, it is observed that as the loading increases from 1 to 2 g, eluted GAE% reduces from 6.92 to 6.53% at 15 min. This difference in GAE% is very small. An increase in loading up to 3 g results in further reduction in the GAE to 5.88%. The reduced GAE% is due to higher loading which can be attributed to the reduction in swelling as observed in Fig. 4i-a. The effect of clogging in tea bed is less dominant with 1 g loading and hence higher infusion kinetics. The infusion profiles of TB with 2 and 3 g tea is lesser than the lower amounts of 0.5–1 g and LT. When compared with conventional TB (6.53% GAE), the best infusion profile was perceived for 0.5 g TB, eluting 6.67% GAE at 15 min with only 0.5 g of tea. A higher concentration of 6.97% GAE was achieved with only 1 g tea. Thus, with lesser loading of 0.5–1 g tea in TB, a reduction of 1 min time was achieved for eluting the same concentration as eluted by 2 g TB. This is of great benefit to the consumer wherein the TB can be dipped for shorter duration to make a cup of tea. From the above results, we can conclude that infusion kinetics of tea granules depends upon swelling kinetics. Hence, tea granules inside the TB must be given sufficient space to swell so as to achieve higher and faster infusion.

Effect of TB shape

The effect of TB shapes on swelling and infusion kinetics of S2 at 60 °C is shown in Fig. 4ii-a, ii-b) respectively. From the Fig. 4ii-a, it is observed that tea particles in DC TB have the highest swelling of about 30% in just 2 min, amongst all the TB studied. This is higher than that of SC TB (19%). The initial rate of swelling is also observed to be faster as compared to other TB. About 27% swelling is achieved in initial 1 min in DC bags. The space available for swelling in DC TB is larger than that of circular and SC TB. The reduced swelling of SC TB can be attributed to the phenomenon of clogging. The swelling of circular TB lies between that of DC and SC TB, with 24% swelling. LT has highest swelling with 42% volume change.

The infusion studies of different shapes of TB were conducted with S2 at 60 °C at 5 and 50 dpm. The infusion profile of 50 dpm is shown in Fig. 4ii-b. It depicts the bubble plot of %fill of tea granules versus height of tea bed formed in different shapes of TB. The size of the bubble indicates the GAE% value at 15 min. Larger the bubble size, higher the GAE% value. The %fill of tea granules on volume basis in DC, SC and circular bags is 15.13, 26.75 and 31.66% respectively. The height of tea bed formed inside the bag will vary depending upon the

Fig. 4 **i** Effect of tea loading on (*a*) swelling profile (static), (*b*) infusion profile in GAE (mg/ml) and (*c*) infusion profile in GAE (%) in DC TB (5 dpm) at 60 °C. **ii** Effect of different shapes of TB on (*a*) swelling profile (static), (*b*) infusion profile considering % filling and height of tea bed (50 dpm) at 60 °C



shape and dipping arrangement (circular bags only) of TB in the water. The height of the tea bed formed in different shapes of TB is in the order of Cir_horizontal < DC < SC < Cir_vertical. The %fill and height of tea bed is same for Cir_steeping and Cir_horizontal arrangement as depicted in Fig. 4ii-b. At higher dipping frequency of 50 dpm, the difference between the infusion kinetics of different shapes of TB is minimal. It can be perceived from the figure that as %fill and height of tea bed increases, the GAE% decreases. The highest GAE% was observed for DC TB (8.30%) at 15 min at 50 dpm which is slightly lesser than LT (8.58%). This can be accounted for least volume occupied (15.13% on volume fill basis) and height of the tea bed formed (16.47 mm) in DC bag, amongst all type of bags studied. The Cir_vertical and Cir_horizontal have comparable GAE% values at 15 min as 7.80 and 7.36% respectively. This is due to same %fill of tea granules in both of these circular bags. The least GAE% is eluted from Cir_steeping type of arrangement (5.11%). This is attributed to initial floating of TB in water. Longer lag time was observed while steeping this TB, as only one side of circular bag was exposed to water. After dipping in the water, the circular bag was kept stationary which resulted in least mixing of the bulk fluid. There is a significant difference of 11.6% on volume fill basis in DC and SC bags, with higher filling in SC bags. This resulted into lower GAE% values of 7.90% for SC TB at 15 min.

All these results indicate that DC TB has faster and higher infusion rate compared to other shapes of TB studied, due to the space available inside the bag. The least %filling in DC TB allows lesser clogging and hence higher swelling is obtained. Also, the %fill and height of the tea bed plays a major role in the swelling kinetics of tea granules and has to be considered while designing a TB for higher infusion profile.

Mathematical model analysis

The experimental swelling data for LT, different tea loading and different shapes of TB was fitted with Weibull model. The Dimensionless swelling parameter was measured using weight measurements than volume measurements. The rate parameter (λ) and the shape parameter (ϕ) obtained for S2 at 60 °C for LT, different tea loadings and TB shapes is shown in Table 2. The λ and ϕ obtained in DC TB with 2 g S2 tea were 0.030 s^{-1} and 1.17 respectively with $R^2 = 0.956$. For tea bed in a separating funnel, the values of λ and ϕ were 0.013 and 1.04 respectively (Joshi et al. 2016). Values of shape parameter more than or equal to 1 suggests the presence of internal diffusion resistance (Joshi et al. 2016). It can be seen that rate constant for the process of swelling is more in DC TB as compared to tea bed in separating funnel. This means that the rate of swelling is faster in DC TB than in separating funnel. The TB is made of a flexible material which provides more space for tea bed as soon as the swelling starts. However, the walls of the separating funnel are rigid which prevents the tea particle expansion. Hence the initial swelling rates are observed to be faster in a TB. However for LT as single particle swelling, the rate parameter (0.034 s^{-1}) is higher than DC TB with 2 g S2. This indicates that swelling kinetics of LT is higher than conventional DC bags. The shape parameter ϕ for LT is very small (0.18). Therefore, it can be deduced that the initial diffusion of water through the tea matrix is faster. Hence, the internal diffusion resistance is minimal during hydration of tea granule (Joshi et al. 2016).

As the loading inside the TB is increased, the swelling rate constant decreases which results in restricted swelling. The value of λ obtained for 1 g loading is 1.27 times higher than that for 3 g loading. When, the loading is doubled from 1 g to 2 g, the rate constant does not change (0.032 to 0.030 s^{-1}). The λ value for same loading of 2 g in LT is similar to that of DC TB (0.034 s^{-1}). The value of ϕ obtained for DC TB with 2 g tea is 1.17 which is 1.3 times higher when compared with that of 1 g TB. All these inferences suggest that faster infusion is more due to shape parameter than the rate constant. This explains the reduced swelling in DC TB due to higher %filling of tea granules. Higher the %filling, lesser will be the swelling. The SC and circular bags have higher ϕ values than that of LT. This indicates that the internal diffusion resistance during hydration is higher in these bags than LT. The value of ϕ varies from 0.18 to 1.28 for all tea loading and TB types.

Conclusion

It was found that the swelling and infusion kinetics of LT was always higher than TB for all particle sizes. TB hinders the process of swelling and infusion kinetics. Reduction in particle size as well as less loading of tea granules in TB increases the swelling rate as well as the extent of swelling, thus resulting into higher infusion kinetics. 0.5 g loading was found to be the optimum amount giving the highest infusion kinetics than the conventional DC TB with 2 g tea. DC TB shows the highest swelling and infusion kinetics as compared to other shapes of TB studied, due to least clogging of tea particles. The effect of %fill of tea granules and height of tea bed formed in different shapes of bags are also considered while explaining infusion kinetics. One of the highlights of the study is that a relation between swelling and infusion quality is observed. The empirical

Table 2 Weibull parameters for TB with different tea loading and different shapes at 60 °C for S2 (*LT* loose tea, *DC* double chambered, *SC* single chambered; Cir-circular)

Parameter	Tea type	Rate parameter (λ) (s^{-1})	Shape parameter (ϕ)	R^2 values
Tea bed	Separating funnel (Joshi et al. 2016)	0.013	1.04	0.881
Loose tea	LT	0.034	0.18	0.944
Effect of tea loading	DC_1 g	0.032	0.88	0.990
	DC_2 g	0.030	1.17	0.956
	DC_3 g	0.026	1.28	0.993
Effect of tea bag shapes	SC_2 g	0.038	0.82	0.968
	Cir_2 g	0.047	1.11	0.957

Weibull model is in good agreement with swelling data. The present study can also be useful for the design aspects of TBs in tea industries.

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