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Koblandy M. Turdybekov[1*], Bibilul B. Rakhimova[2], Almagul S. Makhmutova[2], Yurii V. Gatilov[3], Sergazy M. Adekenov[4]

[1]*Karagandy University of the name of Academician E.A. Buketov, Kazakhstan;*
[2]*Karaganda Medical University, Kazakhstan;*
[3]*N.N. Vorozhtsov Novosibirsk Institute of Organic Chemistry, Russia;*
[4]*JSC "International Research and Production Holding "Phytochemistry", Karaganda, Kazakhstan*
*(*Corresponding author`s e-mail: xray-phyto@yandex.kz)*

Isolation and Spatial Structure of 5,7-Dihydroxy-6,3′,4′-Trimethoxyflavone

The article presents the results of a chemical study of semi-dry wormwood (*Artemisia semiarida*), an endemic plant of Kazakhstan. The amount of extractive substances was obtained by extraction with chloroform from air-dried crushed above-ground part of the plant collected in the vegetative phase. The compound was isolated using a column chromatography method. Silica gel of the KSK brand was used with the ratio of the sum of substances – carrier = 1:10. When the column was eluted with a 13:7 petroleum ether – ethyl acetate mixture, a yellow crystalline substance of the composition $C_{18}H_{16}O_7$ with m.p. 234–237° C was obtained (recrystallization from ethyl acetate). The structure of the obtained compound (5,7-dihydroxy-6,3′,4′-trimethoxyflavone or eupatilin) was established by analysis of IR and NMR spectra. The spatial structure of eupatilin was determined by X-ray diffraction. In the crystal structure of 5,7-dihydroxy-6,3′,4′-trimethoxyflavone the rotation of the phenyl ring relative to the main framework (chromene ring) was found to be only 4.1°. Four conformers with different rotations of the phenyl ring (the torsional angles of O1C2C1′C2′ are 30°, 140°, 210° and 320°, respectively) and small energy barriers (about 8.4 kJ/mol) can be realized in the free state of the molecule.

Keywords: NMR spectroscopy, IR spectroscopy, X-ray analysis, quantum chemistry, *Artemisia semiarida*, endemic, 5,7-dihydroxy-6,3′,4′-trimethoxyflavone, eupatilin, phenolic compounds.

Introduction

Natural phenolic compounds in the form of flavonoids are one of the potential sources of herbal medicines. Flavonoids represent the most numerous class of natural phenolic compounds and due to their structural diversity exhibit high and versatile biological activity with low toxicity [1–3]. The wide range of biological activity of flavonoids is due to the presence in their structure of aromatic and double bonds, keto- and hydroxyl groups in different positions [1–3]. In this regard, in Kazakhstan we continue works on the search for natural biologically active phenolic compounds isolated from plant raw materials, including endemics. In continuation of these works on isolation of polyphenolic compounds from plant raw materials, the chemical composition of semi-dry wormwood (*Artemisia semiarida* (Krasch. & Lavrenko) Filatova), an endemic species of the genus wormwood (*Artemisia* L.) was studied. The aim of this work is to study the stereochemistry of 5,7-dihydroxy-6,3',4'-trimethoxyflavone (eupatilin), a widespread phenolic compound.

Experimental

The melting point was determined on a Boetius heating table. The IR spectrum was recorded on an Avatar 360 instrument (Thermo Nicolet) in KBr tablets. NMR spectra were obtained on a Bruker DRX-300 spectrometer. The X-ray diffraction experiment was carried out on a Bruker APEX-II CCD diffractometer. Column chromatography was carried out on KSK silica gel using mixtures of petroleum ether with ethyl acetate with an increasing (from 0 to 100 %) content of the latter as an eluent. Thin layer chromatography (TLC) was performed using Sorbfil plates, imaging with a 1 % aqueous solution of $KMnO_4$ and a 3 % aqueous solution of $FeCl_3$. The herb of *Artemisia semiarida* was collected in flowering period in May 2009 at Betpakdala desert, Zhanaarka district, Karaganda region and air-dried for 2 weeks.

Isolation of 5,7-dihydroxy-6,3′,4′-trimethoxyflavone (eupatilin) (**1**). Ground plant material (1.6 kg) was extracted with boiled chloroform three times (2 h) with plant : solvent ratio of 1:10. The obtained extracts were combined and filtered through a cellulose filter. The solvent was evaporated in vacuo to obtain a vis-

cous green chloroform extract (105 g) and treated three times with an ethanol : water mixture (2:1) at 70–75 °C (extract : mixture ratio 3:1 *w*/*v*).

The precipitated ballast substances were decanted and the solution was filtered off. The filtrate was extracted with chloroform (4 × 0.5 L) and the chloroform extracts were combined and evaporated to dryness. The dry residue (65 g, yield 4.06 % of air-dry plant) was separated by open-air column chromatography on silica (1235 g, 0.5 ml fraction, KSK, manufacturer LTD QihgdaoHiland Trading CO (China)) using petroleum ether : ethyl acetate (13:7) as an eluent to yield a yellow crystalline substance with m.p. 234–237 °C (ethyl acetate). Molecular formula is $C_{18}H_{16}O_7$; R_f is 2.25 (TLC, silica, petroleum ether : ethyl acetate 1:1).

IR spectrum (KBr, *v*, cm^{-1}): 3069 (OH group), 2949, 2839, 1654 (C=O), 1624, 1600, 1588 (C=C), 1505, 1466, 1440, 1428, 1412, 1376, 1334, 1305, 1269, 1215, 1175, 1149, 1109, 1093, 1044, 1023, 991, 945, 893, 837, 814, 770, 684, 633, 614, 593, 574, 518, 482, 434.

^{1}H NMR spectrum (300 MHz, $CDCl_3/CD_3OD$, δ, ppm, J/Hz): 6.70 (1H, s, H3), 6.67 (1H, s, H8), 7.05 (1H, d, J=2.0, H2′), 7.07 (1H, d, J=2.0, H5′), 7.22 (1H, dd, J=8.0. 2.0, H6′), 3.57 (3H, s, CH_3-C6), 3.63 (3H, s, CH_3-C3′), 3.61 (3H, s, CH_3-C6′).

Quantum chemistry calculations were performed using the MOPAC version 9.0 software package. The PM6 method was used to optimize the metric data of the molecule [4].

X-ray diffraction study of compound **1**. Determination of unit cell parameters and intensity of 12324 diffracted reflections (2689 independent, R_{int} 0.049) were measured on a Bruker Kappa APEXII CCD diffractometer (MoK_α, graphite monochromator, ω-scan, $1.74° \le \theta \le 25.85°$) at 200 K. Monoclinic crystals, space group P21/n, a = 12.9763(9), b = 8.7508(5), c = 15.3679(11) Å, β = 113.998(2)°, V = 1594.4(2) $Å^3$, Z = 4 ($C_{18}H_{16}O_7$), calculated density d = 1.434 g/cm^3, absorption coefficient μ = 0.112 mm^{-1}. The experimental array of reflections was corrected for absorption. The absorptions were counted using SAINT [5] and SADABS [6] programs (multi-scan method, $T_{min.}$ 0.9161, $T_{max.}$ 0.9780).

The structure was deciphered by direct phase determination. The coordinates of non-hydrogen atoms were refined using the anisotropic approximation of thermal vibrations by the full-matrix least-squares method. The positions of hydrogen atoms, with the exception of hydroxyl ones, were calculated geometrically and refined in the isotropic approximation of thermal vibrations (rider model). The H atoms of the hydroxyl groups were revealed from the difference synthesis, and their positions were refined in the isotropic approximation. The structure was deciphered and the coordinates were refined using the SHELXS software package [7] and the SHELXL-2018/3 software [8]. A total of 2040 independent reflections with $I \ge 2\sigma(I)$ were used in the calculations; the number of refined parameters was 230.

The divergence coefficients were $R_1 = 0.0538$, $_wR_2 = 0.1521$ (for reflections with $I \ge 2\sigma(I)$), $R_1 = 0.0772$, $_wR_2 = 0.1756$ (for all reflections), GooF = 1.243. Maximum and minimum residual density were Δρ = 0.623 and –0.457 e/$Å^3$. The coordinates of atoms in the crystal are presented in Table 1.

Table 1

Coordinates of atoms in fractions of the cell (×10^4, H×10^3) and equivalent thermal parameters ($Å^2$, ×10^3) in the structure 1

Atom	*x*	*y*	*z*	$U_{eq.}$
1	2	3	4	5
O1	6481(1)	9115(2)	867(1)	28(1)
O2	4082(2)	6161(2)	937(1)	34(1)
O3	4873(2)	6504(2)	2770(1)	34(1)
O4	6558(2)	7810(2)	4399(1)	35(1)
O5	7949(2)	9973(2)	4153(1)	34(1)
O1′	5028(2)	8108(2)	–3352(1)	35(1)
O2′	6641(2)	9943(2)	–3128(1)	37(1)
C2	5766(2)	8426(3)	54(2)	23(1)
C3	4957(2)	7448(3)	63(2)	27(1)
C4	4834(2)	7068(3)	915(2)	25(1)
C4a	5625(2)	7784(3)	1776(2)	23(1)
C5	5639(2)	7486(3)	2684(2)	26(1)
C6	6437(2)	8162(3)	3489(2)	25(1)
C7	7200(2)	9219(3)	3392(2)	27(1)

Continuation of Table 1

Atom	*x*	*y*	*z*	$U_{eq.}$
1	2	3	4	5
C8	7203(2)	9540(3)	2511(2)	28(1)
C8a	6423(2)	8801(3)	1718(2)	24(1)
C9	5678(3)	8313(4)	4656(2)	60(1)
C1′	5991(2)	8868(3)	–769(2)	23(1)
C2′	5358(2)	8246(3)	–1676(2)	24(1)
C3′	5579(2)	8646(3)	–2447(2)	25(1)
C4′	6458(2)	9690(3)	–2334(2)	26(1)
C5′	7062(2)	10324(3)	–1446(2)	30(1)
C6′	6832(2)	9920(3)	–671(2)	28(1)
C7′	4068(2)	7151(3)	–3546(2)	36(1)
C8′	7454(3)	11082(3)	–3070(2)	46(1)
H3	445(3)	613(4)	220(3)	52(1)
H5	808(3)	949(4)	469(3)	51(1)

Results and Discussions

A yellow substance with $C_{18}H_{16}O_7$ molecular formula (**1**) was isolated from the extract of the aerial part of *Artemisia semiarida* after separation of the chloroform extract by column chromatography on silica eluted with petroleum ether : ethyl acetate (13:7) [9].

In the IR spectrum (KBr, ν, cm^{-1}) (1), there were observed absorption bands, corresponding to the hydroxyl groups OH at 3069 and 3002 cm^{-1}, the carbonyl group C=O at 1654 cm^{-1}, double C=C-bonds of aromatic rings at 1588 and 1505 cm^{-1} conjugated with the C=O group, methoxy groups OCH_3 at 1376 cm^{-1} (bending vibrations), C–O–C bonds at 1094 cm^{-1}. The intensity of the absorption bands at wavelengths of 838, 771, and 685 cm^{-1} indicated the presence of substituents at the C3′ and C4 atoms of the phenyl ring.

In the ^{1}H NMR spectrum of **1**, the methoxyl group protons were observed as singlets at δ_H3.57 (C6′-OCH_3), 3.61 ppm. (C4′-OCH_3) and 3.63 ppm. (C3′-OCH_3). The protons H3 and H8 protons of chromene skeleton appeared as singlets at δ_H6.70 and 6.67 and the protons of the phenyl ring were represented by the spin system AMX at δ_H 7.05 (J=2.0 Hz, H2′), 7.07 (J=2.0 Hz, H5′), and 7.22 (J=8.0, 2.0 Hz, H6).

According to IR and NMR spectroscopy, substance **1** was identified as 5,7-dihydroxy-6,3',4'-trimethoxyflavone (eupatilin). Eupatilin previously isolated from *Eupatorium semiserratum* DC (*Asteraceae*) [10] has anti-inflammatory and antioxidant activity (Fig. 1).

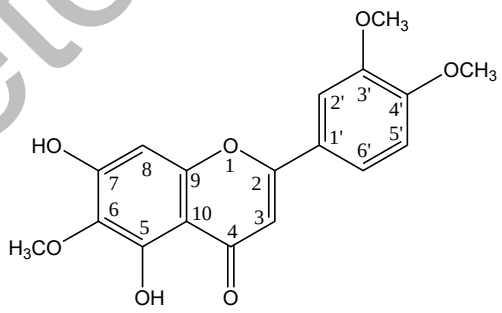

Figure 1. Structure of 5,7-dihydroxy-6,3',4'-trimethoxyflavone (eupatilin) **(1)**

In continuation of the stereochemistry study of phenolic compounds, an X-ray diffraction investigation of 5,7,3′-trihydroxy-6,3′,4′-trimethoxyflavone was carried out. Previously, the spatial structure of molecule **1** was carried out by other authors [11]. In our work, we obtained more accurate data on the metric of the elementary lattice and the crystal structure of the molecule, which will be submitted into the Cambridge Crystallographic Data Center.

The general view of the molecule **1** is shown in Figure 2.

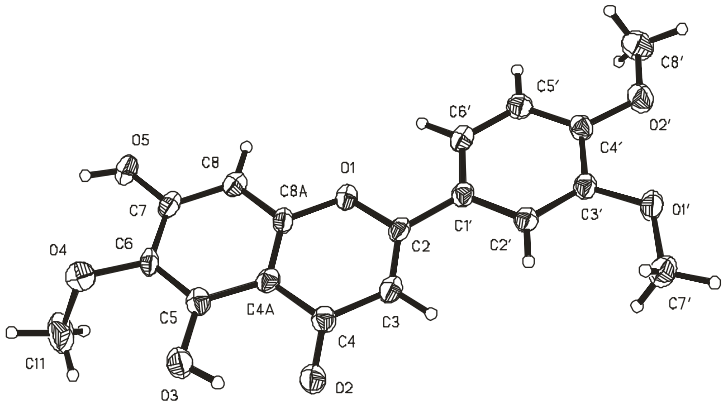

Figure 2. Crystal structural of 5,7-dihydroxy-6,3′,4′-trimethoxyflavone (eupatilin) **(1)** (thermal vibration ellipsoids shown with a probability of 50 %)

From the data obtained, it follows that the bond lengths (Table 2) and bond angles (Table 3) in compound **1** are close to normal ones [12].

Table 2

Bond lengths (d, Å) in the structure 1

Bond	d	Bond	d
O1-C2	1.358(3)	C4a-C5	1.412(4)
O1-C8a	1.368(3)	C4a-C8a	1.395(3)
O2-C4	1.269(3)	C5-C6	1.382(4)
O3-C5	1.360(3)	C6-C7	1.406(4)
O4-C6	1.377(3)	C7-C8	1.384(4)
O4-C9	1.422(3)	C8-C8a	1.388(4)
O5-C7	1.350(3)	C1′-C2	1.462(4)
O1′-C3′	1.363(3)	C1′-C2′	1.407(4)
O1′-C7′	1.429(3)	C1′-C6′	1.388(3)
O2′-C4′	1.354(3)	C2′-C3′	1.373(4)
O2′-C8′	1.427(3)	C3′-C4′	1.416(3)
C2-C3	1.358(3)	C4′-C5′	1.383(4)
C3-C4	1.422(4)	C5′-C6′	1.385(4)
C4-C4a	1.446(3)		

Table 3

Valent angles (ω, deg.) in the structure 1

Angle	ω	Angle	ω
1	2	3	4
C2-O1-C8a	120.5(2)	O5-C7-C6	121.4(2)
C6-O4-C9	116.2(2)	O5-C7-C8	117.4(2)
C3′-O1′-C7′	117.8(2)	C8-C7-C6	121.2(2)
C4′-O2′-C8′	117.0(2)	C7-C8-C8a)	118.3(2)
C3-C2-O1	120.8(2)	O1-C8a-C4a	121.3(2)
O1-C2-C1′	112.1(2)	O1-C8a-C8	116.2(2)
C3-C2-C1′	127.1(2)	C8-C8a-C4a	122.4(2)
C2-C3-C4	122.2(2)	C2′-C1′-C2	120.8(2)
O2-C4-C3	123.1(2)	C6′-C1′-C2	120.5(2)
O2-C4-C4a	120.9(2)	C6′-C1′-C2′	118.7(2)
C3-C4-C4a	116.0(2)	C1′-C2′-C3′	120.9(2)
C5-C4a-C4	122.9(2)	O1′-C3′-C2′	125.9(2)
C8a-C4a-C4	119.1(2)	O1′-C3′-C4′	114.2(2)
C8a-C4a-C5	118.0(2)	C2′-C3′-C4′	119.9(2)

Continuation of Table 3

Angle	ω	Angle	ω
1	2	3	4
O3-C5-C4a	119.7(2)	O2′-C4′-C5′	125.9(2)
O3-C5-C6	119.7(2)	O2′-C4′-C7′	115.0(2)
C6-C5-C4a	120.6(2)	C5′-C4′-C3′	119.0(2)
O4-C6-C5	123.2(2)	C4′-C5′-C6′	120.8(2)
O4-C6-C7	117.4(2)	C5′-C6′-C1′	120.7(2)
C5-C6-C7	119.4(2)		

Flavones compared to other flavonoids have the lowest conformational mobility due to the presence of a large number of double and aromatic bonds as well as substituents in the main skeleton. Thus, in structure **1**, the chromene skeleton is flat with an accuracy of ±0.017 Å, and the oxygen atoms of the OH groups are almost in the plane of the main skeleton. The deviation of O3 and O5 atoms from the middle plane is 0.008 and 0.037 Å, respectively. An exception is the O4 atom of the methoxy group with the deviation of –186 Å. The phenyl ring is flat within ±0.007 Å with the deviation of O1' and O2' atoms by 0.009 and –0.078 Å, respectively. The methoxy groups in the phenyl ring are slightly outside of its middle plane (torsion angles C2′C3′O1′C7' 6.1° and C5′C4′O2′C8′ –6.8°). The angle of rotation of the chromene skeleton and the phenyl ring is insignificant and amounts to –4.1° as well as in most flavones like 6,8-dimethyl-5,4'-dihydroxy-7-methoxyflavone [13], 5-hydroxy-6,7,4'-trimethoxyflavone [14] and 5,6,7-trihydroxyflavone [15].

In the crystal, the molecules are linked by an intramolecular hydrogen bond O3-H....O2 (x, y, z) (distances O3-H 0.89 Å, O3…. O2 2.59 Å, H3…. O2 1.80 Å, angle O3-H…. O2 147°) and intermolecular hydrogen bonds O5-H…. O2 (0.5+x, 1.5-y, 0.5+z) (distances O3-H 0.88 Å, O5….O2 2.72 Å, H5….O2 2.91 Å, angle O5-H….O2 151°), forming flat ribbons along direction [1 0 1] (Fig. 3).

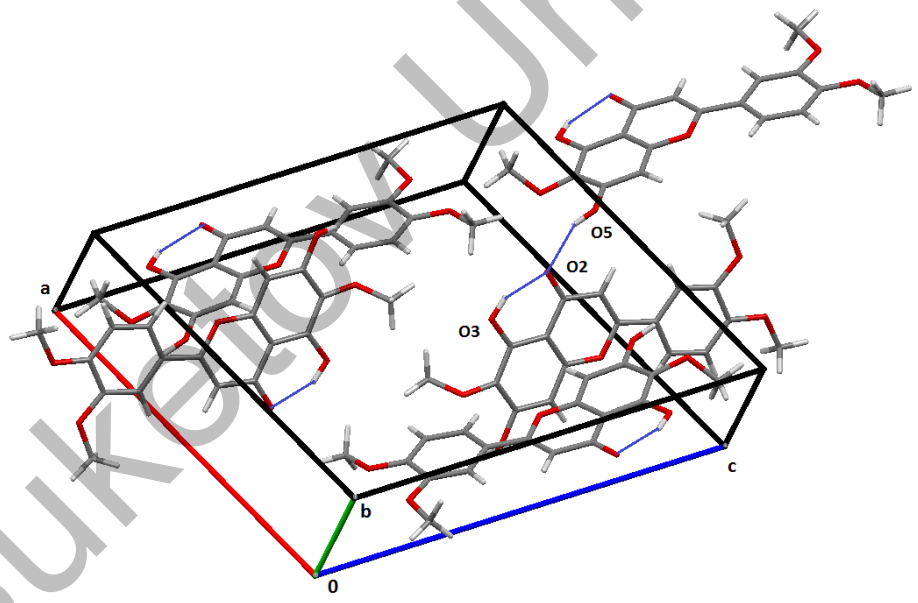

Figure 3. Crystal packing of molecules **1**

As is known, in the crystalline state, molecules of organic compounds can take a conformational state, which is not the most energetically favorable, if based on the close packing principle, its change is beneficial [16]. Based on this principle, quantum-chemical calculations were carried out to determine the various possible conformers of compound **1** using the semi-empirical PM6 method [4]. The conformers were determined by rotating the phenyl ring about the C2-C1' bond and establishing the possible orientation of the methoxy groups relative to the chromene skeleton.

From the calculations obtained, it was found that four conformers could be realized for molecule **1** at various rotations of the phenyl ring along the C2-C1′ bond with the values of the torsion angle O1C2C1′C2′ 30°, 140°, 210° and 320°, respectively. The energy barriers between them were insignificant and were about 8.4 kJ/mol. Similar rotations of the phenyl ring relative to the chromene skeleton were observed in

6-hydroxy-1′,2′,3′-trimethoxyflavone (τ (O1C2C1′C2′) = 161.3°) [17], 5,4'-dihydroxy-6,7-dimethoxyflavone (τ (O1C2C1′C2′) = 337.8°) [18] and 5,6,7,4′-tetramethoxyflavone (τ (O1C2C1′C2′) = 18.3°) [19].

Favorable orientations of the methoxy group in the chromene skeleton of molecule **1** fall on the position of the methoxy group at the torsion angle τ(C5C6O4C11) equal to 70° and 270°.

Conclusions

Artemisia semiarida, an endemic plant of Kazakhstan, was studied and 5,7-dihydroxy-6,3′,4′-trimethoxyflavone (eupatilin) was isolated and identified using IR and NMR data. Result of X-ray diffraction studies showed that the chromene skeleton is flat with an accuracy of ±0.014 Å. The phenyl ring is slightly unfolded relative to the chromene one, the dihedral angle between them is 4.1°. For free molecules of 5,7-dihydroxy-6,3′,4′-trimethoxyflavone, four conformers with the values of the torsion angle O1C2C1'C2' 30°, 140°, 210° and 320°, respectively, can be realized. The energy barriers between them are insignificant and are about 8.4 kJ/mol value. The smallest value of enthalpy during rotation along the C6-O4 bond falls on the position of the methoxyl group at the torsion angle τ(C5C6O4C11) equal to 70° and 270°.

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Information about authors*

Turdybekov, Ҝoblandy Muboryakovich *(correspondent author)* — Doctor of chemical sciences, Professor, Karagandy University of the name of academician E.A. Buketov, Universitetskaya street, 28, 100024, Karaganda, Kazakhstan; e-mail: xray-phyto@yandex.kz; https://orcid.org/0000-0001-9625-0060;

Rakhimova, Bibilul Bagdatovna — Candidate of chemical sciences, Associate Professor, Karaganda Medical University, Gogol str., 40, 100008, Karaganda, Kazakhstan; e-mail: bibigul_rahimova@mail.ru; https://orcid.org/0000-0003-2662-536X;

Makhmutova, Almagul Satybaldievna — Candidate of chemical sciences, Associate Professor, Karaganda Medical University, Gogol str., 40, 100008, Karaganda, Kazakhstan; e-mail: almagul_312@mail.ru; https://orcid.org/0000-0002-0194-8739;

Gatilov, Yurii Vasilevich — Doctor of chemical sciences, Leading researcher, N.N. Vorozhtsov Institute of Organic Chemistry of Siberian Branch of Russian Academy of Sciences, Novosibirsk, Lavrentiev Avenue, 9, 630090, Russia; e-mail: gatilov@nioch.ncs.ru; https://orcid.org/0000-0002-4128-7293;

Adekenov, Sergazy Mynzhasarovich — Doctor of Chemical Sciences, Professor, CEO, JSC "International Research and Production Holding "Phytochemistry", Gazaliev str. 4, 100009, Karaganda, Kazakhstan, e-mail: arglabin@phyto.kz; https://orcid.org/0000-0001-7588-6174

*The author's name is presented in the order: *Last Name, First and Middle Names*