

INVESTIGATION AND COMPARISON OF ANTIOXIDANT POTENTIAL
OF CATECHINS PRESENT IN GREEN TEA: DFT STUDYSanduni S. Wijesooriya¹, Dinesh R. Pandithavidana¹, ✉<https://doi.org/10.23939/chcht16.04.591>

Abstract. DFT calculations were applied to compare the antioxidant potential of four major catechins present in green tea. The thermodynamic parameters related to three key mechanisms of primary antioxidant action were investigated in detail. Molecular orbital energies, absolute hardness, electronegativity, and electrophilicity index, which contributed to the radical scavenging were also investigated. The radical scavenging potential of each hydroxyl group of these polyphenolic antioxidants were investigated independently.

Keywords: DFT, catechins, hydrogen atom transfer, single electron transfer–proton transfer, sequential proton loss–electron transfer, HOMO-LUMO.

1. Introduction

Among numerous types of antioxidant compounds, polyphenolic compounds form an important class of chain-breaking species which have the potential to quench reactive radical intermediates produced during the oxidative processes of both biologically and commercially essential materials.^{1,2} Antioxidants as external supplements are used to maintain the concentration of free radicals as low as possible and to avoid oxidative stress.³ They are heavily used in the food industry to maintain the quality of the ready-to-eat foods and to boost the shelf life.⁴ Among these, plant polyphenolic compounds found in green tea are rich in catechins. The major green tea catechins are (-)-epicatechin (EC), (-)-epigallocatechin (EGC), (-)-epicatechin-3-gallate (ECG), and (-)-epigallocatechin-3-gallate (EGCG), which (shown in Fig.1) have been recognized as potential therapeutic agents.⁵ Among these catechins, (-)-epigallocatechin-3-gallate (EGCG) is the major bioactive polyphenol present in green tea. The phenol rings of the catechin structure serve as electron traps and scavengers of free radicals to inhibit the formation of reactive oxygen species (ROS) and reduce the harm caused by oxidative stress.⁶ This polyphenolic structure allows

electron delocalization, conveying the ability to quench free radicals.⁵ It has been reported that EGCG can effectively hamper oxidative stress-induced protein tyrosine nitration prompted by oxidative stress in blood platelet.⁷ Consequently, these catechins have a direct (antioxidant) or indirect (increase of activity or expression) effect.⁸ Thus, catechins can act as antioxidants as they prevent the oxidation of other antioxidants like vitamin-E but the ingestion of green tea catechins does not modify the plasma status of vitamin-E and vitamin-C.^{9,10} However, the structural features such as the number of galloyl and hydroxyl (-OH) groups in the catechin molecules, play an important part in their biological activities, particularly in their antioxidant properties.⁶

The computational and quantum chemistry have become a versatile tool to investigate atomic-level structures and energetic information of systems which have an accuracy equivalent to or greater than the results obtained from experiments at different laboratories. The efficiency of an antioxidant potential can be successfully predictable by analyzing the potential energy surface (PES) of the reaction.¹¹ This potential energy surface permits calculation of the Gibbs free energies (thermodynamic potential) of activation and reaction progression, entailing that both kinetic and thermodynamic approaches to interested reaction are presented.¹² Thus, the computed parameters provide valuable information on the radical scavenging capability without considering reaction pathway.

The hydrogen atom transfer (HAT) mechanism, the single electron transfer–proton transfer (SET–PT) mechanism and the sequential proton loss–electron transfer (SPLET) mechanisms illustrated in Scheme 1 are three key proposed mechanisms which have been exercised to elucidate how antioxidants release the atomic hydrogen from their conjugated hydroxyl group (-OH) to scavenge free radicals.¹²

One of the most important parameters characterizing the antioxidant or radical scavenging activity of many natural and synthetic compounds is the bond dissociation enthalpy (BDE), that can be used to study the antioxidant potential of the HAT mechanism. The adiabatic ionization potential (IP) and the proton

¹ University of Kelaniya, Kelaniya, 11600, Sri Lanka

✉ dinesh@kln.ac.lk

© Wijesooriya S.S., Pandithavidana D.R., 2022

dissociation enthalpy (PDE) are utilized to interpret the antioxidant capability of the SET–PT mechanism. Consequently, the proton affinity (PA) and the electron transfer enthalpy (ETE) are employed as thermodynamic parameters to investigate the antioxidant efficiency of the SPLET mechanism.^{13,14}

Klein and co-authors have revealed for their investigated reactions that although the Gibbs free energy cha-

racterizes a criterion of the thermodynamically feasible process, the absolute values of the entropic component are much smaller than the enthalpy component.^{15,16} Thus, comparison of BDEs, IPs, PDEs, Pas, and ETEs can illustrate which mechanism is thermodynamically preferred. Although these three mechanisms may or may not co-exist, the net end result of all these mechanisms may be almost the same.

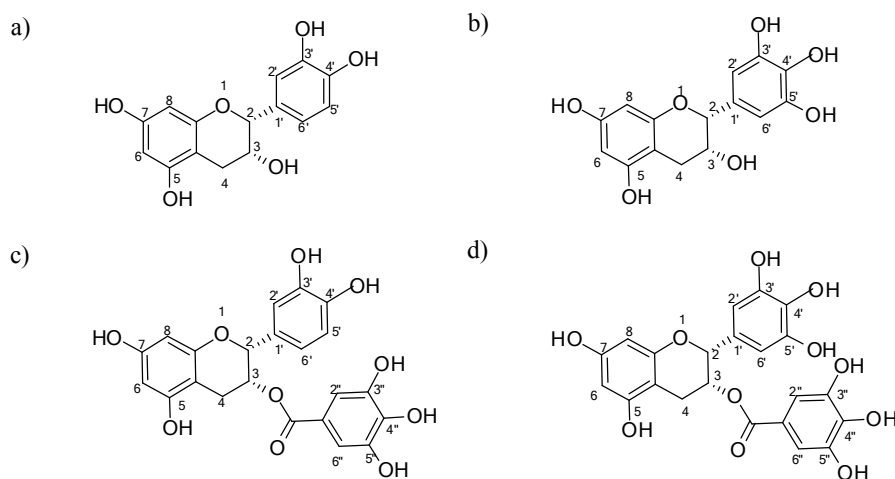
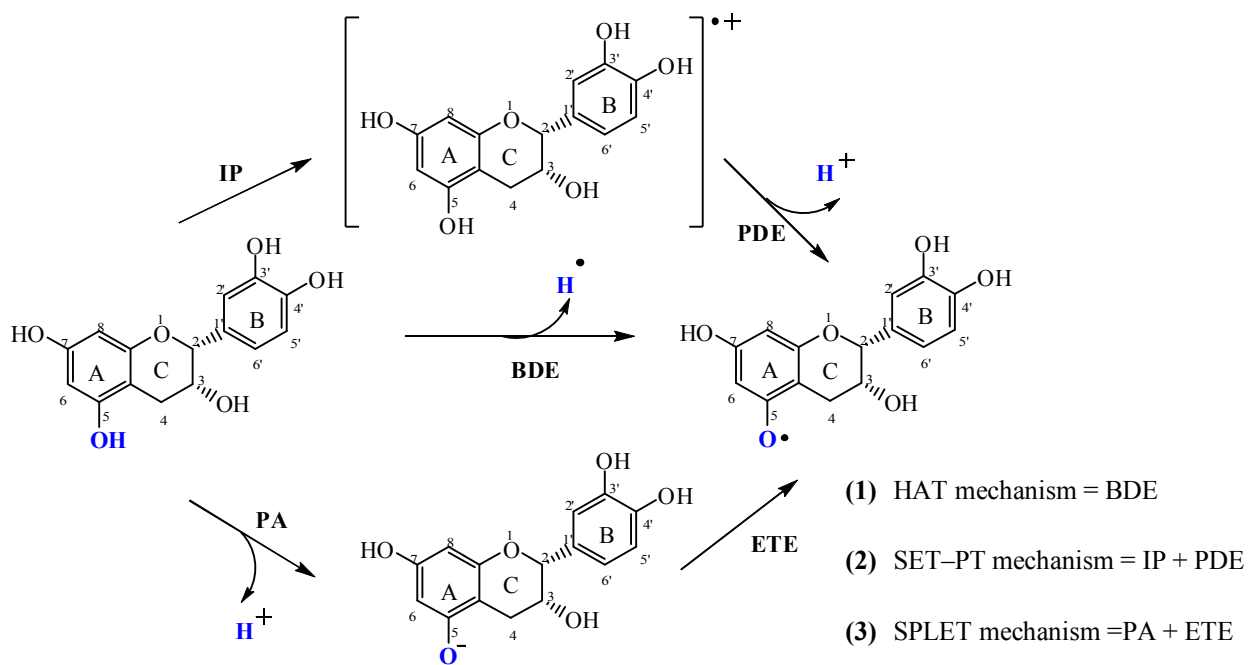


Fig. 1. Chemical structure of catechins: **[a]** (-)-epicatechin (EC), **[b]** (-)-epigallocatechin (EGC), **[c]** (-)-epicatechin-3-gallate (ECG), and **[d]** (-)-epigallocatechin-3-gallate (EGCG)



Scheme 1. Thermodynamic parameters used to investigate proposed mechanisms, using 5th hydroxyl group (-OH) of the (-)-epicatechin (EC) as an example

Although some computational studies have been carried out to investigate the antioxidant activity of individual catechin molecules, a comparative study of antioxidant potentials of these catechins (in Fig. 1) was not computed. In this present study we explore more thermodynamic parameters (as BDEs, IPs, PDEs, Pas, and ETEs) to analyze and compare the antioxidant trends revealed by not only the HAT mechanism but also by the SET–PT mechanism and the SPLET mechanism. All data computed in this study was modeled in aqueous phase because all radical scavenging activities take place in cellular environment which is rich in water.¹⁷ Since these catechins are polyphenolic antioxidants, the radical scavenging potential of each hydroxyl group (-OH) of the four major catechins were investigated independently to build up an expansive picture in comparison.

In addition to the computation of those thermodynamic parameters (BDEs, IPs, PDEs, Pas, and ETEs), the energies of molecular orbitals present in these four catechins were investigated using their highest occupied molecular orbitals (HOMOs) and lowest unoccupied molecular orbitals (LUMOs) because it has been reported that the reactivity of the molecules depends on energies of their molecular orbitals.^{18,19} The energy of HOMO is directly related to ionization potential (IP) whereas the energy of LUMO is related to an electron affinity (EA). The ability of a molecule to donate an electron is represented by the HOMO and the LUMO represents the ability of a molecule to accept an electron. The energy difference between HOMO and LUMO is known as the energy gap (ΔE), which is an important stability index related to electron transport properties.¹⁹ So, the molecules with larger energy gaps are less polarizable, less reactive, and highly stable whereas the molecules with smaller energy gaps are more polarizable, more reactive, and less stable. Hence the HOMO-LUMO energy gap of a molecule accounts for its biological activity as the energy gap explains the charge-transfer interactions of the molecule.²⁰ Thus, the reactivity of epicatechins were further determined by the energy of frontier orbital distributions.

2. Experimental

2.1. Computational Study

The computational DFT calculations have been performed using Gaussian 09 (64-bit, Linux version) computer software package on a Linux Mint 16 cinnamon 64-bit operating system with a desktop computer at the processing speed of 3.3–3.6 GHz with Intel[®] Core i7 5820K CPU, 32 GB RAM, and 1 TB hard drive capacity and Gauss View 5.0.8 software package on Wine in

Linux. The geometries of all catechin molecules, including their radicals and radical cations have been fully optimized by employing the hybrid functional of B3LYP level with the basis set of 6-311++G (d,p). The energies of frontier molecular orbitals (HOMO and LUMO energy gaps) were computed using the same basis set.²¹

The antioxidant activity of catechin molecules was calculated by hydroxyl bond dissociation enthalpy (BDE), ionization potential (IP), proton dissociation enthalpy (PDE), proton affinity (PA), and electron transfer enthalpy (ETE) in the aqueous phase at 298.15 K temperature and 1 atm, pressure which were computed employing the solvation models of CPCM (Conductor-like Polarizable Continuum Model) and the IEFPCM (Integral Equation Formalism PCM).²² The thermodynamic properties have been investigated in aqueous phase as following the formulae already applied on similar molecules.^{23,24}

$$\begin{aligned} \text{BDE} &= \Delta H_{(\text{RO}^\bullet)} + \Delta H_{(\text{H}^\bullet)} - \Delta H_{(\text{ROH})} \\ \text{IP} &= \Delta H_{(\text{RO}^{+\bullet})} - \Delta H_{(\text{ROH})} \\ \text{PDE} &= \Delta H_{(\text{RO}^\bullet)} + \Delta H_{(\text{H}^+)} - \Delta H_{(\text{RO}^{+\bullet})} \\ \text{PA} &= \Delta H_{(\text{RO}^-)} + \Delta H_{(\text{H}^+)} - \Delta H_{(\text{ROH})} \\ \text{ETE} &= \Delta H_{(\text{RO}^\bullet)} - \Delta H_{(\text{RO}^-)} \end{aligned}$$

The enthalpies of the protonated form, the radical form, and the radical cation form of the phenolic compounds have been represented as $\text{H}(\text{ROH})$, $\text{H}(\text{RO}^\bullet)$ and $\text{H}(\text{ROH}^{+\bullet})$, respectively. The computed (H^+) and $\text{H}(\text{e}^-)$ enthalpies were taken as 6.197 kJmol^{-1} and 3.145 kJmol^{-1} , respectively from the literature available.²⁴

The radical scavenging mechanism is also influenced by other molecular parameters such as absolute hardness (η) and electronegativity (χ), electrophilicity index (ω), vertical ionization potentials (IP_v), and electron affinity (EA_v), were determined using the computed HOMO and LUMO energies of the four catechins separately.^{25,26} Vertical ionization potential (IP_v) was determined according to Koopmans' theorem: ($IP_v = -E_{\text{HOMO}}$). Electron affinity was determined according to formula: $EA_v = -E_{\text{LUMO}}$.²⁷⁻²⁹

3. Results and Discussion

3.1. Computation of Antioxidant Potential

To validate the computational procedure, a density functional theory (DFT) method with B3LYP functional was employed to compute enthalpies (BDE, IP, PDE, PA, and ETE) of these four major catechins using both CPCM and IEFPCM solvent models. Since the natural catechins exhibit their antioxidant potential in an aqueous cellular environment in reality,³⁰ optimized structures of catechins in aqueous phase (water) have been used for the computational investigations as they are shown in Fig. 2.

Comparison of the thermodynamic parameters (enthalpies) corresponding to three mechanisms (HAT, SET-PT and SPLET) of the (-)-epicatechin (EC), (-)-epigallocatechin (EGC), (-)-epicatechin-3-gallate (ECG) and (-)-epigallocatechin-3-gallate (EGCG) in aqueous phase is shown in Fig. 3. It was revealed that the HAT mechanism has demonstrated the lowest set of enthalpies compared to other two reaction mechanisms (SET-PT and SPLET). According to the computed data corresponding

to all three mechanisms, the 3'-OH group, located the ring-B (illustrated on Scheme 1) of each catechin molecule has shown the lowest enthalpy as compared to all the other hydroxyl moieties found on these polyphenolic compounds. The radical scavenging capability of the 3'-OH group has remarkably increased via the inductive effect caused by the adjacent 4'-OH group and the resonance effect (the resonance stabilization) caused by the phenolic conjugated system.

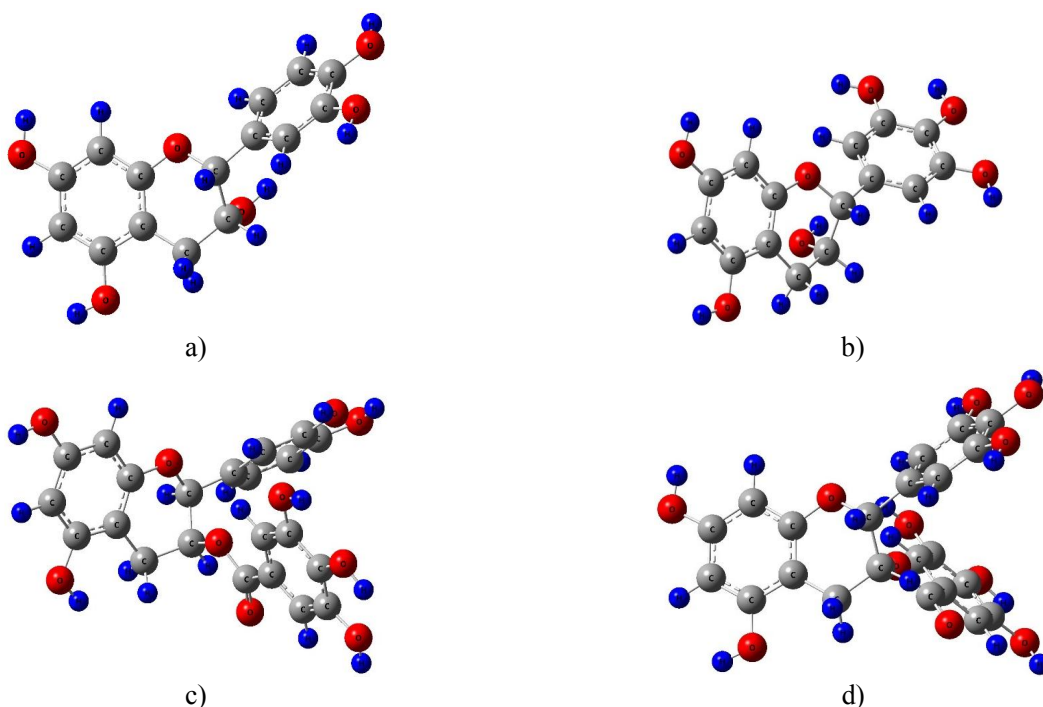


Fig. 2. The optimized geometries of catechins: **[a]** (-)-epicatechin (EC), **[b]** (-)-epigallocatechin (EGC), **[c]** (-)-epicatechin-3-gallate (ECG), and **[d]** (-)-epigallocatechin-3-gallate (EGCG) in aqueous phase. Color atoms: ● for O, ● for C and ● for H

Although bond dissociation enthalpy (BDE) could be directly used to demonstrate the antioxidant potential of the HAT mechanism, the “combined effect” was considered to express the net effect of SET-PT mechanism (enthalpies of IP + PDE) and the SPLET mechanism (enthalpies of PA + ETE).

3.2. Computation of Total (Average) Antioxidant Capacity

Since these catechins are poly-phenolic compounds (having more than one hydroxyl group per molecule), it is essential to average the values of each enthalpy parameter as considering the “net contribution of all hydroxyl groups (-OH)” present at the interested catechin molecule (shown in Table 1). It was evident that all thermodynamic properties computed from both CPCM and IEFPCM solvation models produced almost same final output.

Although the three main antioxidant mechanisms (HAT, SET-PT and SPLET) corresponding to each catechin molecule have demonstrated some deviation of the average value of enthalpy contributions, it was clear that the “trend of the antioxidant potential” revealed by all three mechanisms was similar.

According to the results of Table 1, it is evident that (-)-epigallocatechin-3-gallate (EGCG) possessed the lowest set of average enthalpies (irrespective of the type of the antioxidant mechanism), as showing the highest antioxidant potential as compared to the other catechins. Based on average enthalpies, antioxidant potential of catechins found in green tea can be placed in the following order of ascending: EC < EGC < ECG < EGCG. Due to the presence of the highest number of hydroxyl groups (-OH), EGCG's contribution to radical scavenging activity has become prominent. Most of its phenoxyl radicals are stabilized by effects of resonance, inductive and space.

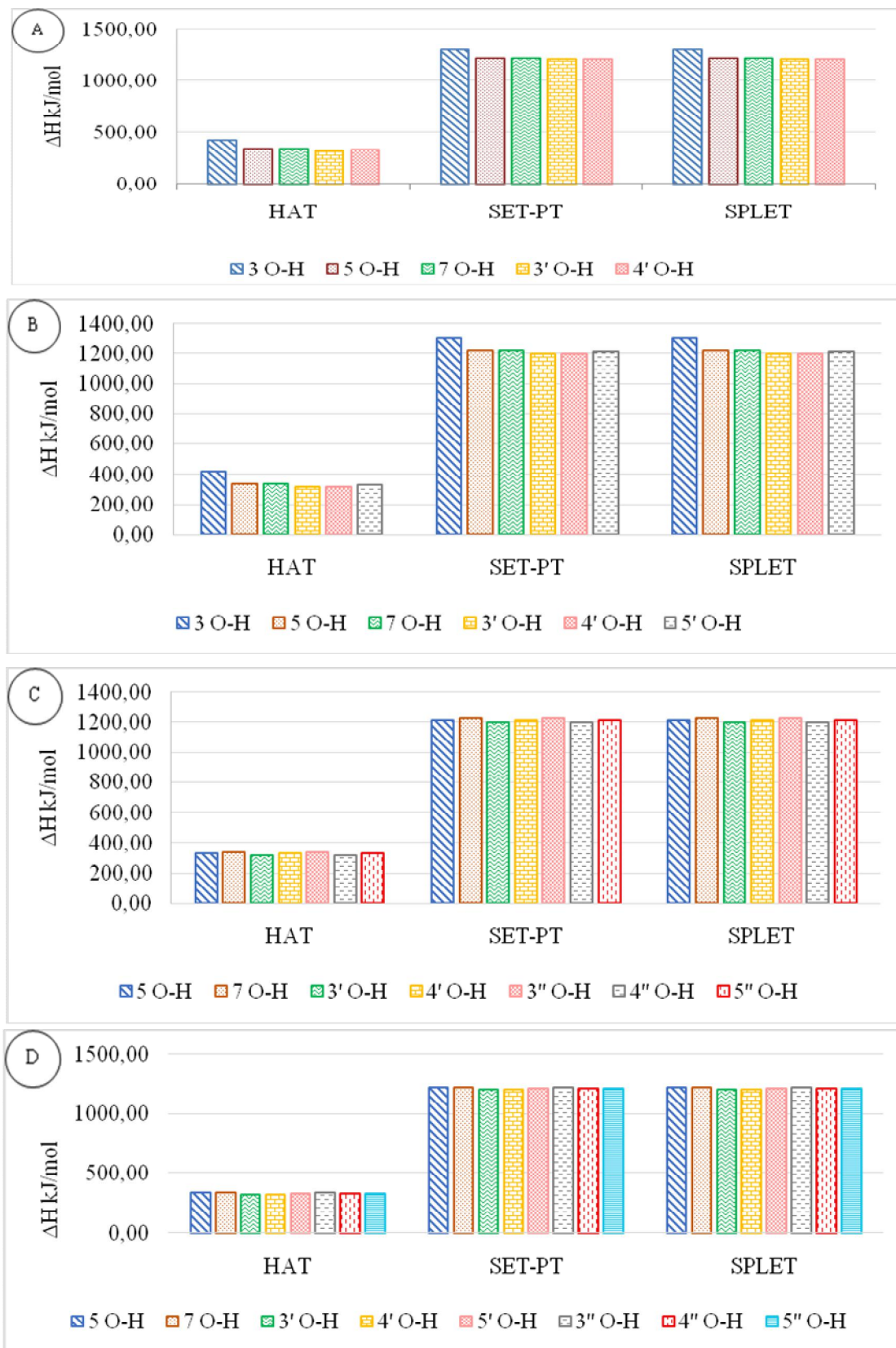


Fig. 3. Comparison of the enthalpy values corresponding to three mechanisms (HAT, SET-PT, and SPLET) of four catechins: (A) EC, (B) EGC, (C) ECG, and (D) EGCG in aqueous phase

Table 1. Averaged reaction enthalpies in kJmol^{-1} of four catechins (EC, ECG, EGC and EGCG), employing functional of B3LYP level of theory with the basis set of 6-311++G (d,p), using CPCM and IEFPCM solvation models at the aqueous phase

Mechanism Solvation Model		EC	ECG	EGC	EGCG
$\Delta H_{(\text{HAT}=\text{BDE})}$	CPCM	347.72	328.76	341.48	327.15
	IEFPCM	347.72	328.80	341.48	327.17
$\Delta H_{(\text{SET-PT}=\text{IP}+\text{PDE})}$	CPCM	1234.41	1215.44	1228.16	1213.83
	IEFPCM	1234.41	1215.48	1228.16	1213.85
$\Delta H_{(\text{SPLET}=\text{PA}+\text{ETE})}$	CPCM	1234.41	1215.44	1228.16	1213.83
	IEFPCM	1234.41	1215.48	1228.16	1213.85

For further confirmation of those computational predictions relevant to free radical scavenging, the energy of the highest occupied molecular orbitals (E_{HOMO}), the energy of the lowest unoccupied molecular orbitals (E_{LUMO}), and the HOMO–LUMO gaps (ΔE) of these four catechins have been computed (as shown in Fig. 4) because the ΔE plays a very important role in stability and reactivity of molecules. Although B3LYP is not parameterized for HOMO and LUMO eigen values, the examination of the concept of stability from a kinetic point of view can be done using the HOMO-LUMO energy gap descriptor.

Recent studies have demonstrated the correlation between energy of HOMO (E_{HOMO}) and the free radical scavenging activity.²⁹ Molecules with lower HOMO energy are less likely to donate electrons. The elect-

ronic density distribution of HOMO enables the prediction of the most probable sites responsible for electron transfer and free radical attack. A high density of HOMO is correlated with more active redox sites in the tested molecules. The HOMO–LUMO energy gap values (ΔE) for these catechins listed in Table 2, increase in the following order: EGCG < ECG < EGC < EC. The high kinetic stability of EC molecule is related to low reactivity and large HOMO-LUMO energy gap. Thus, smaller ΔE always refers to the higher chemical reactivity and lower kinetic stability of investigated species. It is evident that EGCG molecule has possessed the highest radical scavenging capability as proving the “trend of antioxidant potential” observed under the thermodynamic parameters (BDEs, IPs, PDEs, PAs and ETes) previously computed.

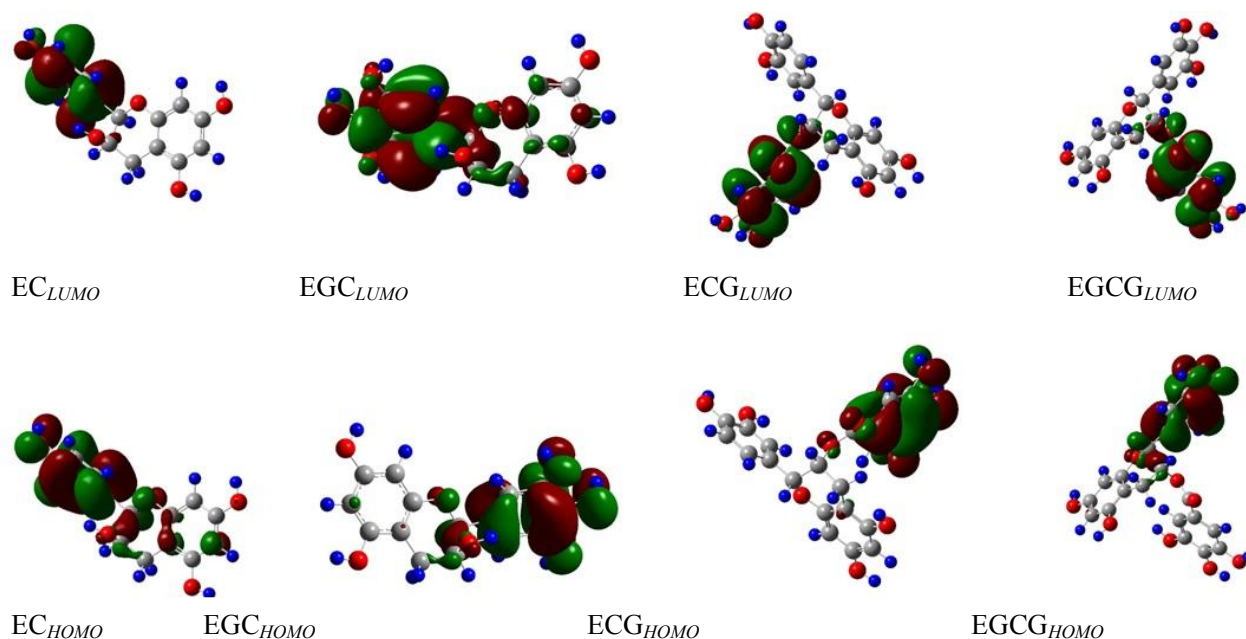


Fig. 4. The HOMO-LUMO orbital distribution of (-)-epicatechin (EC), (-)-epigallocatechin (EGC), (-)-epicatechin-3-gallate (ECG) and (-)-epigallocatechin-3-gallate (EGCG) in aqueous phase

Table 2. Energies (in eV) of frontier molecular orbitals (E_{HOMO} and E_{LUMO}), and HOMO–LUMO gaps (ΔE) of four catechins (EC, ECG, EGC and EGCG) at the aqueous phase

Molecule	E_{HOMO}	E_{LUMO}	$\Delta E = E_{LUMO} - E_{HOMO}$
(-)-Epicatechin (EC)	-0.3124	-0.1613	0.1511
(-)-Epicatechin-3-gallate (ECG)	-0.3171	-0.1869	0.1302
(-)-Epigallocatechin (EGC)	-0.3201	-0.1726	0.1475
(-)-Epigallocatechin-3-gallate (EGCG)	-0.3125	-0.1868	0.1256

Table 3. Calculated quantum chemical properties (in eV) for the most stable conformations of four catechins (EC, ECG, EGC and EGCG) at the aqueous phase

Molecule	Chemical hardness (η)	Electronegativity (χ)	Chemical potential (μ)	Electrophilicity index (ω)
(-)-Epicatechin (EC)	0.0755	0.2464	-0.2464	0.3717
(-)-Epicatechin-3-gallate (ECG)	0.0651	0.2520	-0.2520	0.4877
(-)-Epigallocatechin (EGC)	0.0678	0.2369	-0.2369	0.4113
(-)-Epigallocatechin-3-gallate (EGCG)	0.0621	0.2497	-0.2497	0.4964

Quantum chemical descriptors, such as chemical hardness (η), electronegativity (χ), chemical potential (μ), and electrophilicity index (ω) may yield important information about the bioactivity of these catechins as natural products. The molecule characterized by a low chemical hardness is classified as the reactive one²⁴ and *vice versa*. Thus, it is obvious from computed results of Table 3 that the radical scavenging capacity of (-)-epigallocatechin-3-gallate (EGCG) is the highest as possessing the lowest chemical hardness. The chemical hardness (η) is related to measurement of the “resistance to electron cloud polarization provoked by small perturbation from chemical reactions”.^{28,29} The presence of highest η value for chemical hardness in aqueous medium, indicated that (-)-epicatechin (EC) was most stable kinetically as compared to other catechins and the vice versa was true for (-)-epigallocatechin-3-gallate (EGCG) having the lowest hardness value (Table 3). Since the electrophilicity index (ω) characterizes the capacity of a system to gain an electron is an additive parameter to predict the chemical reactivity of a compound, it gives an indication on the deterioration of the binding energy due to a maximum electron flow between a donor and an acceptor.²⁹ Thus, in terms of electrophilicity index (ω), the most reactive antioxidant compound is confirmed to be EGCG (0.4964 eV), whereas the lowest value (0.3717 eV) matched with EC.

4. Conclusions

In this computational investigation, antioxidant potentials of the four major catechins present in green tea were explored from the thermodynamic point of view. HAT, SET–PT, and SPLET mechanisms were used to illustrate their radical scavenging activities in the aqueous

phase using solvation models of CPCM and IEFPCM. It was revealed that the HAT mechanism has demonstrated the lowest set of enthalpies compared to other two reaction mechanisms (SET–PT and SPLET). Although the three main antioxidant mechanisms (HAT, SET–PT and SPLET) corresponding to each catechin molecule have demonstrated some deviation of the average value of enthalpy contributions, it was clearly revealed that the “trend of the antioxidant potential” revealed by all three mechanisms was similar.

It was positively obvious that (-)-epigallocatechin-3-gallate (EGCG) possessed the lowest set of average enthalpies as showing the highest antioxidant potential as compared to the other three catechins. Based on average enthalpies, antioxidant potential of catechins found in green tea can be placed in the following order of ascending: EC < EGC < ECG < EGCG. According to the computed data corresponding to all three mechanisms, the 3'-OH group, located the ring-B of each catechin molecule had demonstrated the lowest enthalpy as compared to all the other hydroxyl moieties found on these polyphenolic compounds. Energies of molecular orbitals ($E_{HOMO-LUMO}$) present in these four natural catechins exhibited that EGCG molecule has possessed the highest radical scavenging capability as further verifying the “trend of antioxidant potential” observed under the thermodynamic parameters (BDEs, IPs, PDEs, Pas, and ETEs) previously computed. In the same vein, some quantum chemical descriptors (chemical hardness, electronegativity, chemical potential, and electrophilicity index) investigated might yield important information about the bioactivity of these catechins. It can be concluded that modification of the chemical structure of (-)-epigallocatechin-3-gallate (EGCG) provides an insight into the design of structurally novel, potent antioxidants which will be more economical and beneficial in pharmaceutical industry.

Acknowledgement

The authors are thankful to the Department of Chemistry, University of Colombo for giving permission to use the Gaussian 09 program package with a desktop computer having Linux Mint 16 Cinnamon, 64-bit operating system. The authors are also grateful to Dr. Madhuranga Rathnayake at the University of Sydney, Australia for his guidance and sharing his expertise in Computational Chemistry.

References

- [1] Brewer, M.S. Natural Antioxidants: Sources, Compounds, Mechanisms of Action, and Potential Applications. *Compr. Rev. Food Sci. Food Saf.* **2011**, *10*, 221-247. <https://doi.org/10.1111/j.1541-4337.2011.00156.x>
- [2] Nimse, S.B.; Pal, D. Free Radicals, Natural Antioxidants, and their Reaction Mechanisms. *RSC Adv.* **2015**, *5*, 27986-28006. <https://doi.org/10.1039/C4RA13315C>
- [3] Shahidi, F.; Zhong, Y. Novel Antioxidants in Food Quality Preservation and Health Promotion. *Eur. J. Lipid Sci. Technol.* **2010**, *112*, 930-940. <https://doi.org/10.1002/ejlt.201000044>
- [4] Dizdaroglu, M. Oxidative Damage to DNA in Mammalian Chromatin. *Mutat. Res. DNAGing.* **1992**, *275*, 331-342. [https://doi.org/10.1016/0921-8734\(92\)90036-O](https://doi.org/10.1016/0921-8734(92)90036-O)
- [5] Grzesik, M.; Napařo, K.; Bartosz, G.; Sadowska-Bartosz, I. Antioxidant Properties of Catechins: Comparison with Other Antioxidants. *Food Chem.* **2018**, *241*, 480-492. <https://doi.org/10.1016/j.foodchem.2017.08.117>
- [6] Lambert, J.D.; Yang, C.S. Mechanisms of Cancer Prevention by Tea Constituents. *J. Nutr.* **2003**, *133*, 3262S-3267S. <https://doi.org/10.1093/jn/133.10.3262S>
- [7] Chung, J.E.; Kurisawa, M.; Kim, Y.-J.; Uyama, H.; Kobayashi, S. Amplification of Antioxidant Activity of Catechin by Polycondensation with Acetaldehyde. *Biomacromolecules* **2004**, *5*, 113-118. <https://doi.org/10.1021/bm0342436>
- [8] Sabetkar, M.; Low, S.Y.; Bradley, N.J.; Jacobs, M.; Naseem, K.M.; Richard Bruckdorfer, K. The Nitration of Platelet Vasodilator Stimulated Phosphoprotein Following Exposure to Low Concentrations of Hydrogen Peroxide. *Platelets* **2008**, *19*, 282-292. <https://doi.org/10.1080/09537100801915142>
- [9] Chacko, S.M.; Thambi, P.T.; Kuttan, R.; Nishigaki, I. Beneficial Effects of Green Tea: A Literature Review. *Chinese Med.* **2010**, *5*, 13. <https://doi.org/10.1186/1749-8546-5-13>
- [10] Yokozawa, T.; Nakagawa, T.; Lee, K. I.; Cho, E.J. Effects of Green Tea Tannin on Cisplatin-induced Nephropathy in LLC-PK1 Cells and Rats. *J. Pharm. Pharmacol.* **1999**, *51*, 1325-1331. <https://doi.org/10.1211/0022357991776912>
- [11] Škorňa, P.; Rimarćik, J.; Poliak, P.; Lukeš, V.; Klein, E. Thermodynamic Study of Vitamin B6 Antioxidant Potential. *Comput. Theor. Chem.* **2016**, *1077*, 32-38. <https://doi.org/10.1016/j.comptc.2015.10.010>
- [12] Pandithavidana, D.R.; Jayawardana, S.B. Comparative Study of Antioxidant Potential of Selected Dietary Vitamins; Computational Insights. *Molecules* **2019**, *24*, 1646-1654. <https://doi.org/10.3390/molecules24091646>
- [13] Borgohain, R.; Guha, A.K.; Pratihari, S.; Handique, J.G. Antioxidant Activity of Some Phenolic Aldehydes and Their Diamine Derivatives: A DFT Study. *Comput. Theor. Chem.* **2015**, *1060*, 17-23. <https://doi.org/10.1016/j.comptc.2015.02.014>
- [14] Mazzone, G.; Russo, N.; Toscano, M. Antioxidant Properties Comparative Study of Natural Hydroxycinnamic Acids and Structurally Modified Derivatives: Computational Insights. *Comput. Theor. Chem.* **2016**, *1077*, 39-47. <https://doi.org/10.1016/j.comptc.2015.10.011>
- [15] Klein, E.; Lukeš, V.; Ilćin, M. DFT/B3LYP Study of Tocopherols and Chromans Antioxidant Action Energetics. *Chem. Phys.* **2007**, *336*, 51-57. <https://doi.org/10.1016/j.chemphys.2007.05.007>
- [16] Klein, E.; Lukeš, V. DFT/B3LYP Study of the Substituent Effect on the Reaction Enthalpies of the Individual Steps of Single Electron Transfer-Proton Transfer and Sequential Proton Loss Electron Transfer Mechanisms of Phenols Antioxidant Action. *J. Phys. Chem. A* **2006**, *110*, 12312-12320. <https://doi.org/10.1021/jp063468i>
- [17] Kamat, J.P.; Devasagayam, T.P.A. Nicotinamide (Vitamin B₃) as an Effective Antioxidant Against Oxidative Damage in Rat Brain Mitochondria. *Redox Rep.* **1999**, *4*, 179-184. <https://doi.org/10.1179/135100099101534882>
- [18] Orenha, R.P.; Galembeck, S.E. Molecular Orbitals of NO, NO⁺, and NO⁻: A Computational Quantum Chemistry Experiment. *J. Chem. Educ.* **2014**, *91*, 1064-1069. <https://doi.org/10.1021/ed400618j>
- [19] Rajan, V.K.; Muraliedharan, K. A Computational Investigation on the Structure, Global Parameters and Antioxidant Capacity of a Polyphenol, Gallic Acid. *Food Chem.* **2017**, *220*, 93-99. <https://doi.org/10.1016/j.foodchem.2016.09.178>
- [20] Mendoza-Wilson, A.M.; Glossman-Mitnik, D. Theoretical Study of the Molecular Properties and Chemical Reactivity of (+)-Catechin and (-)-Epicatechin Related to Their Antioxidant Ability. *J. Mol. Struct.: THEOCHEM* **2006**, *761*, 97-106. <https://doi.org/10.1016/j.theochem.2006.01.001>
- [21] Wang, J.; Tang H.; Hou, B.; Zhang, P.; Wang, Q.; Zhang, B.-L.; Huang, Y.-W.; Wang, Y.; Xiang, Z.-M.; Zi, C.-T. *et al.* Synthesis, Antioxidant Activity, and Density Functional Theory Study of Catechin Derivatives. *RSC Adv.* **2017**, *7*, 54136-54141. <https://doi.org/10.1039/C7RA11496F>
- [22] Mennucci, B.; Cammi, R. *Continuum Solvation Models in Chemical Physics: From Theory to Applications*; John Wiley & Sons, Ltd: Chichester, UK, 2007.
- [23] Mazzone, G.; Malaj, N.; Russo, N.; Toscano, M. Density Functional Study of the Antioxidant Activity of Some Recently Synthesized Resveratrol Analogues. *Food Chem.* **2013**, *141*, 2017-2024. <https://doi.org/10.1016/j.foodchem.2013.05.071>
- [24] Mazzone, G.; Malaj, N.; Galano, A.; Russo, N.; Toscano M. Antioxidant Properties of Several Coumarin-Chalcone Hybrids from Theoretical Insights. *RSC Adv.* **2015**, *5*, 565-575. <https://doi.org/10.1039/C4RA11733F>
- [25] Anitha, S.; Krishnan, S.; Senthilkumar, K.; Sasirekha, V. Theoretical Investigation on the Structure and Antioxidant Activity of (+) Catechin and (-) Epicatechin – a Comparative Study. *Mol. Phys.* **2020**, *118*, 1745917. <https://doi.org/10.1080/00268976.2020.1745917>
- [26] Wang, A.; Lu, Y.; Du, X.; Shi, P.; Zhang, H. A Theoretical Study on the Antioxidant Activity of Uralenol and Neouralenol Scavenging Two Radicals. *Struct. Chem.* **2018**, *29*, 1067-1075. <https://doi.org/10.1007/s11224-018-1090-8>

[27] Parr, R.G.; von Szentpály, L.; Liu, S.: Electrophilicity Index. *J. Am. Chem. Soc.* **1999**, *121*, 1922-1924.

<https://doi.org/10.1021/ja983494x>

[28] Ardjani, A.T.E.; Mekelleche, S.M. Analysis of the Antioxidant Activity of 4-(5-Chloro-2-hydroxyphenylamino)-4-oxobut-2-enoic Acid Derivatives Using Quantum-Chemistry Descriptors and Molecular Docking. *J. Mol. Model.* **2016**, *22*, 302.

<https://doi.org/10.1007/s00894-016-3160-4>

[29] Vorobyova, V.; Shakun, A.; Chygyrynets, O.; Skiba, M.; Zaporozhets, J. Antioxidant Activity and Phytochemical Screening of the Apricot Cake Extract: Experimental and Theoretical Studies. *Chem. Chem. Technol.* **2020**, *14*, 372-379.

<https://doi.org/10.23939/chcht14.03.372>

[30] Kamat, J.P.; Devasagayam, T.P.A. Nicotinamide (Vitamin B₃) as an Effective Antioxidant against Oxidative Damage in Rat Brain Mitochondria. *Redox Rep.* **1999**, *4*, 179-184.

<https://doi.org/10.1179/135100099101534882>

Received: November 16, 2020 / Revised: December 03, 2020 /
Accepted: January 22, 2021

ДОСЛІДЖЕННЯ ТА ПОРІВНЯННЯ АНТИОКСИДАНТНОГО ПОТЕНЦІАЛУ КАТЕХІНІВ, ЯКІ МІСТЯТЬСЯ В ЗЕЛЕНОМУ ЧАЇ: DFT ДОСЛІДЖЕННЯ

Анотація. Для порівняння антиоксидантного потенціалу чотирьох основних катехінів, які містяться в зеленому чаї, застосовано DFT розрахунки. Детально досліджено термодинамічні параметри, пов'язані з трьома ключовими механізмами первинної антиоксидантної дії. Також досліджено молекулярні орбітальні енергії, абсолютну твердість, електронегативність та індекс електрофільності, які сприяють поглинанню радикалів. Потенціал поглинання радикалів кожної гідроксильної групи цих поліфенольних антиоксидантів досліджено незалежно.

Ключові слова: DFT, катехіни, перенос атома водню, одноелектронний перенос–протонний перенос, послідовна втрата протона–електронний перенос, ВЗМО-НВМО.