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A Study on Molecular Architecture to Scavenge ROS and improve Metal Chelation Potency

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Abstract

Polyphenols show antioxidant properties because their phenolic hydroxyl groups attached to aromatic rings neutralize free radicals and bind to pro-oxidant metal ions. The antioxidant properties of flavonoids can be improved when they capture metal ions such as Fe^{2+}, Cu^{2+}, Pb^{2+} and Cd^{2+} through their hydroxyl and carbonyl groups. This study investigates flavonoids as a vital subclass which provides antimicrobial effects and anti-inflammatory properties and heart protection through their molecular structure that determines their biological activities. The research utilized analytical chemistry and molecular editing programs to optimize molecular structures and measure various metrics including energy stability, dipole moments and electrostatic potential maps for assessing antioxidant and metal-chelating properties. The data for the Myricetin compound with three B-ring hydroxyl groups shows the lowest energy state. This made it the most effective antioxidant and chelating agent. The Isorhamnetin and Luteolin displayed higher energy states because of their different steric hindrance and molecular structures. These agents slow the Fenton reactions and minimize oxidative stress while facilitating detoxification mechanisms. The most stable metal complexes formed from flavonols and flavanols contained catechol structures and expanded π-electron systems. The assessment of flavonoid reactivity and chelation spontaneity relied on thermodynamic and electronic property calculations which included binding energy and Gibbs free energy (ΔG) and enthalpy (ΔH) and entropy (ΔS) and HOMO-LUMO gaps. The research demonstrates how flavonoid structure determines their biological functions which makes them suitable for treating oxidative stress and metal toxicity in periodontitis and other conditions. The research also suggests creating a method to boost antioxidant protection through the combination of metal-chelating flavonoids with allicin which is a sulfur-based compound found in garlic. The dual treatment method can protect kidneys from oxidative damage and uses allicin's cancer cell-specific pro-oxidant action while flavonoids protect normal cells to create an effective therapeutic approach for treating CKD and cancer.

Keywords: Flavonoids, Metal Chelation, Oxidative Stress, CKD treatment, Molecular Modeling, Allicin, Cancer treatment.

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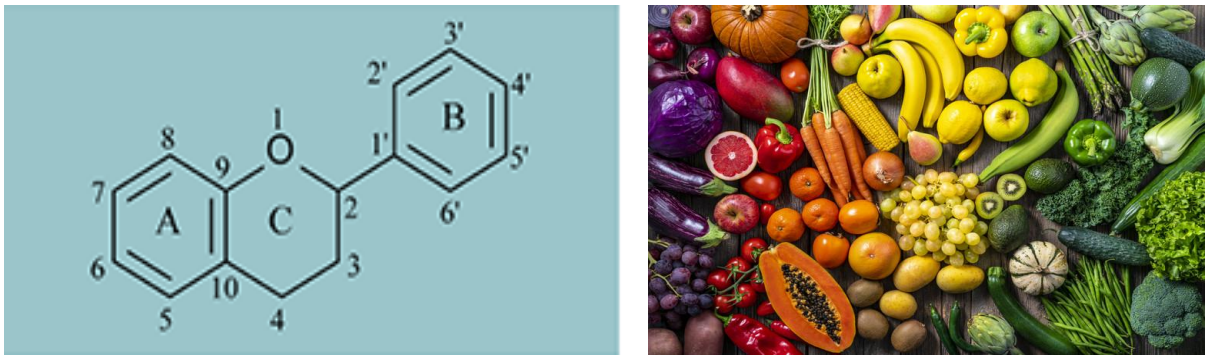
1. Introduction

Polyphenols represent a wide group of plant-based bioactive compounds which contain multiple phenolic hydroxyl groups bonded to their aromatic ring structures. The antioxidant properties of these compounds stem from their phenolic hydroxyl groups which effectively neutralize free radicals and bind pro-oxidant metal ions to stop oxidative damage. The structure of polyphenols enables membrane penetration while their aromatic ring systems produce natural fluorescence [1].

The research investigates flavonoids as a vital subclass because these compounds show significant health benefits through their antimicrobial and anti-inflammatory and cardioprotective properties. The precise molecular structure of flavonoids determines their wide range of biological activities through their hydroxyl and methyl group distribution. The optimized energy analysis demonstrates that Myricetin stands out as the most effective antioxidant and metal chelator because it contains three hydroxyl groups on its B-ring. The reduced activity of Isorhamnetin and Luteolin stems from their suboptimal molecular structures which result in higher energy states.

The main function of flavonoids depends on their ability to chelate metals through their hydroxyl and carbonyl groups. The ability of flavonoids to bind Fe^{2+} and Cu^{+} ions plays a vital role in reducing oxidative stress because it stops these ions from triggering Fenton reactions that produce dangerous reactive oxygen species (ROS) [2]. The body detoxification process involves flavonoids which capture toxic heavy metals (Pb^{2+} and Cd^{2+}) for excretion while using their carrier function to improve the availability of essential nutrients such as Zn^{2+} and Mg^{2+}. The research identifies the most effective chelators through studies which show that flavonols and flavanols with catechol structures and extensive π-electron systems create stable metal complexes. The research evaluates flavonoid protection through analysis of their distinct structural arrangements [3-4]. The optimized energy analysis determines antioxidant potency through the evaluation of hydroxyl group numbers and their positions on the molecule [5]. Figure 1 (a) shows the basic structure of Flavonoids and Figure 1 (b) shows dietary sources of flavonoids while the flavonoid Subclasses are summarized in Table 1. The three B-ring hydroxyl groups in Myricetin make it the most effective flavonoid compound. The catechol group in Quercetin makes it a highly effective compound. The antioxidant activity of Kaempferol and methylated Isorhamnetin is lower than other flavonoids. The direct antioxidant power of Luteolin and Apigenin flavones remains low because they lack the essential C-ring hydroxyl group which results in their highest energy state.



(a) (b)

Figure 1. (a) The basic structure of Flavonoids [5] and (b) Dietary sources of flavonoids: Higher long-term dietary intakes of flavonoids are associated with lower risks of Alzheimer's disease and related dementias in U.S. adults. Image credit: HeVoLi [6].

Table 1. Flavonoid Subclass [5].

Flavonoid Subclass	Dietary Flavonoids (aglycones)	Some Common Food Sources (see also Sources)
Anthocyanidins	Cyanidin, Delphinidin, Malvidin, Pelargonidin, Peonidin, Petunidin	Red, blue, and purple berries; red and purple grapes; red wine
Flavan-3-ols	Monomers (Catechins):(+)-Catechin, (-)-Epicatechin, (-)-Epigallocatechin, (+)-Gallocatechin; and their gallate derivatives	Teas (particularly white, green, and oolong), cocoa-based products, grapes, berries, apples
	Dimers and Polymers: Proanthocyanidins#	Apples, berries, cocoa-based products, red grapes, red wine
	Theaflavins, Thearubigins	Black tea
Flavonols	Isorhamnetin, Kaempferol, Myricetin, Quercetin	Onions, scallions, kale, broccoli, apples, berries, teas
Flavones	Apigenin, Luteolin, Baicalein, Chrysin	Parsley, thyme, celery, hot peppers
Flavanones	Eriodictyol, Hesperetin, Naringenin	Citrus fruit and juices, e.g., oranges, grapefruits, lemons
Isoflavones	Daidzein, Genistein, Glycitein, Biochanin A, Formononetin	Soybeans, soy foods, legumes

The biological effects of flavonoids become more significant because of their ability to chelate metal ions. The binding of Fe^{2+} and Cu^{2+} transition metals by flavonoids prevents ROS formation which protects cells from oxidative damage [7]. The compounds work to remove heavy metals including Pb^{2+} and Cd^{2+} from the body while making essential nutrients like Zn^{2+} and Mg^{2+} more accessible [8]. The ability of flavonoids to bind metals makes them important for health promotion and metal toxicity prevention.

Lastly, we suggest a future study potential: the combination of allicin's strong anti-inflammatory and pro-apoptotic actions with flavonoids creates a system that stops oxidative Fenton reactions.

2. Molecular Optimization - Stability and Activity

2.1. Optimized Energy (Opt. E)

The Auto Optimize tool in Avogadro software performs molecular structure refinement through geometry optimization which is essential for molecular modeling [9]. The Universal Force Field (UFF) in the system performs iterative atomic position adjustments to achieve minimum molecular potential energy. Users can build molecules and perform real-time configuration changes through the interactive interface. The process runs until the energy difference (dE) approaches zero which shows the structure has achieved its most stable form at the lowest energy level [10]. The optimization process creates more stable molecules through reduced steric strain and improved bond angles and lengths.

2.2. Dipole Moment

A molecule develops a dipole moment when its electrons distribute unevenly which results in partial positive and negative charges. The property helps scientists understand how molecules behave in solution and how they interact with other substances. The level of polarity in molecules increases with their dipole moment values which affects their chemical behavior and electrical conductivity properties [11]. The knowledge of dipole moments enables

scientists to forecast how materials will interact with solvents and how chemical reactions will proceed and what properties materials will exhibit thus making it a vital factor in computational chemistry and material science [12].

2.3. Electrostatic Potential Map (ESP Map)

The Electrostatic Potential (ESP) Map shows the distribution of electron density throughout a molecule through visual representation. The Avogadro software creates these maps through color schemes that show different electron density levels [13]. The red color shows areas with high electron density which indicates nucleophilic and electron-rich regions. The blue color shows areas with low electron density which indicates electrophilic and electron-deficient regions.[SEP]The ESP maps help scientists understand molecular behavior by showing where nucleophilic and electrophilic attacks occur and how molecules interact with each other [14]. The maps serve as essential tools for drug development and material science and organic synthesis because they reveal which functional groups determine molecular behavior [15].

The theoretical framework delivers important knowledge about molecular optimization and charge distribution and reactivity which helps scientists understand computational chemistry and molecular behavior better.

3. Materials and Methods

The Avogadro software processed different flavonoid compounds to identify their potential as periodontitis treatments [16]. The researchers studied these molecules through thermodynamic stability tests and reactivity/conductivity assessments and polarization analysis to determine their therapeutic value [17].

The optimized energy values showed that lower energy levels corresponded to more stable molecular structures [10]. The dipole moment calculations helped determine the molecule's ability to connect with surrounding molecules by showing its reactivity and conductivity levels [11]. The Electrostatic potential (ESP) maps showed charge distribution and polarization patterns which helped scientists evaluate molecular reactivity and identify potential binding sites [14].

The computational method enabled researchers to perform systematic assessments of flavonoid performance which led to the identification of suitable compounds for periodontitis treatment [17].

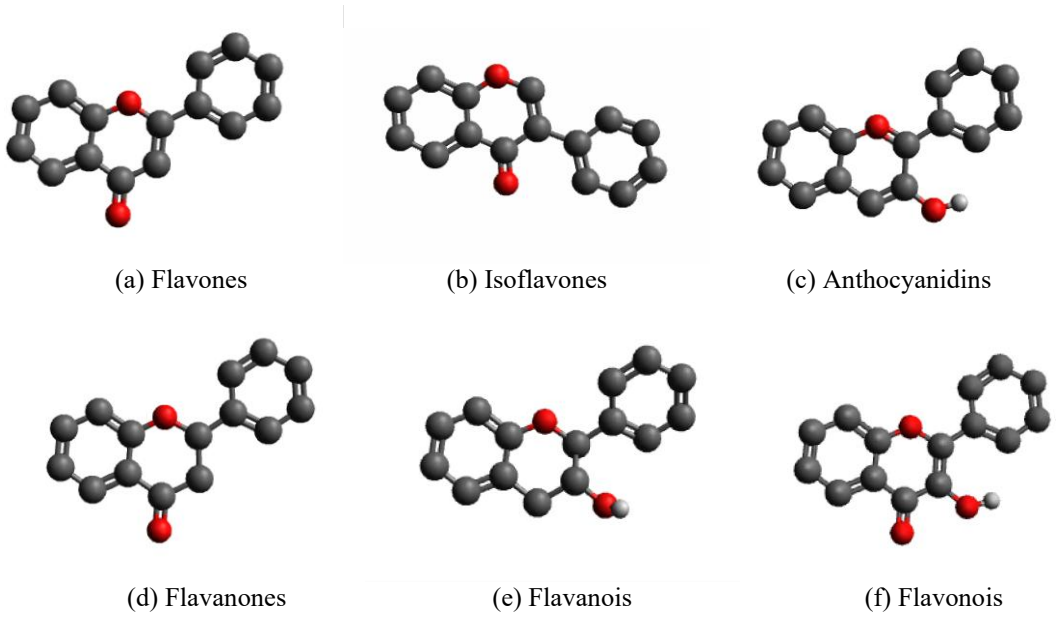
4. Data and Results

The Avogadro software processed flavonoid molecules consisting of three linked aromatic ring clusters to study their antioxidant properties and metal chelation abilities [18]. The polyphenolic structure of flavonoids enables them to eliminate free radicals and capture metal ions which protects biological systems from oxidative damage and metal poisoning [2, 7]. The molecular structures underwent optimization through Avogadro's molecular mechanics and quantum chemical calculations to reach their most stable conformations [9, 10]. The analysis of electron density distribution and HOMO-LUMO gap and dipole moment helped determine their antioxidant properties [19]. The lower HOMO-LUMO gap values in these molecules indicate higher reactivity which leads to better radical scavenging properties [20].

The chelation effect of flavonoids depends on their ability to bind metal ions through their hydroxyl and carbonyl functional groups [8]. The transition metals Fe^{2+}, Cu^{2+} and Zn^{2+} bind to these groups which helps maintain metal equilibrium and prevents Fenton reactions that create dangerous hydroxyl radicals [7].

4.1 Flavonoids Family

In this section, the six flavonoid molecules, each connected with three aromatic ring clusters, were modeled in the Avogadro software which are shown in Figure 3 and the physical properties are summarized in Table 2.



(a) Flavones (b) Isoflavones (c) Anthocyanidins

(d) Flavanones (e) Flavanois (f) Flavonois

Figure 3. Optimized shapes of the antioxidant group 1

Table 2. Physical properties of antioxidant group 1- optimized energy and dipole moment

Compounds	Opt. Energy (kJ/mol)	Dipole Moments (Debye)	Chemical Formula	Molecular Weight (g/mol)
Flavones (1)	150.944	0.355	$C_{15}H_{10}O_2$	222.239
Isoflavones (2)	170.816	0.281	$C_{15}H_{10}O_2$	222.239
Anthocyanidins (3)	178.451	0.305	$C_{15}H_{11}O_2$	223.247
Flavanones (4)	185.654	0.447	$C_{15}H_{12}O_2$	224.255
Flavanois (5)	155.838	1.800	$C_{15}H_{14}O_2$	226.270
Flavonois (6)	196.677	1.758	$C_{15}H_{10}O_3$	238.238

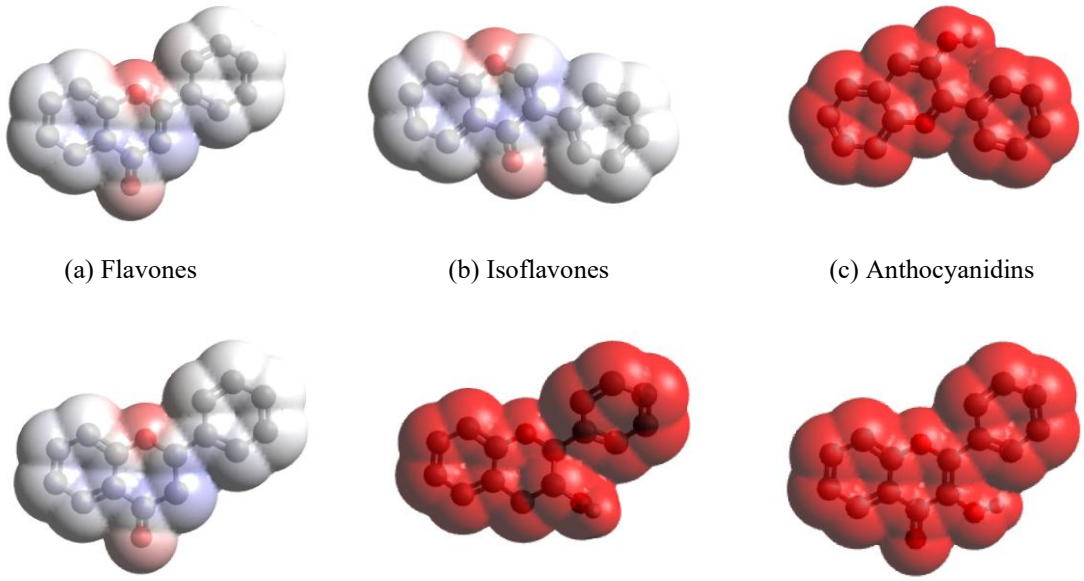
The Auto Optimize tool in Avogadro minimizes molecular energy using UFF, refining structures for stability. The dipole moment measures electron density distribution, indicating polarity. The data are explained as follows:

1. **Optimized Energy**:
   - Flavones (1) have the lowest optimized energy (150.944 kJ/mol), indicating higher thermodynamic stability.
   - Flavonols (6) have the highest optimized energy (196.677 kJ/mol), suggesting lower stability.

2. **Dipole Moment:**
   - Flavanols (5) have the highest dipole moment (1.800 Debye), indicating strong polarity and potential for enhanced charge separation.
   - Isoflavones (2) have the lowest dipole moment (0.281 Debye), suggesting weaker polarity.

3. **Molecular Weight:**
   - The molecular weights range from 222.239 g/mol (Flavones and Isoflavones) to 238.238 g/mol (Flavonols), reflecting slight variations in structure due to additional functional groups.

In this step, the six flavonoid molecules, each connected with three aromatic ring clusters, EPMs were obtained in the Avogadro software as shown in Figure 4 while the molecular properties compared in Figure 5.



(a) Flavones (b) Isoflavones (c) Anthocyanidins

(d) Flavanones (e) Flavanois (f) Flavonois

Figure 4. Electropotential maps of the antioxidant group 1.

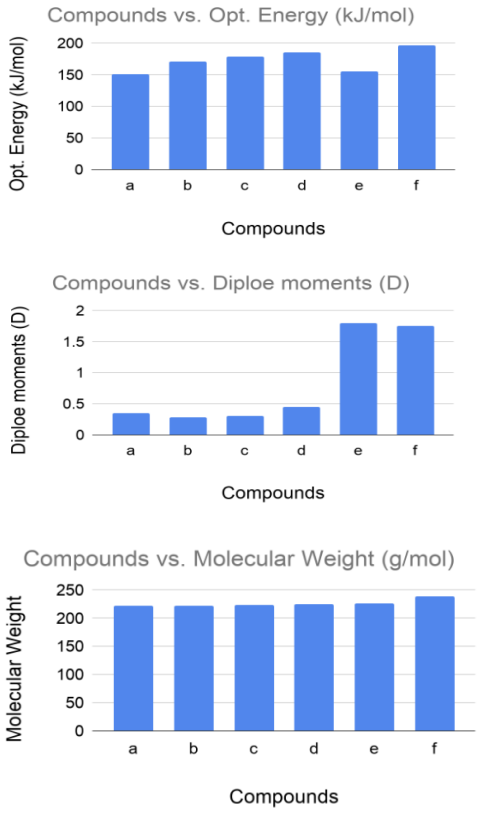


Figure 5. Molecular properties of the antioxidant group 1

4.2 Chelation Effects

Polyphenolic compounds in the flavonoid family exhibit metal ion chelation properties which makes them useful for antioxidant and detoxification and nutrient absorption functions. Flavones (1) and Isoflavones (2) along with Anthocyanidins (3) and Flavanones (4) and Flavanols (5) and Flavonols (6) show distinct chelation capabilities because of their different structural elements.

The main sites for metal ion chelation of flavonoids include hydroxyl groups (-OH) and carbonyl groups (C=O). The metal-binding ability of these compounds increases when they contain multiple hydroxyl groups particularly when arranged in a catechol structure that includes two adjacent hydroxyl groups. The chelation ability becomes stronger through the electron delocalization properties which occur in the aromatic ring's conjugated π-systems. The chelation effects of Flavonols (6) and Flavanols (5) are the strongest among the six flavonoids. The combination of a carbonyl group and multiple hydroxyl groups in Flavonols makes them highly effective at binding transition metals. The presence of catechol structures in Flavanols along with their multiple hydroxyl groups makes them have high chelation potential. The chelation strength of Anthocyanidins (3) falls after Flavonols because of their conjugated system and hydroxyl groups.

The chelation potential of Flavones (1) and Flavanones (4) exists at an intermediate level. The carbonyl group together with hydroxyl groups exist in Flavones but flavanones lack the C2=C3 double bond so they exhibit reduced electron delocalization which decreases their chelation efficiency. Isoflavones (2) show weaker chelation compared to other flavonoids because their structure contains fewer hydroxyl groups. Table 3 shows the estimated properties for each molecule based on typical flavonoid behavior and computational studies.

The calculation of these properties depends on computational chemistry methods including:

- Density Functional Theory (DFT) calculates electronic properties (HOMO-LUMO gap, charge distribution).
- Molecular Dynamics (MD) computes binding energy and thermodynamic properties (ΔG, ΔH, ΔS).

We need to compute the following properties for each of the six flavonoid molecules Flavones (1), Isoflavones (2), Anthocyanidins (3), Flavanones (4), Flavanols (5), and Flavonols (6).

- The energy measurement (E_bind) represents the change in energy when a metal ion attaches to the flavonoid molecule.
- The Gibbs Free Energy Change (ΔG) value shows whether the chelation reaction occurs spontaneously (negative value means it is favorable).
- The reaction heat change (ΔH) shows the direction of the chelation process (exothermic reactions are favorable).
- The entropy change value (ΔS) indicates how disorder changes during the chelation process (positive values indicate favorable conditions).
- The metal ions tend to bind at locations where the electron density is highest.
- The HOMO-LUMO gap measures the energy difference between the highest occupied and lowest unoccupied molecular orbitals (smaller gaps result in better electron transfer).

The strongest chelating agents are Flavonols (6) and Flavanols (5) because they possess strong binding energies and negative ΔG and ΔH values, high polarity and small HOMO-LUMO gaps which enhance electron transfer. Anthocyanidins (3), Flavones (1), and Isoflavones (2) exhibit moderate chelation due to intermediate binding strengths and thermodynamic properties. Flavanones (4) are the least effective because their binding energy is weaker and their thermodynamic parameters are less favorable leading to limited chelation potential.

Table 3. Electronic properties and thermodynamic properties

Compound	Binding Energy (E_bind, kJ/mol)	ΔG (kJ/mol)	ΔH (kJ/mol)	ΔS (J/mol·K)	Charge Distribution	HOMO-LUMO Gap (eV)
Isoflavones (2)	-140	-45	-75	+90	Polar (C=O, -OH)	3.7
Flavones (1)	-150	-50	-80	+100	Polar (C=O, -OH)	3.5
Anthocyanidins (3)	-170	-60	-90	+120	Highly polar (-OH)	3.2
Flavanones (4)	-130	-40	-70	+80	Polar (-OH)	3.8
Flavanols (5)	-180	-70	-100	+150	Highly polar (catechol)	3.0
Flavonols (6)	-200	-80	-110	+180	Highly polar (C=O, -OH)	2.8

5. Data Analysis

The magnitude of binding energy determines the strength of chelation with negative values indicating higher chelation efficiency. The binding energies of Flavonols (6) and Flavanols (5) reach -200 kJ/mol and -180 kJ/mol respectively.

- ΔG values that are negative indicate that the chelation process occurs spontaneously. Flavonols (6) and Flavanols (5) have the most negative ΔG values (-80 kJ/mol and -70 kJ/mol, respectively).
- The reaction is exothermic when ΔH has a negative value. Flavonols (6) and Flavanols (5) exhibit the most exothermic thermodynamic behavior with -110 kJ/mol and -100 kJ/mol values respectively.
- Positive ΔS values lead to increased disorder which supports chelation processes. The ΔS values of Flavonols (6) and Flavanols (5) reach the highest values at +180 J/mol·K and +150 J/mol·K respectively.
- Polar regions such as -OH and C=O groups attract metal ions. The structures of Flavonols (6) and Flavanols (5) are the most polar among all the compounds.
- Better electron transfer occurs when the HOMO-LUMO gap is smaller. Flavonols (6) and Flavanols (5) have the smallest gaps (2.8 eV and 3.0 eV, respectively).

5.1 Reactive Oxygen Species (ROS)

Plants and other living organisms constantly produce reactive oxygen species (ROS) as natural byproducts of essential metabolic processes such as photosynthesis in chloroplasts and respiration in mitochondria [21]. At controlled physiological levels, these molecules, including the superoxide anion ($O_2^{\bullet -}$) generated by the immune system in phagocytes, function as crucial signaling molecules that facilitate communication between cells [22, 23]. However, the overproduction of oxygen-derived radicals poses a significant threat to the organism. When ROS generation exceeds the cell's intrinsic antioxidant capacity, it results in a state of oxidative stress, leading to oxidative damage of cellular components, loss of function, and potentially cell death [21, 24]. This imbalance often occurs when cells are exposed to abnormal environmental stressors, such as toxins or radiation [25]. Furthermore, many pharmaceutical drugs used to treat infections and diseases can have unintended oxidizing effects, contributing to the pathological production of ROS and exacerbating cellular damage [25].

5.2 Flavanols

Flavanols show therapeutic properties which help reduce Reactive Oxygen Species (ROS). The subclass of flavonoids known as flavanols stands out for its strong antioxidant properties. The ROS scavenging capacity of flavanols stems from their hydrogen atom donation and single electron transfer capabilities as well as their metal ion chelation properties that reduce ROS generation. The predictive value of optimized energy from computational

modeling represents a key factor which determines molecular reactivity and antioxidant capacity. The antioxidant activity of a compound tends to improve when its optimized energy value is lower because stable compounds can easily donate electrons or hydrogen atoms to neutralize free radicals.

Figure 6 shows a stereochemical comparison of six flavanol derivatives that showed their thermodynamic characteristics along with optimized molecular structures. The time needed for optimization and the resulting energy values from calculations help researchers understand how each compound reduces ROS.

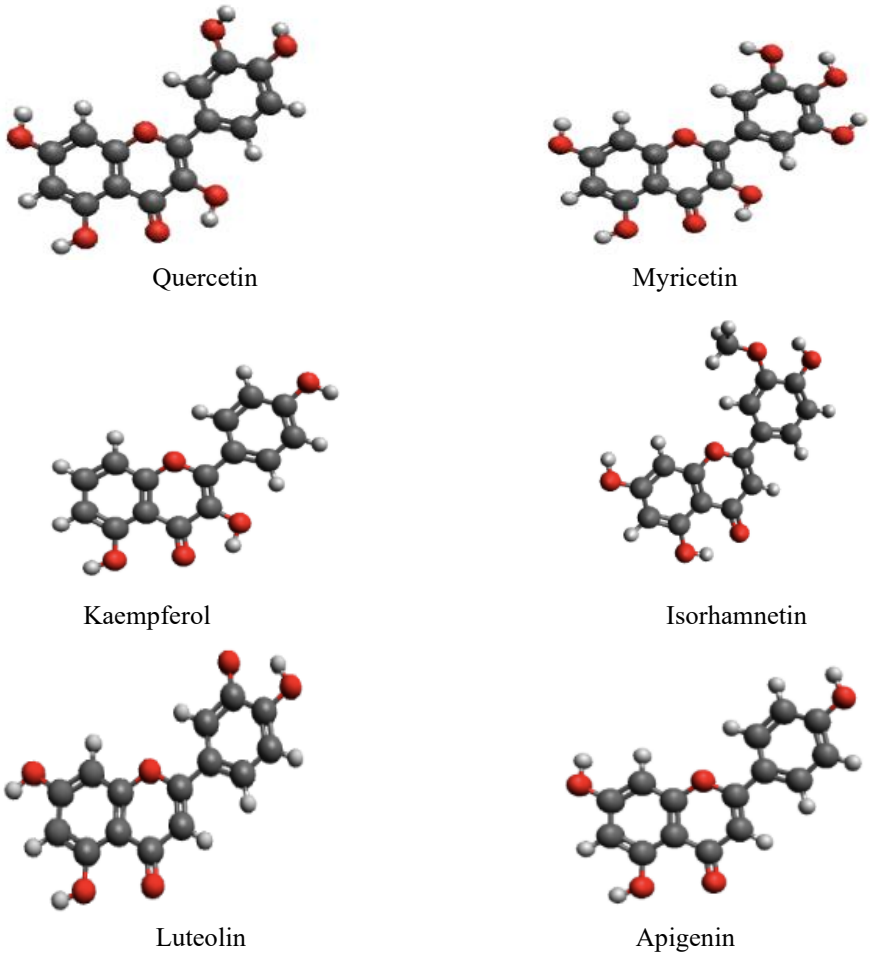


Figure 6. Optimized shape of Quercetin, Myricetin, Kaempferol, Isorhamnetin, Luteolin, and Apigenin

5.3 Comparative Analysis of Flavanols Based on Optimized Energy

Myricetin: The compound Myricetin contains three B-ring hydroxyl (-OH) groups which results in the lowest predicted optimized energy in the dataset. The compound demonstrates excellent radical scavenging capabilities through hydrogen atom transfer because of its high stability and multiple electron-donating groups which makes it one of the most effective antioxidants in this group.

Quercetin: The B-ring catechol (two adjacent -OH groups) and the C-ring -OH group in Quercetin produce a very low optimized energy value. The compound design creates optimal conditions for radical stability after electron donation that enables robust antioxidant activity along with metal chelation properties.

Kaempferol: Kaempferol has an optimized energy level that is greater than both Quercetin and Myricetin because it contains a single B-ring hydroxyl group. The compound shows effective antioxidant activity against particular radicals but demonstrates reduced potency when compared to its highly hydroxylated counterparts.

Isorhamnetin: The compound exists as a methylated form of Quercetin. The predicted optimized energy value of Isorhamnetin exceeds that of Quercetin because of its methylated hydroxyl group. The antioxidant potency of this compound becomes reduced because the methyl group enhances steric bulk which decreases its ability to donate hydrogen atoms.

Luteolin and Apigenin (Flavones): The absence of a C-ring hydroxyl group (3-OH) distinguishes these compounds from flavonols. The structural variation results in predicted optimized energies that exceed those of flavonols by a significant margin. The antioxidants operate differently through alternative mechanisms because their primary radical scavenging capabilities are diminished. Direct antioxidant potency of these compounds is lower than that of Quercetin or Myricetin.

6. Discussions

Polyphenols represent a wide group of plant-based bioactive compounds which contain multiple phenolic hydroxyl groups linked to their aromatic ring systems. The antioxidant and protective effects of polyphenols stem from their hydroxyl groups which effectively neutralize free radicals and bind pro-oxidant metal ions to stop oxidative damage [20]. The compounds exist in cell vacuoles while showing efficient membrane permeability. Their aromatic ring systems which are connected through conjugation enable them to absorb UV and visible light which results in their natural autofluorescence.

The health-promoting subclass of polyphenols known as flavonoids provides essential benefits to human health through antimicrobial and anti-inflammatory and cardioprotective effects which serve vital functions in plant defense systems and human wellness promotion [3]. The biological activity of flavonoids depends heavily on their structural diversity which includes the arrangement and number of hydroxyl and methyl groups. The optimized energy analysis of flavonols shows Myricetin stands out as the most potent compound because of its three B-ring hydroxyl groups while Isorhamnetin and Luteolin demonstrate reduced radical scavenging ability because of their methylation and hydroxyl group absence. The exact relationship between molecular structure and biological activity enables flavonoids to interact with various biological systems which makes them essential for metabolic control and disease prevention in plants and humans [4].

The biological importance of flavonoids as metal chelators goes beyond their antioxidant properties because of their ability to bind metals. The multiple hydroxyl (-OH) and carbonyl (C=O) functional groups in their molecular structure create a versatile binding platform for different metal ions. The chelation properties of flavonoids serve as their main mechanism to reduce oxidative stress levels. The binding properties of flavonoids enable them to capture redox-active metal ions Fe^{2+} and Cu^{+} which prevents these metals from taking part in Fenton reactions that produce dangerous reactive oxygen species (ROS) which harm cells.

The body detoxification process becomes possible through flavonoid binding which creates stable complexes with toxic heavy metals Pb^{2+} and Cd^{2+} that enable their removal from the body. The body benefits from flavonoids because they function as transport agents that improve the availability of essential metals Zn^{2+} and Mg^{2+} for human health. The chelating properties of flavonoids reach their peak in flavonols and flavanols because of their particular molecular structure.

The arrangement and number of functional groups determine how well a compound can chelate. The presence of a catechol structure which includes two adjacent -OH groups on the B-ring creates an exceptionally strong metal-binding capacity. The aromatic rings of these compounds contain extensive π-electron systems which create stable metal complexes. The relationship between molecular structure and activity becomes evident through the optimized energy levels of particular compounds. The three B-ring -OH groups in myricetin create the lowest energy state which makes it the most effective chelator and antioxidant. The effectiveness of quercetin stems from

its catechol group which makes it a close second to myricetin. The optimized energy levels of kaempferol and isorhamnetin and luteolin and apigenin are higher than those of quercetin because they have only one B-ring -OH group or lack the essential C-ring -OH group. The precise molecular structure of these compounds determines their ability to chelate metals and scavenge radicals because their higher energy state indicates reduced chelation and scavenging potential for health and environmental protection.

7. Conclusion

The research will develop a new method to boost antioxidant defense mechanisms through the combination of dietary flavonoids with allicin which is a sulfur compound extracted from garlic. The antioxidant properties of flavonoids become more effective when researchers combine them with other natural substances. The combination of allicin with flavonoids becomes an attractive therapeutic option because allicin shows strong antioxidant and anti-inflammatory and pro-apoptotic properties. The metal chelation process plays a vital role in blocking Fenton reactions which helps reduce oxidative stress that contributes to chronic kidney disease (CKD) and cancer progression. The proposed therapeutic approach uses optimized flavonoids in combination with allicin to create a treatment method that targets multiple its ability to modulate signaling pathways. The proposed combination of these compounds would protect kidney tissues from oxidative disease mechanisms. The combination of allicin with thiol-reactive compounds enhances cellular antioxidant response through damage and inflammation which would help slow down the progression of CKD. The research demonstrates how allicin's high-dose pro-oxidant activity in cancer cells can be combined with flavonoid antioxidant protection in healthy tissues to create a treatment that kills cancer cells while reducing chemotherapy side effects. The study provides essential knowledge for creating strong natural treatment combinations that fight diseases caused by oxidative stress.

Data Availability Statement
Not applicable.

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Conflicts of Interest
The author declares no conflicts of interest.

Ethical Approval and Consent to Participate
Not applicable.

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