Structure-activity relations of rosmarinic acid derivatives for the amyloid β aggregation inhibition and antioxidant properties

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<td>作成者: TAGUCHI, Riho, HATAYAMA, Koki, TAKAHASHI, Tomohito, HAYASHI, Takafumi, SATO, Yuki, SATO, Daisuke, OTA, Kiminori, NAKANO, Hiroto, SEKI, Chigusa, ENDO, Yasuyuki, TOKURAKU, Kiyotaka, UWAI, Koji</td>
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Structure–activity relations of rosmarinic acid derivatives for the amyloid β aggregation inhibition and antioxidant properties.

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Graphical Abstract

Critical functional groups in rosmarinic acid derivatives for Aβ aggregation inhibitory activity

Highlights

• 25 rosmarinic acid derivatives with anti-AD properties have been synthesized
• In vitro anti-Aβ aggregation, antioxidant properties, XOD inhibition were evaluated
• Structure–activity relations were discussed
• Compounds 16d and 19 are the most potent amyloid aggregation inhibitors
Abstract
Amyloid-β aggregation inhibitors are expected to be therapeutic or prophylactic agents for Alzheimer’s disease. Rosmarinic acid, which is one of the main aggregation inhibitors derived from Lamiaceae, was employed as a lead compound and its 25 derivatives were synthesized. In this study, the structure–activity relations of rosmarinic acid derivatives for the amyloid-β aggregation inhibitory effect (MSHTS assay), antioxidant properties, and xanthine oxidase inhibition were evaluated. Among the tested compounds, compounds 16d and 19 were found to be the most potent amyloid aggregation inhibitors. The SAR revealed that the necessity of the presence of the phenolic hydroxyl on one side of the molecule as well as the lipophilicity of the entire molecule. The importance of these structural properties was also supported by docking simulations.

Key words: Alzheimer’s disease, structure–activity relationship, inhibitor, rosmarinic acid, amyloid-beta, aggregation

1. Introduction
Alzheimer’s disease (AD) is one of the most common neurodegenerative diseases in late adult life and accounts for 70 percent of dementia. The onset of AD leads to the progressive loss of learning ability and mental, behavioral and functional decline [1]. The number of the patients with AD is estimated to reach 150 million by 2050 due to the acceleration of demographic aging [2]. Choline esterase inhibitors (donepezil, galanthamine, rivastigmine) and an N-methyl-D-aspartic acid receptor antagonist (memantine) are now used for the medical treatment of AD. However, these treatments are used only for delaying the progression of AD [3]. Thus, the development of a fundamental AD treatment is becoming increasingly urgent.

In the AD patient’s brain, the amyloid β (Aβ) protein is cut out of the amyloid precursor protein by the action of β-secretase and γ-secretase, is oligomerized, and becomes fibrotic by aggregation, finally forming senile plaques. This insoluble Aβ fiber is thought to induce neuronal death and cognitive dysfunction as a result of the deposition of senile plaques formed from the Aβ fiber in the vascular wall in the brain (the Aβ cascade hypothesis) [4]. Thus, Aβ aggregation inhibitors are expected to be therapeutic or prophylactic agents for AD.

Previously, a series of bisphenols [5], alkaloids [6], polyphenols [7], and peptides with C-terminal motif of Aβ [8] have been reported as the target compound Aβ aggregation inhibitors. On the other hand, based on the demonstration of the correlation between the Aβ aggregation inhibitory activity and antioxidant activity [9], it appears that the study of the Aβ aggregation inhibitors based on the polyphenols can make a significant contribution to the development of AD treatment. For example, the relation between the structure of curcumin, an active polyphenol, and the Aβ aggregation inhibitory activity has been well-studied [10,11].
Recently, we established a novel method for the evaluation of the Aβ aggregation inhibitory activity called the “microliter scale high-throughput screening (MSHTS) system” [12], and showed that the results obtained by this method were comparable to those obtained using Thioflavin-T (ThT) assay, which is the standard method for the evaluation of the Aβ aggregation inhibitory activity. Using this new method, we found that of 52 tested spices, a member of Lamiaceae showed the strongest activity, and rosmarinic acid (1) isolated from Satureja hortensis (one of the species of Lamiaceae family) was a main Aβ aggregation inhibitor. Additionally, it was reported that rosmarinic acid led to an improvement in the cognitive function in Tg2576 mice [13].

Rosmarinic acid (1) is also reported to show a high antioxidant activity [14]. Aβ-induced neuronal toxicity is regulated by the reactive oxygen species (ROS) generation that assists subsequent Aβ aggregation and speeds up the AD progression [15, 16] and antioxidants with catechol moiety showed to inhibit Aβ aggregation [17]. Thus, the relations between antioxidant activity and Aβ aggregation in the viewpoint of the compound structure is also of interest.

Herein, we studied the structure–activity relations between the structures of rosmarinic acid derivatives and the Aβ aggregation inhibitory activity and also performed simulations of the docking of these derivatives with the Aβ monomer. Moreover, their potency as scavengers of the superoxide radical, produced by xanthine oxidase (XOD) (enzymatic method) and by the diphenyl picrylhydrazyl (DPPH) assay (chemical method) were also studied.

2. Results and Discussion

2.1 Chemistry

Rosmarinic acid (1) has five key structural groups: a carboxy group, two phenol hydroxy groups, an unsaturated C–C bond, an alkoxy group, and an ester moiety (Fig. 1).
Initially, we directed our attention to the carboxy group and prepared two analogs of rosmarinic acid, rosmarinic amide (2)[18,19] and caffeic acid 3,4-dihydroxyphenethyl ester (12c)[20,21,22] (Scheme 1). Rosmarinic amide (2) was synthesized using Won’s protocol [18,19]. However, since the yield obtained by this approach was quite poor, we attempted to synthesize it via an acid chloride prepared with oxalyl chloride and NH₃ [23]. We attempted to prepare the caffeic acid 3,4-dihydroxyphenethyl ester (12c) by the direct Mitsunobu reaction of 3,4-dihydroxyphenethyl alcohol with caffeic acid (3); however, the target yield was only 4.8%. Examination of the structure of 3,4-dihydroxyphenethyl alcohol shows that it possesses several alcohol groups that can function as a nucleophile in basic conditions. Additionally, the electrophilicity of the carboxy moiety of caffeic acid (3) was decreased because of the conjugation of the phenolic hydroxyls. Therefore, we planned to protect the phenolic hydroxyls in caffeic acid (3) and 3,4-dihydroxyphenethyl alcohol. The phenolic hydroxyls of 3,4-dihydroxyphenethyl alcohol were protected with tert-butyldimethylsilyl (TBS) groups, and the caffeic acid (3) phenolic hydroxyls were protected with the 2-nitrobenzensulfonyl (Ns) groups. NsO-groups exhibit an electron-withdrawing nature, and therefore the electrophilicity of the conjugated carboxy moiety was expected to be increased. In particular, caffeic acid (3) was esterified by Fischer’s ester synthesis and the phenolic hydroxyls were protected by the Ns groups, with acid hydrolysis of the ester giving carboxylic acid (6a). The coupling partner, the protected 3,4-dihydroxyphenethyl alcohol (10a), was synthesized from 3,4-dihydroxyphenylacetic acid (7). Allyl esterification of carboxylic acid (7) followed by TBS-protection of phenolic hydroxyls and reduction of the ester with lithium aluminum hydride gave alcohol (10a). Condensation of the protected carboxylic acid (6a) and alcohol (10a) followed by the deprotection of Ns and TBS groups gave caffeic acid 3,4-dihydroxyphenethyl ester (12c).
Scheme 1. a) oxalyl chloride, NH₃, THF, rt, 19.5 h; b) EDCI, DMAP, MeOH; c) NsCl, Et₃N, CH₃CN; d) AcOH, 0.5 M HCl; e) EDCI, DMAP, Allyl alcohol; f) TBSCl, imidazole, DMF; g) LiAlH₄, THF; h) DEAD, TPP, THF, 0 °C → rt; i) PhSH, Cs₂CO₃, CH₃CN, 0 °C → rt; j) TBAF, THF, 0 °C → rt; k) H₂, Pd/C; l) DIAD, TPP, THF, 0 °C → rt

6a: R₁ = ONs
b: R₁ = H

10a: R₂ = OTBS
b: R₂ = OCH₃
c: R₂ = H

11a: R₁ = R₂ = H
b: R₁ = H, R₂ = OTBS
c: R₁ = ONs, R₂ = OCH₃
d: R₁ = ONs, R₂ = OTBS
e: R₁ = ONs, R₂ = H

11c, e

11d

11b

12a: R₁ = H, R₂ = OH
b: R₁ = OH, R₂ = OCH₃
c: R₁ = OH, R₂ = OH
d: R₁ = OH, R₂ = H

13a: R₁ = R₂ = H
b: R₁ = H, R₂ = OH
c: R₁ = OH, R₂ = OH
d: R₁ = H, R₂ = OCH₃
Similarly, to investigate the effect of phenolic hydroxyls and unsaturated C–C bond, a series of carboxylic acids (6a, b) and alcohols (10a-c) were coupled, followed by deprotection to give esters (11a, 12a-d). Unsaturated C–C bond in compound 11a, 12a, and 12c were reduced by catalytic hydrogenation to give compounds 13a-c.

Caffeic acid alkyl esters (16a-g, i, k) were also prepared by the condensation reaction of caffeic acid (3) and corresponding alkyl alcohols (15a-i) to study the effect of the aromatic ring on one side of the molecule (Scheme 2). Additionally, to confirm the effect of the ester group, ketone (19)[24] and amide (21a, b) were synthesized.

Scheme 2. a) DIAD, PPh3, THF, r.t.; b) PhSH, Cs2CO3, CH3CN, 0 °C → rt; c) TBAF, THF, 0 °C → rt; d) pyrrolidine, AcOH, THF, reflux; e) iPr2NEt, DMAP, EDCI, DMF, rt

2.2 Aβ(1-42) aggregation inhibitory activity

Elucidation of the essential structural factor for the inhibition of the Aβ(1-42) aggregation inhibitory activity would lead to the development of more effective inhibitors and would obtain vital information for the elucidation of the inhibitory action mechanism. Therefore, we directed our attention to the five structural features of rosmarinic acid (1) that show the strong activity: carboxy group, phenolic hydroxyls, unsaturated C–C bond, alkoxy group, and ester moiety. We synthesized various derivatives and evaluated their Aβ(1-42) aggregation inhibitory activities (Table 1).
First, we studied the effect of carboxy group on the activity. Compared to the Aβ(1-42) aggregation inhibitory activity of rosmarinic acid (1, EC₅₀ = 20.3 µM), amide (2) and compound 12c, which eliminate the carboxylic acid, showed almost equivalent activities of 21.9 µM and 20.6 µM, respectively. This suggested that the carboxy group did not affect the activity.

Next, the effect of phenolic hydroxyls was evaluated. Compared to the EC₅₀ value of compound 12c (20.6 µM), the EC₅₀ values of compound 12a, for which the phenolic hydroxyls on the carboxylic side were eliminated, and compound 12d, for which the phenolic hydroxyls on the

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<th>CLogP</th>
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<td>274</td>
<td>4.03</td>
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alkoxy moiety were eliminated, were 7.95 and 8.41 µM, respectively. Thus, the activity was enhanced by the elimination of phenolic hydroxyls. However, interestingly, compound 11a, for which the phenolic hydroxyls on both sides were deleted, exhibited the activity of 1,040 µM. These results suggested that lateral phenolic hydroxyls on odd side were important for the activity.

Similarly, compound 12b, for which the phenolic hydroxyls were masked with methoxyl functional groups, showed significantly lower activity (EC$_{50}$ = 39.5 µM) than compound 12c. In line with the results described above, in contrast to the activity of compound 13a (EC$_{50}$ = 4,536 µM), for which the phenolic hydroxyls on both sides were eliminated, compound 13d, for which hydroxyl groups on the alkoxy side were masked with methoxy groups, showed a higher activity (EC$_{50}$ = 274 µM). Moreover, compound 13b, for which the hydroxyls were present on the alkoxy side, showed significantly higher activity (EC$_{50}$ = 5.93 µM) than compound 13d. These results suggested that not only the existence of polar functional groups but also the functional groups that could make hydrogen bonds or were hydrophilic affected the activity.

To evaluate the effect of the aromatic rings on the activity, we tested the compounds for which one phenyl ring was substituted with an alkyl chain. Compound 16 (EC$_{50}$ = 5.13 µM) for which the alkyl chain was as long as that of compound 12d showed almost the same activity as the parent compound. This result suggested that the existence of the aromatic ring was not important for the activity; rather, the presence of a hydrophobic group in the alkoxy moiety was vital.

Next, the effect of the alcohol substitution for catechol was investigated. The activity of compound 16k (EC$_{50}$ = 54.8 µM) with alcohol in alkoxy moiety was significantly impaired when compared to compound 12c with catechol. This result suggested that catechol was important for the activity, seemingly contradicting the interpretation of the results for 16e and 12d. Nevertheless, this discrepancy may be resolved by considering the fact that it is easier for compound 12c with the catechol moiety to make a hydrophilic bond via π–π stacking than for compound 16k with the Aβ(1–42) peptide.

We then investigated the effect of the alkyl chain length on the alkoxy moiety. The activity of caffeic acid alkyl esters was enhanced in accordance with the elongation of alkyl chain in the 1 to 5 range. The activity was maximum at the C5-ester (16d, EC$_{50}$ = 2.58 µM) and then decreased gradually. Thus, the length of the alkyl side chain (length of the lipophilic moiety) was important for the activity.

The effect of the unsaturated C–C bond in the linker that connected the two catechols was investigated. Comparison of compounds 11a, 12a, and c with the α,β-unsaturated ester and compounds 13a, b, and c with the saturated ester showed that the activities of the corresponding compounds were almost equivalent. This suggested that the unsaturated bond in the linker was not important for the activity.
The mode of connection linking the two catechols was then investigated. The activity of compounds \textbf{21a} (69.0 µM) and \textbf{21b} (11.4 µM) that connected the carboxyl and alkoxy group \textit{via} the amide were significantly impaired compared to the corresponding ester compounds \textbf{12c} and \textbf{16d}. On the other hand, the activity of ketone \textbf{19} (2.82 µM) was almost equivalent to that of compound \textbf{16d}. These results suggested that the resonance effect of amide nitrogen may fix the conformation and affect the activity.

\textbf{2.3 Kinetics of Aβ(1-42) aggregation in the existence of inhibitors}

The aggregation of Aβ(1-42) was followed by an increase in the standard deviation (SD) value of fluorescence intensities owing to the variability of QDAβ(1-42) in coaggregates. The representative aggregation curve on Fig. 2 demonstrates a good fit between the Boltzmann equation used for fitting and experimental data that is confirmed by plotting the residuals versus time in the inset. Parallel measurements at 37°C with 30 µM Aβ(1-42) showed good reproducibility of the maximal SD of fluorescence 6.77 and the aggregation growth rate ($k = 0.533 \text{ min}^{-1}$) in the control (without inhibitor). The lag time of the reaction was 4.44 min. By contrast, by the addition of 20.3 µM (EC$_{50}$) of rosmarinic acid (\textbf{1}) or 5.13 µM of C6-ester (\textbf{16e}), the maximal SD of fluorescence was 3.40 and 3.68 and the aggregation growth rate ($k = 0.508$ and $0.190 \text{ min}^{-1}$), without any change in the lag-period of the reaction, respectively. These results demonstrated that the existence of rosmarinic acid (\textbf{1}) did not affect the aggregation rate but reduced the total amount of aggregates and extended the lag time (5.58 min). On the contrary, the existence of C6-ester (\textbf{16e}) reduced the aggregation rate, the total amount of aggregates and lag-period (1.10 min). Thus, it was suggested that the mechanism of inhibition of rosmarinic acid (\textbf{1}) and C6-ester (\textbf{16e}) was different.
2.4 \( \text{CLogP} \) values of rosmarinic acid derivatives

For exhibiting central nervous system (CNS) activity, compounds need to pass through the blood–brain barrier (BBB). One of the factors relevant to success of CNS drugs is lipophilicity. In the common logarithm of octanol/water partition coefficient (cLogP) that showed the degree of calculated lipophilicity from chemical structure, CNS drugs showed significantly higher value than that of peripheral drugs. The average cLogP value of existing CNS drugs was 3.43 [25]. ClogP values of the compounds were shown in Table 1. On comparing the \( \text{EC}_{50} \) values and cLogP values, the active compounds (12a, 12d, 13b, 16d, 16e, 19) tended to show suitable cLogP values (3.30, 3.30, 3.11, 3.32, 3.85, 3.53, respectively). Thus, these compounds were expected to show the A\( \beta \)(1-42) aggregation inhibitory activity also \textit{in vivo}.

2.5 Docking simulation between rosmarinic acid derivatives and A\( \beta \)(1-42) monomer

Clarifying the binding site of rosmarinic acid derivatives on A\( \beta \)(1-42), we would be able to presume important amino acid residues in A\( \beta \)(1-42) for aggregation and to design more effective inhibitors. Thus, docking simulation between A\( \beta \)(1-42) monomer (PDB: 1Z0Q)[26] and 25 of rosmarinic derivatives were performed using AutoDock [27,28].
The results were shown in S-1. Concerning the lowest energy cluster in 50 calculated clusters for each derivatives, the derivatives could be classified in three groups by the activity and binding site: 1) derivatives with EC$_{50}$ $\leq$ 10 µM tended to bind to amide NH and carboxylate in Ala42 with their phenolic hydroxyls via hydrogen bond (Fig. 3A); 2) derivatives with 10 µM < EC$_{50}$ < 100 µM tended to bind to amide carbonyl oxygen in Ala30 with their phenolic hydroxyl via hydrogen bond (Fig. 3B); 3) derivatives with EC$_{50}$ $\geq$ 100 µM tended to bind to side chain in His14 with their ester functional group via hydrogen bond (Fig. 3C). Concerning this result that higher effective derivatives tended to bind Ala42 with the report that Aβ(1-42) might aggregate faster than Aβ(1-40) [29], it was suggested that Ala42 played an important role in their aggregation process.
Fig. 3. Docking model between Aβ(1-42) monomer and rosmarinic acid derivatives calculated by AutoDock.

2.6 XOD inhibitory effect
Among the 25 tested rosmarinic acid derivatives (Table 2), 10 displayed XOD inhibitory potencies. Compounds 2, 12c, 12d, 14, 16b, 16c, 16d, 16j, 16k, 19 showed better potencies. A detailed evaluation of the chemical structures of the active rosmarinic acid derivatives showed a general requirement for two or three hydrophilic moieties for better potency with compounds 2, 12c, 16i, k being the potent inhibitors in the tested compounds. Additionally, the activity of series of caffeic acid alkyl esters were depending on the length of alkyl side chain. Most potent derivatives were compound 16c and 16d (butyl and pentyl ester).

Table 2. XOD inhibitory and DPPH radical-scavenging activity

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<th>DPPH radical scavenging activity (%)</th>
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<tr>
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<tr>
<td>2</td>
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The antioxidant activities of rosmarinic acid derivatives were based on their interaction with the 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical (Table 2) [30]. As expected, the results suggested that compounds without catechol type aromatic ring did not exhibit significant antioxidant activities, as it is shown by the low inhibition percentages at very high concentrations (<10% at 500 µM concentration). Thus, the significant radical scavenging activity of the tested compounds can be explained by the presence of catechol phenolic hydroxyls that are important in the scavenging action of ROS species. However, we could not find a specific structural feature of caffeic acid-type compounds is present in all the compounds, and caffeic acid itself has significant antioxidant activity.

### 2.7 Antioxidant ability (DPPH radical scavenging assay)

The antioxidant activities of rosmarinic acid derivatives were based on their interaction with the 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical (Table 2) [30]. As expected, the results suggested that compounds without catechol type aromatic ring did not exhibit significant antioxidant activities, as it is shown by the low inhibition percentages at very high concentrations (<10% at 500 µM concentration). Thus, the significant radical scavenging activity of the tested compounds can be explained by the presence of catechol phenolic hydroxyls that are important in the scavenging action of ROS species. However, we could not find a specific structural feature of caffeic acid-type compounds is present in all the compounds, and caffeic acid itself has significant antioxidant activity.

### 3. Conclusions

In summary, rosmarinic acid derivatives were synthesized and their Aβ(1-42) aggregation inhibitory activity was investigated. After detailed consideration of structure–activity relations, it was suggested that the structural requirement of rosmarinic acid derivatives to express the activity was phenolic hydroxyls in unilateral side and the length of the alkoxy moiety. Additionally, normally ester functional group was labile intravitality to hydrolases to metabolite to carboxylic acid and alcohol. Thus, the fact that compound 19 showed the equivalent activity to compound 16d gave us hope to develop in vivo experiment.

Docking simulation of Aβ(1-42) monomer and rosmarinic acid derivatives by AutoDock suggested that potent Aβ aggregation inhibitor tend to dock the Ala42, Ile31, and Val39. This result suggested the importance of C-terminal of Aβ(1-42) for the aggregation. XOD inhibitory effect was affected by the compounds lipophilicity. DPPH antioxidation activity was found in the derivatives with catechol type moiety.

The present study sheds new light on the properties of this interesting group of compounds. Further studies are now underway in our laboratory, including a search for more effective analogs and
studies exploring the mechanism of action of these compounds.

4. Experimental Part

4.1 MSHTS system

The EC_{50} values of compounds were determined by a modified MSHTS system [12]. More specifically, various concentrations of rosmarinic acid derivatives, 30 nM QD-labeled Aβ(1-42) (QDAβ(1-42)), and 30 µM Aβ(1-42) in PBS containing 5% EtOH and 3% DMSO were incubated in a 1536-well plate at 37°C for 24 h, and the formed QDAβ(1-42)–Aβ(1-42) coaggregates in each well were observed by an inverted fluorescence microscope equipped with a color CCD camera. SD values of fluorescence intensities of 10,000 pixels (100 × 100 pixels: 167 × 167 mm) in the central region of each well were measured by the ImageJ software. The SD values, which were approximately proportional to the amount of aggregates, were plotted against the concentrations of added rosmarinic acid derivatives to establish an inhibition curve. EC_{50} values were estimated from the inhibition curve using the EC_{50} shift by the Prism global fitting software.

4.2 Data analysis and kinetic formation

The kinetics of Aβ(1-42) aggregation could be described as sigmoid curves, and aggregation parameters were determined by fitting the plot of the SD values of fluorescence intensities versus time in the Boltzmann equation.

\[ SD = \frac{SD_{max} - SD_{min}}{1 - \exp((t - t_{50})k)} \]

where SD_{min} is the initial SD level, SD_{max} is SD of maximal aggregation level, t_{50} is the time when fluorescence reaches half maximal, and k is the rate constant of aggregate formation. The lag time is calculated as

\[ lag = t_{50} - \frac{2}{k} \]

4.2 Molecular Docking [27,28]

AutoDock, PytonMolecularViewer, and Cygwin were used for the docking simulation of interactions between Aβ(1-42) and inhibitors. ChemBioDraw was used for the preparation of chemical structure data of inhibitors for the docking simulation. ChemBio3D was used for the calculation of molecular dynamics and the most stable conformation of inhibitors. The results of docking simulation were analyzed by using Discovery Studio. PDB: 1Z0Q [26] was used for the docking simulation with Aβ(1-42) aggregation inhibitors. The compounds used for the docking simulation were 25 rosmarinic acid derivatives.

4.3 XOD inhibition test
35 µL of phosphate buffer (100 mM, pH=7.6), 50 µL of a solution of allopurinol and rosmarinic acid derivatives in DMSO, 30 µL of a solution of XOD (from butter milk, Oriental Yeast Co., Ltd.) in phosphate buffer were added in 96 well micro plate. Then, 60 µL of a solution of 500 µM xanthine in phosphate buffer was added to the solution at rt. After 8 min, 1N HClaq was added and absorbance at 290 nm was measured. The inhibition rate (%) was calculated according to the following equation:

\[
\text{Inhibition rate} \ (\%) = \left[ 1 - \frac{\text{Abs}(\text{XOD inhibition activity}) - \text{Abs}(\text{sample})}{\text{Abs}(\text{XOD activity}) - \text{Abs}(\text{Blank})} \right] \times 100
\]

4.4 1,1-Diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay

40 µL of 1 mM DPPH solution and 150 µL of EtOH were added to 96 well plate. Then, 10 µL of 2 mM or 10 mM of edaravone, or rosmarinic acid derivatives in DMSO was added at rt. And then, the absorbance at 517 nm was continuously measured for 60 min, and radical trapping capacity was calculated with the data at 20 min following the equation:

\[
\text{DPPH radical trapping capacity} \ (\%) = \left\{ \frac{\text{Abs}(\text{20 min}) - \text{Abs}(\text{sample})}{\text{Abs}(\text{DPPH}) - \text{Abs}(\text{blank})} \right\} \times 100
\]

4.5 Typical reaction procedure for the construction of rosmarinic acid derivatives (12c)

4.5.1 Methyl caffeate (4)

A mixture of caffeic acid (309.2 mg, 1.72 mmol), EDCI (385.3 mg, 2.01 mmol) and DMAP (22.1 mg, 0.181 mmol) in methyl alcohol (400 µL) was stirred at 60°C for 13 h. The resulting mixture was quenched with 2N HCl and extracted with AcOEt. The combined organic phases were washed with sat. NaHCO₃, dried over anhydrous magnesium sulfate, and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (MeOH–CHCl₃) (1:5 v/v) to give a title compound (287.5 mg, 86%) as a white solid. Mp: 161°C–164°C [31], IR ṽ: 3489, 3303, 2955, 2925, 1679, 1601, 1519 cm⁻¹. ¹H-NMR (500 MHz, acetone-d₆) δ: 7.51 (d, 1H, J = 16.1 Hz), 7.13 (d, 1H, J = 2.0 Hz), 7.02 (dd, 1H, J = 2.0, 8.0 Hz), 6.84 (d, 1H, J = 8.0 Hz), 6.26 (d, 1H, J = 16.1 Hz), 3.69 (s, 3H). ¹³C-NMR (125 MHz, acetone-d₆) δ: 167.0, 147.9, 145.5, 144.9, 126.8, 121.7, 115.6, 114.5, 114.4. High-resolution MS calcd. for C₁₀H₁₀O₄ (M⁺): 194.0579. Found: 194.0585. All spectral data agreed with previously reported data [32].

4.5.2 Methyl 3,4-bis[[2-(nitrophenyl)sulfonyl]oxy] cinnamate (5)

To a solution of 4 (194.6 mg, 1.00 mmol) in CH₃CN (2.2 mL) were added triethylamine (0.63 mL, 4.50 mmol) and 2-nitrobenzenesulfonyl chloride (487.1 mg, 2.30 mmol) at 0°C. The mixture was stirred at 0°C for 0.5 h. The reaction mixture was quenched with 2M HCl and extracted with
CH₂Cl₂. The combined organic phases were washed with brine, dried over anhydrous magnesium sulfate and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (AcOEt–n-hexane) (3:2 v/v) to give a title compound (562.9 mg, 99%) as white solid. Mp: 118°C–123°C, IR ν: 3099, 1714, 1542, 1390, 1191, 850, 814, 693 cm⁻¹. ¹H-NMR (500 MHz, CDCl₃) δ: 8.03 (dd, 2H, J = 1.3, 7.9 Hz), 7.89–7.84 (m, 2H), 7.81–7.74 (m, 4H), 7.58 (d, 1H, J = 16.0 Hz), 7.48 (dd, 1H, J = 2.0, 8.5 Hz), 7.45 (d, 1H, J = 2.0 Hz), 7.36 (d, 1H, J = 8.5 Hz), 6.39 (d, 1H, J = 16.0 Hz), 3.82 (s, 3H).

13C NMR (125 MHz, CDCl₃) δ: 166.4, 148.2, 148.1, 141.6, 141.4, 141.1, 136.0, 135.1, 132.5, 131.6, 128.2, 128.1, 127.8, 124.9, 123.4, 120.7, 51.8.

4.5.3 3,4-Bis[(2-nitrophenyl)sulfonyl]oxycinnamic acid (6)
To a solution of 5 (113.3 mg, 0.20 mmol) in AcOH (3.1 mL) was added 0.5M HCl aq (3.1 mL) at 0°C. The mixture was stirred at 85°C for 37 h. The reaction mixture was added H₂O and extracted with AcOEt. The combined organic phases were washed with brine, dried over anhydrous magnesium sulfate and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (MeOH–CHCl₃) (1:20 v/v) to give a title compound (110.4 mg, 99%) as white solid. Mp: 182°C–186°C, IR ν: 3104, 1687, 1544, 1378, 1355, 1180, 1124, 851, 821, 721 cm⁻¹. ¹H NMR (500 MHz, acetone-d₆): δ 8.12–8.04 (m, 6H), 7.97–7.92 (m, 2H), 7.79 (dd, 1H, J = 2.1, 8.6 Hz), 7.67 (d, 1H, J = 2.1 Hz), 7.64 (d, 1H, J = 16.0 Hz), 7.41 (d, 1H, J = 8.6 Hz), 6.55 (d, 1H, J = 16.0 Hz). ¹³C NMR (125 MHz, acetone-d₆) δ: 167.1, 148.49, 148.77, 142.3, 142.0, 141.8, 137.3, 136.1, 133.44, 133.40, 132.1, 128.8, 128.0, 125.8, 125.5, 125.3, 124.3, 121.9, 78.7. High-resolution MS calcd for C₂₁H₁₄N₂O₁₂S₂ (M⁺): 549.9988. Found: 549.9969.

4.5.4 Allyl (3,4-dihydroxyphenyl)acetate (8)
To a mixture of (3,4-dihydroxyphenyl)acetic acid (7, 1.01 g, 6.02 mmol), EDCI (1.38 g, 7.21 mmol) and DMAP (73.4 mg, 0.60 mmol) was added allyl alcohol (4.5 mL) at room temperature, then heated at 60°C for 2 h. The resulting mixture was quenched with 2N HCl and extracted with AcOEt. The combined organic phases were washed with sat. NaHCO₃, dried over anhydrous magnesium sulfate and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (acetone–n-hexane) (1:5 v/v) to give a title compound (1.11 g, 89%) as yellow oil. IR ν: 3389, 1706, 1606, 1281, 988, 961, 795 cm⁻¹. ¹H NMR (500 MHz, acetone-d₆): δ 6.77 (d, 1H, J = 2.2 Hz), 6.73 (d, 1H, J = 8.2 Hz), 6.59 (dd, 1H, J = 2.2, 8.2 Hz), 5.93–5.85 (m, 1H), 5.24 (dq, 1H, J = 1.6, 17.3 Hz), 5.13 (dq, 1H, J = 1.6, 10.6 Hz), 4.52 (dt, 2H, J = 1.6, 5.5 Hz), 3.47 (s, 2H). ¹³C NMR (125 MHz, acetone-d₆): δ 171.8, 145.6, 144.8, 133.5, 126.7, 121.5, 117.7, 117.1, 115.9, 65.4, 40.8. High-resolution MS calcd for C₁₁H₁₂O₄ (M⁺): 208.0736. Found: 208.0727.
4.5.5 Allyl [3,4-bis(tert-butyldimethylsilyl)oxyphenyl]benezeneacetate (9)
To a solution of compound 8 (1.06 g, 5.11 mmol), TBSCl (1.86 g, 12.3 mmol) and imidazole (1.75 g, 25.7 mmol) in DMF (2.3 mL) was stirred at 0°C for 0.5 h. The reaction mixture was added sat. NH₄Cl and extracted with AcOEt. The combined organic phases were washed with sat. NaHCO₃ and brine, dried over anhydrous magnesium sulfate, and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (AcOEt–n-hexane) (1:20 v/v) to give a title compound (2.16 g, 97%) as colorless oil. IR ν: 2930, 1739, 1228, 905, 836 cm⁻¹. ¹H NMR (500 MHz, CDCl₃): δ 6.79 (d, 1H, J = 2.0 Hz), 6.76 (d, 1H, J = 8.0 Hz), 6.71 (dd, 1H, J = 2.0, 8.0 Hz), 5.91–5.84 (m, 1H), 5.24 (dq, 1H, J = 1.6, 17.2 Hz), 5.18 (dq, 1H, J = 1.3, 10.1 Hz), 4.58 (dt, 2H, J = 1.4, 5.7 Hz), 3.51 (s, 2H), 0.99 (s, 9H), 0.98 (s, 9H), 0.193 (s, 6H), 0.188 (s, 6H).

13C NMR (125 MHz, CDCl₃): δ 171.5, 146.8, 146.1, 132.2, 127.0, 122.3, 122.2, 121.0, 118.2, 65.4, 40.8, 26.0, 18.5, −4.0. High-resolution MS calcd for C₂₃H₄₀O₄Si₂ (M⁺): 436.2466. Found: 436.2463.

4.5.6 2-[3,4-bis(tert-butyldimethylsilyl)oxyphenyl]ethanol (10a)
To a suspension of LiAlH₄ (278.9 mg, 4.90 mmol) in THF (2.00 mL) at 0°C were added compound 9 (2.13 g, 4.88 mmol) in THF (17.5 mL). The reaction mixture was stirred at room temperature for 0.5 h. The mixture was filtered through a Celite pad and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (AcOEt–n-hexane) (1:4 v/v) to give a title compound (1.83 g, 98%) as colorless oil. IR ν: 3326, 2929, 1463, 980, 834 cm⁻¹. ¹H NMR (500 MHz, CDCl₃): δ 6.69 (d, 1H, J = 8.3 Hz), 6.62 (d, 1H, J = 2.0 Hz), 5.18 (dq, 1H, J = 1.3, 10.1 Hz), 4.58 (dt, 2H, J = 1.4, 5.7 Hz), 3.51 (s, 2H), 0.99 (s, 9H), 0.98 (s, 9H), 0.193 (s, 6H), 0.188 (s, 6H). ¹³C NMR (125 MHz, CDCl₃): δ 171.5, 146.8, 146.1, 132.2, 127.0, 122.3, 122.2, 121.0, 118.2, 63.7, 38.5, 25.8, 18.4, −4.1. High-resolution MS calcd for C₂₀H₃₈O₃Si₂ (M⁺): 382.2360. Found: 382.2370.

4.5.7 2-[3,4-bis(tert-butyldimethylsilyl)oxyphenyl]ethyl 3,4-bis[[2-nitrophenyl]sulfonyl]oxy)cinnamate (11d)
To a cooled (0°C) solution of 6a (278.5 mg, 0.51 mmol) and 10a (118.7 mg, 0.31 mmol) in dry THF (1.6 mL) were added PPh₃ (205.5 mg, 0.78 mmol) and DEAD (0.12 mL, 0.78 mmol). The reaction mixture was stirred at room temperature for 21 h. Then, the reaction was worked up by removal of the solvent, redissolved on AcOEt, and extracted with sat. NaHCO₃. The organic phase was washed with brine, dried over anhydrous magnesium sulfate, and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (AcOEt–CHCl₃) (1:30 v/v) to give a title compound (266.1 mg, 94%) as yellow-green solid. Mp: 57°C–61°C, IR ν: 2930, 2858, 1714, 1544, 1471, 1391, 1193, 1128, 903, 827, 781 cm⁻¹. ¹H NMR (500 MHz, CDCl₃): δ
8.04–8.01 (m, 2H), 7.88–7.84 (m, 2H), 7.80–7.73 (m, 4H), 7.55 (d, 1H, \( J = 16.1 \) Hz), 7.47–7.45 (m, 2H), 7.35 (d, 1H, \( J = 8.3 \) Hz), 6.77 (d, 1H, \( J = 8.2 \) Hz), 6.71 (d, 1H, \( J = 2.3 \) Hz), 6.68 (dd, 1H, \( J = 2.3, 8.2 \) Hz), 6.37 (d, 1H, \( J = 16.1 \) Hz), 4.36 (t, 2H, \( J = 7.0 \) Hz), 2.88 (t, 2H, \( J = 7.0 \) Hz), 0.981 (s, 9H), 0.979 (s, 9H), 0.192 (s, 6H), 0.189 (s, 6H).

13C NMR (125 MHz, CDCl3): \( \delta \) 165.8, 148.2, 148.1, 146.5, 245.4, 141.6, 141.3, 141.1, 135.9, 135.1, 132.4, 131.7, 130.6, 128.2, 128.2, 127.8, 124.9, 124.7, 123.4, 121.7, 121.6, 121.0, 120.965.5, 34.3, 25.8, 18.3, −4.2.

4.5.8 2-(3,4-Dihydroxyphenyl)ethyl caffeate (12c)

2-[3,4-bis(tert-butyldimethylsilyloxy)phenyl]ethyl caffeate

To a suspension of Cs2CO3 (1.19 g, 3.55 mmol) in CH3CN (1.90 mL) were added thiophenol (0.18 mL, 1.79 mmol) and 11d (132.2 mg, 0.14 mmol) at 0°C. The mixture was stirred at room temperature for 1.5 h. The reaction was quenched with sat. NH4Cl and extracted with AcOEt. The organic phase was dried over anhydrous magnesium sulfate and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (MeOH–CHCl3) (1:100 v/v) to give a title compound (64.6 mg, 82%) as yellow-green solid. Mp: 130–134°C, IR \( \tilde{\nu} \): 3463, 2929, 1670, 1278, 980, 906, 836, 782 cm\(^{-1}\). 1H NMR (500 MHz, CDCl3): \( \delta \) 7.56 (d, 1H, \( J = 16.1 \) Hz), 7.08 (s, 1H), 7.60 (dd, 1H, \( J = 2.0, 8.0 \) Hz), 6.87 (d, 1H, \( J = 8.0 \) Hz), 6.76 (d, 1H, \( J = 8.0 \) Hz), 6.72 (d, 1H, \( J = 2.0 \) Hz), 6.68 (dd, 1H, \( J = 2.0, 8.0 \) Hz), 6.25 (d, 1H, \( J = 16.1 \) Hz), 4.34 (t, 2H, \( J = 7.0 \) Hz), 2.89 (t, 1H, \( J = 7.0 \) Hz), 0.98 (s, 18H), 0.19 (s, 12H). 13C NMR (125 MHz, CDCl3): \( \delta \) 167.7, 146.6, 146.3, 145.5, 150.0, 143.7, 130.8, 127.5, 122.4, 121.8, 121.7, 121.0, 115.6, 115.5, 114.4, 65.4, 34.5, 25.9, 18.4, −4.1. High-resolution MS calcd for C29H44O6Si2 (M\(^+\)): 544.2677. Found: 544.2688.

To a solution of above compound (60.4 mg, 0.11 mmol) in THF (3.6 mL) were added TBAF (1.1 M in THF) (0.40 mL, 0.44 mmol) at 0°C. The mixture was stirred at room temperature for 2.5 h. Then, the reaction was worked up by removal of the solvent, redissolved on AcOEt, and extracted with H2O. The organic phase was washed with brine, dried over anhydrous magnesium sulfate, and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (MeOH–CHCl3) (1:20 v/v) to give a title compound (29.6 mg, 84%) as white solid. Mp: 118–120°C [28], IR \( \tilde{\nu} \): 3283, 1680, 1394, 1168, 853, 810 cm\(^{-1}\). 1H NMR (500 MHz, MeOH-d4): \( \delta \) 7.51 (d, 1H, \( J = 15.7 \) Hz), 7.02 (d, 1H, \( J = 2.0 \) Hz), 6.92 (dd, 1H, \( J = 2.0, 8.0 \) Hz), 6.76 (d, 1H, \( J = 8.0 \) Hz), 6.70–6.68 (m, 2H), 6.56 (dd, 1H, \( J = 2.0, 8.0 \) Hz), 6.23 (d, 1H, \( J = 15.7 \) Hz), 4.27 (t, 2H, \( J = 7.2 \) Hz), 2.82 (t, 2H, \( J = 7.2 \) Hz). 13C NMR (125 MHz, MeOH-d4): \( \delta \) 169.3, 149.5, 146.9, 146.8, 146.2, 145.0, 144.9, 130.8, 127.7, 123.0, 121.2, 117.0, 116.5, 116.4, 115.1, 66.5, 35.6. High-resolution MS calcd for C17H16O4 (M\(^+\)): 316.0947. Found: 316.0962. All spectral data agreed with previously reported data [33].
4.6 Calculation of cLogP value of tested compounds

CLogP values of synthesized compounds were calculated using ChemBio3D Ultra 12.0 (PerkinElmer).

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