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Yellow tea (*Camellia sinensis* L.), a promising Chinese tea: Processing, chemical constituents and health benefits

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Abstract

Yellow tea, also known as *huángchá* in Chinese, is a lightly fermented tea unique to China. As a rare and precious variety of tea, it has gained increasing popularity in recent years because of its pleasant mellow taste and known health benefits such as anti-oxidation, anti-inflammation and anti-cancer properties. Yellow tea is similar to green tea in many ways. The initial production process of both teas is the same, but the production of yellow tea requires additional steps. A unique step called “sealed yellowing” is always involved in yellow tea processing to reduce the oxidation level and remove the characteristic grassy smell associated with green tea while still preserving its health benefits. Compared to other types of teas, yellow tea is much less well-known and studied. In this review, the history and classification of yellow tea is introduced. The processing procedure, including detailed information about “sealed yellowing” is presented. The bioactive chemical compounds common in various types of teas or unique to yellow tea are discussed. Finally, future needs in research and development of yellow tea are discussed and proposed.

Keywords: yellow tea; classification; processing techniques; sealed yellowing; chemical compounds; biological activities

1. Introduction

Tea is one of the most popular drinks in the world. The production and consumption of tea has increased dramatically in recent years. Over two billion people drink tea in more than 125 countries (Mei, 2015) mainly because of its significant health benefits (da Silva Pinto, 2013). Tea can generally be classified into six major categories based on their different processing techniques and characteristics special to each individual group, namely green tea (non-fermented), yellow and white teas (lightly fermented, 10-20%), Oolong tea (semi-fermented, 30-60%), black tea (fully fermented, 80-100%) and dark tea (post-fermented, $\leq 100\%$) (Zhou, Chen, & Han, 2015). The manufacturing processes of these six types of teas are illustrated in Fig. 1. Each type of tea has its own particular characteristics. Green and black teas are the most consumed and therefore have been most extensively studied. Recently, with the increasing popularity of dark tea, other types of teas have also attracted much attention (Zhang, Zhang, Zhou, Ling, & Wan, 2013). Yellow tea, the least well-known type of tea, is gradually gaining recognition in Western countries because of its unique flavor, refreshing silky taste, excellent quality, and health-promoting effects on human health (Kujawska, Ewertowska, Adamska, Jodynis-Liebert, Ignatowicz, & Gramza-Michalowska, 2016).

Yellow tea is a historical tea unique to China, mainly produced in Sichuan, Anhui, Hunan, Hubei, Guangdong, Zhejiang and Guizhou provinces. Although all the true teas are derived from the leaves of an evergreen shrub *Camellia sinensis*, yellow tea is processed differently compared to other types of teas. It is lightly fermented with enticing characteristics similar to green tea. Yellow tea is the second tea after green tea discovered in China, and its history can be dated back to the mid-Tang Dynasty in 618-907 A.D. (Wang, 2011). Compared to green tea, an additional step called “sealed yellowing” is utilized during the yellow tea processing. The combined

processes of thermochemical reaction and exogenous enzymes make the ingredients of yellow tea change significantly, resulting in a fresher and mellower taste compared to other teas. The unique processing step “sealed yellowing” also gives yellow tea its beautiful appearance known as “three yellows” (yellow dry tea, yellow infusion and yellow tea dregs) with sweet taste unlike the grassy taste from green tea (Wang, Zhao, Qian, & Wang, 2013). Yellow tea usually has a higher amino acid content than green tea, and is rich in polyphenols, soluble sugars, vitamins and other nutrients (Horžić, Jambrak, Belščak-Cvitanović, Komes, & Lelas, 2012). With 85% of natural substances retained, yellow tea possesses special effects on anti-cancer, free radical scavenging, anti-bactericidal and gastrointestinal protecting effects (Wang, Zhao, Qian, & Wang, 2013; Zhao, 2009), which makes yellow tea not only delicious in flavor, but also serve as a healthy drink. Because of the tremendous health benefits, yellow tea is recommended as the most suitable drinking tea by tea experts (Deng & Zhao, 2012; Zhou, Ni, Chen, Zhan, & Yuan, 2004).

The taste and chemical composition of tea are significantly affected by tea processing, leaf maturation, botanical varieties, geographical origin and agricultural practices (Gonzalez de Mejia, Ramirez-Mares, & Puangpraphant, 2009). Different teas contain different bioactive compounds with different potential health benefits. The high content of polyphenols detected in green tea is beneficial in preventing cancer and radiation-scavenging free radicals (Ahmad, Butt, Huma, & Sultan, 2013; Basu, Betts, Mulugeta, Tong, Newman, & Lyons, 2013; Zhang, Li, Liu, & Holman, 2012). Dark tea usually contains more polysaccharides than other types of teas, which can lower the risk of cardiovascular diseases (Kubota, Sumi, Tojo, Sumi-Inoue, Hou, Oi, et al., 2011; Lin & Lin-Shiau, 2006). Black and oolong teas have been reported to possess strong antioxidative activities (Adhikary, Yadav, Roy, Bandyopadhyay, & Chattopadhyay, 2011; Zhu, Hackman, Ensunsa, Holt, & Keen, 2002). Recently, the antioxidant properties and beneficial

health effects for amino acids contained in white tea have also been studied and reported (Dias, Tomás, Teixeira, Alves¹, Oliveira, & Silva, 2013).

With the recovery of the tea industry in China in recent years, numerous research on biological components and health effects have been published. However, the knowledge of yellow tea classification and advanced processing techniques is not widely received outside China. The chemical components of various types of yellow teas are less well-known and studied compared to other teas. In response to this need, processing techniques, chemical components, health effects and new findings concerning yellow tea are reviewed and discussed for the first time. Challenges and future prospects for the integration of yellow tea practice are also outlined in this review.

2. The quality characteristics and types of yellow tea products

2.1 The quality characteristics of yellow tea

The history of yellow tea started more than 1200 years ago (Zhu & Ning, 2016). It was a tribute tea to be dedicated to the emperor in the Tang Dynasty. Historically yellow tea can be classified into two different types: variety yellow tea and process yellow tea. Variety yellow tea is the oldest yellow tea discovered in China and its history of use can be dated back to the Tang Dynasty (about 7th century A.D.). The fresh leaf of variety yellow tea has a yellow color and is plucked from albino tea cultivars and processed with the same processing technology used for green tea. Therefore, in ancient time, variety yellow tea was called yellow tea, but contemporarily, it is usually categorized as green tea in order to be distinguished from process yellow tea. Process yellow tea originated from the fried green tea and was invented in 1570 A.D. (Yang, Liu, Xie, Cheng, & Liu, 2010). It is produced by using a unique procedure known as

“sealed yellowing”, in which the green color of the fresh leaves turns into yellow, and the quality of the tea also changes. Unlike ancient times, yellow tea now only refers to process yellow tea, and the tea production must go through the "sealed yellowing" process, which makes the yellow tea distinguishable from other types of teas. The classification of different types of yellow teas is given in Fig. 2.

For the “sealed yellowing” step in yellow tea processing, the damp tea leaves are allowed to become yellow, and a unique quality of yellow tea is created (Huang, 2001). During “sealed yellowing”, chlorophyll and polyphenols contained in fresh leaves undergoes oxidation, cracking and transformation under the effects of heat and humidity; resulting in the yellow appearance. This is the major procedure to make yellow tea yellow. Moreover, "sealed yellowing" gives yellow tea the unique qualities of three yellows (yellow dry tea, yellow infusion and yellow brewed leaves). In addition, ester-type catechins present in fresh leaves are significantly reduced due to oxidation and transformation so that the convergence of tea leaves is weakened and the taste becomes mellow and thick (Yang & Zhou, 2013). Compared to green tea, the flavor of yellow tea is cleaner and fresher, the taste is mellower and less bitter without the grassy taste of green tea (Yang & Zhou, 2013; Zhu & Ning, 2016), and the color is bright yellow. Yellow tea also contains more amino acids compared with green tea, which makes yellow tea sweeter and fresher than green tea. Therefore, yellow tea has attracted much attention in recent years and gained its popularity in tea consumers (Chen, 2008).

2.2 Types of yellow tea products

Nowadays, almost all the yellow teas sold in the commercial market are process yellow tea. Yellow tea can be further categorized into three categories according to the tenderness of the

fresh tea leaves: yellow bud tea, yellow little tea and yellow big tea (Wang, 2011) (Figs. 2 and 3A). Yellow bud tea is mainly produced in Sichuan, Hunan, Anhui and Zhejiang provinces in China, and is prepared only using buds and leaves. The popular commercial products of yellow bud tea include “Mengding yellow bud”, “Junshan Yinzhen”, “Huoshan yellow bud” and “Mogan yellow bud” (Fig. 2 and 3B). Yellow bud tea is produced before the Qingming festival in the early spring, and the yield of yellow bud tea is usually very low. It is not only the rarest tea in the market, but also possesses the best quality among other yellow teas (Zhu & Ning, 2016). Yellow little tea commercial products, including “Beigang Maojian” from Hunan Yueyang, “Weishan Maojian” from Hunan Ningxiang, “Yuan’an Luyuan” from Hubei, “yellow little tea” from West Anhui and “Pingyang yellow liquid” from Zhejiang are processed using fresh tea plants plucked with one bud and two leaves. Yellow big tea is manufactured with crude leaves and stems, therefore its quality is lower than other yellow teas. “yellow big tea” from West Anhui, “Haimagongcha” from Guizhou and “Dayeqing” from Guangdong are the main yellow big tea products (Yu, 1999). Due to the differences in “sealed yellowing” processing procedure and geographical location, different yellow teas have different concentrations of chemical substances (Liu, Qi, & Xu, 2009). “Mengding yellow bud tea”, “Huoshan yellow bud tea”, “Junshan Yinzhen”, “Weishan Maojian”, “Wenzhou yellow liquid” and “Yuan’an Luyuan” are the most popular yellow tea products (Tian, Sun, Liu, & Ding, 2014). In 2013, the total production of yellow tea in China was about 6,980 tons, accounting for 0.39% of total output of all types of teas in China. The production of “Junshan Yinzhen”, “Mengding yellow bud tea” and “Huoshan yellow bud tea” accounts for about 90% of the yellow tea market share (Tian, Sun, Liu, & Ding, 2014). “Mengding yellow bud tea” produced from the Mengding Mountain, a famous tea region in Sichuan Province, has excellent flavor and fat buds. It is a historically well-known “holy”

and tribute tea in history (Li, Qi, Liu, Yang, Zou, & Chen, 2015; Liu, 2011). This very special type of tea can only be harvested during a short time period in the early spring from Mengding Mountain where the natural climatic conditions are very unique (Yi, 2008). “Junshan Yinzhen”, produced at Junshan Mountain of Yueyang County, Hunan Province, is one of the top ten teas in China (Yang & Li, 2002). The tea is known as “yellow feathers” because it is made by a single fat bud full with golden hair which looks like upright feathers after the buds brown. “Junshan Yinzhen”, also called “gold and jade”, is famous for its high quality, beautiful color, and pleasant aroma and taste (Zhu, Zhu, & Shi, 2006). “Huoshan yellow bud tea”, produced in Huoshan County of Anhui Province with a buxus-like shape, excellent aroma and taste (He & Cao, 2009), was famous in Tang Dynasty and also a tribute tea in Ming Dynasty (Xu, 2015). The tea is typically prepared with one bud and one leaf, or one bud and two early unfolding leaves.

3. Manufacturing process and chemical constituents of yellow tea

The manufacturing process of yellow tea could greatly influence the quality and characteristics of the tea. Due to the tenderness of fresh leaves and the geographical origins of tea cultivation, different processing methods are applied to meet the quality requirements of various yellow teas. However, most yellow teas undergo the same basic procedures, including withering, fixing, rolling, sealed yellowing and drying, in which “sealed yellowing” is the key process for yellow tea. The traditional manufacturing process of yellow teas is illustrated in Fig. 4.

3.1 Processing of fresh tea leaves—withering

All types of yellow teas are produced from *Camellia sinensis* L.. Yellow bud tea is

prepared from plant buds. Before the tea preparation, the deadwood or diseased buds are excluded. One bud and two or three leaves are chosen for the preparation of yellow little tea and yellow big tea. After the harvesting, the fresh leaves are spread indoor and set aside at room temperature for about 6 hours (Liu, Wang, Zhang, Fan, Chao, & Ouyang, 2010; Zheng, Wan, & Bao, 2015). The procedure is called withering. Withering is usually necessary for fresh leaves before fixing. Appropriate withering will increase the concentration of amino acids, evaporate water in fresh leaves, and effectively decrease the ratio of polyphenols over amino acids (Yang & Zhou, 2013).

3.2 Fixing

Fixing is an important procedure in the yellow tea processing, which helps to eliminate the enzyme activity, promote chemical transformations of contained substances, evaporate water and reduce the grassy taste. It plays an important role in the late change of yellow tea and the quality of yellow tea products (Zhu & Ning, 2016). Compared to green tea, yellow teas use more fresh leaves, lower temperature and longer time for the fixation process. Thus a special fixing method called “ more sealing and less throwing” should be used to control the processing temperature to completely deactivate the enzyme activity (Li, Li, Li, & Xiao, 2015). Although there is little difference in the degree of fixation between green tea and yellow tea, some of the yellow teas require light rolling and shaping to lower moisture content (Yang & Zhou, 2013).

In the fixing process, the fresh tea leaves are subjected to panfrying or firing to deactivate enzymes. In this step the endogenous polyphenol oxidase (PPO) are deactivated by heat. The prevention of tea leaves color change and the reduction of grassy gas also occur in this procedure (Liang, Zhang, & Lu, 2005; Lv, Zhang, Lin, & Liang, 2013). During the fixing process, heating

with high temperature causes a series of chemical reactions, such as the auto-oxidation and isomerization of polyphenols, the partial hydroxylation of starch into simple sugars, the partial decomposition of proteins into amino acids, and the deconstruction of chlorophyll. This step is essential for the formation of the mellow taste, bright yellow color, and shape of yellow tea (Yang & Zhou, 2013; Zhong, 1989). A suitable temperature during the roasting process is 140-100 °C, gradually decreasing from high to low (Li, Zhu, Gai, & Zhang, 2014). Rolling is not a necessary processing step for yellow tea. When this step applied, the time is shorter than that of green tea, resulting in a relatively low rate of cell breakage, producing the loose shape, and facilitating ventilation and fermentation for the yellow tea processing.

3.3 Rolling

Rolling is an effective means to remove the wax layer on the surface of tea leaves. This allows for the tea sap to interact with the external environment. All the yellow bud teas and some of yellow little teas, such as “Junshan Yinzen” and “Mengding yellow bud tea”, are subject to this “rolling” process. However, “Beigang Maojian”, “Luyuan Maojian” and “Huoshan yellow bud tea” are only slightly rolled in the pan in the late stage of fixation, and no independent rolling process is required (Chen, 2008). Rolling can promote the yellow color of yellow tea. However, heavy rolling can cause the excessive loss of tea sap, resulting in negative effect on the quality of yellow tea (Zhu & Ning, 2016). Therefore, rolling is only applied to coarse and old tea leaves.

3.4 Sealed yellowing

Unlike green tea, yellow tea undergoes a special process called “sealed yellowing”, the

key process for the unique characteristics of yellow tea. In this procedure, fixed leaves are packed and set aside for a period of time, during which a series of chemical reaction occur because of the heating and microbial effects. Some of the favorable changes occurred for fresh tea leaves during this step, such as chlorophyll destruction, polyphenol auto-oxidation and isomerization, starch hydrolysis and proteins decomposition. Those changes are responsible for the special sensory characteristics of mellow flavor and bright yellow color of yellow tea (Zhou, Chen, & Han, 2015; Gong, Cai, Cai, & Jin, 2000).

“Sealed yellowing” can be classified into two types: wet dhool (semi- finished tea product) sealed yellowing and dry dhool sealed yellowing. Wet dhool sealed yellowing is a yellowing process in which piling occurs after fixing or rolling, and the conversion of chemical composition of tea dhool is rapid due to high water content. During this stage, the duration of “sealed yellowing” is shortened to 6-8 hours (Shi, 1997; Yang, 2014). Excessive “sealed yellowing” can cause the tea infusion to become dark yellow. Dry dhool “sealed yellowing” is a piling process after initial drying, where the chemical change is slowed due to the low water content of tea dhool. In this case, the duration of “sealed yellowing” should be extended to 5-7 days. If the “sealed yellowing” duration is not long enough, the tea infusion and brewed leaves can become blue-yellow, and the taste will be thick and astringent.

The main factors affecting “sealed yellowing” are the water content and the processing temperature. The higher the water content and leaf temperature are, the faster the yellowing process will be (Chen, 2008). The time used for “sealed yellowing” is closely related to yellowing requirement, moisture content and leaf temperature (Li, Li, Li, & Xiao, 2015; Zhou & Ni, 2003). The duration for “sealed yellowing” of “Pingyang Huangtang” is usually 2-3 days, the longest among all the yellow teas aside from yellow big tea. The duration for “sealed yellowing”

of “Beigang Maojian” is 30-40 minutes, and the yellowing degree is the lightest. For this reason, “Beigang Maojian” is often mis-identified as green tea. For “Weishan Maojian”, “Luyuan Maojian” and “Guangdong Dayeqing”, the “sealed yellowing” duration is usually between 5 to 6 hours. “Sealed yellowing” for “Junshan Yinzhen” and “Mengding yellow bud tea” are carried out by frying several times a day, and the whole process usually lasts 2-3 days. The duration for “sealed yellowing” of “yellow big tea” is 5-7 days because of low water content (Yang, 2014; Zhao, 2009).

Many microorganisms, including *Aspergillus niger*, rhizopus, yeast and bacterium, are involved in the “sealed yellowing” of yellow tea. These microorganisms play crucial roles in the formation of yellow tea by producing a variety of extracellular enzymes to decompose macromolecules, such as carbohydrates and crude lipase, resulting in a mellower and sweeter flavor (Liu, Qi, & Xu, 2009). Furthermore, microorganisms have distinctive effects on the formation of chemical compositions of yellow tea. Studies showed that fungi first develop early in the “sealed yellowing” process, followed by a gradual decrease in the number of bacteria, and finally an increase in yeast towards the end of the process. The PPO secreted by *Aspergillus niger* could oxidize polyphenols into theaflavins, a group of compounds responsible for the many health benefits (Zhang, Zhang, Zhou, Ling, & Wan, 2013), aroma, color and taste of the yellow tea (Shi, 1997). However, the humidity and heat could pose negative influences that outweigh the benefits provided by microorganisms on the quality of yellow tea (Yang, 2014).

3.5 Drying

Drying is the final procedure of tea processing, in which the water content of tea products is reduced to a low range (< 6%) by the heat (usually around 80 °C) applied. The heat in this step

does not only evaporate the water, but also facilitates a series of chemical reactions, which is very important in the formation of the taste and aroma of tea products (Zhu & Ning, 2016). Two different drying techniques are often employed: baked drying and fried drying. The temperature during the drying of yellow tea is usually lower than that of other teas. The temperature is usually low at beginning, and then increased later. By this means, the water dispersion is slow, and the yellow tea can continue the “sealed yellowing” process while drying under hot and humid conditions (Chen, 2012).

4. Chemical components of yellow tea

Studies have shown that yellow tea has many health benefits such as neural protection, physiological and psychological stress reduction, and anti-oxidation and anti-anxiety properties (Kim, Lee, Park, Choi, Ban, Park, et al., 2009; Kimura, Ozeki, Juneja, & Ohira, 2007; Peng, Liu, Lin, Lin, & Huang, 2014). Although tea is categorized into different groups, all true teas are derived from the fresh tea leaves of *Camellia sinensi*, and each type of tea contains polyphenols, methylxanthines, polysaccharides, minerals and trace elements, and amino and organic acids. On the other hand, each group of tea has its own distinct constituents due to the differences in processing techniques, geographical locations and growing conditions. Because of the “sealed yellowing” procedure, the chemical compositions of yellow teas are qualitatively and quantitatively changed. Yellow tea has proven to be a rich source of bioactive compounds. The major chemical compounds have been isolated and identified from yellow tea are summarized in Table 1. Comparative studies for the contents of polyphenols, caffeine, and amino acids with other teas were also reported (Ning, Li, Luo, Ding, Song, Zhang, et al., 2016; Wu & Bao, 2009; Yi, Zhu, Peng, He, Chen, Li, et al., 2015). These compounds are described as follows:

4.1 Polyphenols

Polyphenols are the main bioactive substances in tea accounting for 20-30% by dry weight. They are also the most important ingredients influencing the color, the aroma and the taste of tea (Dias, Tomás, Teixeira, Alves¹, Oliveira, & Silva, 2013). Due to the differences in tea leaves and processing methods, polyphenol contents significantly differ across various types of teas. Many studies showed that the polyphenol content detected in yellow tea is comparable to or sometimes higher than green tea. The content is often higher than Oolong tea, black tea and dark tea (Anna, 2008; Gao, Huang, & Li, 2016; Jin, Li, Ding, Zou, & Tian, 2016). This could be a result of the chemical constituents changing in the fresh leaves during tea processing. In the “fixing” process, polyphenol oxidase and peroxidase enzymes are deactivated and further oxidation of tea polyphenols are forbidden. Although tea polyphenols are retained, studies have reported that new chemical constituents were formed and the contents of catechins were decreased during the “sealed yellowing” process (Jin, Li, Ding, Zou, & Tian, 2016).

Catechins, flavone and flavone glycosides, anthocyanidin and leucoanthocyanidin, and phenolic acids and depside are the four major groups of polyphenols in various types of teas. Among those, catechins (also known as flavan-3-ols) are the most abundant accounting for 60-80% of the total amount of polyphenols. They are the major component contributing to health-promoting properties and the bitter, astringent taste of teas (Seely, Mills, Wu, Verma, & Guyatt, 2005). Yellow tea was found to be particularly rich in catechins. Seven major catechins were quantitatively studied in yellow tea, *viz.* (+)-catechin (C), (-)-epicatechin (EC), (+)-gallocatechin (GC), (-)-epigallocatechin (EGC), (-)-gallocatechin-3-O-gallate (GCG), (-)-epigallocatechin-3-O-gallate (EGCG), and (-)-epicatechin-3-O-gallate (ECG). The structures of these compounds

are shown in Fig. 5.

Among these compounds, simple catechins are present in higher concentration level than ester-type catechins (Han, Zhao, Wang, Wang, Sun, Ning, et al., 2016; Kujawska, Ewertowska, Adamska, Jodynys-Liebert, Ignatowicz, & Gramza-Michalowska, 2016; Mihelj, Belščak-Cvitanović, Komes, Cvrtila, & Tomašić, 2014; Yi, et al., 2015). It was reported that EGCG accounted for the largest catechin proportion in yellow tea, while C and GC are the least abundant (Mihelj, Belščak-Cvitanović, Komes, Cvrtila, & Tomašić, 2014). Studies showed no significant difference in the total amount of catechins between green and yellow teas (Kujawska, Ewertowska, Adamska, Jodynys-Liebert, Ignatowicz, & Gramza-Michalowska, 2016; Ning, et al., 2016), but the content of each individual catechin components is significantly different. For example, the amounts of C and GCG are higher in yellow tea, but are almost undetectable in green tea (Kujawska, Ewertowska, Ignatowicz, Adamska, Szafer, Gramza-Michalowska, et al., 2016). However, the content of EGCG is much lower in yellow tea than in green tea (Gramza, Korczak, & Amarowicz, 2005; Hashimoto, Goto, Sakakibara, Oi, Okamoto, & Kanazawa, 2007). Moreover, yellow tea contains 10 times more gallic acid than green tea (Kujawska, Ewertowska, Adamska, Jodynys-Liebert, Ignatowicz, & Gramza-Michalowska, 2016). This could be attributed to the “sealed yellowing” process, during which heat and humidity cause ester type catechins, e.g., EGCG and EGC to be oxidized and hydrolyzed into complex compounds such as gallic acid (released from catechins gallates) (Gramza, Korczak, & Amarowicz, 2005), theaflavins and thearubigenes (Fig.5). In addition, tea variety and production area can also influence the catechins compositions (Anna, 2008). Gallic acid is a powerful antioxidant, and was reported to suppress CCl₄-induced liver injury. The consumption of yellow tea significantly suppressed the CCl₄-decreased GST activity by 60% (Table. 2), which could be partially due to gallic acid

(Hashimoto, Goto, Sakakibara, Oi, Okamoto, & Kanazawa, 2007). Four main theaflavins evaluated in yellow tea are theaflavin (TF), theaflavin-double gallates (TFDG), theaflavin-3-gallates (TF-3-G), and theaflavin-3'-gallates (TF-3'-G). Yellow tea has almost the same content and close proportion of the four main theaflavins as white tea and oolong tea, but contains higher content than green tea (Ye, Zhou, & Xu, 2015). Theaflavins are mainly produced from catechins oxidization during the fermentation. This group of compounds exhibits a bright orange-red color and the astringency in solution, and is also important for the beneficial effects of all kinds of teas (Sang, Lambert, Ho, & Yang, 2011).

4.2 *Methylxanthines*

Among all groups of methyl purine derivatives detected in various types of teas, methylxanthines have the highest contents. Methylxanthines found in different teas include, but are not limited to caffeine, theophylline and theobromine. Caffeine is one of the characteristic ingredients of tea. Its content in tea is the highest (Horžić, Jambrak, Belščak-Cvitanović, Komes, & Lelas, 2012) among all different types of plants such as coffee and cocoa, accounting for 2-4% of the dry weight of tea, followed by theobromine, accounting for about 0.05%, and theophylline for about 0.002% (da Silva Pinto, 2013). Methylxanthines were also detected in yellow tea at relatively high concentrations, similar to caffeine, while theobromine and theophylline were detected at lower concentrations (Horžić, Jambrak, Belščak-Cvitanović, Komes, & Lelas, 2012; Mihelj, Belščak-Cvitanović, Komes, Cvrtila, & Tomašić, 2014). It was found that the content of caffeine in yellow tea is the highest among other types of teas (Shi, 1997), or similar to green tea (Ning, et al., 2016). The content of caffeine in yellow teas is in the order: “Mengding yellow bud tea” > “Junshan Yinzhen” > “Huoshan yellow bud tea”. In

addition, research also reported that the caffeine content increased about 2-6% during the lightly fermented process of yellow tea (Huang, Xu, Wang, Li, Wang, & Sheng, 2015; Wu, 2013).

4.3 Amino acids

The amino acids present in yellow tea were studied extensively. A total of 18 amino acids were detected in yellow tea, among which the concentrations of theanine, glutamic acid and glycine, compounds responsible for the fresh taste of yellow tea, were significantly high (Liu, 2011). Yellow tea has relatively high concentrations of theanine, even higher than white tea which has been considered to be rich in theanine (Ning, et al., 2016). Theanine is one of the most important functional components in tea, and is also a unique non-protein amino acid, accounting for 1-2% by dry weight of yellow tea (Chen, Chen, Zhang, & Wan, 2009).

4.4 Volatile components

“Sealed yellowing” and the drying methods with the “first low and later high” temperature are responsible for the special aroma of “fresh and sweet” of yellow tea. The major volatile components detected in yellow tea were benzyl alcohol and dimethyl sulfide (Hou, Dao, Wu, Li, & Hui, 2014). Thirty volatile constituents were identified from the volatile oil of “Huoshan yellow bud tea” by GC/MS. The major volatile components were alcohols, aldehydes and ethers. Many aldehydes, hydrocarbon, ketones and alcohols are also abundant in “Mengding yellow bud tea”. In addition, compared with other types of teas, the predominant volatile components present in “Mengding yellow bud tea” are alcohols with special fragrances such as incense, wood and rose. These compounds together with other components detected in “Mengding yellow bud tea” are responsible for the special sweet and faint scent for this type of

yellow tea (Meng, Pang, Wen, Wei, & Si, 2014).

4.5 Other compounds

Higher levels of polysaccharides present in yellow tea were also reported (Han, et al., 2016). In addition, the vitamin C content and procyanidins B1 and B2 in yellow tea are also higher than that in white tea. Among all the yellow teas, “Huoshan yellow bud tea” contains the highest level of vitamins while “Junshan Yinzhen” has the highest contents of procyanidins B1 and B2.

5. Biological activities of yellow tea

Yellow tea was reported to have special effects on anti-cancer, potential antioxidant and anti-inflammation effects due to its rich concentrations of polyphenols, amino acids, soluble sugars and caffeine. The reported biological activities are summarized in Table 2.

5.1 Antioxidant effects

Andlauer *et al.* (Andlauer & Heritier, 2011) reported a series of anti-oxidant tests with yellow tea using several experimental models such as rapid electrochemical screening of antioxidant capacity (RESAC), FRAP and DPPH radical and chelating activity on metal ions. All the experiments showed that yellow tea extracts had strong protective effects on oxidative damage *in vitro*. Aqueous and ethanol extracts of yellow tea exhibited the highest antiradical and antioxidant activities and the strongest inhibitions on lipid oxidation in emulsified lipid system among all the six types of teas (green, oolong, black, white, dark and yellow teas) (Anna, 2008; Gramza-Michalowska, Hes, & Korczak, 2008; Wang, Zhao, Qian, & Wang, 2013; Zhao, 2009).

These results suggested that yellow tea contained potential antioxidative compounds formed during the “sealed yellowing” process.

5.2 Anticarcinogenic and antimutagenic activities

In recent years, the anti-cancer effects of yellow tea have attracted much attention. Zhao (Zhao, 2009) evaluated the anti-cancer effect of yellow tea on HT- 29 human colon cancer cells *in vitro* by apoptosis analysis of DAPI staining, RT- PCR and MTT assay. The research discovered that yellow tea induced apoptosis accompanied by increased Bax and decreased Bcl- 2 in mRNA expression. It also exhibited higher inhibitory effects on the growth of HT- 29 colon cancer cells than green tea. It was also reported that yellow tea could strongly inhibit the growth of both AGS and HT- 29 colon cancer cells, outperforming green tea (Zhao, Deng, & Xie, 2008). These results suggested that yellow tea has strong chemo preventive effects.

5.3 Antimicrobial activities

Studies have shown that yellow tea has better antimicrobial activity compared to other types of teas and can inhibit the growth of various intestinal microorganisms. Xin, *et al.* and Gramza, *et al.* (Gramza, Korczak, & Amarowicz, 2005; Xin, Zhan, Liu, Zhang, Wang, Tang, et al., 2014) reported that all of the six types of teas were effective in inhibiting *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis* and *Bacillus cereus*, and their effects were positively correlated with the concentrations of polyphenols in tea extracts. In addition, the antimicrobial activities of yellow tea are comparable to green tea and better than other types of tea, probably due to the presence of high polyphenol contents in yellow tea extracts.

The studies by Xu, *et al.* (Xu, Cui, Chen, & Du, 2013) on pathogenic enterobacteria

showed that the yellow tea could inhibit *Staphylococcus aureus* at a low concentration level of 6 mg/mL, and could inhibit *Escherichia coli* at the concentration of 24 mg/mL. The higher the concentration of tea extract, the stronger the antibacterial activities were. In the six types of teas, the antimicrobial activities of yellow tea are slightly lower than green tea and Oolong tea, but higher than other types of teas (Xu, Cui, Chen, & Du, 2013).

5.4 Cardiovascular disease (CVD)

Yellow tea has demonstrated a protective effect against cardiovascular diseases via a number of different mechanisms. The protective effects of yellow tea were studied on mice liver induced by high-fat diet-triggered blood glucose elevation. Thioredoxin-interacting protein (TXNIP) plays an important role in hepatic glucose synthesis and glucose release from hepatocytes and its overexpression can cause serum glucose levels to elevate. A high-fat diet can cause elevation of fasting blood glucose and a rapid hepatic TXNIP protein enhancement, which was effectively reversed by yellow tea rather than green and black teas without promoting food intake (Han, et al., 2016).

Studies showed that yellow tea has beneficial effects on lipid metabolism. Peroxisome proliferator-activated receptor (PPAR) is involved in the regulation of various energy metabolism and cell active substances in the body, and can improve glucolipid metabolism. It was reported that water extracts of yellow tea demonstrated obvious effects on activating PPAR γ and δ receptors and showed the potential in lipid-lowering (Jiang, Li, & Xu, 2014).

“Junshan Yinzhen”, a famous yellow tea product in China was reported to effectively regulate lipid metabolism imbalance of liver cell steatosis, improve lipid metabolism disorder and liver tissue injury in hyperlipidemia mice. It can also interfere with glucolipid metabolism

imbalance of insulin resistance cells and improve insulin resistance and glucose lipid metabolism disorder in diabetic rats. These effects could be related to the high contents of polyphenols, sugars and alkaloids in yellow tea (Xiao, 2014).

5.5 Other health effects

Gastric injury can cause damage to the stomach organs. Ethanol promotes the rapid formation of injuries in the stomach, which occurs mainly due to an inflammatory reaction (Szabo, Trier, Brown, & Schnoor, 1985). High concentrations of yellow tea (usually 1000 mg/kg) can significantly reduce the levels of the serum pro-inflammatory cytokines interleukin (IL)-6 and tumor necrosis factor (TNF)- α . The extent of the gastric injury can also be decreased significantly by yellow tea due to its demonstrated anti-inflammatory properties (Wang, Zhao, Qian, & Wang, 2013). In addition, yellow tea can significantly ameliorate the increase in the activities of the alanine- and aspartate-aminotransferases in plasma. Thus consumption of yellow tea may contribute to protection against liver injury (Hashimoto, Goto, Sakakibara, Oi, Okamoto, & Kanazawa, 2007).

6. Future Perspectives

With the increasingly popularity of yellow tea, more studies will be conducted on this special kind of tea. Although some research findings demonstrated biochemical compositions and potential benefits of yellow tea for human health, the special bioactive ingredients and their mechanisms that produce yellow tea's distinctive qualities and activities need to be further studied. In addition, the processing technology of yellow tea needs to be improved and automated, and the production procedure should be standardized. As the least studied tea, we

expect to expand future research on yellow tea and to promote its health benefit, development and consumption.

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Declaration of interest

The authors declare no competing financial interest.

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Table 1. The major chemical compounds isolated and identified from yellow tea and other five teas

Chemical composition		Contents (%)						References
		Yellow tea	Green tea	White tea	Oolong tea	Black tea	Dark tea	
Polyphenols (Catechins)	EGC	1.23-2.41	2.19-3.47	0.59-1.07	1.94-2.92	0.35-0.83	0.35-0.85	Yi <i>et al.</i> (2015) Ning <i>et al.</i> (2016)
	+ C	0.05-0.13	0.04-0.14	0.09-0.33	0.05-0.10	0.01-0.05	0.02-0.06	
	EC	0.351-0.81	0.59-1.05	0.27-0.47	0.59-0.79	0.19-0.48	0.12-0.32	
	EGCG	4.17-6.75	6.03-8.47	3.24-5.84	3.76-6.18	0.39-1.31	0.31-0.87	
	ECG	1.69-2.79	1.29-2.63	0.87-2.03	0.92-1.44	0.42-0.92	0.13-0.33	
	Total catechins	7.49-12.89	10.14-15.39	5.06-9.74	7.26-11.43	1.36-3.59	0.93-2.43	
Methylxanthines	Caffeine	2.98-3.80	2.56-3.96	3.43-4.31	1.71-2.85	3.09-4.31	1.97-3.63	Yi <i>et al.</i> (2015) Ning <i>et al.</i> (2016)
Amino acids	Theanine	1.04-1.70	0.91-1.57	0.72-1.82	0.17-0.38	0.65-1.09	0.03-0.09	Han <i>et al.</i> (2016) Ning <i>et al.</i> (2016)
Polysaccharide	Polysaccharide	10.8	3.9			8.4		Han <i>et al.</i> (2016)

Table 2: Summary of protective effects of yellow tea evaluated through various experimental studies

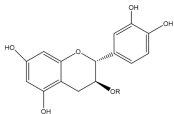
Tea sample	Protective effects	Dose, duration, object	Indexes changed	References
Mengding Huangcha	Gastric injury	250, 500 or 1,000 mg/kg, 14days, rats	Reducing (IL)-6, (TNF)- α	Wang, Zhao, Qian & Wang. (2013)
Yellow tea	Lipid Accumulation	25, 50, and 100 μ M, 4 h or 8 days, 3T3-L1 cells	Decreasing the content of FGs against Lipid accumulation	Bai <i>et al.</i> (2017)
Huang big tea	Liver Toxicity	54 mL/rat, 7 days, rats	Suppressing the increase of plasma AST and ALT and GST activity	Hashimoto, Goto and Sakakibara (2007)
Yellow big tea	Anti-hyperglycemia	Yellow tea infusion (1:30, w/v), 36 days, ICR mice	Reducing blood glucose	Han <i>et al.</i> (2016)
Kekecha	Liver carcinogenesis	10 g/kg feed, 13 weeks, rats	Decreasing lipid peroxidation, protein carbonyl formation, and DNA degradation, protecting SOD, CAT and GSH, normalizing the activities of PON1 and GPx	Kujawska <i>et al.</i> (2016)
Junshan Yinzhen	Antimicrobial activity	100, 50, 25, 12.5, 6.25, 3.125 mg/mL, 24h, bacterial	Increasing the diameter of the inhibition zone	Xin <i>et al.</i> (2014)
Mengding Huangcha	Anticancer activity	200, 400 μ g/mL, 53h, cells	Inhibiting AGS and HT-29 cancer cell	Zhao, Deng & Xie. (2008)
Mengding Huangya	Gastric damage	250, 500 and 1000 mg / kg, 2 weeks, rats	Decreasing IL-6 and TNF- α	Deng & Zhao (2012)
Mengding Huangya	Anticancer effect	200, 400 μ g mL, human colon cancer cells	Increasing Bax and decreasing Bcl- 2	Zhao (2009)
Beigang Maojian	Lipid-lowering activity	50 μ g/mL	Activating antagonists of PPAR γ and PPAR δ	Jiang, Li & Xu (2014)
Junshan Yinzhen	Glucose and Lipid Metabolism	50, 100 μ g/mL, L-O2, HepG2 cell and rats	Reducing TG, TC, LDL-C, MDA, AST and ALT, down-regulating DGAT2, ACC1, ACAT1 and HMGR, up-regulating CPT-1a	Xiao (2014)
Mengding Huangya	Antibacterial activities	96, 48, 24, 12, 6 mg/mL, 20h, Escherichia coli and Staphylococcus aureus.	Inhibiting Escherichia coli and Staphylococcus aureus.	Xu, Cui, Chen & Du (2013)
Huoshan yellow big tea	Myocardial contractility	1, 10, 20, 50 μ g/mL, SD rats	Enhancing myocardial contractility, increasing the phosphorylation of Akt and ERK1/2	Xiang (2016)

Mengding Huangcha		100, 200 and 500µg/ml	Inhibiting DPPH and OH	Wang, Zhao, Qian and Wang (2013)
Junshan Yin Zhen		39.52, 32.31 mmol/L Trolox 30.5 mmol/L Fe(II)) , 30 min extraction.	Inhibiting DPPH, ABTS+, FRAP,	Horžić, Jambrak, Belščak-Cvitanović, Komes & Lelas (2012)
Kekecha		2, 6, 10 g /kg feed, 90 days, rats	Increasing activity of antioxidant enzymes(SOD, CAT, GPx, GR)	Kujawska <i>et al.</i> (2016)
Junshan Yinzhen, Wenzhou Huangcha, Mengding Hhuang cha Kekecha	Anti-oxidative activity	25 mg tea,48h, Canola oil	Inhibiting oxidation of lipids, preventing loss of linoleic and linolenic acids	Chen, Chan, Ma, Fung & Wang (1996)
		4849.24 µmol Trolox/g	Reducing superoxide anion-radical (O ₂ ^{•-})	Gramza-Michałowska, Sidor, Reguła & Kulczyński (2015)
Thé jaune		1.143, 0.709, 0.338 mg TE/mL, 3 min, 30 min	Inhibiting DPPH, FRAP, RESAC	Andlauer & Héritier (2011)
Yellow tea		100, 200,500,1000 ppm,19 h	High Aec	Gramza-Michałowska Hes & Korczak (2008)
Junshan Yinzhen		Trolox (0-1000 µmol·l ⁻¹), 30 min,6 min,4 min	Inhibiting DPPH, FRAP, ABTS+	Mihelj, Belščak-Cvitanović, Komes, Cvrtila & Tomašić (2014)
Junshan Yinzhen		Water, 10%, 25%, 50%, 75% and absolute ethanol and multiple extractions (1st, 2nd, 3rd)	Inhibiting DPPH, ABTS, FRAP	Mihelj, Belščak-Cvitanović, Komes, Horžić & Tomašić (2014)
Yellow tea		0-20ppm,	Inhibiting DPPH	Andzi Barhe & Feuya Tchouya (2016)
Kekecha		100,200, 500, 1000 ppm, 2 h	Inhibiting DPPH,ABTS, FRAP	Anna (2008)

Junshan Yinzhen	100, 50, 25, 12.5, 6.25, 3.125 mg/mL, 24 h, bacterial	Increasing the diameter of the inhibition zone /mm	Xin <i>et al.</i> (2014)
Huoshan Huangya,	1% and 2%, 3days, channel catfish	Increasing SOD, CAT, γ -GT	Chen <i>et al.</i> (2015)

HIGHLIGHTS

- Yellow tea is a precious variety of tea unique to China
- It is also much less well-known and studied among various types of teas
- The processing techniques, chemical compounds and health benefits of yellow tea are reviewed for the first time
- This review could provide comprehensive information about yellow tea



Biochemical composition



Multiple health benefits



Yellow tea



Unique manufacturing



Graphics Abstract

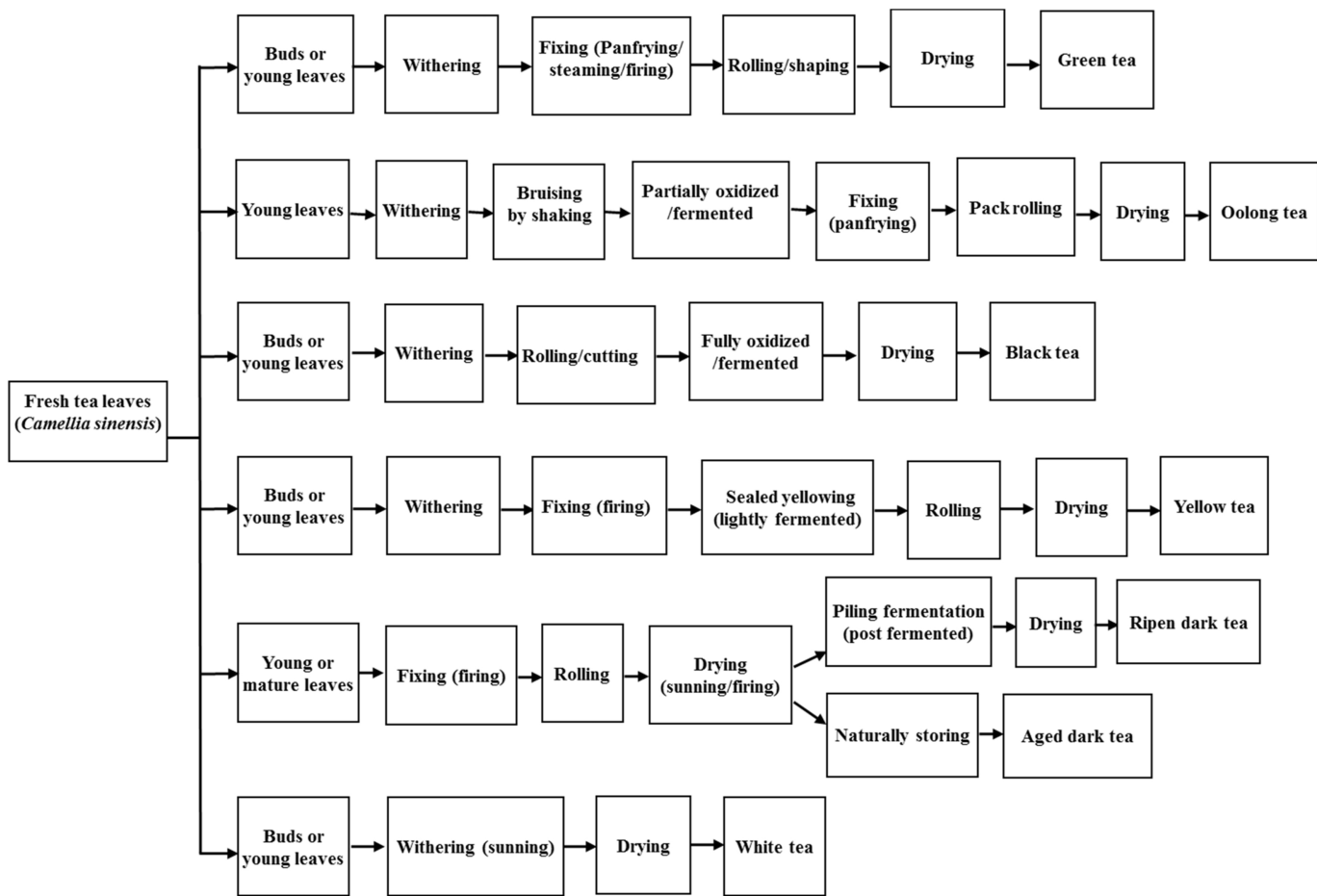


Figure 1

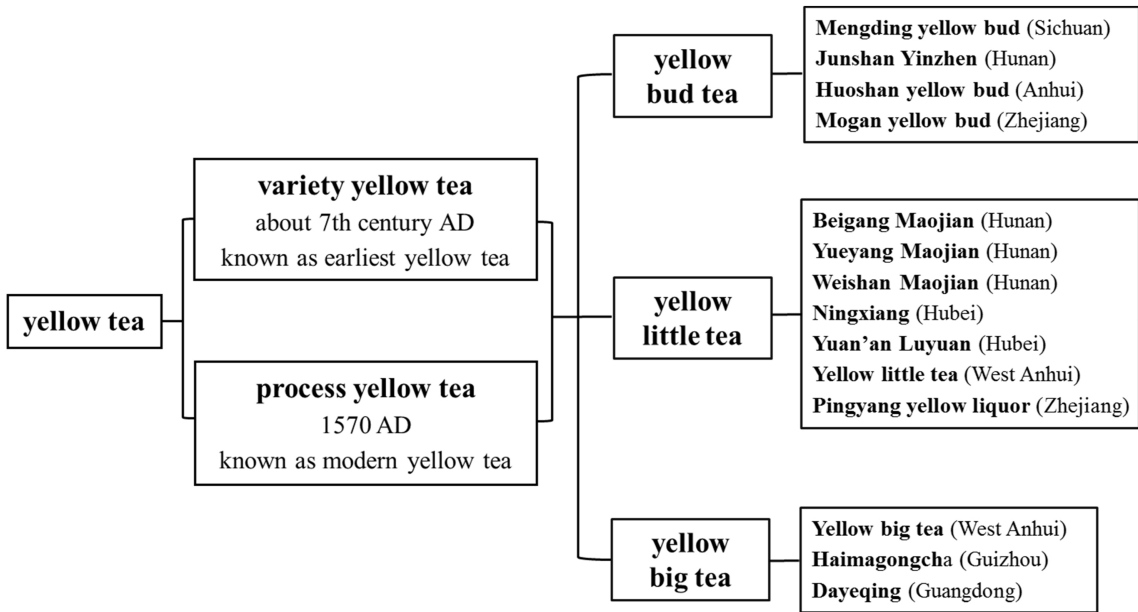


Figure 2

A



Yellow bud tea



Yellow little tea



Yellow big tea

B



Junshan Yinzhen



Mengding Huangya



Huoshan Huangya

Figure 3



Fresh tea leaves
(*C. sinensis* var)



Withering



Fixing



Rolling



Sealed yellowing



Piling fermenting

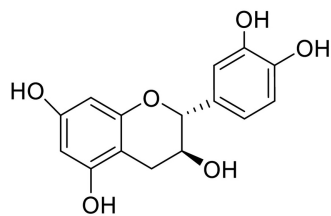


Drying

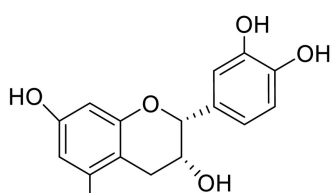


Yellow tea

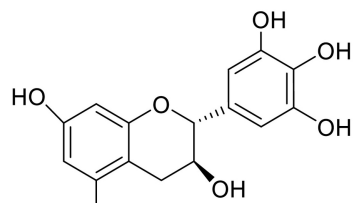
Figure 4



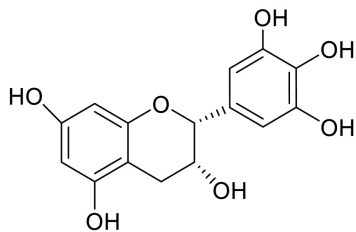
(+)-catechin (C)



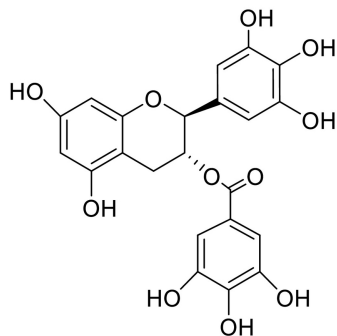
(-)-epicatechin (EC)



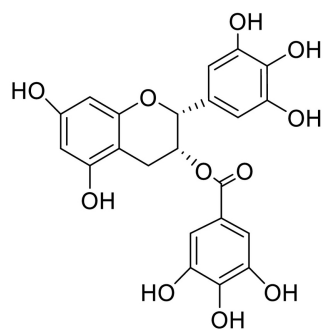
(+)-gallocatechin (GC)



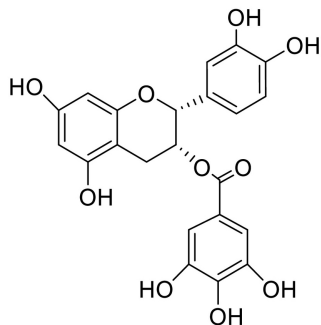
(-)-epigallocatechin (EGC)



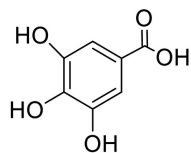
(-)-gallocatechin-3-O-gallate (GCG)



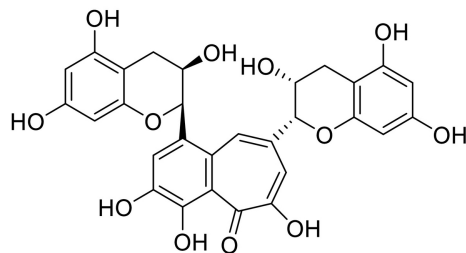
(-)-epigallocatechin-3-O-gallate (EGCG)



(-)-epicatechin-3-O-gallate (ECG)



Gallic acid (GA)



Theaflavins (TF)

Figure 5