International Journal of Food and Fermentation Technology
Citation: *Int. J. Food Ferment. Technol.*, **15**(01): 205-223, June 2025
DOI: 10.30954/2277-9396.01.2025.11

ASSOCIATION FOR AGRICULTURE ENVIRONMENT AND BIOTECHNOLOGY

REVIEW PAPER

Modelling and Infusion Kinetics Mechanism of Tea a Comprehensive Review

Prashant Pandurang Gosavi and Shrikant Baslingappa Swami*

Department of Post-harvest Engineering, Post-graduate Institute of Post-harvest Technology and Management, Killa-Roha. Dist: Raigad (Maharashtra State) (Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli-Campus Roha) India

*Corresponding author: swami_shrikant1975@yahoo.co.in

Paper No.: 321 **Received:** 21-03-2025 **Revised:** 08-05-2025 **Accepted:** 30-05-2025

ABSTRACT

Tea infusion is a complex process influenced by various factors, including tea type, particle size, temperature, and steeping time. It is a centuries-old practice that has evolved into a sophisticated art and science. Understanding the infusion kinetics mechanism is crucial for optimizing brewing conditions, predicting flavor profiles, and developing novel tea products. This review provides a comprehensive overview of the current state of knowledge on tea infusion kinetics, including empirical, semi-empirical, and mechanistic models. The review discusses various factors affecting the infusion rate and infusion kinetics for the complex interactions between tea solids, water, and brewing conditions. Furthermore, the review elucidates the infusion kinetics mechanism, including the effects of tea type, particle size, temperature, and steeping time on the extraction of soluble compounds. This review aims to provide a valuable resource for researchers, tea producers, and industry stakeholders seeking to optimize tea production, processing, and brewing practices.

Keywords: Tea infusion kinetics, modeling, brewing conditions, flavor profile, tea production

One of the most popular drinks consumed worldwide is tea. The methods used to prepare tea vary throughout the world. In Europe and the United States, tea bag infusion is a popular technique. In India, people typically use boiling water to brew loose tea leaves or tea particles. Each method has a varied infusion period ranging from one to ten minutes, resulting in distinct characteristics for the tea infusion. Therefore, it is crucial to research the kinetics of tea infusion. Many substances, including flavanols, catechins, derivatives of gallic acid (GA), etc., are found in tea (Harbowy and Balentine, 1997). These constituents have various physical characteristics, including diffusivity and solubility. Additionally, the locations of these components within the tea leaf matrix vary. (Suzuki *et al.* 2003; Van Breda The hydration of tea occurs during the infusion process, during which the contents of the tea dissolve in water (within the leaves or granules) and diffuse through the tea leaf matrix to the majority of the infusion. Tea leaves and/or pieces swell as a result of the hydration stage. Because of all these going on at once, tea infusion is a complicated phenomenon.

With almost 20 billion cups consumed every day, tea infusion is the beverage that is consumed more often worldwide than water. According to the Department of Health in Taiwan (2004), each person drinks 2.5 cups of tea infusion on average per day. The processed leaves of the plants are used to make

How to cite this article: Gosavi, P.P. and Swami, S.B. (2025). Modelling and Infusion Kinetics Mechanism of Tea a Comprehensive Review. *Int. J. Food Ferment. Technol.*, **15**(01): 205-223.

Source of Support: None; **Conflict of Interest:** None

tea. Based on the level of fermentation, the three most widely consumed varieties of tea—green, oolong, and black—are differentiated. While the leaves of black tea are further fermented, those of green tea are only dried and roasted. The outcome is oolong tea if the leaves are just partially fermented. According to Fujihara *et al.* (2007), tea is graded based on its flavor, color, and scent following fermentation.

Brewing techniques differ between nations and among people living in those nations. Most infusion periods are less than two minutes, however they can range from less than thirty seconds to five minutes. In an effort to expedite the infusion process, customers have also been observed to exhibit a variety of agitated behaviors. While some tea drinkers just leave the teabag to steep for a certain amount of time, others swirl the water or move the teabag up and down (Lian and Astil, 2002).

There are significant differences in the infusion features, including look and flavor, as well as potential health benefits that have been proposed in numerous recent studies, depending on the type of teabag and brewing practices (Charles, 1991; Hertog *et al.* 1995; Hollman *et al.* 1996; Jha *et al.* 1996; Kada *et al.* 1985; Stagg and Millin, 1975; Tijburg *et al.* 1997). It is vital to comprehend these impacts in order to maximize the delivery of the health benefits and flavor of tea that are included in a teabag. But given how popular tea is, it's remarkable that so few studies on teabag infusion have been conducted. Fig. 1 describes different shapes of tea bags available.

Most of the early studies have considered the infusion kinetics of loose tea leaves under well-controlled experimental conditions. Aqueous extraction of black loose-leaf tea was first studied by Long (1978 and 1979) but much of the work has been conducted by Spiro and co-workers (Spiro and Siddique, 1981; Spiro *et al.* 1992; Spiro *et al.* 1992; Spiro and Price, 1987; Spiro *et al.* 1987; Spiro and Price, 1987; Spiro and Jago, 1982; Price and Spitzer, 1994; Price and Spitzer, 1993; Price and Spiro, 1985; Price and Spiro, 1985).

Spiro introduced a simple model to explain the observed rates of extraction of individual tea compounds into aqueous solution. The results yield so-called infusion curves in which the liquor concentrations of the measured tea soluble solids

Fig. 1: Different shapes of tea bags

increase with brew time in accordance with first order kinetics. Most of the research to date has also been concerned with the dissolution process over comparatively long time periods. Of increasing interest is an understanding of the factors that affect the infusion process when a teabag is infused for a relatively short time period (Lian and Astill, 2002).

Process of Tea Bag Infusion

A number of physical processes occur at once when a teabag is infused in hot water. The main physical processes include the tea leaves' hydration and swelling, the solids' disintegration, and the solutes' subsequent release from the tea leaf into the bulk infusion. The bag's leaf particles resemble a packed bed. First, the solute release from the leaf particles is considered into account. Crank, (1956) and Sherwood *et al.* (1975), respectively, have proven the mathematics of solute release from a solid particle submerged in a fluid. The Crank equation assumes that the mass transfer is rate-limited by the solid particle and the Sherwood approach considers release as rate-limited by the transfer in the fluid. Fig 2 shows the different methods of tea infusion.

Modelling the kinetics of tea and coffee infusion

The kinetic expression created by Spiro and Siddique (1981) has served as the foundation for the majority of the kinetic research of tea and coffee infusion.

$$ln\left(\frac{c_{aq\infty}}{c_{aq\infty} - c_{aq}}\right) = k_{obs}t \quad \ldots (1)$$

where c_{aq} is the concentration of the component in the aqueous phase at time *t*, is its concentration in the aqueous phase at equilibrium, k_{obs} is an observed first-order rate constant and *t* is the infusion time.

This kinetic equation is calculated using a lumped parameter model[2], in which the difference between the average concentrations in the solid and aqueous phase (adjusted by a partition coefficient) determines the mass transfer rate. The solute's diffusion coefficient in the solid can be calculated using the model and the observed rate constant. Because tea and coffee are believed to have distinct geometries, various equations are utilized. Assuming a slab geometry for tea leaves, equation 3 is produced.

$$k_{obs} = \frac{2D}{L^2}\left(1 + \frac{V_s}{KV_{aq}}\right) \quad \ldots (2)$$

where *D* is the diffusion coefficient, *L* is the half-thickness of the leaf, V_s is the volume of solids in the system, V_{aq} is the volume of the aqueous phase and *k* is the partition coefficient, defined as;

(i)

(ii)

Fig. 2: Methods of tea infusion; **(i)** Tea Bag Infusion; **(ii)** Loose leaf Tea infusion

$$K = \left(\frac{c_{aq}}{c}\right)_{equilibrium} \quad \text{...(3)}$$

where c is the concentration of the component within the solid.

A spherical geometry is assumed for coffee particles, giving;

$$k_{obs} = \frac{12D}{R^2}\left(1 + \frac{V_s}{KV_{aq}}\right) \quad \text{...(4)}$$

where R is the radius of the particle.

When examining experimental data, it is thus customary to plot $ln[c_{aq\infty}/(c_{aq\infty} - c_{aq})]$ *versus t.* The above theory predicts that the data will fall on a straight line which passes through the origin. Many experimental studies have since found that although an acceptable linear fit is usually obtained, the line of best fit often misses the origin by a significant amount (Stapley, 2002). The data are therefore commonly fitted to a revised expression, namely.

$$Ln\left(\frac{c_{aq\infty}}{c_{aq\infty} - c_{aq}}\right) = k_{obs}t + a \quad \text{...(5)}$$

Spiro (1984) has proposed an analysis for tea infusion that uses Fick's second law to directly estimate the intercept. This explains transient diffusion behavior and has been used to extract coffee as well as other leaching/extraction issues in food processing18. The complex nature of the ensuing mathematical solutions to problems is a barrier to the application of Fick's second law. By using a "long-time approximation" to the diffusion curves, Spiro's result significantly simplified them and yielded an equation with the same shape as equation (5).

Coffee particles and tea leaves are explained by various equations because of their differing geometries. Here, it is assumed that tea leaves can be represented by thin "slabs" and that diffusion mostly takes place along an axis that is perpendicular to the slab's main face. Thus, Fick's second law in one dimension can be applied:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \quad \text{...(6)}$$

where x is the distance co-ordinate in the direction of diffusion. The leaf extends between x=L and x=L. For coffee infusion it is assumed that the particles are spherical, and hence Fick's second law is used in its spherical polar form:

$$\frac{\partial c}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D\frac{\partial c}{\partial r}\right) \quad \text{...(7)}$$

where r is the radial co-ordinate. Mass transfer via any other potential route (for example through the vascular system of a leaf) is thus neglected. It is also assumed that the solute diffusivity is constant. This is an untested assumption, as the diffusivity may be affected by variations in moisture content, for example before the solid has had enough time to hydrate fully. The boundary condition for both geometries is mass flux exiting at surface;

$$J_{surface} = \pm D\left(\frac{\partial c}{\partial x}\right)_{surface} = h_m\left(c_s - \frac{c_{aq}}{K}\right) \quad \text{...(8)}$$

where h_m is the surface mass transfer coefficient and c_s is the concentration of solute present in the surface of the solid.

The rise in concentration of solute in the aqueous phase is obtained via a mass balance:

$$M_0 = M + c_{aq}V_{aq} \quad \text{...(9)}$$

where M_0 is the initial amount of solute in the solid and M is the general amount of solute in the solid. It is assumed that the initial concentration in the aqueous phase is zero. The analysis can be extended to a large number of leaves or particles in solution, providing they all behave similarly to each other, i.e. they are of the same thickness or diameter and possess the same diffusion properties. Variations in these are most likely to be the greatest source of error in modelling the infusion kinetics of real systems.

Modelling of teabag Infusion

The process of teabag infusion is modelled as a three-step procedure that includes (i) the solutes' solubilization and release from the tea leaf; (ii) the solutes' washing through the packed bed of the tea leaf via porous flow; and (iii) the solutes' convection and diffusion in bulk fluid. The process has been simulated using a computational fluid dynamics (CFD) model in both static (no agitation) and dynamic (mechanically agitated) settings. According to the findings, when using static infusion, significant solute concentrations accumulate in the porous fluid of the packed bed of tea leaves, causing natural convection to form around the teabag. The primary source of control over the infusion rate is the buoyancy-induced recirculation of the fluid through the teabag. The external agitation during dynamic infusion causes a forced fluid flow through the teabag that is significantly larger than the natural convection driven by buoyancy. As a result, the rate of infusion is significantly higher and the solute concentration is more evenly distributed throughout the teabag and bulk fluid (Lian and Astill, 2002).

Model Development

Compared to loose tea, tea infusion with a tea bag is a more complicated process. A tea bag is submerged in hot water during the brewing process. As the hot water enters and exits the tea bag paper, the soluble ingredients are leached off. Fig. 2 depicts a schematic of this procedure. A bed of granules prevents water from flowing in and out of the tea bag. There are several processes involved in this infusion process through the tea bag: (i) water flowing through tea bag paper from bulk water to the tea granule bed; (ii) water flowing through the tea bed's pores; (iii) water being absorbed by the tea granules; (iii) tea constituents dissolving from the solid to the liquid phase inside the tea granules; (iv) tea constituents diffusing from the water inside the granules to the granules' outer surface; (v) transporting dissolved soluble solids from the granules' outer surface to the tea bed's pores; and (vi) convective transfer of soluble solids in the fluid (Dhekne, 2020).

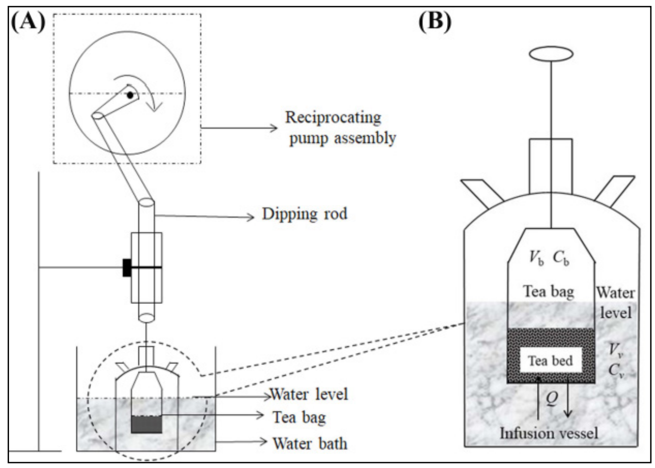

Fig. 3: Schematic representation of **(A)** tea bag dipping set-up **(B)** magnified image of the tea bag in an infusion vessel (Dhekne, 2020)

Tea Infusion Kinetics

Adding a tea bag with a certain amount of tea to a tea cup filled with boiling water is the best standard method for making tea (Chin *et al.* 2013). Due to the high rate of tea consumption worldwide, tea infusion is a crucial solid-liquid extraction procedure. Table 1 shows detailed specifications of different tea bag papers.

Table 1: Detailed specifications of different tea bag papers

Sl. No.	Material of tea bag paper	Grammage (g/ m²)	Thickness l_M (μm)	Advancing contact angle mean (ACA, °)	Receding contact angle mean (RCA, °)	Average void size, D (m) × 10^5	Porosity, ε (%)	Permeance (m/s) × 10^5
1	100% cellulose	13.3	65 ± 1.61	50.49 ± 2.6	39.22 ± 2.2	4.69	28.27	2.43
2	Cellulose/PP	16.00	70 ± 2.10	87.40 ± 2.6	40.07 ± 4	5.32	32.56	4.38
3	Polylactic acid (PLA)	20.23	129 ± 1.31	84.90 ± 2.6	47.52 ± 1.1	5.22	38.49	5.87
4	Nylon (woven)	20.89	75 ± 1.71	91.50 ± 1.2	9.36 ± 3.0	17.66	62	23.9
5	Nylon (hybrid)	16.56	73 ± 1.98	88.70 ± 0.8	6.3 ± 10.9	6.46	46.79	8.81

Jha et al. 2020.

Factors Influencing Quality of Tea blends and infusions:

Jin *et al.* (2019) conducted study on the effects of green tea brewing conditions on the chemical profiles of metabolome and catechin components, as well as the antioxidant activity, at 60 ◦C and 95 ◦C for a duration of 5–300 min. The tea infusions' antioxidant capabilities were evaluated. Temperature had a greater influence on 2,2-diphenyl-1-picryl-hydrazyl hydrate (DPPH) radical scavenging activity than did time. The results of a metabolomics study using ultra-high performance liquid chromatography-quadrupole-time-of-flight mass spectrometry (UHPLC-QTOF/MS) showed that temperature and time had a significant impact on the metabolic profiles, which included 33 differential metabolites. The effects of time were more pronounced at 95 °C starting after 30 minutes. In a hierarchical clustering study, infusions that were brewed at 95 °C for more than 30 minutes produced unique profiles..Eight catechins were quantified using UHPLC-QqQ/MS, and the results indicated that the overall catechin level peaked. The levels of four catechin epi-forms declined while those of four non-epi-forms increased after 10 minutes of brewing at 95 °C, suggesting the gradual epimerization of catechins. The results of this study indicate that, in research including the use of green tea extracts as aqueous infusions, great consideration should be given to the brewing parameters for green tea sample production.

Green tea comprises both Chinese and Japanese steamed and parched (fired) teas, albeit with different blanching techniques. The study results presented conducted by Lin *et al.* (2014) includes data regarding the effect of various brewing temperatures (cold or hot water) on the quality of tea blends made from several types of green tea (parched or steamed) in varying dosages (2, 6 or 10%). The quantity of soluble solids, sugars, free amino acids, caffeine, and antioxidant components were comparable in tea infusions made from parched and steamed green tea, but they differed in pH, color, and sensory effects. Infusions of tea that were lighter, less colored, and had higher sensory ratings were produced by cold brewing with decreased extraction efficacy. Lower amounts of caffeine, epigallocatechin gallate, and epigallocatechin were found in cold-brewed tea infusions. Infusions made from cold-brewed tea have reduced levels of caffeine, gallate and epigallocatechin, as well as being less bitter and astringent. All things considered; the public would have an alternative in cold-brewed tea infusions made from parched green tea.

Yadav *et al.* (2018) studied the infusion patterns of four popular tea brands at temperatures ranging from 50 to 100°C. The results of the studies demonstrate the clear correlation between brewing temperature and various particle size fractions and infusion characteristics. When compared to other components under study, the HPLC analysis of the brew reveals that the epicatechin gallate (ECG) and catechin gallate (CG) dissolve rapidly. It has been determined what the principal catechin and methyl xanthine partition constants are between swollen tea granules and aqueous solution. All components have partition constants (K) ranging from 0.23 to 0.82 g/mL at 60-80°C. There is now an established connection between delivered polyphenol content (DPP), UV spectrophotometry, and HPLC—the three techniques most frequently employed in ordinary tea brew analysis.

Eleven varieties of tea were studied by Winiarska-Mieczan *et al.* (2024): hibiscus tea, yerba mate, raspberry tea bags, black tea, red tea, green leaf tea, white lychee plum tea, butterfly pea flower (Clitoria ternatea) tea, and white tea bags tea with flowers. Spectrophotometric assays were used to assess the level of total polyphenol (TPC), flavonoids, and anthocyanins, as well as the antioxidant and antiradical capacity utilizing the DPPH and ABTS radical cations. The ideal brewing time for green tea (leaf and bags), black tea (leaf and bags), butterfly pea flower tea, white tea, white lychee plum tea, raspberry tea, and yerba mate is 15 minutes because of the antioxidant activity of tea infusions. Ten minutes is the recommended brewing time for red tea and hibiscus it should be five minutes. The ideal brewing time for green tea (leaf and bags), black tea (bags), butterfly pea flower tea, white tea, white lychee plum tea, raspberry tea, and yerba mate is 15 minutes because of the antioxidant activity of tea infusions. It is ideal to steep black tea (leaf) for 15 minutes. DPPH's ability to eliminate free radicals peaked after 10 minutes. The recommended brewing time for red tea is ten minutes, while hibiscus flower tea should only take five minutes. The results correspond to the temperature at which tea producers recommend brewing. Future research should consider different tea brewing temperatures for complete results, enabling people to reap the full benefits of consuming tea.

Murugesh *et al.* (2016) conducted the study with the goal of choosing the appropriate type of water to use to prepare ready-to-drink (RTD) beverages and green tea infusion. Both the sensory qualities and the nutrients' extractability are essential for infusion. For this reason, the preparation can be done using reverse osmosis (RO), packaged drinking (PD), or ultra-pure (UP) water. However, because RTD beverages are distributed and stored before being consumed, their aesthetic appeal and physical stability are also crucial factors in determining customer approval. Additionally, the findings showed that the stability of catechins should be taken into account when choosing a water source. Despite the fact that UP, PD, or RO satisfy all of these requirements, RO water is driven by economic factors for the creation of RTD. The conclusions drawn from this scientific investigation are therefore useful in choosing the right water quality to use when making green tea beverages.

Six different kinds of tea leaves were studied for their antioxidant properties by Hajiaghaalipour *et al.* (2016) at different temperatures and times throughout the extraction process. Overall, the study's studied samples showed significant levels of both antioxidant activity and capacity. The findings show that steeping time and temperature have a major impact on antioxidant activity, with variation having the greatest influence. Under varying extraction conditions, the amounts of antioxidants in white, green, and black teas varied. Overall, extended hot and cold extracts yielded the most activity for white tea, while short hot water infusion yielded the highest activity for black tea and prolonged cold steeping for green tea. The results of the research proved that white and green teas have higher antioxidant capacities than black tea.

Factors influencing the Quality of tea such as time, temperature, water type etc and the results obtained after studies with infusions are mentioned in table 2.

Jaganyi and Mdletshe, (2000) conducted tea extraction tests using tea-bag material at various temperatures. Black orthodox Assam tea's caffeine extraction rates into distilled water were measured. The findings obtained were compared to loose tea with a leaf size of 1.18±1.40 mm. In comparison to loose tea, the tea-bag tea's first order rate constants were discovered to be 29% lower. The results showed that the activation energy for tea-bag tea and loose tea were 43±2 and 45±2 kJ mol^{-1}, respectively. According to these findings, the tea-bag material slows down the rate of infusion.

The theory used for the analysis by (Spiro & Jago, 1982) presupposes that the leaf swells initially upon contact with water, followed by infusion. This indicates that a tea leaf's swelling is not altering over time. Thus, it is evident that the volume within the tea bag is the sole variable in this investigation. Due to the limited space in the 16 cm^2 tea bag, the tea leaves are compressed together after swelling. This makes it harder for water to get to the leaf in the middle of the tea bag. Additionally, the caffeine that is removed from the centre of the tea leaf must travel through the leaf particles in a more convoluted manner before reaching the majority of the solution. This results in a slow infusion process, as seen from the k_{obs} values.

Jaganyi and Ndlovu, (2001) measured the caffeine infusion rate from loose Ceylon Orange Pekoe tea leaves measuring 1.4–2 mm and within a tea bag membrane at 80°C. The tea bags came in a variety of shapes and sizes. Up until the ratio of tea leaf to tea bag size was 1:10, it was discovered that the rate constant dramatically rose as the size of the tea bag increased. The findings also show that the tea bag

Table 2: Effect of the various factors on the Infusion Quality

Sl. No.	Study	Influencing Factor	Tea Infusions	Results	Reference
1	Effects of green tea brewing conditions on the chemical profiles of metabolome and catechin components, as well as the antioxidant activity	Temperature, Time	Green Tea	Temperature and time had a significant impact on the metabolic profiles, which included 33 differential metabolites. The effects of time were more pronounced at 95°C starting after 30 minutes. In a hierarchical clustering study, infusions that were brewed at 95 °C for more than 30 minutes produced unique profiles.	Jin *et al.* (2019)
2	Effect of various brewing temperatures (cold or hot water) on the quality of tea blends made from several types of green tea (parched or steamed) in varying dosages (2, 6 or 10%). The quantity of soluble solids.	Brewing Temperature	Chinese and Japanese steamed and parched (fired) teas	Infusions made from cold-brewed tea have reduced levels of caffeine, gallate and epigallocatechin, as well as being less bitter and astringent	Lin *et al.* (2014)
3	The infusion patterns of four popular tea brands at temperatures ranging from 50 to 100°C.	Brewing Temperature	Four popular tea brands	Studies demonstrate the clear correlation between brewing temperature and various particle size fractions and infusion characteristics	Yadav *et al.* (2018)
4	Ideal brewing time for different types of teas.	Brewing Time	Hibiscus tea,yerba mate, raspberry tea bags, black tea, red tea, green leaf tea, white lychee plum tea, butterfly pea flower (*Clitoria ternatea*) tea, and white tea bags tea with flowers.	The ideal brewing time for green tea (leaf and bags), black tea (leaf and bags), butterfly pea flower tea, white tea, white lychee plum tea, raspberry tea, and yerba mate is 15 minutes because of the antioxidant activity of tea infusions. The recommended brewing time for red tea is ten minutes, while hibiscus flower tea should only take five minutes	Winiarska-Mieczan *et al.* (2024)
5	Selection of appropriate type of water to use to prepare ready-to-drink (RTD) beverages and green tea infusion	Water used for Infusion.	Green tea made using reverse osmosis (RO), packaged drinking (PD), or ultra-pure (UP) water	UP, PD, or RO satisfy all of the requirements (sensory qualities and the nutrients' extractability are essential for infusion), RO water is driven by economic factors for the creation of RTD.	Murugesh *et al.* (2016)
6	Antioxidant properties of tea at different temperatures and times throughout the extraction process	Temperature, Time of brewing.	White, green, and black teas	Extended hot and cold extracts yielded the most activity for white tea, while short hot water infusion yielded the highest activity for black tea and prolonged cold steeping for green tea.	Hajiaghaalipour *et al.* (2016)

membrane provided some resistance to the infusion of caffeine and that the form of the tea bag had no effect on the rate of infusion.

Sharif *et al.* (2014) dissolved pure caffeine in four distinct solvents—distilled water, ethyl acetate, chloroform, and dichloromethane—and used the Beer-Lambert law to calculate each solvent's molar decadic absorption coefficient. In comparison to the other three solvents (distilled water, chloroform, and ethyl acetate), dichloromethane was shown to be the most effective for decaffeination. Additionally, temperature and brewing time have an impact on the decaffeination process. It is evident that the rate of diffusion is dependent on the initial concentration of caffeine in hot water because it is high at first and decreases with longer brewing times. Additionally, the extracted solution's caffeine level rises as the brewing temperature does, indicating that both the solubility and diffusion rate rise with temperature. Lastly, it is discovered that the caffeine levels in tea brands offered in Pakistani markets range from 1% to 5%, which is within the permitted range.

Ramalho *et al.* (2013) analyzed eight distinct tea brands, three of which were in granule form and five of which were in tea bag form. Using the Folin-Cicoalteau reagent and a spectrophotometer, the total phenolic content was ascertained. Caffeine and a few phenolic chemicals were identified and quantified using a Diode Array Detector and High Performance Liquid Chromatography equipment. Brazilian samples had higher levels of propyl gallate (43 $mg.g^{-1}$), caffeine (67 $mg.g^{-1}$), gallic acid (0.9 $mg.g^{-1}$), catechin (48 $mg.g^{-1}$), and rutin (12 $mg.g^{-1}$) compared to Indian teas, which had higher levels of p-coumaric acid (7 $mg.g^{-1}$) and chlorogenic acid (4 $mg.g^{-1}$). At all infusion times, including the maximum of 30 minutes attempted in this study, chlorogenic acid was not found in Brazilian teas. These teas were found to be good sources of dietary phenolic compounds, and the longer the infusion time, the higher the concentration of these compounds in the beverage.

Yang *et al.* (2007) studied the effects of steeping time on caffeine, catechins, and gallic acid in tea infusions using bag teas that contained 3 g of ground black, green, oolong, paochoung, and pu-erh tea leaves (the particle size used was 1-2 mm). The bag tea was steeped eight times, 30 seconds each time and steeping durations (0.5–4 min). It was also examined how tea infusions changed when stored at 4 or 25 °C for 0–48 hours and how these components changed when bag tea was infused with 150 mL of cold water at 4 or 25 °C for 0.5–16 hours. The Results showed that different steeping methods, tea species and its manufacturing conditions would affect the contents and compositions of GA, catechins and CA in tea infusions. The infusion rates of these compounds in cold water were significantly lower than those in hot water. The infusing efficiencies of non-gallated catechins and GA were higher than gallated catechins and CA under cold water steeping. EGC was the highest catechin in cold water infusions, whereas EGCG was the highest one as steeping in hot water. It would retard the oxidation of catechins as tea infusions were stored at 4 ◦C after steeping; however, there were larger changes in the contents of catechins and GA at 25 ◦C storage for over 36 h.

The process of infusing tea bags combines the effects of Nerst layer mass transfer resistance (Biot number, Bi ~ 1) and intra-particle diffusion. Due to increased Reynold's number and GA liquid diffusivity, respectively, an increase in dipping frequency and temperature results in an increase in the mass transfer coefficient. Because a smaller particle has a larger interfacial area and a lower loading causes a larger swelling, the mass transfer coefficient is inversely correlated with particle size and loading (Dhekne and Patwardhan, 2020).

Effect of Dipping Temperature, Infusion Time and Dipping Frequency of Tea Infusion Kinetics

The main elements affecting the Infusion Kinetics of tea bags are the tea bed placed within, the size and form of the tea bag, stirring outside the bag, the Particle Size of the tea grains, loading the tea bag, brewing temperature, and frequency of dipping (Yadav *et al.* 2017). Increases in temperature and the frequency (rate) at which tea bags were dipped in hot water were found to raise the tea bags' Infusion Kinetics (Yadav *et al.* 2017). Increases in brewing temperatures and decreases in Particle Size are thereby improving the infusion profile of tea (Yadav *et al.* 2018). In contrast to single-layered tea bags, which showed the lowest kinetics and a decrease in Infusion Kinetics as tea loading increased, double-chambered tea bags also improved edema and Infusion Kinetics.

Tea Infusions

Manikanta *et al.* (2023) observed that, the nutritious composition and acceptability of the green tea improved with the addition of Tulsi and moringa leaf powder. Comparing the mixes to green tea alone, the nutrients were better distributed in the mixtures. When compared to green tea, the herbal tea brews were likewise quite good. Tulsi and moringa leaves were cleaned, dried using a tray dryer, and then blended in various proportions with green tea. The powdered herbal blend's moisture content, water activity, TSS, phenol content, and antioxidant content were assessed. Tea was brewed using these blends, and an organoleptic investigation was conducted. The herbal tea produced from drumstick, Tulsi, and green tea leaves has a unique flavour that is therapeutic and antioxidant-rich in addition to being nutrient-dense properties.

Das *et al.* (2019) reported that by blending black and green tea with cloves, clove-based herbal infusions were developed. Phytochemical analysis was carried out to determine that, when combined in very high concentration (1000 mg), the tea and clove herbal preparation had the highest amounts of phenolic content mg/GAE (1007.25 1.75), flavonoid content mg/CE (158.17 2.14), free radical scavenging capacity in terms of % inhibition (96.81 0.16) as well as improved antimicrobial property in comparison to the others. The total phenolic content, total flavonoid content, antioxidant potential, and antibacterial activity against Gram-positive bacteria *S. aureus* and Gram-negative bacteria *E. coli* were increased significantly with the incorporation of clove to the herbal infusion.

Kumar *et al.* (2018) observed that blending of moringa with a variety of herbs and Flavors, such as Tulsi, ginger, and lemon grass. The total polyphenol content of the infusions varied from 685 to 1567 mg GAE/100 mL. The most frequent phenolic acid across all of the treatments was gallic acid. The organoleptic evaluation of an infusion including Tulsi and moringa was very positive.

Vyshali *et al.* (2022) concluded that using a cabinet tray dryer, guava leaves, lemon grass, mint leaves, moringa leaves, Tulsi leaves, and curry leaves are dried. These dried powders are blended in various combinations with various ratios, with green tea serving as the control. The guava leaf-based herbal tea powder's physico-chemical properties were assessed. In terms of phenol content (111.90 mg GAE g^{-1}), antioxidant activity (90.33%), and ascorbic acid content (121.37 mg 100 g^{-1}), the treatment combination (T9) 50% guava leaf powder + 10% lemon grass + 10% mint powder + 5% moringa leaf powder + 5% basil leaf powder + 20% curry leaf powder performed well. The major flavonoid in guava leaf extract powder is quercetin, which is hydrolysed in the body to produce glyconequercetine, which is what provides the leaves their spasmolytic properties. Additionally, it guards against intestinal motility and lowers belly capillary permeability.

Namdev and Gupta, (2015) observed that, after blending green tea with *Withania somnifera* stems, Terminalia arjuna bark, Cinnamon bark and *Tinospora cordifolia* stems. Although several health benefits are also credited to green tea, but according to some unpublished reports it has been observed that the sensory appeal of green tea is not much attractive due to the lack of distinct flavor properties. It may therefore can be a good idea to combine green tea with other herbs (*Withania somnifera)* stem, Cinnamon bark, *Tinospora cordifolia* stems and *Terminalia arjuna* bark) for developing flavored green tea, which not only adds to its appeal, but also palatability & thereby making it a wonder product in the context of human health. As sensory appeal matters the most to consumers more than health or nutritional benefits, so the above infusion will provide them with new alternatives to traditional flavored teas which can impart health benefits too.

Selvan and Sivasamy, (2009) conducted studies on blending to enhance the quality of tea produced. Various ratios of seedling leaves were combined with a known number of clonal leaves. There was a considerable decrease in the polyphenol content of the produced tea when the ratio of seedling teas to clonal leaves increased to 3:1 or 1:1. Conversely, there was a significant increase in polyphenol content when the proportion of clonal leaves increased. The biochemical components of clonal tea are highly valued for their nutritional and therapeutic properties. However, clonal tea is not widely available. The majority of seedlings are employed on tea plantations throughout southern India. Consequently, an attempt was made to blend in order to improve the quality of the tea made from seedlings, and the techniques that were available were used to quantify the biochemical components. The study's findings indicate that adding clonal leaves to seedling-produced food enhanced its quality.

Kim *et al.* (2018) conducted a study to identify the volatile ingredients in blended tea made from Korean fermented tea and a variety of herbs. This study examined 161 volatile components from 4 samples of BT (blended tea), FT (fermented tea), BT2, and BT3. The FT sample included the majority of the hydrocarbons, with 61 volatile chemicals in total. Three-methyldecane (10.48%), 2,2,4, 6,6-pentamethylheptane (10.00%), and 2,3,6-trimethyloctane (7.90%) were the main constituents. The BT1 sample, which included fermented tea, orange cosmos, lemon grass, chamomile, and peppermint, included a total of 75 volatile chemicals. The largest percentages of compounds were L-(p)-menthol (36.79%), menthone (24.92%), and isomenthone (8.70%). The BT2 sample, which included fermented tea, rose hip, lemongrass, lavender, and peppermint, included 76 different volatile chemicals. The most prevalent compounds were found to be alcohols, with the main constituents being linalool (26.32%), linalyl acetate (18.45%), and L-(p)-menthol (11.99%). In the BT3 sample, which included fermented tea, citrus peel, chamomile, hibiscus, and beet, 85 volatile chemicals were found. The most prevalent compounds were found to be sesquiterpenes, which include L-limonene (74.45%), -myrcene (3.06%), and δ-terpinene (7.47%).

Makanjuola *et al.* (2015) observed that Water was the most efficient extraction solvent to maximize peroxide scavenging and iron chelating activity under the examined extraction circumstances of ginger, tea, and their blends. The best solvent to maximize DPPH radical scavenging activity was ethanol, whereas the most effective solvent to maximize ABTS radical scavenging activity was aqueous ethanol. With R2 and Q2 of 0.93 and 0.83, respectively, a strong multivariate regression model explaining the connection between the extracts' total flavonoid concentration and antioxidant activity was found. Blended tea and ginger extracts shown combined benefits in their capacity to scavenge radicals DPPH and ABTS.

Mu'tamar *et al.* (2021) Conducted a study to create the ideal blended eucalyptus tea formula that satisfies consumer needs. Because it lowers blood sugar and cholesterol, eucalyptus tea is a useful herbal beverage. Nevertheless, eucalyptus tea's acceptability as a whole was poor, therefore in order to enhance its sensory qualities, it must be combined with black tea and cinnamon. The response surface method (RSM) with central composite design (CCD) was employed in this investigation utilizing two factors: the proportion of cinnamon and black tea powder on eucalyptus leaf powder. In order to determine the ideal formula, the following factors were examined: moisture content, extract content, colour, and sensory score, which takes into account colour, flavor, scent, and overall preference. of mixed tea with eucalyptus. The findings indicated that the ideal combination of eucalyptus tea was s 48.5% black tea and 29.8% cinnamon.

Ramya *et al.* (2021) conducted study to prepare hibiscus tea and evaluate its potential as an antioxidant when combined with different formulations of green tea. Seven remedies made out of shade-grown tea blends green tea was produced along with dried red single cultivar hibiscus flowers, which were then preserved at various intervals. The tea infusions' overall anthocyanin content, potential as an antioxidant, and colour value were evaluated. Hippophaerus tea had the highest anthocyanin concentration of all the infusions, but green tea had a much higher potential as an antioxidant, followed by infusions of green tea and hibiscus tea. Because of the anthocyanin Colour and flavor, the blend of green tea and hibiscus tea was more acceptable to consumers.

Spirulina, or *Arthrospira platensis*, is a type of blue-green algae that is known as a dietary single-cell protein because of its high protein concentration. Three separate formulations were used to brew the spirulina and green tea together: formulation A included 0.5 g of spirulina powder and 1.5 g of green tea; formulation B included 1 g of spirulina powder and green tea; and formulation C included 1.5 g of spirulina powder and five g of green tea. Every formulation was steeped for two minutes at 80°C in 100 millilitres of hot water. Subsequently, a quantitative protein estimation assay (Lowry method) and a 2,2-diphenylpicrylhydrazyl free radical scavenging assay were performed on each formulation. Formulation B displayed the highest protein and antioxidant levels out of the three. Formulation B exhibited a straight proportionality between its concentration and antioxidant activity, with an IC50 value of 37.98 μL/mL. In a similar vein, formulation B had a greater protein level at 287.33 μg/100 μL. Formulation B had 47.61 mg of ascorbic acid equivalent as total antioxidant. In addition, 80 mL of the total volume of Prot-Tea output included 229.86 mg of total protein (Gopal and Govindaraj, 2024).

Various herbs have been used along with green tea to create a new blend by researchers which have given positive results along with increased consumer acceptability with improved nutritional aspects which adds to the health benefits of the blends. Such green tea blends new blend developed by the researchers are mentioned in the table 3.

Herbal tea blends

Dongmo *et al.* (2024) Developed herbal tea blends using three different plant species, then evaluate which combination has the best antioxidant and antiobesogenic qualities. According to a study, the ideal tea mix sample contains (80% *Hibiscus sabdariffa*, 10% *Zingiber officinale* and 10% *Mentha spicata*) When compared to the control groups, it demonstrated strong antiobesogenic qualities with a significant decrease in food intake, body mass index, adipose tissue, blood triglycerides, total cholesterol, LDL-cholesterol, glucose, and atherogenic index, and an increase in the blood levels of HDL-cholesterol. The developed herbal blend exhibited promising results when used as a safer solution for managing and preventing obesity as well as other health problems linked to oxidative stress.

Acar *et al.* (2022) conducted a study to determine whether food wastes may be used to make herbal tea and to identify the characteristics of these wastes, including their bioactive component content, physical characteristics, and sensory appeal. Three fresh blends made of walnut shell, banana, pomegranate, mandarin, eggplant, and red onion skins. 3, 4, and 5 minutes were given for the infusion of cherry stalk and corn tassel at varying temperatures (70 and 100 °C). Because of its bitter aftertaste, corn tea, with a high phenolic component level (677.7 mg GAE/L), was not as well regarded by tasters. The most preferred tea blend, then, was walnut shell tea with a moderate phenolic concentration. The colour indices of teas were also shown to be significantly impacted by varying infusion periods and temperatures.

Malongane *et al.* (2022) studied that many herbal teas with anti-oxidant, anti-inflammatory, and anti-diabetic properties can be found in South Africa, including rooibos tea (*Aspalathus linearis (Burm.f.) R. Dahlgren*), honeybush tea (*Cyclopia intermedia* E. Mey and *C. subternata Vogel*), special tea (*Monsonia burkeana* Planch. ex-Harv.), and bush tea (*Athrixia phylicoides DC.*). The aim of this investigation was to evaluate the in vitro antioxidant capacity of specific tea blends through the utilisation of 2,20-azino-bis (3-ethylbenzthiazoline-6-sulfonic acid) (ABTS) and 1,1-diphenyl-2-picrylhydrazyl (DPPH) assays. Additionally, the 15-lipoxygenase inhibitory

Table 3: Various Developed Green Tea Infusions

Sl. No	Infusions	Results	References
1	Green Tea + Tulsi leaf Powder + Moringa Leaves Powder	Improved nutritious Composition and Acceptability	Manikanta *et al.* (2023)
2	Black tea + Green Tea + Clove	Highest amounts of phenolic content mg/GAE (1007.25 1.75), flavonoid content mg/CE (158.17 2.14), free radical scavenging capacity in terms of % inhibition (96.81 0.16)	Das *et al.* (2019)
3	Moringa Leaf + Tulsi + Lemon grass + Ginger	The positive organoleptic evaluation of an infusion observed. The total polyphenol content of the infusions varied from 685 to 1567 mg GAE/100 mL. The most frequent phenolic acid across all of the treatments was gallic acid	Kumar *et al.* (2018)
4	Guava leaf powder + lemon grass + mint powder + moringa leaf powder + basil leaf powder +curry leaf powder	Phenol content (111.90 mg GAE g-1), antioxidant activity (90.33%), and ascorbic acid content (121.37 mg 100 g-1), The major flavonoid in guava leaf extract powder is quercetin, which is hydrolysed in the body to produce glyconequercetine	Vyshali *et al.* (2022)
5	Green tea + *Withania somnifera* stems + *Terminalia arjuna* bark + *Cinnamon bark* + *Tinospora cordifolia* stems	Increased sensory appeal and palatability of the blend with added health benefits of constituents of the blend.	Namdev and Gupta, (2015)
6	Seedling leaves + Clonal leaves of tea plant.	Decrease in the polyphenol content of the produced tea when the ratio of seedling teas to clonal leaves increased to 3:1 or 1:1.	Selvan and Sivasamy (2009)
7	Eucalyptus tea	The ideal combination of eucalyptus tea the ideal blended eucalyptus tea that satisfies consumer needs was 48.5% black tea and 29.8% cinnamon. Because it lowers blood sugar and cholesterol.	Mu'tamar *et al.* (2021)
8	Green Tea + Hibiscus Tea	Because the anthocyanin Colour and flavor, the blend of green tea and hibiscus tea was more acceptable to consumers. Hippophaerus tea had the highest anthocyanin concentration of all the infusions, but green tea had a much higher potential as an antioxidant, followed by infusions of green tea and hibiscus tea.	Ramya *et al*. (2021
9	Spirulina + green tea	Formulation B (1 g each of Spirulina powder and green tea) displayed the highest protein and antioxidant levels out of the three with an IC50 value of 37.98 μL/ml\L, a greater protein level at 287.33 μg/100 μL. had 47.61 mg of ascorbic acid equivalent as total antioxidant. In addition, 80 mL of the total volume of Prot-Tea output included 229.86 mg of total protein.	(Gopal and Govindaraj, 2024).

assay was employed to evaluate the blends' anti-inflammatory characteristics. Moreover, the investigation assessed the utilisation of glucose in C_2C_{12} myotubes. The 3-(4, 5-dimethylthiazol-2-yl)-2, 5-diphenyltetrazolium bromide (MTT) assay was the last technique employed to evaluate the tea extracts' safety on Vero cells, a cell line derived from African green monkey kidneys. Both the special tea and the bush tea mix showed strong anti-inflammatory and antioxidant properties. Increased antioxidant activity was seen when varied ratios of bush tea and special tea were blended together. Special tea was somewhat cytotoxic to cells; however, this toxicity was reduced in the blending process. When compared to insulin, the anti-diabetic effects of tea were not as strong in any of the samples. The use of blended herbal teas is supported by the current study, and more research is necessary to fully understand the beneficial anti-inflammatory effects of special tea.

Builders *et al.* (2020) investigated that the herbal teas are made from single herbs, occasionally many herbs, that have been shown to have numerous health advantages. They are frequently made as decoctions or infusions. *Herbiscus sapdariffa*, *Moringa oleifera, Citrus limon*, and *Zingiber officinale* were the ingredients of three different poly-herbal teas that were made and assessed for their stability and physicochemical characteristics. Both intrinsic and non-intrinsic physicochemical parameters were identified, including moisture content, granule flow and particle size, extractive matter, pH of brew solutions, and organoleptic dust leak from teabags. Additionally, an assessment was conducted on the impact of demanding storage conditions on specific physicochemical attributes. Significant variations were observed in the physicochemical parameters of the various tea blends. When kept in various storage environments, the items also shown variations in stability metrics such appearance, brew pH, and antioxidant characteristics. Overall, the tea's physicochemical and stability qualities were good, which is indicative of a well-made herbal product.

Şahin, (2013) determine and contrast the phenolic content and antioxidant qualities of sixteen distinct fruit teas. Fruit teas' total phenol content and antioxidant characteristics were investigated using the Folin-Ciocalteu method and the ABTS (2,2-azinobis (3-ethylbenzothiazoline6-sulphonic acid)) method, respectively, based on the extraction condition (water temperature). Using the UV/Vis spectrophotometric technique, the total flavonoid and total anthocyanin contents of fruit teas were ascertained. Using photodiode array detection and high-performance liquid chromatography, the phenolic composition was ascertained and quantified (HPLC-PDA). Pomegranate (I) was shown to have the greatest total phenol content and antioxidant capacity. Peaches (III) and blackberries (I) had the greatest total flavonoid and total anthocyanin levels, respectively. Fruit teas were tested for chlorogenic acid, quercetin, myricetin, rutin, rosmarinic acid, and ferulic acid. The greatest extraction of total phenols, total flavonoids, total anthocyanins, and total antioxidant capacity from 16 distinct fruit teas was achieved at a water temperature of 100 °C. Also determine using the HPLC method, ascertain the impact of water temperature on the extraction process and quantify the different phenolic components present in fruit teas for use in extract production.

Table 4 shows Herbal tea Infusions developed from blending herbs with non-conventional components and the results obtained from the blend by researchers.

Future Outlook for Tea infusion and Tea infusion Kinetics

Recent study and improvement in food process engineering provides good possibility for the production of novel value-added goods that are both nutritionally beneficial to the consumers and conveniently processed for consumption. Commercial tea products come in a variety of forms, from black tea to flavor-infused instant tea. These products are sold in tea bags or loose tea, however because of consumer demand and the rate at which the tea infuses, it is necessary to make tea with tiny PS that increase the rate of absorption even at low liquid temperatures because temperature affects the tea's Infusion Kinetics. Additionally, tea must be packaged in non-toxic, cost-effective, and ecologically friendly tea bags that, most significantly, speed up the infusion process. It is also possible to create instant tea tablets containing therapeutic herbs that are equally flavored and reasonably priced for end users. Additionally, some customers might favour iced tea that is made and packaged in tetra packs that are sold to final customers and kept in the refrigerator (Etti *et al.* 2002).

For tea-infused foods to have the greatest possible health advantages and market appeal, technological developments in infusion techniques are essential. To thoroughly examine the phenolic profiles of tea infusions, cutting-edge techniques like ultra-performance liquid chromatography-electrospray ionization-quadrupole time-of-flight mass

Table 4: Various Herbal Tea Infusions

Sl. No.	Tea name	Component of tea Infusions	Finding	References
1	Instant Tea	Broken mixed fannings produced from tea leaves (two leaves and bud) plucked from three different tea estates, Pedro and Nuwara Eliya from the elevation category upcountry (UC) (>600 m MASL) and Halgolla estate from the low country (LC).	The aroma escape during the process affects the quality of instant tea used for application in the food and beverage industries. Capturing and adding back aroma to the instant tea is commercially important to overcome this drawback.	Dalpathadu *et al.* (2022)
2	Addition of milk to tea infusions	Two major species of tea, *Camellia sinensis* var. sinensis and *Camellia sinensis* var. assamica, are used and milk.	The negative effects of the addition of milk on the activity of tea antioxidant have been broadly reported, there is lack of information about the effect of milk addition on the activity or bioavailability of caffeine in tea infusions.	Rashidinejad *et al.* (2017)
3	Herbal Teas and Bush Tea Blends	Tea samples selected for the study included 100% bush (B100), 100% fermented honeybush from species *Cyclopia subternata* (H100), 100% special (S100) and 100% fermented rooibos tea (R100) as well as nine blends of bush tea, special tea (BS25:75) and 25% bush tea plus 75% rooibos tea (BR25:75).	The study provides scientific evidence supporting the use of rooibos, honeybush tea, special, and bush tea as potential anti-inflammatory, anti-oxidant and anti-diabetic agents, respectively. This study highlighted the potential benefit of the two indigenous teas (bush tea and special tea). Moreover, blending bush tea with the other three selected herbal teas increased its anti-oxidant activities, thus suggesting that blending of bush tea and special provides the insight for further research of its nutraceutical's potential.	Malongane *et al.* (2022)
4	Fruit Tea	—	Total phenolic content, flavonoid content, anthocyanin and antioxidant capacity of fruit teas were higher by increasing the water temperature for the extraction and they reached maximum values at 100 °C.	Şahin, (2013)

spectrometry (UPLC-ESI-Q-TOFMS) have been used (Liu *et al.* 2016). These methods make it possible to precisely identify and measure bioactive substances, which can be applied to improve infusion procedures. Furthermore, adding tea extracts to food systems like oil-in-water emulsions has demonstrated potential for improving the oxidative stability of these goods (Almajano *et al.* 2008). To improve the functional qualities and consumer appeal of tea-infused foods, future research should concentrate on honing these methods and investigating their applications in diverse food matrices.

With an increasing amount of research demonstrating the various health advantages and bioactive qualities of tea, the field of tea-infused foods is developing quickly. Due to their high phenolic content and catechins, different tea varieties—including green, black, oolong, white, yellow, and dark teas—have been the subject of recent research that have concentrated on their antioxidant properties (Almajano *et al.* 2008; Zhao *et al.* 2019). Furthermore, research on the mineral composition of tea infusions has shown that, although they do not provide substantial sources of critical minerals in a single serving, they can supplement dietary consumption when taken in higher amounts (Gallaher *et al.* 2006). The possible health advantages of herbal infusions, such as better sleep, better glucose regulation, and lower oxygen.

Because of their distinct flavors and health advantages, tea-infused food products have become more and more popular. A number of popular products that highlight the adaptability of tea as an ingredient have hit the market. For example, because of its high antioxidant content and health-promoting qualities, green tea has been used in a variety of foods, including pastries, chocolates, and beverages (Atoui *et al.* 2005; Almajano *et al.* 2008; Zhao *et al.* 2019). Due to its stronger antibacterial qualities and gentler taste, white tea has also been incorporated into culinary products, especially in Europe where consumers are more receptive to its taste (Almajano *et al.* 2008). Furthermore, functional meals that aim to lower oxidative stress and improve sleep quality have included herbal infusions such chamomile and peppermint (Etheridge and Derbyshire, 2019).

The quality and appeal of tea-infused dishes have been greatly improved by advancements in tea infusion techniques. To ensure the best extraction of bioactive components, sophisticated techniques like electrospray ionization (ESI) and ultra-performance liquid chromatography (UPLC) have been used to detect and quantify phenolic compounds in tea (Atoui *et al.* 2005; Liu *et al.* 2016). These methods have made it possible to precisely regulate the infusion settings, producing goods with reliable flavor and health advantages. Additionally, the creation of synergistic combinations, like adding bovine serum albumin (BSA) to tea infusions, has increased food products' oxidative stability and increased their appeal to customers who are health-conscious (Almajano *et al.* 2008).

Future research directions should focus on:

1. Investigating the effects of novel brewing methods and technologies on tea infusion kinetics.
2. Exploring the kinetics of tea infusion in non-traditional tea varieties and sources.
3. Developing predictive models that account for the complex interactions between tea solids, water, and brewing conditions.
4. Investigating the impact of tea infusion kinetics on the bioavailability and nutritional content of brewed tea.
5. Developing more sophisticated models that account for the complex interactions between tea solids, water, and brewing conditions.
6. Investigating the applicability of machine learning and artificial intelligence techniques to predict tea infusion kinetics.
7. Exploring the kinetics of tea infusion in non-traditional tea varieties and sources.
8. Investigating the impact of tea infusion kinetics on the bioavailability and nutritional content of brewed tea.

CONCLUSION

The kinetics of tea infusion is a complex process influenced by various factors, including tea type, particle size, temperature, and steeping time. This review has comprehensively summarized the current state of knowledge on tea infusion kinetics, highlighting the key mechanisms, models, and influencing factors and delved into the intricacies of tea infusion kinetics, elucidating the complex interactions between tea solids, water, and brewing conditions. The kinetics of tea infusion has been extensively explored, highlighting the influences of tea type, particle size, temperature, and steeping time on the extraction of soluble compounds.

The findings of this review suggest that optimizing tea infusion kinetics can significantly impact the quality and flavor profile of brewed tea. Furthermore, understanding the kinetics of tea infusion can inform the development of new tea products, brewing technologies, and sustainable production methods. Furthermore, this review has provided an in-depth examination of mathematical modeling approaches used to describe tea infusion kinetics. The discussed models, including empirical, semi-empirical, and mechanistic models, have demonstrated varying degrees of success in predicting the extraction dynamics of tea solubles. By advancing our understanding of tea infusion kinetics and modeling, researchers and industry stakeholders can work together to create high-quality, sustainable, and innovative tea products that meet the evolving demands of consumers.

REFERENCES

Acar, A., Aydın, M. and Arslan, D. 2022. Development of infusion tea formulations with food wastes: Evaluation of temperature and time effects on quality parameters. *Applied Food Research*, **2**(1): 100087.

Almajano M., Carbó R., Jiménez J. and Gordon M. 2008. Antioxidant and antimicrobial activities of tea infusions, *Food Chemistry*, **108**(1): 55-63.

Atoui A., Mansouri A., Boskou G. and Kefalas P. 2005. Tea and herbal infusions: Their antioxidant activity and phenolic profile, *Food Chemistry*, **89**(1): 27-36.

Builders, P.F., Mohammed, B.B. and Sule, Y.Z. 2020. Preparation and evaluation of the physicochemical and stability properties of three herbal tea blends derived from four native herbs. *Journal of Phytomedicine and Therapeutics*, **19**(2): 448-465.

Chin, F.S., Chong, K.P., Markus, A. and Wong, N.K. 2013. Tea polyphenols and alkaloids content using soxhlet and direct extraction methods. *World J. Agric. Sci.*, **9**(3): 266-270.

Charles, D. 1991. A cup of green tea a day may keep cancer away, *New Scientist*, September 14, pp. 17.

Crank, J. 1956, *The Mathematics of Diffusion* (Oxford University Press, London, UK).

Dalpathadu, K.A.P., Rajapakse, H.U.K.D.Z., Nissanka, S.P. and Jayasinghe, C.V.L. 2022. Improving the quality of instant tea with low-grade tea aroma. *Arabian Journal of Chemistry*, **15**(10): 104147.

Das, C., Kothari, S., Muhuri, A., Dutta, A., Ghosh, P. and Chatterjee, S. 2019. Clove based herbal tea: Development, phytochemical analysis and evaluation of antimicrobial property. *Journal of Pharmaceutical Sciences and Research*, **11**(9): 3122-3129.

Department of Health, Taiwan 2004. Annual report of Taiwan public health. Taipei, Taiwan.

Dhekne, P.P. and Patwardhan, A.W. 2020. Mathematical modeling of tea bag infusion kinetics. *Journal of Food Engineering*, **274**: 109847.

Dongmo, F.F.D., Touohou, S.V.N., Etame, R.M.E., Lienou, L.L., Koule, J.C.M., Mbiatat, H.D.G., Tchuenbou-Magaia, F.L. and Gouado, I. 2024. An herbal tea blend of *Hibiscus sabdariffa, Zingiber officinale,* and *Mentha spicata*: a potent source of antioxidant and anti-obesity properties. *European Journal of Medical and Health Research*, **2**(1): 63-74.

Etheridge C. and Derbyshire E. 2019. *Herbal infusions and health, Nutrition & Food Science,* **50**: 969-985.

Etti, C.J., Alonge, A.F., Oladejo, A.O., Akpan, M.G., Okoko, J.U. and Etuk, N.I. 2022. Effects of particles Size on tea processing: a perspective on zobo production. *European Journal of Agriculture and Food Sciences*, **4**(4): 11-18.

Fujihara, T., Nakagawa-Izumi, A., Ozawa, T. and Numata, O. 2007. Highmolecular-weight polyphenols from oolong tea and black tea: purification, some properties, and role in increasing mitochondrial membrane potential. *Biosci. Biotechnol. Biochem.*, **71**: 711– 719.

Gallaher, R., Gallaher, K., Marshall, A. and Marshall, A. 2006, Mineral analysis of ten types of commercially available tea, *Journal of Food Composition and Analysis,* **19**: S53-S57.

Gopal, R.K. and Govindaraj, S. 2024. A Study on the brewing of "prot-tea" by blending spirulina (*Arthrospira platensis*) With Green Tea. *Cureus*, **16**(2).

Hajiaghaalipour, F., Sanusi, J. and Kanthimathi, M.S. 2016. Temperature and time of steeping affect the antioxidant properties of white, green, and black tea infusions. *Journal of Food Science*, **81**(1): H246-H254.

Harbowy, M.E. and Balentine, D.A. 1997. Tea chemistry. *CRC Crit. Rev. Plant Sci.*, **16**: 415–80.

Hertog, M.G., Kromhout, D., Aravanis, C. and Blackburn, H. 1995. Flavonoid intake and long-term risk of coronary heart disease and cancer in the seven countries study, *Arch. Intern. Med.*, **155**: 381–386.

Hollman, P.C., Hertog, M.G. and Katan, M.B. 1996. Role of dietary flavonoids in protection against cancer and coronary heart disease, *Biochem. Soc. Trans.*, **24**: 785–789.

Jaganyi, D. and Mdletshe, S. 2000. Kinetics of tea infusion. Part 2: the effect of tea-bag material on the rate and temperature dependence of caffeine extraction from black Assam tea. *Food Chemistry*, **70**(2): 163-165.

Jaganyi, D. and Ndlovu, T., 2001. Kinetics of tea infusion. Part 3: The effect of tea bag size and shape on the rate of caffeine extraction from Ceylon orange pekoe tea. *Food Chemistry*, **75**(1): 63-66.

Jha, A., Mann, R.S. and Balachandran, 1996. Tea: A refreshing beverage, *Indian Food Ind.*, **15**: 22–42.

Jha, D.K., Dhekne, P.P. and Patwardhan, A.W. 2020. Characterization and evaluation of tea bag papers. *Journal of Food Science and Technology*, **57**: 3060-3070.

Jin, Y., Zhao, J., Kim, E.M., Kim, K.H., Kang, S., Lee, H. and Lee, J. 2019. Comprehensive investigation of the effects of brewing conditions in sample preparation of green tea infusions. *Molecules*, **24**(9): 1735.

Kada, T., Kaneko, K., Matsuzaki, S., Matsuzaki, T. and Hara, Y. 1985, Detection and chemical identification of natural bio-antimutagens: A case of the green tea factor, *Mutation Res.*, **150**: 127–132.

Kim, J.H., Cha, J.Y., Shin, T.S. and Chun, S.S. 2018. Volatile flavor components of blended tea with fermented tea and herbs. *Preventive Nutrition and Food Science*, **23**(3): 245.

Kumar, P.C., Azeez, S. and Roy, T.K. 2018. Development of moringa infusion for green tea and its evaluation. *Journal of Horticultural Sciences*, **13**(2): 192-196.

Lian, G. and Astill, C. 2002. Computer simulation of the hydrodynamics of teabag infusion. *Food and Bioproducts Processing*, **80**(3): 155-162.

Lin, S.D., Yang, J.H., Hsieh, Y.J., Liu, E.H. and Mau, J.L. 2014. Effect of different brewing methods on quality of green tea. *Journal of Food Processing and Preservation*, **38**(3): 1234-1243.

Liu, Z., Chen, Z., Guo, H., He, D., Zhao, H., Wang, Z., Zhang, W., Liao, L., Zhang, C. and Ni, L. 2016. The modulatory effect of infusions of green tea, oolong tea, and black tea on gut microbiota in high-fat-induced obese mice, *Food & Function*, **7**(12): 4869-4879.

Long, V.D. 1978. Aqueous extraction of black leaf tea. II. Factorial experiments with a fixed-bed extractor, *Journal of Food Technology*, **13**: 195–210.

Long, V.D. 1979, Aqueous extraction of black leaf tea. III. Experiments with a stirred column, *Journal of Food Technology*, **14**: 449–46.

Makanjuola, S.A., Enujiugha, V.N., Omoba, O.S. and Sanni, D.M. 2015. Combination of antioxidants from different sources could offer synergistic benefits: a case study of tea and ginger blend. *Natural Product Communications*, **10**(11): 1934578X1501001110.

Malongane, F., McGaw, L.J., Olaokun, O.O. and Mudau, F.N. 2022. Anti-inflammatory, anti-diabetic, anti-oxidant and cytotoxicity assays of South African herbal teas and bush tea blends. *Foods*, **11**(15): 2233.

Manikanta, S.V.V., Srihari, D. and Salomi Suneetha, D.R. 2023 Blended Tulsi-drumstick herbal tea: Quality and organoleptic properties. *The Pharma Innovation Journal*, **12**(3): 19-23.

Mu'tamar, M.F.F., Fakhry, M. and Ulya, M. 2021, May. Optimization of the Different Formulations for the Eucalyptus Blended Tea Based on Response Surface Method. In *IOP Conference Series: Earth and Environmental Science*, 757(1), pp. 012067 IOP Publishing.

Murugesh, C.S., Manoj, J.B., Haware, D.J., Ravi, R. and Subramanian, R. 2017. Influence of water quality on nutritional and sensory characteristics of green tea infusion. *Journal of Food Process Engineering*, **40**(5): e12532.

Namdev, P. and Gupta, R.K. 2015. Herbal green tea formulation using *Withania somnifera* stems, *Terminalia arjuna* bark, cinnamon bark and *Tinospora cordifolia* stems and nutritional & phytochemical analysis. *Journal of Pharmacognosy and Phytochemistry*, **4**(2): 282-291.

Price, W.E. and Spiro, M. 1985. Kinetics and equilibria of teainfusion: Part 5 – Rates of extraction of theaflavin, caffeine and theobromine from several whole teas and sieved fractions, *J. Sci. Food Agri.*, **36**: 1309–1314.

Price, W.E. and Spiro, M. 1985. Kinetics and equilibria of tea infusion: Part 4 – Theaflavin and caffeine concentrations and partition constants in several whole teas and sieved fractions, *J. Sci. Food Agri.*, **36**: 1303–1308.

Price, W.E. and Spitzer, J.C. 1993. The temperature dependence of the rate of extraction of soluble constituents of black tea, *Food Chem.*, **46**: 133–136.

Price, W.E. and Spitzer, J.C. 1994, The kinetics of extraction of individual flavanols and caffeine from a Japanese green tea (Sen Cha Uji Tsuyu) as a function of temperature, *Food Chem.*, **50**: 19–23.

Ramalho, S.A., Nigam, N., Oliveira, G.B., de Oliveira, P.A., Silva, T.O.M., dos Santos, A.G.P. and Narain, N. 2013. Effect of infusion time on phenolic compounds and caffeine content in black tea. *Food Research International*, **51**(1): 155-161.

Ramya, A., Jawaharlal, M., Thamarai Selvi, S.P. and Vennila, P. 2021. Assessment of Anti-oxidant potential and consumer acceptability of hibiscus and green tea infusions. *The Pharma Innovation Journal*, **10**(5): 116-121.

Rashidinejad, A., Birch, E.J., Sun-Waterhouse, D. and Everett, D.W. 2017. Addition of milk to tea infusions: Helpful or harmful? Evidence from *in vitro* and *in vivo* studies on antioxidant properties. *Critical Reviews in Food Science and Nutrition*, **57**(15): 3188-3196**.**

Şahin, S., 2013. Evaluation of antioxidant properties and phenolic composition of fruit tea infusions. *Antioxidants*, **2**(4): pp.206-215.

Selvan, V.S. and Sivasamy, P. 2009. Blending of clonal tea leaves with leaves from seedlings in order to improve the quality of made tea. *American-Eurasian Journal of Scientific Research*, **4**(3): 148-153.

Sharif, R., Ahmad, S.W., Anjum, H., Ramzan, N. and Malik, S.R. 2014. Effect of infusion time and temperature on decaffeination of tea using liquid–liquid extraction technique. *Journal of Food Process Engineering*, **37**(1): 46-52.

Sherwood, T.K., Pigford, R.L. and Wilke, C.R. 1975, *Mass Transfer* (McGraw-Hill, New York, USA)

Spiro, M. 1997. Factors affecting the rate of infusion of black tea, in Chemical and Biological Properties of Tea Infusions, Ed by Schubert R and Spiro M, Umwelt und Medizin, Frankfurt/ Main, pp. 38–62.

Spiro, M. and Jago, D.S. 1982, Kinetics and equilibria of tea infusion, Part 3. Rotating-disc experiments interpreted by a steady-state model, *J. Chem. Soc. Faraday Trans.*, **1**(78): 295–305.

Spiro, M. and Price, W.E. 1987. Kinetics and equilibria of tea infusion: Part 6 – The effects of salts and pH on the concentrations and partition constants of theaflavins and caffeine in Kapchorua Pekoe Fannings, *Food Chem.*, **24**: 51–61.

Spiro, M. and Price, W.E. 1987. Kinetics and equilibria of tea infusion: Part 7 – The effects of salts and pH on the rate of extraction of caffeine from Kapchorua Pekoe Fannings, *Food Chem.*, **25**: 49–59.

Spiro, M. and Siddique, S. 1981, Kinetics and equilibria of tea infusion: Kinetics of extraction of theaflavins, thearubigins and caffeine from Koonson Broken Pekoe, *J. Sci. Food Agric.*, **32**: 1135–1139.

Spiro, M. and Siddique, S. 1981. Kinetics and equilibria of tea infusion: Kinetics of extraction of theaflavins, thearubigins and caffeine from Koonsong broken pekoe. *Journal of the Science of Food and Agriculture*, **32**(11): 1135-1139.

Spiro, M. and Jago, D.S. 1982. Kinetics and equilibria of tea infusion. Part 3: Rotating-disc experiments interpreted by a steady-state model. *Journal of Chemical Society. Faraday Transaction*, **1**(78): 295–305.

Spiro, M., Jaganyi, D. and Broom, M.C. 1992, Kinetics and equilibria of tea infusion: Part 9 – The rates and temperature coeffcients of caffeine extraction from green Chun Mee and black Assam Bukial teas, *Food Chem.*, **45**: 333–335.

Spiro, M., Price, W.E., Miller, W.M. and Arami, M. 1987. Kinetics and equilibria of tea infusion: Part 8 – The effects of salts and pH on the rate of extraction of theaflavins from black tea leaf, *Food Chem.*, **25**: 117–126.

Stagg, G.V. and Millin, D.J. 1975. The nutritional and therapeutic value of tea, *J. Sci. Food Agric.*, **26**: 1439–1459.

Stapley, A.G.F., 2002. Modelling the kinetics of tea and coffee infusion. *Journal of the Science of Food and Agriculture*, **82**(14): 1661-1671.

Suzuki, T., Yamazaki, N., Sada, Y., Oguni, I. and Moriyasu, Y. 2003. Tissue distribution and intracellular localization of catechins in tea leaves. *Bioscience, Biotechnology, and Biochemistry*, **67**(12): 2683-2686.

Tijburg,L. N. M., Mattern, T., Folts,J. D., Weisberger, U. M. and Kata, M. B., 1997, Tea flavonoids and Cardiovascular Diseases: A review, *Crit Rev Food Sci Nutri*, 771–785.

van Breda, S.V., van der Merwe, C.F., Robbertse, H. and Apostolides, Z. 2013. Immunohistochemical localization of caffeine in young *Camellia sinensis* (L.) O. Kuntze (tea) leaves. *Planta*, **237**: 849-858.

Yang, D.J., Hwang, L.S. and Lin, J.T., 2007. Effects of different steeping methods and storage on caffeine, catechins and gallic acid in bag tea infusions. *Journal of Chromatography A.*, **1156**(1-2): 312-320.

Yadav, G.U., Farakte, R.A., Patwardhan, A.W. and Singh, G. 2018. Effect of brewing temperature, tea types and particle size on infusion of tea components. *International Food Research Journal*, **25**(3): 1228-1238.

Yadav, G.U., Joshi, B.S., Patwardhan, A.W. and Singh, G. 2017. Swelling and infusion of tea in tea bags. *Journal of Food Science and Technology*, **54**: 2474-2484.

Zhao C., Tang G., Cao S., Xu X., Gan R., Liu Q., Mao Q., Shang A. and Li H. 2019, Phenolic profiles and antioxidant activities of 30 tea infusions from green, black, oolong, white, yellow and dark teas, *Antioxidants*, **8**(7): 215.