

Article

New *fac*-[Re(CO)₃(OO)(L)] and [Re(CO)₂(OO)(L)₂] Complexes Bearing Two Natural Food Additives, Maltol and Kojic Acid, as OO Ligands

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Abstract: The synthesis and structural characterization of new “2+1” mixed ligand *fac*-[Re(CO)₃(OO)(L)] and Re(CO)₂(OO)(L)₂ complexes are reported herein. Maltol and kojic acid were chosen as bidentate OO ligands, while imidazole, isocyanocyclohexane or triphenylphosphine were selected as the monodentate ligands. The synthesis of the rhenium complexes was based on the reaction of [NEt₄]₂[Re(CO)₃Br₃] with maltol and kojic acid to generate the intermediate aqua complex *fac*-[Re(CO)₃(OO)(H₂O)], followed by the replacement of the labile aqua ligand by the monodentate ligand. Structural characterization of all Re complexes was established by NMR and IR spectroscopies, as well as two of them by single-crystal X-ray crystallography, revealing distorted octahedral geometry around the Re center. In the crystal lattice, the complexes form supramolecular networks due to the development of intermolecular interactions of the N-H···O, C-H···O and C-H···π type.

Keywords: rhenium; tricarbonyl complexes; kojic acid; maltol; crystal structure



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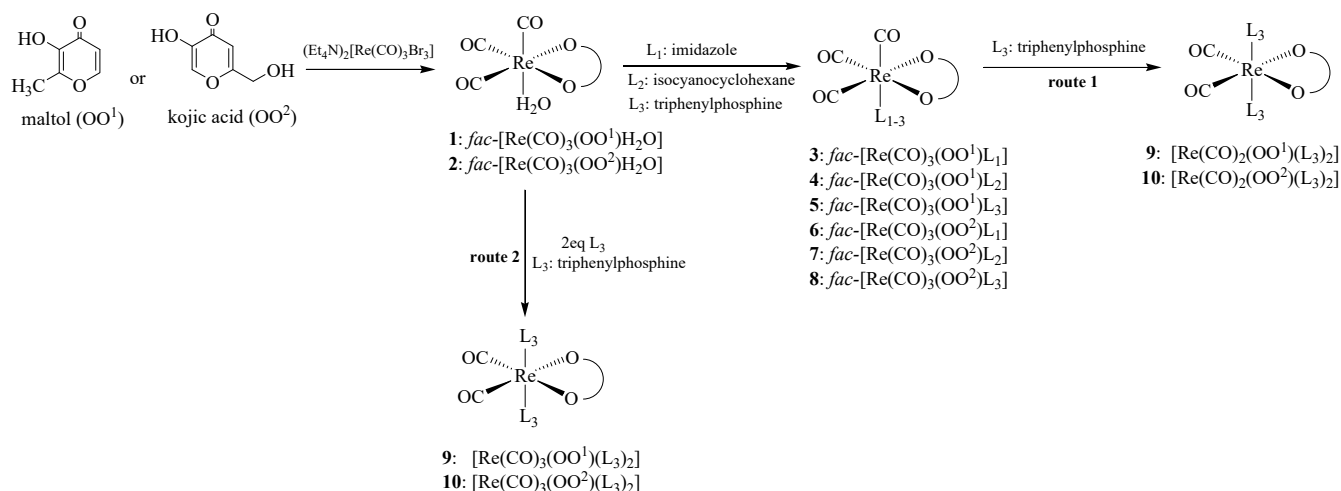


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1. Introduction

Rhenium (Re) coordination compounds have important applications in the chemical industry, especially in catalysis [1], and are intensively investigated for medical applications, among other uses, particularly in targeted anticancer therapy and nuclear medicine [2,3] or as luminescent probes for cell imaging [4]. The increasing interest in Re complexes for targeted applications requires exact knowledge of the metal–ligand coordination mode. It is worth mentioning that the chemistry and structural characterization of rhenium complexes are used as a model for the synthesis of the widely used technetium-99m radiopharmaceutical agents [5]. Moreover, reports regarding X-ray diffraction analysis of rhenium complexes with coordinated imidazole nitrogen [6,7] and phosphorus [8,9] are scarce. As a contribution to this field, we herein describe the synthesis and structural characterization of rhenium complexes bearing the widely used tricarbonyl Re(CO)₃⁺ core with maltol and kojic acid. Maltol (3-hydroxy-2-methyl-4H-pyran-4-one, Scheme 1), a bidentate OO ligand (abbreviated here as OO¹), was chosen mainly for its lack of toxicity, being an approved food additive, and for its capacity as a ligand to form stable complexes with transition metals [10]. Similarly, the non-toxic food additive kojic acid (5-hydroxy-2-(hydroxymethyl)-4H-pyran-4-one, Scheme 1, abbreviated here as OO²), closely related to maltol, was also employed in this study as an OO ligand. Kojic acid is a natural product employed in health and beauty products as a skin lightening agent [11]. To complete the

$\text{Re}(\text{CO})_3^+$ coordination sphere, the stable and versatile monodentate ligands imidazole (L_1), isocyanocyclohexane (L_2), and triphenylphosphine (L_3) were used (Scheme 1).



Scheme 1. The new mixed ligand Re complexes obtained in the current study.

New rhenium complexes bearing the tricarbonyl core $\text{Re}(\text{CO})_3^+$ with various ligands and biologically active compounds are thoroughly investigated for potential application of radioactive Technetium-99m radiopharmaceutical agents.

The mixed ligand complexes synthesized are shown in Scheme 1. Complexes 3–8 of the general formula $\text{fac}[\text{Re}(\text{CO})_3(\text{OO})^{1,2}(\text{L}_{1-3})]$ belong to the [2+1] strategy with one bidentate and one monodentate ligand combination. The [2+1] strategy has been widely employed in the design of new tricarbonyl Re complexes, providing stability and versatility. Bidentate ligands with a variety of donor atom sets, like SS [12,13], NS [14], NO [15,16], and OO [17–19], have been employed in the generation of stable complexes, while common monodentate ligands typically include heterocyclic amines (N) isocyanides (C), and phosphines (P). Complexes 9–10 of the general formula $[\text{Re}(\text{CO})_2(\text{OO})^{1,2}(\text{L}_3)_2]$ belong to the [2+1+1] strategy with combination of one bidentate and two monodentate ligands. These types of dicarbonyl complexes are usually obtained from the corresponding tricarbonyl through the action of excess of monodentate ligand and the displacement of one carbonyl group from the $\text{Re}(\text{CO})_3^+$ core [15,19–22], even though the employment of alternative Re precursors has been also reported [14,19,20,23]. The Re complexes of this work were prepared and isolated in high yield and their structures were characterized by NMR and IR spectroscopic methods, while for two of them (3 and 9) single-crystal X-ray diffraction analysis was possible.

2. Materials and Methods

All reagents and organic solvents used in this study were purchased from commercial suppliers at a reagent grade purity and used without being further purified. IR spectra were recorded on a Nicolet 6700 ATR-IR (Thermo Scientific, Waltham, MA, USA) in the region $4000\text{--}500\text{ cm}^{-1}$. NMR spectra were obtained in $\text{DMSO-}d_6$ at $25\text{ }^\circ\text{C}$ on a Bruker Avance DRX 500 MHz (Rheinstetten, Germany), with ^1H at 500.13 MHz, ^{13}C at 125.77 MHz, and ^{31}P at 202.46 MHz. Tetramethylsilane (TMS) was used as the internal reference for the ^1H and ^{13}C spectra, while for the ^{31}P spectra, phosphoric acid 85% in a sealed capillary tube was employed as the external standard. All ^{13}C NMR and ^{31}P spectra were measured with complete proton decoupling. The electrospray mass (ESI-MS, Thermo Fisher Scientific Inc., Waltham, MA, USA) spectra were recorded in the range of m/z 250–1400 on a Finnigan MAT TSQ 7000. For the mass spectrometric studies, samples were initially dissolved in DMSO and further diluted with acetonitrile. The resulting solution was brought to the electrospray capillary through a syringe pump. The activity was measured using a dose

calibrator (Capintec CRC-12, Florham Park, NJ, USA). HPLC analysis was performed on a Waters 600 chromatography system (Waters) coupled to both a Waters 2487 Dual λ absorbance detector (Waters) and a Gabi γ detector (Raytest). Separations were achieved on a Macherey–Nagel Nucleosil C-18 RP column, 250×4 mm, $10 \mu\text{m}$, eluted with a binary gradient system at 1 mL/min flow rate; mobile phase A was methanol containing 0.1% trifluoroacetic acid (TFA), while mobile phase B was water containing 0.1% TFA. The elution gradient was 0–1 min 100% B (0% A), followed by a linear gradient to 70% A (30% B) in 9 min; this composition was held for 10 min followed by a linear gradient to 95% A (5% B) in 1 min.

2.1. Compound Preparations

2.1.1. Synthesis of *fac*-[Re(CO)₃(OO¹)H₂O] (1)

To a solution of *fac*-[NEt₄]₂[Re(CO)₃Br₃] (231 mg, 0.3 mmol) in water (4 mL), a solution of an equivalent amount of the maltol (OO¹) ligand in 4 mL of water was added (37.8 mg, 0.3 mmol). After three hours of stirring under reflux, complex **1** precipitated as a white solid and was collected by filtration. Aqua complex **1** was obtained with good yield (111.5 mg, 90%) and was fully characterized. HPLC: $t_R = 14.7$ min. FT-IR (cm^{−1}): 2017, 1866, 1597. ¹H NMR (500 MHz, DMSO-*d*₆): $\delta = 8.28$ (d, $J = 5.0$ Hz, 1H, -CH-O-), 6.84 (d, $J = 5.0$ Hz, 1H, -CH-CH-), 2.42 (s, 3H, -CH₃) ppm.

2.1.2. Synthesis of *fac*-[Re(CO)₃(OO²)H₂O] (2)

fac-[NEt₄]₂[Re(CO)₃Br₃] (231 mg, 0.3 mmol) was dissolved in water (4 mL) and a solution of the kojic (OO²) ligand (42.6 mg, 0.3 mmol) in water (4 mL) was added. The reaction mixture was refluxed for three hours and complex **2** was collected, removing the solvent by lyophilization. Aqua complex **2** was obtained at 85% yield (111.44 mg) and was fully characterized. HPLC: $t_R = 13.6$ min. FT-IR (cm^{−1}): 2004, 1863, 1612. ¹H NMR (500 MHz, DMSO-*d*₆): $\delta = 6.88$ (s, 1H, -CH-O), 6.68 (s, 1H, -C-CH-O-), 5.71 (t, $J = 5.8$ Hz, 1H, -OH), 4.34 (d, $J = 6.0$ Hz, 2H, CH₂-OH) ppm.

2.1.3. Synthesis of *fac*-[Re(CO)₃(OO¹)L₁] (3)

To a solution of complex **1** *fac*-[Re(CO)₃(OO¹)H₂O] (41.3 mg, 0.1 mmol) in methanol (5 mL), imidazole (L₁) (6.8 mg, 0.1 mmol) dissolved in methanol (5 mL) was added. The solution was refluxed for two hours and a clear solution was formed. The mixture was concentrated in vacuo and the residue was crystallized from dichloromethane/methanol to afford Re complex **3** at 84% yield (38.9 mg). Crystals appropriate for X-ray diffraction analysis were obtained for rhenium complex **3** from CH₂Cl₂/CH₃OH by slow evaporation. HPLC: $t_R = 15.5$ min. FT-IR (cm^{−1}): 2012, 1859, 1639. ¹H NMR (500 MHz, DMSO-*d*₆): $\delta = 12.78$ (br s, 1H, -NH), Im), 8.17 (d, $J = 5.0$ Hz, 1H, -CH-O-), 7.83 (s, 1H, -N-CH, Im), 7.19 (s, 1H, -CH Im), 6.88 (s, 1H, -CH, Im), 6.72 (d, $J = 5.0$ Hz, 1H, -CH-CH-), 2.39 (s, 3H, -CH₃) ppm.

2.1.4. Preparation of *fac*-[Re(CO)₃(OO¹)L₂] (4)

To a solution of the Re complex **1** (41.3 mg, 0.1 mmol) in methanol (5 mL), isocyanocyclohexane (L₂) (10.9 mg, 0.1 mmol) dissolved in methanol (3 mL) was added. The reaction took place at ambient temperature for two hours under stirring. The solvent was removed on a rotary evaporator and the remaining solid was recrystallized from dichloromethane/hexane to give complex **4** (42.1 mg) at 83% yield. HPLC: $t_R = 19.6$ min. FT-IR (cm^{−1}): 2191, 2012, 1878. ¹H NMR (500 MHz, DMSO-*d*₆): $\delta = 8.24$ (d, $J = 5.0$ Hz, 1H, -CH-O-), 6.83 (d, $J = 5.0$ Hz, 1H, -CH-CH-), 4.18 (t, $J = 4$ Hz, 1H, HC-CN IsoCN), 2.39 (s, 3H, -CH₃) 1.65–1.60 (m, 2H, HC-CH-CN), 1.36–1.29 (m, 2H, C-H'-CH'- IsoCN), ppm.

2.1.5. Preparation of *fac*-[Re(CO)₃(OO¹)L₃] (5)

The aqua Re complex **1** (41.3 mg, 0.1 mmol) dissolved in methanol (5 mL) reacted readily for two hours with equimolar quantity of triphenylphosphine (L₃) (26.2 mg, 0.1 mmol) in 5 mL refluxing methanol, producing Re complex **5**. The solvent was removed by rotary evaporation and the residue was triturated with cold methanol to afford complex **5** as a yellowish solid. The yield was calculated to be 75% (49.5 mg). HPLC: *t_R* = 27.8 min. FT-IR (cm^{−1}): 2011, 1875, 1604, 742, 693. ¹H NMR (500 MHz, DMSO-*d*₆): δ = 8.24 (d, *J* = 5.0 Hz, 1H, -CH-O-), 7.34 (m, 3 Ph), 6.80 (d, *J* = 5.0 Hz, 1H, -CH-CH-), 2.37 (s, 3H, -CH₃) ppm. ³¹P NMR (DMSO-*d*₆): δ = 31.8 ppm.

2.1.6. Preparation of *fac*-[Re(CO)₃(OO²)L₁] (6)

Complex **2** *fac*-[Re(CO)₃(OO²)H₂O] (43.7 mg, 0.1 mmol) was dissolved in methanol (5 mL) and imidazole (L₁) (6.8 mg, 0.1 mmol) in 5 mL methanol was added. The solution was refluxed under stirring for two hours until a clear solution formed. Methanol was subsequently removed on the rotary evaporator and the remaining orange solid was recrystallized from dichloromethane/methanol to give complex **6** at 78% yield (37.6 mg). HPLC: *t_R* = 15.3 min. FT-IR (cm^{−1}): 2011, 1855, 1607. ¹H NMR (500 MHz, DMSO-*d*₆): δ = 12.83 (br s, -NH, Im), 8.12 (s, 1H, -CH, Im), 7.89 (s, 1H, -CH, Im), 7.21 (s, 1H, -CH, Im), 6.89 (s, 1H, -CH-O), 6.71 (s, 1H, -C-CH-O-), 5.73 (t, *J* = 5.8 Hz, 1H, -OH), 4.37 (d, *J* = 6.0 Hz, 2H, CH₂-OH) ppm.

2.1.7. Synthesis of *fac*-[Re(CO)₃(OO²)L₂] (7)

To a stirred solution of complex **2** (43.7 mg, 0.1 mmol) in 5 mL of methanol, a solution of isocyanocyclohexane (L₂) (10.9 mg, 0.1 mmol) in 3 mL of methanol was added. The reaction took place at ambient temperature for two hours with stirring. The solvent was removed under reduced pressure and the solid residue was recrystallized from dichloromethane/hexane to give complex **7** at 72% yield (37.7 mg). HPLC: *t_R* = 17.7 min. FT-IR (cm^{−1}): 2192, 2014, 1965, 1881, 1604. ¹H NMR (500 MHz, DMSO-*d*₆): δ = 6.88 (s, 1H, -CH-O), 6.39 (s, 1H, -C-CH-O-), 5.84 (s, 1H, C-CH-O-C-), 5.66 (t, *J* = 5.8 Hz, 1H, -OH), 4.41 (d, *J* = 6.0 Hz, 2H, CH₂-OH), 4.18 (t, *J* = 4 Hz, 1H, HC-CN IsoCN), 1.61–1.60 (m, 2H, HC-CH-CN), 1.58–1.39 (m, 2H, C-H'-CH'- IsoCN) ppm.

2.1.8. Synthesis of *fac*-[Re(CO)₃(OO²)L₃] (8)

A solution (5 mL methanol) of aqua Re complex **2** (43.7 mg, 0.1 mmol) reacted readily for two hours with equimolar quantity of triphenylphosphine (L₃) (26.2 mg, 0.1 mmol) in 3 mL refluxing methanol, producing complex **8**. The purified compound was crystallized from dichloromethane/methanol and the yield was calculated to be 72% (48.7 mg). HPLC: *t_R* = 26.6 min. FT-IR (cm^{−1}): 2011, 1875, 1604, 740, 690. ¹H NMR (500 MHz, DMSO-*d*₆): δ = 7.34 (m, 3 Ph), 7.08 (s, 1H, -CH-O), 5.72 (s, 1H, -C-CH-O-), 5.46 (tr, *J* = 5.8 Hz, 1H, -OH), 4.26 (d, *J* = 6.0 Hz, 2H, CH₂-OH) ppm. ³¹P NMR (DMSO-*d*₆): δ = 30.1 ppm.

2.1.9. Synthesis of [Re(CO)₂(OO¹)(L₃)₂] (9)

Method A: A solution of *fac*-[Re(CO)₃(OO¹)L₃], complex **5** (66.1 mg, 0.1 mmol) in toluene (10 mL), and an equivalent amount of triphenylphosphine (26.2 mg, 0.1 mmol) in toluene (6 mL) was readily reacted in refluxing methanol for six hours to give [Re(CO)₂(OO¹)(L₃)₂], complex **9**. After the removal of the solvent, the purified compound was recrystallized to afford yellow crystals and the yield was calculated to be 85% (78.0 mg).

Method B: Aqua Re complex **1**, *fac*-[Re(CO)₃(OO¹)H₂O] (41.3 mg, 0.1 mmol) in 5 mL methanol reacted readily with two equivalents of triphenylphosphine (L₃) (52.5 mg, 0.2 mmol) in 10 mL refluxing methanol for eight hours, producing diphosphino Re complex **9**, [Re(CO)₂(OO¹)(L₃)₂]. The compound was recrystallized to afford yellow crystals and the yield was calculated to be 81% (72.4 mg).

Method C: To a stirred solution of *mer*-[Re(CO)₃(L₃)₂Cl] precursor (83.2 mg, 0.1 mmol) and triethylamine (10.1 mg, 0.1 mmol) in benzene (5 mL), a solution of the maltol (OO¹) ligand (12.6 mg, 0.1 mmol) in methanol (2 mL) was added. The mixture was refluxed under heating for six hours. Yellow crystals were obtained (yield of 76%, 67.9 mg).

Crystals suitable for X-ray diffraction analysis were obtained for complex **9** from dichloromethane/methanol in all three methods. HPLC: t_R = 28.6 min. FT-IR (cm⁻¹): 1936, 1886, 742, 690. ¹H NMR (500 MHz, DMSO-*d*₆) δ = 8.28 (d, J = 5.0 Hz, 1H, -CH-O-), 7.37 (m, 3 Ph), 6.84 (d, J = 5.0 Hz, 1H, -CH-CH-), 2.38 (s, 3H, -CH₃) ppm. MS (ESI negative ionization): m/z (M)^{002D} = 892.151 (calculated for C₄₄H₃₅O₅P₂¹⁸⁷Re, 892.151). ³¹P NMR (DMSO-*d*₆): δ = 34.9 ppm.

2.1.10. Synthesis of [Re(CO)₂(OO²)(L₃)₂] (**10**)

Method A: A solution of *fac*-[Re(CO)₃(OO²)L₃], complex **8** (67.7 mg, 0.1 mmol) in toluene (10 mL), and an equivalent amount of triphenylphosphine (26.2 mg, 0.1 mmol) in toluene (6 mL) was readily reacted in refluxing methanol for six hours to give [Re(CO)₂(OO²)(L₃)₂], complex **10**. After the removal of the solvent, the purified compound was recrystallized from dichloromethane/methanol and the yield was calculated to be 73% (66.4 mg).

Method B: Aqua Re complex **2**, *fac*-[Re(CO)₃(OO²)H₂O] (43.7 mg, 0.1 mmol) in a solution of 5 mL methanol reacted readily with two equivalents of triphenylphosphine (L₃) (52.5 mg, 0.2 mmol) in 10 mL refluxing methanol for eight hours, producing diphosphino Re complex **10**. The compound was recrystallized and the yield was calculated to be 71% (64.6 mg).

Method C: To a stirred solution of *mer*-[Re(CO)₃(L₃)₂Cl] precursor (83.2 mg, 0.1 mmol) and triethylamine (10.1 mg, 0.1 mmol) in benzene (5 mL), a solution of the kojic (OO²) ligand (14.2 mg, 0.1 mmol) in methanol (2 mL) was added. The mixture was refluxed under heating for six hours. The solution was then removed to afford, after vacuum drying, compound **10** as a yellow solid (63.7 mg, yield 70%).

HPLC: t_R = 28.0 min. FT-IR (cm⁻¹): 1909, 1833, 1601, 741, 692. ¹H NMR (500 MHz, DMSO-*d*₆) δ = 7.37 (m, 3 Ph), 7.06 (s, 1H, -CH-O), 5.69 (s, 1H, -C-CH-O-), 5.46 (t, J = 5.8 Hz, 1H, -OH), 3.95 (d, J = 6.0 Hz, 2H, CH₂-OH) ppm. ³¹P NMR (DMSO-*d*₆): δ = 33.2 ppm. MS (ESI negative ionization): m/z (M)⁻ = 908.152 (calculated for C₄₄H₃₇O₅P₂¹⁸⁷Re, 908.152).

2.2. Single Crystal X-Ray Crystallography

A crystal of **3** (0.18 × 0.26 × 0.51 mm) and **9** (0.04 × 0.05 × 0.40 mm) was taken from the mother liquor and immediately cooled to −113 °C. Diffraction measurements were made on a Rigaku R-Axis SPIDER Image Plate diffractometer using graphite monochromated Cu K α radiation. Data collection (ω -scans) and processing (cell refinement, data reduction, and empirical absorption correction) were performed using the CrystalClear-SM 1.4.0 rc7 (1 March 2007) program package (Rigaku Corporation, Tokyo, Japan) [24]. Important crystallographic data are listed in Table 1. The structures were solved by direct methods using SHELXS v.2013/1 and refined by full-matrix least-squares techniques on F² with SHELXL ver.2014/6 [25,26]. All hydrogen atoms were located by difference maps and were refined isotropically or were introduced at calculated positions as riding on bonded atoms. All non-hydrogen atoms were refined anisotropically. Plots of the structure were drawn using the Diamond 3 program package [27].

The d_{norm} and fingerprint plots as provided in the *CrystalExplorer* package V.17.5 [28] were applied for the Hirshfeld surface (HS) analysis of compounds **3** and **9**. d_{norm} is a normalized contact distance, and is defined in terms of d_e , d_i and the Van der Waals (VdW) radii of two atoms at a distance d_e outside from a point on the HS and at a distance d_i inside the surface correspondingly [29].

Table 1. Crystallographic data for **3** and **9**.

	3	9
Formula	C ₁₂ H ₉ N ₂ O ₆ Re	C ₄₄ H ₃₅ O ₅ P ₂ Re
<i>F</i> _w	463.41	891.86
Space group	<i>Pccn</i>	<i>Pnma</i>
<i>a</i> (Å)	16.5983(3)	10.6486(2)
<i>b</i> (Å)	13.2655(2)	23.7433(4)
<i>c</i> (Å)	12.2935(2)	14.9528(2)
α (°)	90	90
β (°)	90	90
γ (°)	90	90
<i>V</i> (Å ³)	2706.84(8)	3780.56(11)
<i>Z</i>	8	4
<i>T</i> (°C)	160	160
Radiation	Cu K α (λ = 1.54178 Å)	Cu K α (λ = 1.54178 Å)
$2\theta_{\max}$ (°)	134	134
ρ_{calcd} (g cm ^{−3})	2.274	1.567
μ (mm ^{−1})	17.867	7.455
Reflections collected/unique/used	33,712/2385 [<i>R</i> _{int} = 0.1228]/2385	24,613/3421 [<i>R</i> _{int} = 0.0800]/3421
Reflections with <i>I</i> > 2 σ (<i>I</i>)	2285	2626
Parameters refined	192	308
(Δ/σ) _{max}	0.000	0.009
($\Delta\rho$) _{max} /($\Delta\rho$) _{min} (e/Å ³)	1.982/−1.533	1.128/−1.347
<i>R</i> ₁ / <i>wR</i> ₂ (observed reflections) ^a	0.0370/0.0902 ^b	0.0441/0.1033
<i>R</i> ₁ / <i>wR</i> ₂ (all data) ^a	0.0381/0.0915	0.0560/0.1108

^a $w = 1/[\sigma^2(F_o^2) + (aP)^2 + bP]$ and $P = [\max(F_o^2, 0) + 2F_c^2]/3$, $a = 0.0253$, $b = 11.6737$ (**3**); $a = 0.0359$, $b = 7.3770$ (**9**); $R_1 = \Sigma(|F_o| - |F_c|)/\Sigma(|F_o|)$ and $wR_2 = \{\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[w(F_o^2)^2]\}^{1/2}$.

CCDC 2345512 and 2345513 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via <https://www.ccdc.cam.ac.uk/structures/> (accessed on 4 April 2024, or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; Fax: +44 1223 336033; E-mail: deposit@ccdc.cam.ac.uk).

3. Results and Discussion

In the present work, stable rhenium complexes combining two different bidentate ligands and the monodentate ligands imidazole, isocyanocyclohexane, and triphenylphosphine were prepared. Monophosphino rhenium complexes **5**, **8** were obtained in good yield by first coordinating the bidentate ligands OO¹ and OO², respectively. Diphosphino complexes **9**, **10** were each formed by different methods, either by starting the reaction from the monophosphino rhenium complexes, or by starting the reaction using *fac*-[Re(CO)₃(OO)(H₂O)] with two equivalents of L₃ under heating. In these Re complexes, the CO ligand in the apical position is substituted by a second triphenylphosphine ligand (L₃) due to the *trans* effect, yielding the final complex [20]. Complexes **9** and **10** can be also synthesized using *mer*-[Re(CO)₃(L₃)₂Cl] as precursor. All Re complexes were isolated in good yield and the HPLC analysis of all Re complexes showed a single peak. The Re complexes were characterized by IR and NMR spectroscopic methods. Rhenium diphosphino complexes **9** and **10** were also characterized by mass spectroscopy. The NMR data are in agreement and show similar behavior of the coordinated imidazole nitrogen, phosphorous, and isocyanide carbon with the data reported by our group with various Re(CO)₃⁺ complexes (Figures 1 and 2) [12,19]. The ³¹P NMR spectra of diphosphino Re complexes **9** and **10** display just a single peak with no splitting, as do the monophosphino Re complexes **5** and **8**, which is consistent with their symmetrical structures (Figure 2).

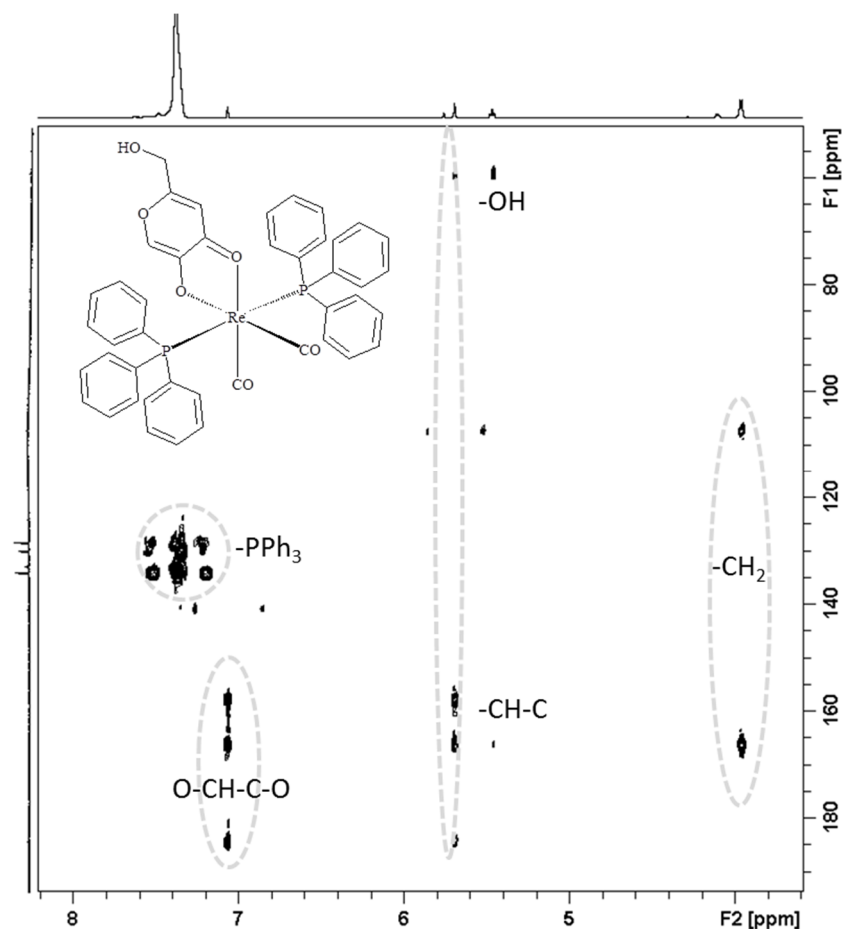


Figure 1. ^1H - ^{13}C HMBC NMR spectrum of $[\text{Re}(\text{CO})_2(\text{OO}^2)(\text{L}_3)_2]$ in $\text{DMSO}-d_6$ (10).

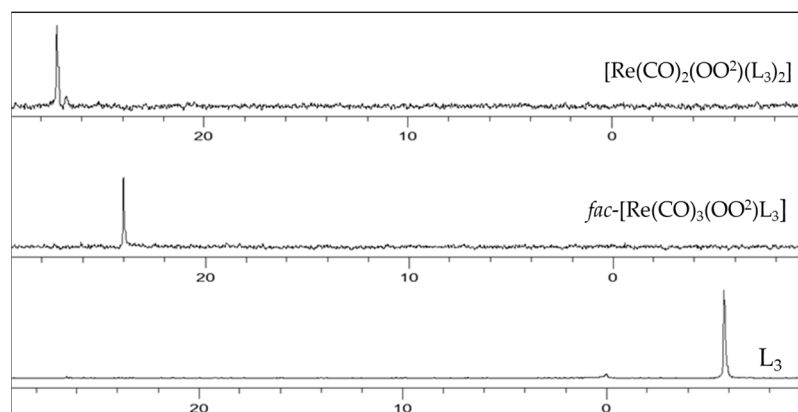


Figure 2. Characteristic ^{31}P NMR spectra of L_3 , $\text{fac}-[\text{Re}(\text{CO})_3(\text{OO}^2)\text{L}_3]$ (8) and $[\text{Re}(\text{CO})_2(\text{OO}^2)(\text{L}_3)_2]$ (10).

In the Re complexes bearing phosphine substituent (L_3) $\text{fac}-[\text{Re}(\text{CO})_3(\text{OO}^2)\text{L}_3]$, downfield shifts of the coordinated phosphorous (by 30.1 ppm in monophosphino Re complex 8 and 33.2 ppm in diphosphino complex 10, followed by similar chemical shifts for 5 and 9, respectively) compared to the corresponding free ligand are noted in ^{31}P NMR (Figure 2).

Crystals suitable for X-ray diffraction analysis were obtained for complex 3 ($\text{fac}-[\text{Re}(\text{CO})_3(\text{OO}^1)\text{L}_1]$) and complex 9 ($[\text{Re}(\text{CO})_3(\text{OO}^1)(\text{L}_3)_2]$) by recrystallization from dichloromethane/methanol.

The molecular structures of **3** and **9** are shown in Figures 3 and 6, respectively. Selected bond distances are listed in Table 2. The molecular structure of **3** consists of an octahedrally coordinated Re^{I} ion which is bound to three CO ligands in the *fac*-arrangement, two O-atoms from the bidentate maltol (OO^1) ligand and one nitrogen from the monodentate imidazole L_1 ligand. The five-membered ring in the coordination sphere is planar with largest deviation 0.091 Å for C(1). The two Re-CO bond distances are ~ 1.90 Å, and the third is slightly longer at ~ 1.91 Å. The Re-O and Re-N bond distances are substantially longer at ~ 2.15 and ~ 2.20 Å, respectively. In the crystal lattice, the molecules of **3** are linked through intermolecular hydrogen bonds (Table 3) which involve the imidazole H-atom and the coordinated O(1) of (OO^1) ligand ($\text{N}(12)\text{-H}(12\text{N})\cdots\text{O}(1)^{\text{ii}}$ [symmetry code (ii): $x, 0.5 - y, -0.5 + z$] and $\text{C}(6)\text{-H}(6\text{C})\cdots\text{O}(23)^{\text{iii}}$ [symmetry code (iii): $1 - x, 1 - y, 1 - z$] hydrogen bonds, and form layers parallel to (001) planes (Figure 4). Further $\text{C4-H4}\cdots\text{O23}^{\text{xviii}}$ [symmetry code (xviii): $0.5 + x, 1 - y, 0.5 - z$] hydrogen bonds link complexes belonging to neighboring layers which are stacked along the *a*-axis (Table 3, Figure 4). In Figure 5a the intermolecular interactions and the symmetries for each complex with its neighbors are shown. The Hirshfeld analysis below reveals that the hydrogen bonds are the main contributing interactions in the present structure.

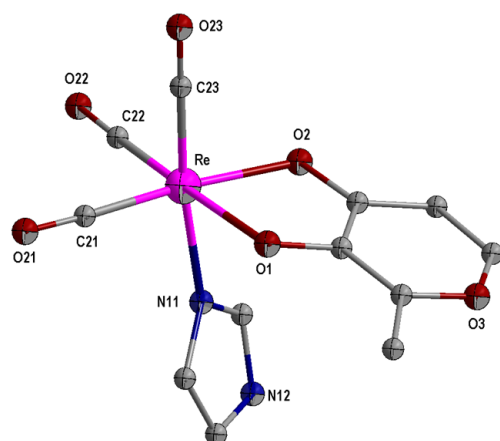


Figure 3. Partially labeled plot of the molecular structure of **3**. Thermal ellipsoids are drawn at 50% probability level.

Table 2. Selected bond distances (Å) in **3** and **9**.

	3		9
Re-C(22)	1.900(5)	Re(1)-C(31)	1.880(8)
Re-C(23)	1.902(6)	Re(1)-C(32)	1.910(9)
Re-C(21)	1.914(5)	Re(1)-O(22)	2.169(6)
Re-O(1)	2.146(3)	Re(1)-O(21)	2.184(6)
Re-O(2)	2.157(3)	Re(1)-P	2.414(1)
Re-N(11)	2.195(4)	Re(1)-P'	2.414(1)

Table 3. Intermolecular interactions in the crystal structures of **3** and **9**.

Interaction	D $\cdots$ A (Å)	H $\cdots$ A (Å)	D-H $\cdots$ A (°)
3			
N(12)-H(12N) $\cdots$ O(1) ⁱⁱ	2.739(5)	1.86	176.1
C(4)-H(4) $\cdots$ O(23) ^{xviii}	3.428(6)	2.70	134.0
C(6)-H(6C) $\cdots$ O(23) ⁱⁱⁱ	3.377(7)	2.40	172.0

Table 3. Cont.

Interaction	D···A (Å)	H···A (Å)	D-H···A (°)
9			
C(22)-H(22)···O(32) ^{ii'}	3.517	2.57	178.6
C(23)-H(23)···O(32) ^{iii'}	3.279	2.64	125.3

Symmetry operations: (ii) $x, 0.5 - y, -0.5 + z$; (xviii) $0.5 + x, 1 - y, 0.5 - z$; (iii) $1 - x, 1 - y, 1 - z$; (ii') $0.5 + x, 0.5 - y, 0.5 - z$; (iii') $1 + x, y, z$.

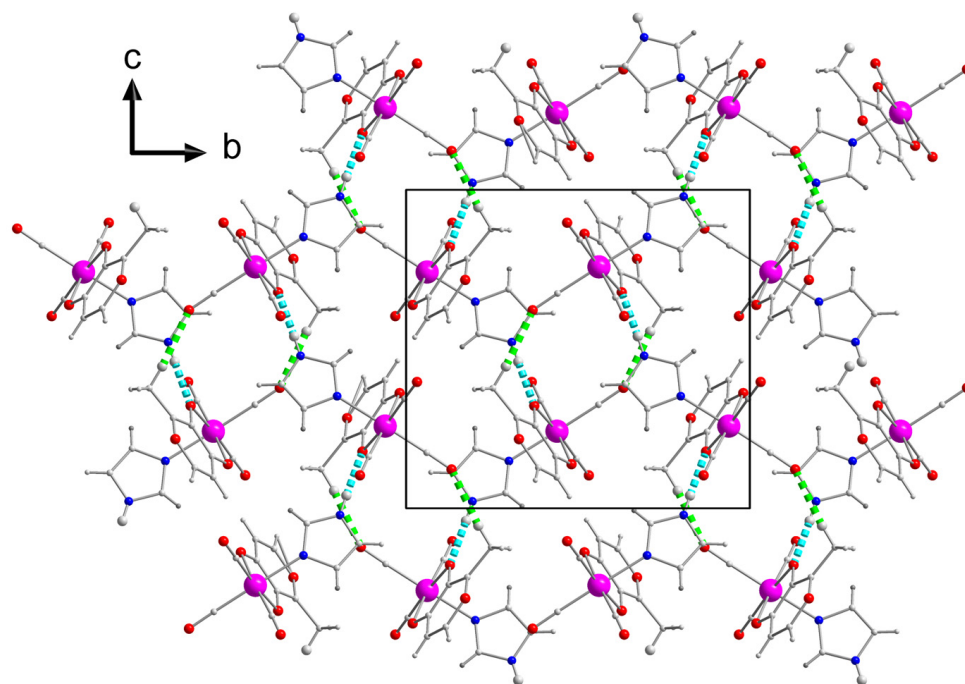


Figure 4. Part of the layered supramolecular structure of **3** due to N(12)-H(12N)···O(1) and C(6)-H(6C)···O(23) hydrogen bonds, which are indicated with cyan and light green dashed lines, respectively. Symmetry operations: (i): x, y, z ; (ii): $x, 0.5 - y, -0.5 + z$; (iii): $1 - x, 1 - y, 1 - z$; (iv): $1 - z, 0.5 + y, 1.5 - z$; (v): $1 - x, -0.5 + y, 1.5 - z$; (vi): $1 - x, -y, 1 - z$; (vii): $x, y, 1 + z$; (viii): $x, 0.5 - y, 0.5 + z$; (ix): $1 - x, -0.5 + y, 0.5 - z$; (x): $1 - x, -y, -z$; (xi): $x, 1 + x, 1 + z$; (xii): $x, 1.5 - y, 0.5 + z$; (xiii): $1 - x, 0.5 + y, 0.5 - z$; (xiv): $1 - x, 1 - y, -z$; (xv): $x, 1 + y, z$; (xvi): $x, 1.5 - y, -0.5 + z$. Color code for atoms: Re, magenta; O, red; N, blue; C, grey; H, grey.

The molecular structure of **9** consists of a Re^I ion which is bound to two CO ligands in *cis*-positions, the two oxygen atoms of the (OO¹) ligand and two phosphorus atoms from PPh₃ ligands in *trans*-positions. The Re^I ion, the two CO and all the atoms of the (OO¹) ligand lie on a crystallographic mirror plane; therefore, the two PPh₃ ligands are symmetrically related through symmetry operation (') $x, 0.5 - y, z$, and lie above and below the mirror plane. The coordination geometry around the Re^I ion is distorted octahedral. The Re-CO bond distances are ~ 1.90 Å, and the Re-O bond lengths are 2.17–2.18 Å and are slightly longer than the respective bonds in **3**. The Re-P bond distances are longer in the coordination sphere at ~ 2.40 Å. In the crystal lattice, the molecules of **9** are linked through the C(22)-H(22)···O(32)^{ii'} and C(23)-H(23)···O(32)^{iii'} intermolecular hydrogen bonds [symmetry codes: (ii') $0.5 + x, 0.5 - y, 0.5 - z$; (iii') $1 + x, y, z$] and form double chains (Table 3, Figure 7). Complexes belonging to neighboring chains interact through weak C-H··· π interactions, a result confirmed by the Hirshfeld surface analysis presented below, and build the 3D architecture of the structure of compound **9**.

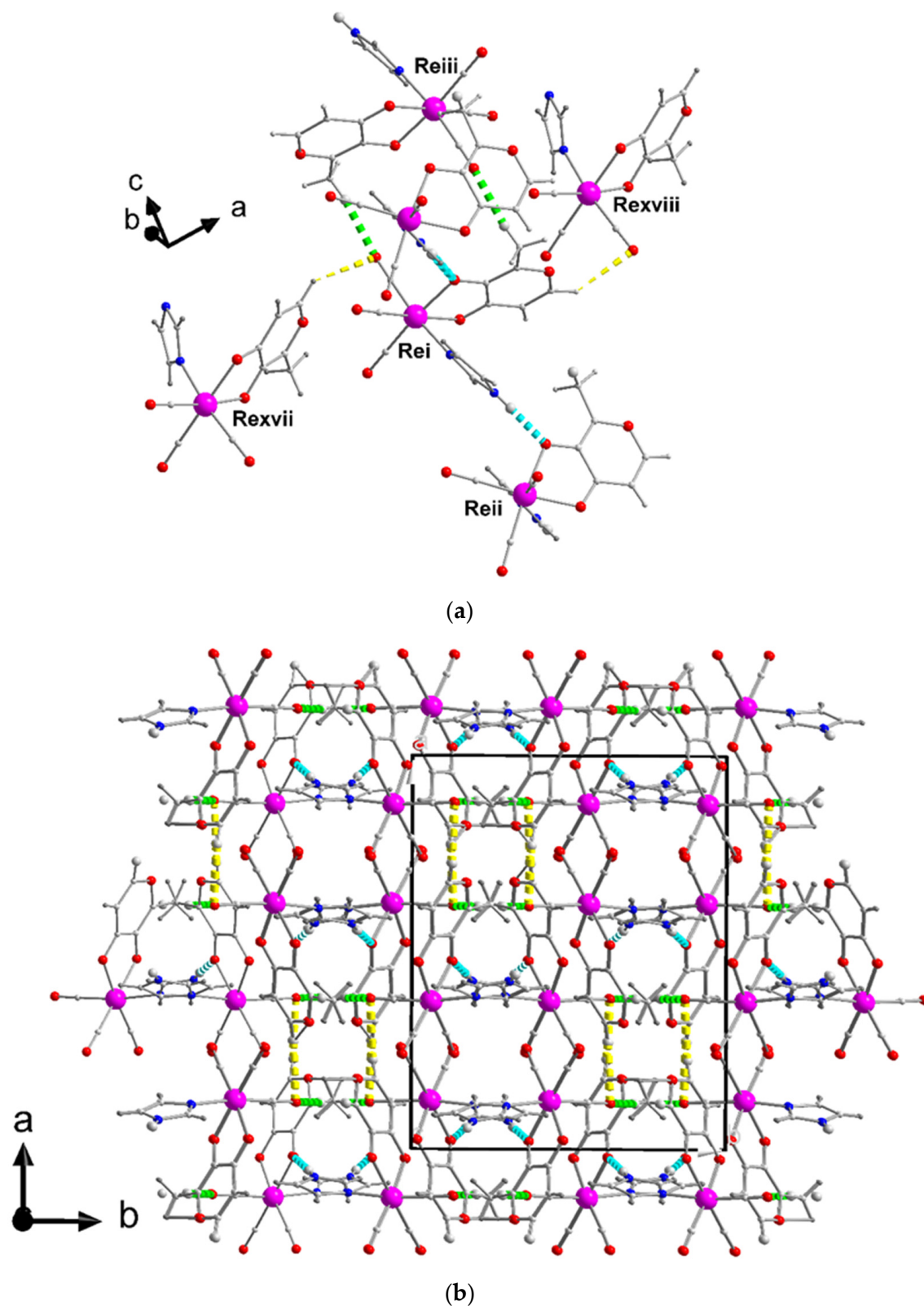


Figure 5. (a) Intermolecular interactions and symmetries for each complex with its neighbors in the structure of complex 3. (b) Part of the 3D supramolecular structure of 3 representing the stacking of layers along *a* crystallographic axis. Neighboring layers along *a*-axis interact through C4-H4...O23 hydrogen bonds, indicated with yellow dashed lines. The coloring scheme of intermolecular interactions within the layers is as in Figure 4. Symmetry codes: (i), (ii), and (iii) are as in Figure 4; (xvii): $-0.5 + x, 1 - y, 0.5 - z$; (xviii): $0.5 + x, 1 - y, 0.5 - z$. Color codes for atoms are as in Figure 4.

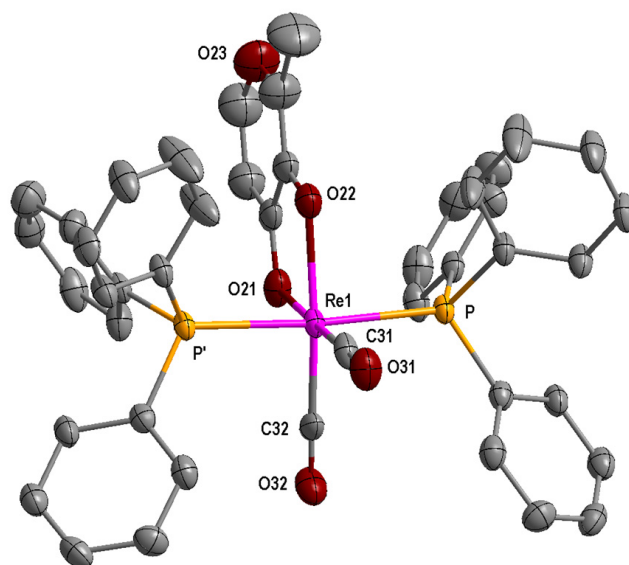


Figure 6. Partially labeled plot of the molecular structure of **9**. Primed atoms are generated through symmetry operation (i') $x, 0.5 - y, z$. Thermal ellipsoids are drawn at 30% probability level.

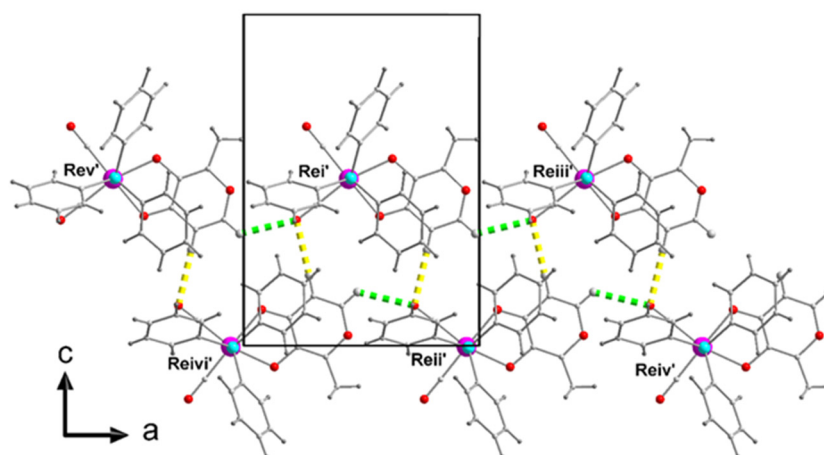


Figure 7. Part of the double chains in the lattice structure of **9** due to $C(22)-H(22) \cdots O(32)$ and $C(23)-H(23) \cdots O(32)$ hydrogen bonds, indicated with yellow and light green dashed lines, respectively. Symmetry codes: (i'): x, y, z ; (ii'): $0.5 + x, 0.5 - y, 0.5 - z$; (iii'): $1 + x, y, z$; (iv'): $1.5 + x, 0.5 - y, 0.5 - z$; (v'): $-1 + x, y, z$; (vi'): $-0.5 + x, 0.5 - y, 0.5 - z$. Color code: Re, magenta; P, cyan; O, red; C, grey; H, grey.

The metal-to-monodentate ligand bond distance and metal–bidentate ligand bond distance depends on the nature of the coordinating atom and has similar behavior with other coordinated phosphorous, as reported in the literature [30,31]. Complexes which contain the *fac*-[Re^I(CO)(imidazole)]⁺ moiety and bidentate OO ligands, such as acetylacetonate and/or aromatic bidentate ligands similar to maltol, have been reported in the literature [6,7,32–34]. In all complexes, the Re–N and Re–O bonds distances are ~ 2.19 Å and 2.12–2.16 Å, respectively, and the Re–CO bond lengths are 1.90–1.93 Å. These values fully agree with the coordination bond distances in complex **3** (Table 2). Diphosphino complexes which contain the *cis*-[Re^I(CO)₂]⁺ moiety and bidentate OO ligands have been also reported previously [8,9,14,19]. In all cases, the Re–O, Re–P, and Re–CO bonds lengths are 2.12–2.16 Å, 2.38–2.43 Å, and 1.87–1.89 Å, respectively. These values are analogous to the bond distances in the coordination sphere of complex **9** (Table 2). Complexes of Re^V with the bidentate maltolate ligand (OO¹) were also reported previously [9,35–38]. In the latter complexes, the Re–O bond distances are in the range 1.96–2.13 Å, which are shorter than the respective bond lengths in **3** and **9**, due to the smaller ionic radius of Re^V with respect to Re^I.

Hirshfeld surface analysis for compounds **3** and **9**.

In Figure 8a,b the HS decorated with the d_{norm} parameter and the fingerprint plots of compound **3** are presented respectively. The percentage contribution of the different type of interactions $\text{H}\cdots\text{H}$, $\text{O}\cdots\text{H}/\text{H}\cdots\text{O}$, $\text{C}\cdots\text{H}/\text{H}\cdots\text{C}$, $\text{C}\cdots\text{O}/\text{O}\cdots\text{C}$, $\text{O}\cdots\text{O}$, $\text{N}\cdots\text{O}/\text{O}\cdots\text{N}$, and $\text{C}\cdots\text{C}$, are 18.6, 42.7, 16.5, 8.2, 8.1, 2.6, and 2.0% respectively. All the hydrogen bond interactions discussed in the intermolecular interactions section for compound **3** are clearly indicated in Figure 8a,b.

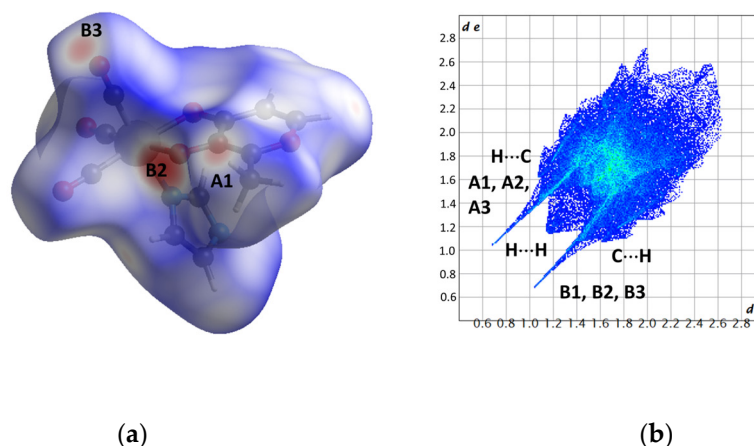


Figure 8. (a) d_{norm} decorated Hirshfeld surface and (b) fingerprint plot for compound **3**. A1, A2, A3 and B1, B2, B3 are the donor and acceptor contact points of $\text{C6—H6C}\cdots\text{O23}$, $\text{N12—H12N}\cdots\text{O1}$, and $\text{C4—H4}\cdots\text{O23}$ hydrogen bond interactions, respectively. $\text{H}\cdots\text{H}$ represents the area that contributes the H/H contacts and $\text{H}\cdots\text{C}/\text{C}\cdots\text{H}$ the area of contribution of H- π donor/acceptor contacts.

The HS decorated with the d_{norm} parameter and the fingerprint plots of compound **9** are presented in Figure 9a,b, respectively. The percentage contribution of the different type of interactions $\text{H}\cdots\text{H}$, $\text{O}\cdots\text{H}/\text{H}\cdots\text{O}$, and $\text{C}\cdots\text{H}/\text{H}\cdots\text{C}$ are 58.2, 15.8, and 25.4% respectively. All the hydrogen bond interactions discussed in the intermolecular interactions section for compound **9** are clearly indicated in Figure 9a,b. An $\text{H}\cdots\text{H}$ contact is equal to or less than the 2.4 Å which is the sum of the VdW radius (1.2 Å) of hydrogen atoms.

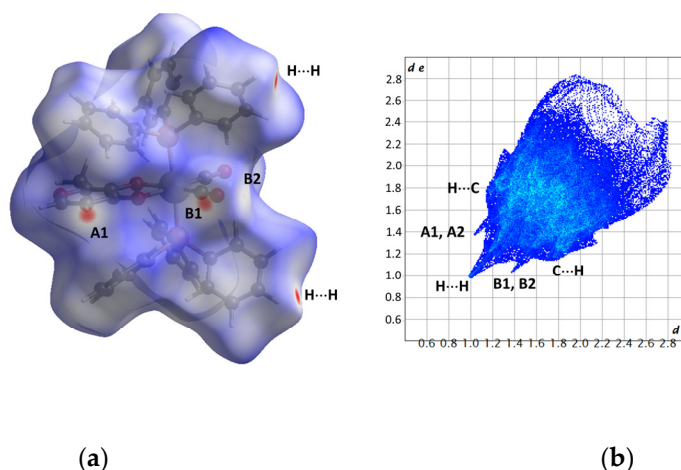


Figure 9. (a) d_{norm} decorated Hirshfeld surface and (b) fingerprint plot for compound **9**. A1, A2 and B1, B2 are the donor and acceptor contact points of $\text{C22—H22}\cdots\text{O32}$ and $\text{C23—H23}\cdots\text{O32}$ hydrogen bond interactions, respectively. $\text{H}\cdots\text{H}$ represents the area that contributes the H/H contacts and $\text{H}\cdots\text{C}/\text{C}\cdots\text{H}$ the area of contribution of H- π donor/acceptor contacts.

The Re complexes that were synthesized and characterized in this work will serve in the immediate future as prototypes for the synthesis of the corresponding radioactive ana-

logues with ^{99m}Tc in place of Re. The two metals have similar physicochemical properties and give complexes of the same structure and size [5], so the synthesis of the complexes can be transferred at the radioactive ^{99m}Tc level within the specialized facilities of NCSR “Demokritos”. As ^{99m}Tc is the most commonly used radioisotope in clinical practice for γ -tomographic imaging with SPECT, the ^{99m}Tc complexes will be evaluated through in vivo biodistribution studies as potential radiopharmaceuticals.

4. Conclusions

The [2+1] mixed ligand combination used in this study led to neutral and stable rhenium complexes of the general formula $[\text{Re}(\text{CO})_3(\text{OO})\text{L}]$ in high yields. These complexes serve as a successful illustration of utilizing the OO donor atom system, acting as a bidentate ligand for the *fac*- $[\text{Re}(\text{CO})_3]^+$ core. They encourage further investigation as prototypes for developing other innovative precursors with diverse applications. Additionally, the ligand system $(\text{OO})^{1,2}/\text{L}_{(1-3)}$ demonstrates the ability to form stable complexes with rhenium, indicating its promise for generating compounds tailored to specific targets by adjusting and derivatizing both maltol and kojic acid.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cryst14060515/s1>. Figure S1. FT-IR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{H}_2\text{O}]$ (2). Figure S2. FT-IR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^2)\text{H}_2\text{O}]$ (2). Figure S3. FT-IR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{L}_1]$ (3). Figure S4. FT-IR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{L}_2]$ (4). Figure S5. FT-IR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{L}_3]$ (5). Figure S6. FT-IR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^2)\text{L}_1]$ (6). Figure S7. FT-IR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^2)\text{L}_2]$ (7). Figure S8. FT-IR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^2)\text{L}_3]$ (8). Figure S9. FT-IR of $[\text{Re}(\text{CO})_2(\text{OO}^1)(\text{L}_3)_2]$ (9). Figure S10. FT-IR of $[\text{Re}(\text{CO})_2(\text{OO}^2)(\text{L}_3)_2]$ (10). Figure S11. ^1H NMR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{H}_2\text{O}]$ (1) in $\text{DMSO}-d_6$ at 25 °C. Figure S12. ^1H NMR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^2)\text{H}_2\text{O}]$ (2) in $\text{DMSO}-d_6$ at 25 °C. Figure S13. ^1H NMR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{L}_1]$ (3) in $\text{DMSO}-d_6$ at 25 °C. Figure S14. ^1H NMR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{L}_2]$ (4) in $\text{DMSO}-d_6$ at 25 °C. Figure S15. ^1H NMR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{L}_3]$ (5) in $\text{DMSO}-d_6$ at 25 °C. Figure S16. ^1H NMR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^2)\text{L}_1]$ (6) in $\text{DMSO}-d_6$ at 25 °C. Figure S17. ^1H NMR of $[\text{Re}(\text{CO})_2(\text{OO}^2)(\text{L}_3)_2]$ (10) in $\text{DMSO}-d_6$ at 25 °C. Figure S18. $^1\text{H}-^{13}\text{C}$ HSQC NMR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)\text{L}_1]$ (3) in $\text{DMSO}-d_6$ at 25 °C. Figure S19. $^1\text{H}-^{13}\text{C}$ HSQC NMR of *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^2)\text{L}_1]$ (6) in $\text{DMSO}-d_6$ at 25 °C. Figure S20. (ESI-MS) spectrum of $[\text{Re}(\text{CO})_2(\text{OO}^1)(\text{L}_3)_2]$ (9). Figure S21. (ESI-MS) spectrum of $[\text{Re}(\text{CO})_2(\text{OO}^2)(\text{L}_3)_2]$ (10). Figures S22–S33. HPLC/Autoscaled Chromatograms for $\text{OO}^{1,2}$ and Re complexes (1–10). Figure S34. Characteristic ^{31}P NMR of L_3 , *fac*- $[\text{Re}(\text{CO})_3(\text{OO}^1)(\text{L}_3)]$ (6) and $[\text{Re}(\text{CO})_2(\text{OO}^1)(\text{L}_3)_2]$ (9). The supporting information can be downloaded free of charge via <http://www.ccdc.cam.ac.uk/conts/retrieving.html> (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; Fax: +44 1223 336033; E-mail: deposit@ccdc.cam.ac.uk).

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