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Antibacterial and Antibiofilm Effects of Camellia sinensis: Mechanisms and Therapeutic Potential

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Abstract

Green tea, from Camellia sinensis, is a source of bioactive polyphenols, mainly catechins with antibacterial properties. Various types of catechins include epigallocatechin gallate (EGCG), epicatechin gallate (ECG), epigallocatechin (EGC) and epicatechin (EC), among which EGCG is the most abundant and bioactive. This review summarises the antibacterial and antibiofilm activities of these catechins against some clinically important Gram-positive and Gram-negative bacterial pathogens.

Catechins have been studied for their broad - spectrum antibacterial property through multiple pathways. For example, they can interfere with DNA and RNA synthesis, block key enzymes in bacterial metabolism and replication, disrupt the bacterial cell membrane, causing loss of intracellular components that are important to maintain bacterial viability.

Studies show that catechins disrupt quorum-sensing systems, which lowers the production of virulence factors, biofilm formation, and bacterial communication. Moreover, catechins cause oxidative stress in bacterial cells by producing reactive oxygen species (ROS), which damages bacterial cells, resulting in cell death.

Polyphenols found in green tea also demonstrate synergistic interactions with conventional antibiotics, enhancing their efficacy against multidrug-resistant (MDR) strains such as Staphylococcus aureus, Escherichia coli, and Pseudomonas aeruginosa. When it comes to addressing antibiotic resistance mechanisms, this synergy is especially intriguing.

Keywords: Camellia sinensis, catechins, ROS, polyphenols, antibacterial, antimicrobial.

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1.0 Introduction

Antibiotic-resistant bacteria are becoming a serious public health problem due to their fast appearance and global spread, which severely limits the efficacy of traditional antimicrobial medicines. *Pseudomonas aeruginosa, Escherichia coli*, and *Staphylococcus aureus* are among the pathogens that have become resistant to several antibiotic classes, such as aminoglycosides, fluoroquinolones, and β-lactams. In addition to raising morbidity and mortality rates, this increasing resistance places a significant financial strain on healthcare systems across the globe. Therefore, it is imperative to investigate complementary and alternative antimicrobial approaches, especially those that come from natural sources and have less adverse effects and a lower chance of developing resistance (Reygaert, 2018; Wu et al., 2021; Bazzaz et al., 2016).

Bioactive substances derived from plants have gained more popularity as substitutes for traditional antimicrobials because of their ability to act on several biological mechanisms and reduce the chances of resistance. There is considerable scientific literature that attests to the strong antibacterial action of plant extracts. For example, according to Singh et al. (2016), Indian plants like *Azadirachta indica* and *Acacia nilotica* have exhibited a strong inhibitory action against bacteria. Moreover, recent studies conducted by Bhattacharjee et al. (2024) have shown the strong antimicrobial action of members of the genus Plumeria.

Green tea, derived from *Camellia sinensis,* has gained significant attention due to its wide range of pharmacological properties, including antibacterial, anti-inflammatory, antioxidant, and anticancer effects. This is mainly due to the higher concentration of polyphenols in the extract, especially catechins. The major catechins found in green tea are epicatechin (EC), epicatechin gallate (ECG), epigallocatechin gallate (EGCG), and epigallocatechin (EGC). Of these, EGCG is present in the highest concentration and is the most biologically active compound. Numerous studies have shown that EGCG demonstrates strong antibacterial properties against a wide range of pathogens (Taylor et al., 2005; Jeon et al., 2014).

Over the past decade, plant-based bioactive molecules have become the subject of intensive research in attempts to develop alternative therapeutic strategies to antibiotics. The use of natural polyphenols has attracted considerable interest as an alternative means to fight pathogens due to the ability of compounds found in green tea to target more than one bacterial site at once. While antibiotics often affect a single cellular component, catechins, including EGCG, can be classified as multi-target substances and thus decrease the likelihood of resistance generation. There is information about the potential of catechins to alter the DNA structure, damage bacterial membranes, and block vital enzymatic activity. All this suggests the possibility of using green tea compounds for managing multidrug-resistant (MDR) bacterial infections (Steinmann et al., 2013; Reygaert, 2018; Renzetti et al., 2020).

In addition to these studies, much effort has been devoted to understanding the synergy between green tea compounds and antibiotics. It is believed that the presence of catechins helps improve the action of antibiotics by increasing the cell permeability, blocking efflux pumps, and downregulating resistance genes such as β-lactamases. This not only increases the efficiency of the treatment but can help achieve better results through lower dosages of both medications, resulting in reduced toxicity. In addition, catechins can modulate bacterial virulence by affecting the quorum-sensing pathway involved in biofilm formation. Together, these findings highlight the potential of green tea polyphenols as supportive agents in modern antibacterial strategies (Hu et al., 2002; Taylor et al., 2005).

Catechins have been shown in recent studies to have broad-spectrum antibacterial action against both Gram-positive and Gram-negative bacteria. Antimicrobial effects of such substances are achieved due to various factors, namely, membrane disruption, enzymatic inhibition, and the inhibition of metabolic reactions of microbes. Indeed, according to Noormandi et al. (2014), EGCG is capable of disrupting membranes of bacteria, inhibiting their growth, and interfering with metabolic activity, leading to cell death.

Green tea polyphenols not only possess strong antibacterial effects but also demonstrate high levels of antibiofilm activity. Biofilms are colonies of bacteria that are protected by an extracellular polymeric substance formed from the products of the metabolism of microorganisms. Such biofilms protect bacteria from destruction by antibiotics and antibodies of organisms. Therefore, biofilm infections are challenging for treatment and cause persistent and recurrent problems for patients. Green tea polyphenols, more specifically catechins, can disrupt biofilms through several mechanisms, namely, inhibition of adhesion of bacteria, EPS synthesis, and stabilisation of mature biofilms (Wu et al., 2021; Higuchi et al., 2024).

All things considered, catechins' diverse antibacterial and antibiofilm qualities make them attractive options for the creation of cutting-edge medicinal substances. Nevertheless, despite promising in vitro results, more in vivo research and clinical trials are needed to confirm their effectiveness and determine their potential contribution to the fight against antibiotic-resistant diseases.

2.0 Phytochemical Composition of *Camellia sinensis*

Camellia Sinensis has a rich phytochemical profile, with about 30-40% of its dry weight consisting of polyphenols, mainly catechins. The determination of phytochemical profiles is of great importance when studying the bioactivity of natural products extracted from plants. In many studies, sophisticated methods such as LC-MS were used in identifying bioactive compounds that contribute to antimicrobial action. According to Bhattacharjee and Singh (2024), the LC-MS technique was employed for screening the banana pseudostem for different phenolics and antioxidants, which may account for the bioactivity. Indeed, plant polyphenols like catechins are known to exhibit antimicrobial and antioxidative properties.

These catechins are the main bioactive compounds responsible for the pharmaceutical properties of green tea. The most common and active of the major catechins are epigallocatechin gallate (EGCG), epigallocatechin (EGC), epicatechin gallate (ECG), and epicatechin (EC) (Cabrera et al., 2006; Friedman, 2007; Steinmann et al., 2013; Reygaert, 2018).

Structurally, catechins are flavan-3-ols containing multiple hydroxyl groups and sometimes a gallate group. These hydroxyl groups contribute to antioxidant activity by helping them donate hydrogen atoms and neutralise reactive oxygen species (ROS). By promoting stronger connections with bacterial cell membranes and proteins, the gallate group—especially in EGCG and ECG—plays a critical role in boosting antimicrobial activity (Chacko et al., 2010; Khan & Mukhtar, 2013; Balentine et al., 1997).

Other significant phytochemicals found in green tea include catechins, flavonols (including quercetin, kaempferol, and myricetin), phenolic acids (like gallic acid), alkaloids (like caffeine), amino acids (particularly L-theanine), vitamins, and trace minerals. These compounds might synergise with catechins, thus increasing the total biological effects of green tea (Renzetti et al., 2020; Yang et al., 2009). The structure of catechins is directly related to their antimicrobial effects. As amphiphilic molecules, they can interact with the lipid bilayer of bacterial cell membranes, thus making them permeable, promoting cell lysis, and leakage of intracellular contents from the cells. Furthermore, catechins can interact with the enzymes involved in important metabolic processes in bacteria. They can also interact with DNA and interfere with its replication process.

Some studies also claim that catechins can cause oxidative stress in microbial cells, disturb redox equilibrium, and chelate metal ions. Their antibacterial effectiveness is further enhanced by their capacity to obstruct biofilm formation and quorum sensing. Green tea is a promising source of natural antibacterial agents due to the phytochemicals' structural variety and multipurpose qualities.

Overall, green tea's strong antioxidant and antibacterial effects are mainly due to its rich catechin content, which also supports its prospective uses in the pharmaceutical, food preservation, and medical industries.

3.0 Inhibitory Effects on Bacterial Growth

The anti-bacterial efficiency of plant-based extractions can be explained by the way they interfere with various biological activities in bacteria. This hypothesis is validated by research that has been done on the anti-bacterial properties of extracts from *Azadirachta indica* and *Vachellia nilotica*, which has revealed their effectiveness in eliminating Enterococcus faecalis (Singh & Singh, 2025). This interference can occur as a result of changes in membrane permeability, enzymatic activity inhibition, and metabolic processes. Thus, this mechanism of antibacterial activity is analogous to that of catechins present in green tea.

Green tea catechins are considered potential alternatives for antimicrobial therapy because of their strong, broad-spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria. The main catechins, epigallocatechin gallate (EGCG), epicatechin gallate (ECG), epigallocatechin (EGC), and epicatechin (EC), target the bacterial structure and function in different types of methods (Reygaert, 2018; Friedman, 2007; Taylor et al., 2005).

Catechins mainly damage the integrity of the cytoplasmic membrane and thick peptidoglycan cell wall of Gram-positive bacteria like *Staphylococcus aureus*. Studies show that EGCG binds to lipid bilayers, increasing membrane permeability and causing leakage of important intracellular components, ultimately resulting in cell lysis. Furthermore, catechins can also reduce bacterial pathogenicity by preventing the synthesis of virulence components such as toxins and enzymes. They can also block vital enzymes involved in bacterial metabolism and disrupt cell division (Ikigai et al., 1993; Steinmann et al., 2013).

In Gram-negative bacteria, the outer membrane acts as an additional barrier to antimicrobial agents, in Gram-negative bacteria like *Escherichia coli* and *Pseudomonas aeruginosa*. However, because catechins are amphipathic, they can pass through this barrier. After entering the cell, they interfere with intracellular functions like DNA replication and protein synthesis, damage membrane integrity, and destabilise lipopolysaccharides (LPS). They also produce certain reactive oxygen species (ROS), catechins can cause oxidative stress, which damages bacterial cells (Wu et al., 2021; Gopal et al., 2016).

Their synergistic interaction with traditional antibiotics is another significant feature of their antibacterial efficacy. It has been demonstrated that catechins, especially EGCG, increase the efficacy of β-lactam antibiotics by blocking resistance mechanisms, including β-lactamase activity. This combination is particularly useful against multidrug-resistant (MDR) bacterial strains (Stapleton et al., 2004; Hu et al., 2002).

The bioactive compounds contained within green tea, obtained from *Camellia sinensis* plants, are catechins, which include EGCG (epigallocatechin gallate). These substances possess highly effective bactericidal and antibiofilm properties that affect not only Gram-positive but also Gram-negative bacteria. Catechins exert their antimicrobial effects on the body by interfering with the function of cellular membranes and inhibiting the synthesis of enzymes and DNA, as well as producing oxidative damage and preventing bacterial communication and biofilm development. In addition, studies have shown that green tea catechins can produce synergistic effects with antibiotics on antibiotic-resistant strains like *Staphylococcus aureus, Escherichia coli*, and *Pseudomonas aeruginosa* (Boudou et al., 2026).

4.0 Inhibition of Biofilm Formation

Biofilms are structured communities of microorganisms that are enclosed in an extracellular polymeric substance (EPS) matrix that they make on their own. This matrix protects the microorganisms from host immune reactions and antibiotics. Chronic and recurrent infections are largely caused by biofilm-associated illnesses, which are very difficult to treat.

Green tea catechins have shown very strong antibiofilm activity by targeting different stages of biofilm formation. They can also change the hydrophobicity of cell surfaces and interfere with adhesin proteins. Catechins prevent bacterial adhesion to surfaces during the initial stage. As a result, stable biofilms are less likely to form (Borges et al., 2012; Taylor et al., 2005).

Catechins also reduce the production of extracellular polymeric components, such as proteins, polysaccharides, and extracellular DNA, which are critical for the stability and structure of biofilms throughout the maturation phase. This weakens the biofilm structure by disrupting the EPS matrix, which increases the susceptibility of bacterial cells to antimicrobial agents (Wu et al., 2021).

Catechins are also responsible for disrupting quorum sensing, a system of cell-to-cell communication that controls bacterial coordination, virulence factor production, and biofilm formation. Catechins hinder the development of biofilms and lower bacterial virulence by interfering with quorum-sensing signals (Reygaert,2018). In addition, catechins can affect existing biofilms by breaking into the extracellular matrix and causing structural destruction. This leads to the detachment of bacteria, making it easier for antibiotics to work effectively. Because of their antimicrobial and anti-biofilm characteristics, green tea catechins could play a significant role in managing infections that persistently occur.

5.0 Modes of Action include

The green tea catechins possess antimicrobial properties by virtue of their actions at various levels that affect bacterial proliferation, survival, and pathogenicity through both intracellular disruption and physicochemical interference. Due to their multi-target mode of action, the four major catechins, namely EGCG, ECG, EGC, and EC, prevent the emergence of resistance in bacteria (Steinmann et al., 2013; Reygaert, 2018; Renzetti et al., 2020).

5.1 Membrane Destruction

Catechins induce bacterial cell death mainly by damaging the bacterial membrane structure. Given their amphiphilic nature, catechins bind to lipid bilayers, particularly phospholipids and membrane proteins, leading to increased membrane porosity. Subsequently, there is a leakage of essential cellular contents such as proteins, nucleotides, and ions. Catechins penetrate the outer membrane of Gram-negative bacteria and interfere with the arrangement of lipopolysaccharides (LPS). At the same time, the catechins destabilise the internal cytoplasmic membrane beneath the peptidoglycan layer in Gram-positive bacteria. In sum, the above processes culminate in cell death and lysis.

5.2 Inhibition of Enzymes

The catechins have the capability to attach to enzymes present in bacteria via hydrophobic interactions and hydrogen bonds. The process causes enzyme inhibition. The attachment blocks the necessary enzymes involved in vital processes like energy production and fatty acid synthesis. Additionally, it is reported that catechins like EGCG block β-lactamase enzymes, thus increasing the effectiveness of β-lactam antibiotics towards antibiotic-resistant bacteria (Hu et al., 2002).

5.3 Oxidative Stress

The other notable mechanism involves oxidative stress in bacterial cells. The catechins produce reactive oxygen species such as hydrogen peroxide and superoxide radicals. ROS oxidises lipids, proteins, and DNA, causing oxidative stress. The stress results in the disruption of homeostatic mechanisms and causes bacterial cell death. It is important to note that catechins may act as pro-oxidants in microorganisms even though they act as antioxidants in host organisms.

5.4 Interaction with Genetic Material

It is also possible for catechins to bind to bacterial nucleic acid molecules in order to prevent transcription as well as DNA replication. This occurs by hindering DNA supercoiling and replication through the inhibition of DNA gyrase, which plays an integral role in the latter process. The result is decreased growth and cell division among the bacteria. It is also possible for catechins to hinder RNA formation and thus affect protein synthesis.

5.5 Interference with Cell Signalling and Virulence

Furthermore, catechins can interfere with quorum sensing, which is the process by which bacteria communicate in order to regulate genes involved in resistance, biofilm development, and virulence. This interference hinders their movement and toxin production. Even in cases where total eradication is not attained, this greatly reduces bacterial pathogenicity (Reygaert, 2018).

Overall, green tea catechins act as effective antibacterial agents by targeting multiple cellular pathways, which lowers the risk of resistance development. Their potential utility in combination treatments with traditional antibiotics is further supported by their multimodal method of action.

5.6 Synergism Effects with Antibiotics

The catechins of green tea, especially epigallocatechin gallate, have been considered promising agents in combating the development of antibiotic resistance and have shown synergy when used with several antibiotics. Synergy is achieved by various mechanisms, including enhancement of the effectiveness of the drug and assistance in counteracting mechanisms of defence in bacteria (Stapleton et al., 2004; Hu et al., 2002; Reygaert, 2018; Steinmann et al., 2013).

One of the mechanisms of enhancing antibiotic activity is penetration. Catechins disrupt bacterial cells' outer membrane, which increases accumulation of such antibiotics as β-lactams, tetracycline and fluoroquinolones. It is especially useful in Gram-negative bacteria since their outer layer functions as a physical barrier to the entry of medications into the cell. Another way of enhancing the activity of antibiotics is by interfering with the mechanisms of developing resistance. For example, experiments have proven that EGCG blocks β-lactamases, enzymes involved in the degradation of β-lactam antibiotics. Moreover, catechins might block efflux pumps that help bacteria eject antibiotics from the cell (Hu et al., 2002). Another important factor to consider is how bacteria's ability to induce virulence and respond to stress is regulated. Catechins interfere with quorum-sensing mechanisms, leading to a down-regulation of genes involved in resistance, biofilms, and virulence. Pathogens become more vulnerable to antibiotics, making them more susceptible to treatment due to their inability to defend themselves.

Synergistic interactions have been noted when treating MDR strains of *Pseudomonas aeruginosa, Escherichia coli,* and *Staphylococcus aureus*, such as methicillinresistant *Staphylococcus aureus* (MRSA). This suggests that using catechins along with currently available antibiotics can lead to reduced dosages, reduced side effects, and extended half-life of the drugs.

6.0 Limitations and Future Prospects

While green tea catechins demonstrate substantial antibacterial properties and synergism, some limitations prevent their wide utilisation in practice. Firstly, catechins have low bioavailability, meaning that the systemic distribution of these substances is limited. Moreover, catechins are characterised by fast metabolism and poor gastrointestinal absorption (Yang et al., 2009; Reygaert, 2018).

Secondly, catechins are chemically unstable. They are sensitive to pH changes, light, temperature, and oxygen, making them subject to degradation and diminishing their biological activity. This issue affects the formulation and storage of drugs containing catechins.

Thirdly, the number of well-conducted human clinical trials investigating the antibacterial effects of green tea catechins is insufficient. Although there are multiple in vitro and animal studies, there is a lack of randomised controlled trials on humans, limiting the development of standard therapeutic protocols regarding dose, route of administration, and safety (Steinmann et al., 2013). Fourthly, standardisation is necessary to achieve consistent results. Inconsistent levels of catechins due to differences in sources, extraction, and processing of teas result in variability in efficacy, which makes it important to establish consistent formulations and quality control procedures.

There are several strategies currently being investigated to address the aforementioned limitations. Some of the most common ones include the use of liposomes, nanoencapsulation, and modification of catechins to improve stability and bioavailability (Yang et al., 2009).

7.0 Conclusion

The natural ability of green tea polyphenols, and more specifically EGCG, to exert their antibacterial and antibiofilm properties is significant. Their efficiency is attributed to various mechanisms involving damage of bacterial membranes, enzyme inhibition, oxidative stress, alteration of bacterial DNA, and quorum-sensing pathway interference (Reygaert, 2018; Steinmann et al., 2013; Friedman, 2007). As compared to traditional antibiotics, which target only one spot, this multidimensional approach may be beneficial in improving antibacterial activity and reducing the risk of developing antibiotic resistance.

In addition to their direct antimicrobial activity, catechins can be effective in preventing biofilm formation and disrupting existing ones, thus playing an important role in overcoming persistent and resistant infections. Catechins decrease bacteria's defence mechanisms by interfering with intercellular communication and EPS production, thus increasing bacteria's susceptibility to antimicrobial agents and reducing bacteria's adherence.

Finally, catechins may have synergic effects on traditional antibiotics, helping to overcome their adverse impact when treating MDR infections. Thus, catechins can improve the penetration of drugs into tissues, interfere with efflux pumps, and β-lactamase enzyme activity, hence regaining the sensitivity of bacteria to antibiotics (Reygaert, 2018; Steinmann et al., 2013). As a result, catechins can be useful as an adjuvant to combination therapies that attempt to minimise antibiotic resistance. However, there are several obstacles. There are challenges related to the clinical use of catechins, including poor bioavailability, chemical instability, inconsistent composition, and lack of human-based evidence. The majority of data comes from in vitro and animal studies, highlighting the necessity of conducting human clinical trials (Yang et al., 2009).

Future research should focus on methods of improving the stability and bioavailability of catechins, such as nanotechnologies, targeted drug delivery systems, and modification of catechin molecules. In addition, standardisation of extraction methods and proper quality control are important to ensure consistent results and reproducibility.

8.0 Declarations

The authors hereby declare that the manuscript submitted for consideration is an original work and has not been published or submitted elsewhere for publication. The authors take full responsibility for the integrity, accuracy, and ethical compliance of the work presented in the manuscript, including all revisions made in response to reviewer comments.

AI Usage Statement

The authors declare that AI tools, if used, were solely employed to improve the clarity, grammar, and language of the manuscript. No data, results, or scientific content were generated or altered using AI.

Conflict of Interest and Ethical Compliance

All authors confirm that:

i. Any potential conflicts of interest, whether financial or non-financial, have been fully disclosed. – ~~Yes~~ / Not Applicable

ii. All sources of funding and financial support received for the conduct of the study have been appropriately acknowledged, including any updates made during revision. – ~~Yes~~ / Not Applicable

iii. Necessary ethical approvals have been obtained from the relevant institutional or regulatory bodies for studies involving human participants, animals, or sensitive data, wherever applicable, and are clearly stated in the manuscript. – ~~Yes~~ / Not Applicable.

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