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Comparative biochemistry of black and green tea processing

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Abstract
Around the world, tea is one of the most popular drinks. Commonly available tea formulations are separated into three categories according to how they are processed: completely fermented black tea (CTC and orthodox), partially fermented oolong tea, and non-fermented teas (white and green tea). The fundamental distinction between black tea and green tea lies in the level of oxidation they undergo after being harvested. Oxidation is a chemical reaction that occurs when the plant's enzymes interact with oxygen, leading to a series of changes in colour, flavour, and chemical composition. Black tea is a fully oxidized tea with dark colour and a robust flavour. The process of oxidation involves withering, rolling, and exposing the leaves to air, which allows them to turn brown and develop more complex flavours. Black tea generally has a stronger, bolder taste and higher caffeine content than other types of tea. Green tea is a minimally processed tea to preserve its natural green colour and retain high levels of antioxidants and other beneficial compounds. The leaves are typically steamed or pan-fired shortly after harvesting to prevent oxidation, which helps maintain the fresh, grassy flavours. The primary antioxidants found in green tea are polyphenols, particularly catechins. Among these catechins, epigallocatechin gallate (EGCG) is considered the most powerful. Theaflavins and Thearubigins are oxidized forms of polyphenol available in black tea where catechins are available in green tea. Polyphenol oxidase and Peroxidase are the main enzyme which converted the polyphenols to theaflavin and thearubigins in black tea. Caffeine content of black tea is higher than green tea. Amino acid specially L-theanine is present in black tea but in lower concentration compared to green tea. Astringency of black tea is high due to polymerized tannins. The comparative biochemistry of black and green tea offers profound insights into the complex interplay of chemical compounds that contribute to their distinct health benefits, flavours, and processing methods.

Keywords: Black tea, green tea, processing, biochemical changes

Introduction

Tea is one of the most consumed beverages worldwide. Both the black and green tea are derived from the tender shoots of varieties of the species *Camellia sinensis* (L) O. Kuntze. Commonly available tea formulations are divided based on their manufacturing process such as non-fermented teas (white tea, green tea), partially fermented (oolong tea) and fully fermented black tea (Zhao *et al.*, 2011) [11]. Despite originating from the same plant, these two types of tea are markedly different in taste, colour, aroma, and health benefits, which are primarily a result of the distinct processing methods they undergo. Understanding the processing differences between black tea and green tea is crucial not only for tea connoisseurs but also for those interested in the science behind their unique qualities

The fundamental distinction between black tea and green tea lies in the level of oxidation they undergo after being harvested. Oxidation is a chemical reaction that occurs when the plant's enzymes interact with oxygen, leading to a series of changes in colour, flavour, and chemical composition. While both black tea and green tea are made from the same type of tea leaves, it is the way these leaves are processed that differentiates the two. Black tea is fully oxidized, resulting in a darker colour, more robust flavour, and a higher caffeine content. On the other hand, green tea is minimally oxidized, which preserves its lighter colour, delicate taste, and a lower caffeine concentration.

In the processing of black tea, after the leaves are plucked from the tea plant, they undergo a series of steps, including withering, rolling, oxidation, and drying. Each of these steps plays a critical role in developing the characteristic deep colour and strong, malty flavour that black tea is known for.

Green tea processing, by contrast, takes a different approach. The goal in green tea production is to minimize oxidation to preserve the natural colour and fresh, grassy flavours of the leaves.

Beyond the basic steps of processing, the geographic location and the specific cultivars of *Camellia sinensis* used also influence the characteristics of the tea. Black tea is typically produced in regions with a warmer climate and longer growing seasons, such as India (notably Darjeeling and Assam) and Sri Lanka (Ceylon). These regions are known for their full-bodied, robust black teas that vary in flavour from malty to floral, depending on the altitude and soil conditions. Green tea, on the other hand, is often associated with cooler, more temperate climates, with notable production areas in China, Japan, and Taiwan. The processing methods in these regions vary widely, influencing the final flavour profiles of the tea—from the grassy, vegetal notes of Japanese green tea to the more floral and delicate flavours of Chinese varieties.

While the processing methods of black tea and green tea differ significantly, both types offer unique health benefits due to their distinct chemical compositions. Black tea, being fully oxidized, contains higher levels of theaflavins and thearubigins, compounds associated with improved heart health and antioxidant activity. Green tea, with its minimal oxidation, retains higher levels of catechins, particularly epigallocatechin gallate (EGCG), which is credited with a range of health benefits, from weight management to anti-cancer properties.

Fig 1: Different types of tea commercially available in India

Black Tea

Black tea is a fully oxidized tea famous for colour, flavour and aroma. The process of oxidation involves withering, rolling, and exposing the leaves to air, which allows them to turn brown and develop more complex flavours. Black tea generally has a stronger, bolder taste and higher caffeine content than other types of tea.

Black tea offers several potential health benefits. Rich in antioxidants, such as flavonoids, black tea helps in many health issues like stress and also may reduce the risk of chronic diseases, including heart disease and stroke. The moderate caffeine content in black tea (typically about 40-70 mg per cup) can improve. Black tea also contains compounds that may support digestive health, improve gut flora, and boost metabolism. Also, black tea can help reduce blood pressure, improve cholesterol levels, and aid in weight management.

Fig 2: Major steps in black tea manufacturing

Green Tea

Green tea is a unoxidized tea famous for its natural green colour and retain high levels of antioxidants and other beneficial compounds. The leaves are typically steamed or pan-fired shortly after harvesting to prevent oxidation, which helps maintain the fresh, grassy flavour. The primary antioxidants found in green tea are polyphenols, particularly catechins. Among these catechins, epigallocatechin gallate (EGCG) is considered the most powerful.

The production of green tea varies by region, and different countries produce distinct varieties. In China, green tea is often pan-fired in large woks, while in Japan, steaming is the primary method of processing. Some of the most popular types of green tea include *sencha* (Japan), *longjing* (China), and *matcha* (Japan). Each type offers unique flavour notes, ranging from sweet and floral to vegetal and grassy.

Fig 3: Major steps in green tea manufacturing

Major Steps of Black and Green Tea Processing

Black tea

i) CTC black tea

Plucked shoots
↓
Wither
↓
Rolling
↓
CTC
↓
Oxidation
↓
Drying
↓
CTC black tea

ii) Orthodox black tea

Plucked shoots
↓
Wither
↓
Rolling
↓
(Deb and Pou,2016)
Oxidation
↓
Drying
↓
` Orthodox black tea

Different steps and their biochemical changes during black and green tea processing

Plucking and initial handling

The liquor characteristic of a tea is depended on polyphenol, caffeine, standard of plucking etc. Fine leaf plucking is preferred as it gives good liquor. Fine leaf comprises one leaf and a bud, two leaf and a bud and the soft banji. Coarse plucking results poor liquor quality. An average plucking standard should have ideally about 75% fine leaf. There is various method of leaf quality assessment like- ballometric count, leaf/bud count, damaged leaf count.

Biochemical changes after plucking

Anabolic reactions practically cease once the leaf is plucked the and catabolic reactions starts to the breakdown of large organic compounds to simpler molecules. The energy required to run these biochemical reactions in the shoots is provided by burning of sugar molecules produced earlier through photosynthesis. After the plucking when the leaves were stored, the temperature increases due to respiration. Organic substances present in the cell (usually sugar) oxidised to carbon dioxide and water during respiration.

After plucking, metabolic reaction started which leads the biological degradation of the leaves. Rigid shoots become flaccid as the larger molecules (cellulose, lignin) degraded to simpler one. Carbohydrates breakdown to sugar, which help to run the biochemical reaction in presence of oxygen. Insufficient oxygen leads to the anaerobic reactions, which is not prefer to produce quality tea.

Some quality attributes are obtained from the lipid degradation. So, it is very important to breakdown of lipids before cell rupture during manufacturing to get proper quality attributes. Therefore, providing proper condition (temperature and time) is very essential.

Steaming or pan-firing

Steaming

The leaves are steamed at high temperatures (typically between 160-180°C) for a short period, usually 30 seconds to 2 minutes. This heat treatment deactivates the enzymes that cause oxidation, effectively preserving the green colour of the leaves and maintaining their flavour. In Japan, the steaming technique is so integral to the production of green tea that the specific length of time and method of steaming can affect the flavour profile of the final product. Steaming makes the leaves soft and pliable, which is important for the next steps of shaping and drying.

Pan-Firing

The leaves are placed in a hot pan and are rapidly stirred or tossed to ensure even heating. The temperature can reach around 180-220 °C and the leaves are often roasted for several minutes. This high heat quickly deactivates the enzymes responsible for oxidation, preserving the green colour and freshness.

Biochemical changes after steaming or pan-firing

The biochemical changes that occur during the steaming or pan-firing of green tea leaves are crucial for shaping the final flavour, aroma, colour, and nutritional profile of the tea. Both methods, although different in technique, aim to halt the enzymatic oxidation (or polyphenol oxidase activity) that would otherwise degrade the quality of the tea. However, the specific biochemical effects of steaming and pan-firing differ due to the distinct temperatures and mechanisms involved.

- **Enzyme deactivation:** The inactivation of enzymes prevents oxidation of catechins, preserving their fresh and bitter characteristics.
- **Polyphenol preservation:** Catechins, such as EGCG (epigallocatechin gallate), are stabilized.
- **Aromatic changes:** Heat also releases volatile compounds, which influence the flavour profile.

Withering

In the manufacturing unit the first step of processing is withering. Where fresh leaves are conditioned both physically and chemically. Proper withering is an insurance of good quality tea.

The main objective of withering is to reduce the moisture content of the fresh leaves which ranges between 74-83%. To make the leaf flaccid and rubbery. Withering of shoots for 16-18 hrs considered adequate for achieving both physical and chemical wither.

Right after plucking chemical withering starts and it depends on time and temperature. The catabolic reaction initiated after plucking will take time so it is necessary to continue to supply sufficient air and wait for breakdown of large organic molecules to simpler one during this period.

Moisture content of the leaves reduced through physical withering. Correct point of withering is difficult to determine but it is essential for quality tea. Physical withering can get in shorter time but chemical withering take time, so physical wither is regulated slower by controlling the air flow to reach both the withering in the same time interval. The main purpose of physical withering is to make the tea shoot flaccid and to concentrate the sap in the cells.

Biochemical changes during withering

Many biochemical changes have been noted in the green leaf during withering.

Proteins: Proteins break down to amino acids during withering. The level of proteins in the green shoots has been documented to change during withering with an increase in soluble proteins. This has been attributed to the action of peptidase present in tea shoots resulting in an increase of free amino acids level. The increase in amino acid concentration effects black tea quality as amino acids undergo transformation to form volatile flavour compounds during fermentation.

- **Carbohydrate and simple sugar:** The carbohydrates breakdown to simple sugars in withering and a portion of simple sugars are incorporated with amino acids to form certain volatile flavour components. The amino acids thus produced contribute to flavour of black tea.
- **Caffeine:** An increase in caffeine content during withering was observed in various tea clones and jats. Caffeine is well known as a stimulant of central nervous system and its role in black tea quality is recognised by many workers.
- **Chlorophyll:** High chlorophyll content normally produces inferior quality tea with grassy aroma. However, conversion of chlorophyll to phaeophytin during fermentation and firing contributes black appearance to tea. During withering 15% of chlorophyll are degraded.

Leaf Maceration

The main objective of maceration of leaf is to rupture the cell sap. Which results intermixing of enzymes to the chemical constituent in presence of oxygen. These chemical constituents are responsible for good quality tea.

Primary oxidation (fermentation) starts from the moment of maceration. The breaking of shoots results in different size and shape of particle formation and extent of cell damage. These factors have strong effect on the processing steps that would follow as well as market choices for the made teas.

Biochemical changes during leaf maceration

Cell disruption of all structures is progressive in rolling which leads to increase interaction of substrates with the O_2. It also influences the availability of O, required both for catechins oxidation and more importantly for the formation of benzotropolone ring.

Maceration in North East India is carried out by orthodox and/or CTC rolling, which directly affects the generation of volatile flavour components (VFC) in black tea. It is the rolling process that ruptures the labile bound membranes to release macromolecules like proteins, lipids, carotenoids etc., the precursors of volatile flavour components to generate different aroma components by enzymic or autoxidation. Most of the volatile flavour components are formed during withering and rolling stages as a result of hydrolytic action of enzymes.

CTC

The machine achieves the three actions of Crushing, Tearing and Curling at one go. The CTC takes a fast, thin, but steady stream of leaf to pave the way to continuous processing in place of the batch mode of orthodox rollers. Leaf appearance, make, grade percentage, fibre content, liquor and infusion depend on the cut obtained in the CTC machine.

Biochemical changes during CTC

CTC rolling directly affects the generation of volatile flavour components in black tea. It is the rolling process that ruptures the labile bound membranes to release macromolecules like proteins, lipids, carotenoids etc., the precursors of volatile flavour compounds to generate different aroma components by enzymic or autoxidation.

Oxidation

The principal difference between black teas and other forms of teas like green tea is the presence of condensed catechins, i.e. polyphenols. Through enzymatic oxidation, enzyme polyphenol oxidase (PPO) and peroxidase (PO) convert the polyphenols to theaflavin and thearubigin. The temperature (27-29 °C) and relative humidity (95-98%) also have a role in these oxidation reactions and should be kept at a level at which the enzymes activity is at the peak. Higher rolling temperatures adversely affects the liquor characters. The surface on which leaf is oxidized i.e. floor, gumla, etc should be good conductors of heat. The macerated leaf being acidic in nature is likely to corrode aluminium slowly and, therefore, use of aluminium sheets for oxidation should be avoided.

The capacity of oxidation differs with the sources of plucked leaf. Therefore, planting materials are classified as slow, fast and medium fermenter depending on their oxidizability. Uneven oxidation was observed when the leaves are mixed. Planning of plucking and segregation of leaf at the withering stage required to reduces heterogeneity and helps in producing better quality tea (Kimutai *et al.*, 2020) [6].

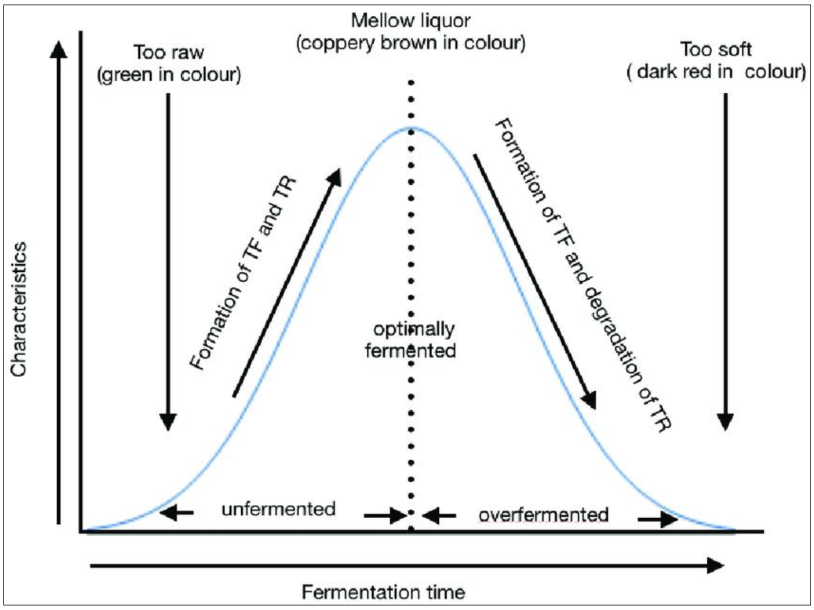

Fig 4: Fermentation curve

Biochemical changes during oxidation

The colour of leaf changed to green to coppery red during oxidation step and also liquor characteristics developed during this phase. Briskness, brightness, astringency and strength also developed and reached optimum in the oxidation period at different time. Therefore optimum oxidation time is very important for liquor quality purpose. The oxidation period for orthodox manufacture will vary between 2 hour 30 minutes to 3 hour 45 minutes and for CTC it will vary between 55 minutes (fast fermenting) to 110 minutes (slow fermenting). In all cases, however, oxidation starts from the time of rolling or rotorvaning and therefore, the macerated leaf should be laid on the floor, put on the gumla or Continuous fermenting machine at the earliest.

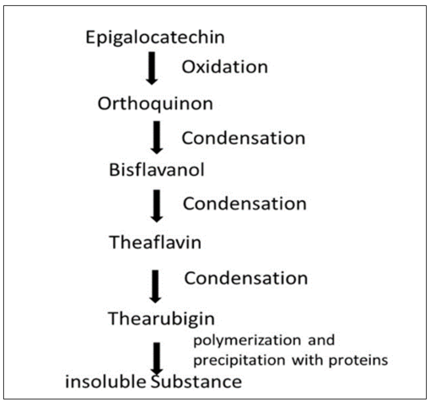

Fig 5: Enzymatic oxidation in tea leaves

Catechins present in tea shoots are catechin (C), epicatechin (EC), epicatechin gallate (ECG), gallocatechin (GC), epigallocatechin (EGC), and epigallocatechin gallate (EGCG). These catechins are oxidized by PPO, first forming intermediate compounds called orthoquinones that are very reactive and then combine in pairs to form theaflavins (TF), which are larger molecules and are unique in chemistry. The catechins react in pairs to form six theaflavins (Yulianto *et al.*, 2022) [10].

Theaflavin are less bright and brisker than theaflavin monogallates and theaflavin digallate is brighter and brisker than theaflavin monogallate.

Thearubigins (TR) are formed by action of PO from the same catechins, but the reaction is much more complex. TRs are also formed from TFs. The chemistry of thearubigins is highly complex and their structures have not yet been established. When the TFs start getting oxidized to TRs, it has deleterious effect on quality. Thus, the skill in carrying out the oxidation leads to formation of a right combination of TFs and TRs to give brightness, body and colour of black tea, but unless the epigallates are present in sufficient quantities, the desired TFs cannot be formed.

Drying

The main objective of the drying is to stop the enzymatic reaction and remove moisture to produce a stable product with good keeping quality. On an average 100 kg of fresh leaf produces 22.5 kg of dried tea containing residual 3% moisture. The difference of 77.5 kg between the figures represents the moisture evaporated during the process. During the early stage of drying the solid is so wet, so a continuous layer of moisture exists over the entire surface. The temperature of the solid particles will be near the wet bulb temperature of the drying air. Removal of this layer of film of moisture is easier, such evaporation rate is independent of the moisture content of the particle, and the moisture will be evaporated at the constant rate and known as the constant rate drying.

Under this condition diffusion process controls the drying rates. The moisture trapped inside the drying particle travels to the surface before being evaporated. With reduction of moisture the drying now takes place at a falling rate. The quantity of moisture removed during the "Falling rate period" is small but the time taken is quite long. Hence the falling rate period has a very important effect on the time of drying and is dependent on size of the particle, thickness of spread and external variables like volumetric flow, temperature and humidity of air.

Factors influencing drying are - Temperature of inlet (82-99 °C) and exhaust air (49-54 °C), Volume of air, Quantity of leaf fed (i.e. thickness of spread), Period of drying (through put time).

Biochemical changes during drying

Drying deactivate the enzyme (like PPO, PO etc.) and almost all the biochemical reactions are brought to an end. Chlorophyll is degraded to pheophytin and pheophorbide at elevated temperature during drying, contribution towards the blackness of made tea. At elevated temperature, by binding with proteins, polyphenols make complex chemicals, which brings down the level of astringency. Interaction between carbohydrates with amino acids at elevated temperature leads to the formation of flavoury components. Several physical and chemical changes take place in this stage of processing which give special taste, colour and odour of black tea. Structural changes of chloroplasts are associated with degradation of chlorophylls during withering which is converted to pheophytins in drying to impart blackness. During drying there is loss of low boiling volatile compounds with simultaneous formation of some other important aroma constituents.

Sorting and Grading

After drying, the tea leaves are sorted by size and quality. This is mostly a physical process, but it can affect the final flavour profile by removing certain leaf grades or blends. The sorting process may also involve breaking up larger leaves into smaller fragments, affecting the release of flavour compounds during brewing.

Table 1: Key biochemical differences of black tea and green tea

Component	Black Tea	Green Tea
Oxidation	Fully oxidized (fermented)	Minimally oxidized (not fermented)
Polyphenols	Theaflavins and Thearubigins (oxidized forms)	Catechins (EGCG, ECG, unoxidized)
Caffeine	Higher (40-70 mg per cup)	Lower (20-45 mg per cup)
Amino Acids	L-theanine, but in lower concentration	Higher concentration of L-theanine
Flavour Profile	Malty, robust, astringent, complex	Fresh, grassy, vegetal, sweet, less astringent
Astringency	Higher, due to polymerized tannins	Milder, due to catechins
Colour	Dark brown to reddish	Light green to yellowish-green

Table 2: Health benefits of black tea and green tea

Health Benefit	Green Tea	Black Tea
Antioxidant Properties	High in EGCG, powerful antioxidants	Rich in theaflavins, supports heart health
Weight Management	Boosts fat burning, aids metabolism	May help with weight regulation via gut microbiota
Blood Sugar Control	Improves insulin sensitivity, controls blood sugar	Helps regulate blood sugar, supports insulin sensitivity
Mental Alertness	L-theanine & caffeine boosts cognitive function	Stronger caffeine content for alertness
Cognitive Health	Neuroprotective, may reduce Alzheimer's risk	May help protect against cognitive decline
Gut Health	Positive effects on gut microbiome, anti-inflammatory	Supports gut bacteria and digestion, anti-inflammatory
Oral Health	Reduces bacteria, prevents cavities	Reduces bacteria, helps with oral hygiene

Conclusion

The comparative biochemistry of black and green tea offers profound insights into the complex interplay of chemical compounds that contribute to their distinct health benefits, flavours, and processing methods. Despite both types of tea originating from the same plant, *Camellia sinensis*, the differences in their biochemical profiles—primarily due to varying levels of oxidation and fermentation—result in distinct concentrations of polyphenols, flavonoids, amino acids, and other bioactive compounds. These variations have significant implications for human health, including antioxidant activity, cardiovascular protection, metabolic regulation, and potential cancer prevention.

By delving into the biochemical composition of both black and green tea, this study underscores the importance of processing techniques in shaping the nutritional and therapeutic potential of tea. Green tea, rich in catechins such as EGCG, is especially noted for its antioxidant and anti-inflammatory properties, while black tea, with its unique theaflavins and thearubigins, offers distinct health benefits, particularly for heart health and cognitive function.

Additionally, the study highlights the broader implications of tea biochemistry in agricultural practices, sustainable farming, and the development of functional beverages tailored to specific health goals. The ongoing exploration of tea's impact on the gut microbiome, coupled with its potential to modulate metabolic processes, positions both black and green tea as key players in the evolving landscape of functional foods and wellness.

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