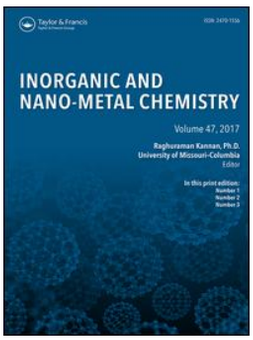


Inorganic and Nano-Metal Chemistry

ISSN: 2470-1556 (Print) 2470-1564 (Online) Journal homepage: http://www.tandfonline.com/loi/lsrt21

Synthesis, thermal properties, and biological study of metal(II) nicotinamide complexes containing fumarate dianion and fumaric acid: Crystal structure of $[Ni(H_2O)_4(nia)_2](fum)\cdot(H_2fum)$

Adedibu C. Tella, Samson O. Owalude, Gift Mehlana, Sunday J. Olatunji, David O. Adetitun, Mathew O. Kolawole, Nzikahyel Simon & Lukman O. Alimi

To cite this article: Adedibu C. Tella, Samson O. Owalude, Gift Mehlana, Sunday J. Olatunji, David O. Adetitun, Mathew O. Kolawole, Nzikahyel Simon & Lukman O. Alimi (2017) Synthesis, thermal properties, and biological study of metal(II) nicotinamide complexes containing fumarate dianion and fumaric acid: Crystal structure of $[Ni(H_2O)_4(nia)_2](fum)\cdot(H_2fum)$, Inorganic and Nano-Metal Chemistry, 47:6, 859-864, DOI: 10.1080/15533174.2016.1212234

To link to this article: http://dx.doi.org/10.1080/15533174.2016.1212234

Accepted author version posted online: 17 Aug 2016.
Published online: 17 Aug 2016.

INORGANIC AND NANO-METAL CHEMISTRY
2017, VOL. 47, NO. 6, 859–864
http://dx.doi.org/10.1080/15533174.2016.1212234

Taylor & Francis
Taylor & Francis Group

Synthesis, thermal properties, and biological study of metal(II) nicotinamide complexes containing fumarate dianion and fumaric acid: Crystal structure of $[Ni(H_2O)_4(nia)_2](fum)\cdot(H_2fum)$

Adedibu C. Tella[a], Samson O. Owalude[a], Gift Mehlana[b], Sunday J. Olatunji[a], David O. Adetitun[c], Mathew O. Kolawole[c], Nzikahyel Simon[d], and Lukman O. Alimi[e]

[a]Department of Chemistry, University of Ilorin, Ilorin, Nigeria; [b]Department of Chemistry, Centre for Supramolecular Chemistry Research, University of Cape Town, Cape Town, South Africa; [c]Department of Microbiology, University of Ilorin, Ilorin, Nigeria; [d]Department of Chemistry, University of Uyo, Uyo, Nigeria; [e]Department of Chemistry and Polymer Science, Stellenbosch University, Stellenbosch, South Africa

ABSTRACT

New divalent transition metal nicotinamide (nia) complexes containing fumarate (fum) dianion and fumaric acid (H_2fum), $[M(H_2O)_4(nia)_2](fum)\cdot(H_2fum)$ [M = Co (**1**), Cu (**2**), and Ni (**3**)] have been synthesized. The compounds were characterized by elemental analyses, infrared, UV-vis, XRPD, and TGA. Structural analysis of **3** using single-crystal X-ray diffraction technique revealed that the Ni(II) ion is coordinated by four aqua and two nia ligands in an octahedral geometry. The structure of **3** is completed with fumarate (fum^{2-}) dianion acting as a counterion while fumaric acid (H_2fum) is present as a molecule of solvation. The three complexes were investigated for biological activities.

ARTICLE HISTORY
Received 18 December 2015
Accepted 9 July 2016

KEYWORDS
Fumarate complexes; nicotinamide; crystal structure; XRPD analysis; biological activity

Introduction

Design and synthesis of new complexes with potent biological activities often require the preparation of derivatives of the existing ones.[1] This can be achieved by introducing transition metals into the structures of the existing drugs, and literature reports have revealed that in some cases the efficacy of the drugs was enhanced on coordination to metals.[2] Numerous reports on the effects of metal-drug interaction with the objective of finding more effective pharmaceutical agents have, therefore, appeared in the chemical literature.[3] Apart from other exciting properties and applications,[4–6] metal carboxylate complexes have been reported to be highly active as pharmaceutical agents.[7–9] For this purpose, dicarboxylates are the most widely employed as biological molecules due to the four electron oxygen donor atoms in their structure, which enhances non-covalent bonds interactions between inorganic moieties through their carboxylate groups.[10] Fumarate (fum) dianion is a typical dicarboxylate generated from dicarboxylic acid, fumaric acid (Scheme 1a).

A number of transition metal dicarboxylate complexes having mononuclear and dinuclear structures constructed from fum dianion framework have been reported.[11] Reports on the antimicrobial properties of metal complexes derived from dicarboxylic acids exist in the literature.[12–14] Nicotinamide (nia) (Scheme 1b), also known as niacin, is a derivative of vitamin B; it is water soluble and contains a coenzyme NAD^+ that acts as an oxidizing agent in the conversion of alcohols to aldehydes and ketones.[15] Deficiency of nia results in the disease condition known as pellagra, and nia is one of the nitrogen donor ligands that have been employed in the treatment of a number of diseases such as atopic eczema, hypercholesteremia, and some psychological disorders.[15–17] Increase in the solubility of some physiologically potent pharmaceutical agents has been reportedly enhanced by complexation with nia.[18]

Transition metal ions play a very significant role in the biological processes in human systems; they are found to be abundant in the active sites or as components in structures of most enzymes.[15] Our choice of metals in this study stems from the fact that cobalt is an essential element in the formation of cobalamin or vitamin B12 and is also required for the normal functioning of the pancreas [17] while copper and nickel are among the most abundant transition metals in the human body.[19–21] We hereby report the synthesis, characterization, and antimicrobial activity of cobalt(II), copper (II), and nickel(II) complexes containing both nia and fumaric acid in their structures in continuation of our studies on synthesis and characterization of biologically important ligands.[22–24] The crystal structure of a new nickel(II) complex containing fumaric acid and nia is herein reported.

Experimental

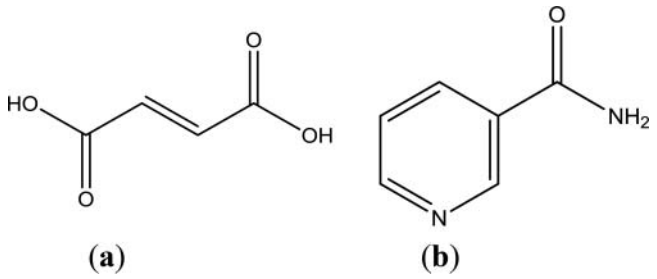
Materials and instrumentation

All chemicals were commercially sourced from Sigma-Aldrich and were used as received. Elemental analyses (C, H, N) were

CONTACT Adedibu C. Tella ac_tella@yahoo.co.uk Department of Chemistry, University of Ilorin, P.M.B.1515, Ilorin, Kwara Nigeria.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/lsrt.

CCDC 956975 contains the supplementary crystallographic data for complex **3**. Copies of the data can be obtained free of charge at www.ccdc.cam.ac.uk/conts/retrieving.html or from the Cambridge Crystallographic Data Center, 12 Union Road, Cambridge CB2 1EZ, UK, Fax: +44-1223-336-033; E-mail: deposit@ccdc.cam.ac.uk.



Scheme 1. The chemical structure of (a) fumaric acid, and (b) nicotinamide.

performed by standard methods using a Carlo Erba Model EA1108 elemental analyzer at Medac Laboratory, UK. Infrared (IR) spectra were recorded on a FTIR-8501 Shimadzu spectrophotometer using KBr pellets between 4000 and 400 cm^{-1}. A Jenway 6405 UV-Vis spectrophotometer was used for the UV-vis spectra analyses while the XRPD patterns were recorded on a Bruker D8 Advance X-ray diffractometer. A TGA Q500 V20.13 Build 39 instrument was used for thermal analysis. Measurements were made under a nitrogen atmosphere at a heating rate of 10°C min^{-1} from room temperature up to a temperature of 600°C.

Synthesis of the metal(II) nicotinamide complexes

a. $[Cu(H_2O)_4(Nia)_2](Fum)\cdot(H_2Fum)$ (**2**) was prepared as its cobalt analog **1** except that $Cu(NO_3)_2\cdot4H_2O$ (0.260 g, 1 mmol) was used instead of $Co(NO_3)_2\cdot6H_2O$. The product was obtained as blue crystals. Mr.: 609.82 g mol^{-1}, Yield: 55.3%, m. pt: 258°C, Anal. Calcd for $C_{20}H_{26}N_4CuO_{14}$ (%): C, 39.56; H, 4.26; N, 9.18; Found: C, 39.54; H, 4.23; N, 9.20. IR (KBr pellet, cm^{-1}) 3443s, 3379m, 3186w, 2360vw, 1934m, 1704vs, 1695vs, 1608m, 1577vs, 1558vs, 1427m, 1371vs, 1327w, 1197w, 1155w, 1058w, 997w, 802vw, 690m, 657vw.
b. $[Co(H_2O)_4(Nia)_2](Fum)\cdot(H_2Fum)$ (**1**), $Co(NO_3)_2\cdot6H_2O$ (0.291 g, 1 mmol) in 10 mL ethanol was added drop wise to a stirred mixture of 10 mL methanolic solution of fumaric acid (0.232 g, 2 mmol) and 10 mL ethanolic solution of nia (0.244 g, 2 mmol). The stirring was continued for 1 h at room temperature. The solution was left to stand at room temperature; brown crystals were produced after several days. The crystals were collected through filtration, washed several times with a mixture of ethanol and methanol in ratio 2:1, and dried under vacuum. Mr.: 605.38 g mol^{-1}, Yield: 51.6%, m.pt: 215°C, Anal. Calcd for $C_{20}H_{26}N_4CoO_{14}$ (%): C 39.64; H 4.29; N 9.25; Found: C, 39.63; H, 4.31; N, 9.24. IR (KBr pellet, cm^{-1}) 3447s, 3377m, 3205s, 2320vw, 1934m, 1911m, 1705vs, 1674vs, 1573vs, 1541vs, 1429m, 1371vs, 1311w, 1198w, 1118w, 779m, 688m, 644vw, 561m.
c. $[Ni(H_2O)_4(Nia)_2](Fum)\cdot(H_2Fum)$ (**3**) was prepared as the previous two complexes except that $Ni(NO_3)_2\cdot6H_2O$ (0.291 g, 1 mmol) was used instead of $Co(NO_3)_2\cdot6H_2O$ in **1** and $Cu(NO_3)_2\cdot4H_2O$) in **2**. The product was obtained as green crystals suitable for X-ray crystallography. Mr.: 605.16 g mol^{-1}, Yield: 65.6%, m. pt: 202°C, Anal. Calcd for $C_{20}H_{26}N_4NiO_{14}$ (%): C 39.66; H 4.29; N 9.25; Found: C, 39.62; H, 4.29; N, 9.20. IR (KBr pellet, cm^{-1}) 3445 s, 3377 m, 3207w, 3057vw, 2852m, 2486w, 1934 m, 1705vs, 1674vs, 1575vs, 1541vs, 1426m, 1371vs, 1311w, 1201w, 1178w, 1120w, 1016w, 976w, 808vw, 779 m, 688 m, 646 s, 561w, 503 m.

Antibacterial experiments

Isolation and detection of bacteria from jet fuel

Isolation of microorganisms was done using nutrient agar, brain heart infusion agar, and trypticase soy broth agar. The isolates were characterized morphologically, biochemically, and eventually sequenced analytically and blasted after DNA extraction and polymerase chain reaction analysis. Four bacterial isolates: *Staphylococcus aureus, Bacillus flexus, Brevibacillus* sp., and *Exiguobacterium* sp. were isolated from jet fuel. The isolates were screened for antibacterial properties using standardized sensitivity test agar. The four laboratory isolates were subjected to different concentrations of the metal complex using the agar diffusion method and zones of inhibition were interpreted using standard procedure of the Clinical and Laboratory Standards Institute.[25]

Minimum inhibitory concentration (MIC)

MIC of the samples was determined using the broth dilution technique. Nutrient broth was seeded with standardized inocula of the test organisms. These were subjected to varying concentrations of the nickel complex, fumaric acid, and nia samples.

Ten clinical antibiotics with their concentrations given in parentheses were used as control, as recommended by the Clinical and Laboratory Standards Institute.[25] The antibiotics used to challenge isolates were those for Gram-positive bacteria since all the isolates are Gram-positive. The clinical antibiotics used are amoxycillin (21 μg), ofloxacin (1 μg), streptomycin (10 μg), chloramphenicol (20 μg), ceftazidime (30 μg), gentamycin (10 μg), pefloxacin (1 μg), cotrimoxazole (20 μg), ciprofloxacin (10 μg), and erythromycin (30 μg).

Crystallographic analysis of 3

Suitable crystals of complex **3** for single-crystal X-ray diffraction were obtained by slow evaporation of its solution in a mixture of ethanol and methanol (2:1). Data were collected at 100 K on a Bruker D8 Venture Dual Source diffractometer equipped with a CMOS detector using graphite-monochromated Mo Kα radiation ($\gamma = 0.71073$ Å). The crystal structure was solved by charge flipping using Superflip [26] and refined by full-matrix least-squares methods based on F^2 using SHELXL.[27] Molecular graphics or complete structure solution, refinement and analysis program was achieved using OLEX2.[28] Crystal data and refinement details are listed in Table 1 while selected bond distances and angles are summarized in Table 2.

Results and discussion

The structural composition of the complexes was determined by elemental analysis, FT-IR and UV-vis spectroscopy, and XRPD analysis. The compounds were generally soluble in distilled water and DMSO, but insoluble in other common organic

Table 1. Crystal data and structure refinement for complex **3**.

Empirical formula	$C_{20}H_{26}N_4NiO_{14}$
Formula weight	605.16
Temperature (K)	100.0
Crystal system	triclinic
Space group	P-1
a (Å)	7.2272(4)
b (Å)	8.2329(5)
c (Å)	11.2178(7)
α (°)	89.209(4)
β (°)	73.639(4)
γ (°)	71.596(4)
Volume (Å^3)	605.61(6)
Z	1
ρ_{calc} (mg/mm^3)	1.659
m/mm^{-1}	1.903
F(000)	314.0
2θ range for data collection	8.242–136.824°
Index ranges	$-8 \le h \le 8$, $-9 \le k \le 9$, $-8 \le l \le 13$
Reflections collected	5231
Independent reflections	2137 [R(int) = 0.0363]
Data/restraints/parameters	2137/0/181
Goodness-of-fit on F^2	1.075
Final R indexes [I $\ge 2\sigma$ (I)]	$R_1 = 0.0473$, $wR_2 = 0.1237$
Final R indexes [all data]	$R_1 = 0.0605$, $wR_2 = 0.1337$
Largest diff. peak/hole (e Å^{-3})	0.94/−0.72

solvents. The elemental analysis data of the complexes are in good agreement with the formula $[M(H_2O)_4(nia)_2](fum)\cdot(H_2fum)$, which indicate that the complexes contain two molecules of nia, a fum dianion, and fumaric acid ligands as well as four coordinated water molecules per mole formula unit. Determination of stoichiometric ratio using Job's method also suggests a mole ratio of 1:2:2 metal to nia to fumaric acid to fum dianion in agreement with the proposed structure. The structure of **3** was confirmed by X-ray single-crystal diffraction analysis.

Infrared spectra studies

The IR spectra of the metal carboxylates recorded in the region of 4000–400 cm^{-1} were compared with those of the ligands as shown in Figure S1. The IR spectra of the metal carboxylates were not entirely the same as those of the ligand; there is either a shift or a complete disappearance of some characteristic frequencies in the reactant and appearance of some new frequencies in the complexes.

The characteristic bands of fum, fumaric acid (H_2fum), and nia were observed in the IR spectra of complexes **1–3**. The presence of strong but broad bands between 3450 and 2500 cm^{-1}, which were generally centered at around 3337 cm^{-1} in all the three complexes, were assigned to the ν(OH) vibrations of coordinated water molecules with overlapping N–H and C–H stretches of the organic ligands.[1] The ν(NH) in free nia normally appear at 3366 and 3157 cm^{-1}, but in compounds **1–3** the amide absorption bands were observed at higher wavenumber between 3445 and 3200 cm^{-1} due to the involvement of this group in the hydrogen bonding.[13] The bands between 2952 and 3058 cm^{-1} are due to aromatic and aliphatic ν(CH) stretching vibrations.[13] The stretching bands of the amide carbonyl group were observed in the complexes at 1674, 1695, and 1674 cm^{-1} for **1**, **2**, and **3**, respectively, and when compared with that of free nia usually observed at 1681 cm^{-1} it can be concluded that the carbonyl group is not involved in coordination.[29,30] The presence of strong bands at 1705, 1704, and 1705 cm^{-1}, respectively, in **1**, **2**, and **3** is attributed to the ν(C = O) stretch of the COOH group.[14] The C–O stretching and O–H bending vibrations were observed in **1** at 1429 and 1198 cm^{-1}, in **2** at 1425 and 1197 cm^{-1}, and in **3** at 1426 and 1201 cm^{-1}.[31] The $\Delta\nu$ ($\nu_{as} - \nu_s$) values for the carboxylate group in **1**, **2**, and **3** are 202, 206, and 204 cm^{-1}, respectively, which suggest monodentate coordination of fum ions in the three complexes.[32] This result is in variance with a bidentate coordination mode predicted for a copper(II) complex containing analogous succinate ligand.[13] The medium and strong bands in the 1000–500 cm^{-1} region are attributed to ring stretching, deformation, and lattice vibrations occurring in the complexes.[1]

Table 2. Selected bond distances (Å) and angles (°) for complex **3**.

Bond length (Å)		Bond angles (°)	
Ni1–O3	2.0594	O3w–Ni1–O3w	180.00(9)
Ni1–O4	2.0519	N8–Ni1–O4w	91.08(9)
Ni1–N8	2.1199	O4w–Ni1–O3w	90.45(8)
		O4w–Ni1–O4w	180.00(9)

Thermal analysis of 1 and 3

The thermal stabilities of the complexes were investigated using thermogravimetric (TG) analysis carried out in a nitrogen atmosphere at a heating rate of 10°C min^{-1} from room temperature to 600°C. The TG diagrams of complexes **1** and **3** are shown in Figure 1a and b, respectively. Complex **1** starts to decompose at 53°C and this step continues up to 205°C attributable to simultaneous loss of both the fum ions and fumaric acid ligands (calcd./found: 37.71/37.5%).[33] Loss of the four coordinated water molecules follows between 205°C and 230°C (calcd./found: 11.81/11.10%). The third weight loss between 230°C and 598°C was attributed to the departure of the nia ligand (calcd./found: 40.01/38.9%). The TG diagram of complex **3** is shown in Figure 1b. The complex was thermally stable

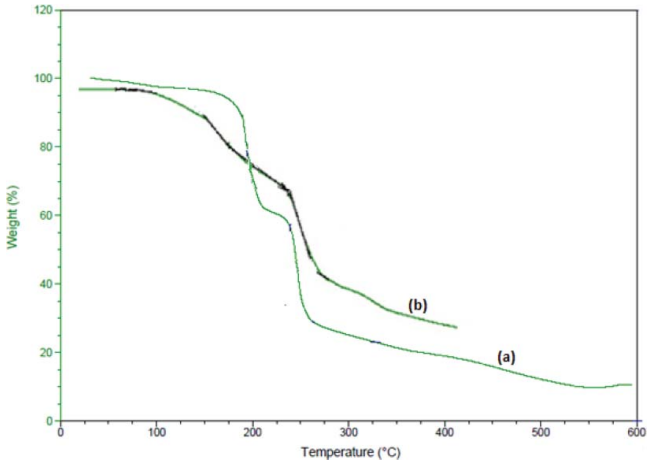


Figure 1. The TGA curve for (a) $[Cu(H_2O)_4(Nia)_2](Fum)\cdot(H_2Fum)$ (**1**) and (b) $[Ni(H_2O)_4(Nia)_2](Fum)\cdot(H_2Fum)$ (**3**).

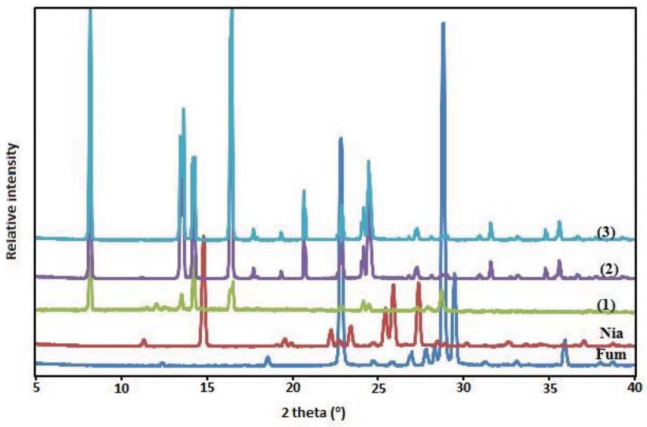


Figure 2. XRPD pattern of fumaric acid, nicotinamide, $[Cu(H_2O)_4(Nia)_2](Fum)\cdot(H_2Fum)$ **(1)**, $[Co(H_2O)_4(Nia)_2](Fum)\cdot(H_2Fum)$ **(2)**, and $[Ni(H_2O)_4(Nia)_2](Fum)\cdot(H_2Fum)$ **(3)**.

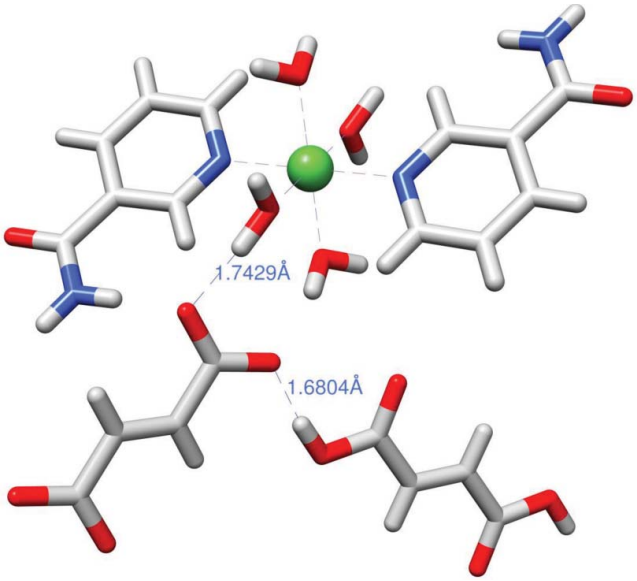


Figure 3. ORTEP diagram of **3** with numbering scheme adopted. Ellipsoids are shown at 50% probability level.

up to 133°C and starts to decompose at this temperature up to 186°C; this step is assigned to simultaneous loss of four coordinated water and fumaric acid molecules (calcd./found: 30.71/26.99%).[34] The results indicate that the metal-water bond strength is almost the same for all the water molecules.[34] The experimental values for the mass loss of the partial dehydration stage and loss of fumaric acid molecule are well consistent with the calculated values. At the temperature of 226°C, loss of all the ligands except the two coordinated nia molecules was evident from the TGA curve in Figure 1b (calcd./found: 50.00/52.24%). The final decomposition step involves the release of nia ligands as well as formation of metal oxide as the final product.

X-ray powder diffraction analysis

The XRPD patterns of the metal carboxylates **1, 2**, and **3** were obtained and compared with those of the ligands as shown in Figure 2. The XRPD patterns of the metal carboxylates were found to be different from those of the ligand and the appearance of some new peaks in the three compounds and also either a shift or disappearance of some characteristic peaks in the ligands were noticed, indicating the formation of new compounds. For example, in compound **3**, new peaks were observed at 2θ = 8.2, 13.7, 16.5, 17.7, 20.7, 22.8, 24.5. 27.2, 31.6, and 34.8. Quantitative estimation of the 2θ values in the PXRD patterns of **2** and that of **3** was carried out. The major peaks in the PXRD pattern of **2** were observed at 2θ = 8.15, 12.04, 13.5, 14.3, 16.5, 22.8, 24.5, 27.1, 28.7, 29.5, 33.2, and 36.5 while those of **3** were observed at 2θ = 8.2, 13.7, 16.5, 17.7, 19.8, 20.7, 22.8, 24.2, 27.2, 31.6, and 34.8. It can be observed that the 2θ values for products **1** are also in close agreement with those of **2** and **3**—an indication that the three compounds are isostructural in agreement with the IR spectral data.

Description of the crystal structure of 3

The ORTEP representation of the structure of **3**, indicating atom numbering scheme, is shown in Figure 3. The crystal data are summarized in Table 1 while the selected bond length and angles are given in Table 2. The structure of **3** consists of a $[Ni(H_2O)_4(Nia)_2]^{2+}$ monomeric complex cation with the nickel (II) center coordinated to four water molecules in plane and two nia molecules at the axial positions in an almost ideal octahedral arrangement. The structure of **3** is completed with a fum dianion and one fumaric acid molecule, another case of a very rare situation encountered in coordination compounds.[13] The complex crystallizes in a triclinic space group P-1 with the asymmetric unit consisting of exactly half the molecule. Bond distances and angles in **3** did not deviate significantly from those reported for similar structures in the literature [13,14] and also the geometrical parameters of the nia ligands are normal.[35]

The coordinated water molecules are involved in intramolecular hydrogen bonding; this is evident in the fum anions and the H_2fum molecules that are linked by the O–H···O hydrogen bonds resulting in a one-dimensional alternating chain as reported for a closely related molecule.[13] The effect of these hydrogen bonds on the IR was well pronounced in the spectra of the three complexes. The carboxylic group of the fumaric acid molecule is connected to the fum dianion O7 atom through the O–H resulting in a short hydrogen bond. The Ni–O distances 2.0594(19) and 2.0519(19) Å are slightly shorter than those found in the related structures [1,13,14,36] but have the Ni–N bond distance of 2.120(19) Å longer than those reported for similar compounds.[1,36] The measured fum dianion and fumaric acid C–O, C = C, C = O, C–C (1.261(3), 1.328(6), 1.212(3), and 1.484(4) Å, respectively) bond lengths in **3** are very close to those reported for the neutral fumaric acid molecule (1.293, 1.348, 1.224, and 1.465 Å, respectively).[37] The determined mean values of the angles, C = C–C 121.3(3)°, C–C–O 112.5(2)°, and O = C–O 123.8(3)°, in the fumaric acid moiety are all within the range usually found in carboxylic acids except C–C = O 123.8(3)°, which is much longer than the reported value of 119.9°.[37] The other geometrical parameters in **3** are all close to the expected values. The complex cation, $[Ni(H_2O)_4(Nia)_2]^{2+}$, fumaric acid, and fum dianion in **3** are connected by a network of hydrogen bonds. The

Table 3. Antibacterial activities of complex **3**, nicotinamide, and fumaric acid at different concentrations on test bacteria.

	Zones of inhibition (mm)			
Concentration (g L^{-1})	*S. aureus*	*B. flexus*	*B.* sp.	*E.* sp.
Complex **3**				
0.01	0.00	0.00	0.00	0.00
0.10	0.00	0.00	0.00	0.00
1.00	0.00	0.00	0.00	0.00
10.00	0.00	24.00	15.00	0.00
Nicotinamide				
3.00	0.00	0.00	0.00	0.00
7.50	0.00	0.00	0.00	0.00
15.00	0.00	0.00	13.00	0.00
35.00	16.00	0.00	12.00	0.00
Fumaric acid				
2.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
10.00	0.00	0.00	0.00	0.00
19.10	0.00	11.00	12.00	0.00

complex cation interact with the fum through the coordinated water molecules via O–H···O and the fum connects with H_2 fum molecule through the carboxylic acid O–H via O–H···O hydrogen bonds.

Antibacterial results

The results of the sequenced and blasted DNA extracts of the organisms yielded four bacterial isolates: *S. aureus, B. flexus, Brevibacillus* sp., and *Exiguobacterium* sp. Table S1 shows the names of the organisms, and their domain/phylum and origin.

The results of the antibacterial screening as displayed in Tables 3 and 4 show the activity of the test compounds when challenged with test organisms at different concentrations. The nickel complex had its greatest effect on *B. flexus* followed closely by *Brevibacillus* sp., but did not show any effect on *S. aureus* and *Exiguobacterium* sp. Nia showed high activity against *S. aureus* and *Brevibacillus* sp. at 35 g L^{-1}, but did not exhibit any effect on the other two organisms. At concentration of 15 g L^{-1}, nia was able to inhibit the growth of *Brevibacillus* sp., but was unable to do the same for others at this concentration. Fumaric acid displayed antibacterial activity against *B. flexus* and *Brevibacillus* sp. The highest susceptibility to the nickel complex was recorded for *B. flexus* while that to nia was recorded for *S. aureus* and that to fumaric acid was recorded for *Brevibacillus* sp.

All the test samples did not show activity at lower concentrations as portrayed in Tables 3 and 4. The results are in harmony with the work of previous workers that antibacterial property is usually dependent on concentration.[38,39] The higher the concentration, the higher the antibacterial activity. This study further shows that organisms from the same domain and phylum can still behave differently to test compounds when their genus and species are different. The test compounds were not bactericidal but bacteriostatic.

Table 4. Inhibition zones (mm) of control clinical antibiotics on the test organisms.

Organism	Amx	Ofl	Str	Chl	Cfx	Gen	Pef	Cot	Cpx	Ery
S. aureus	0.00	18	0.00	10	0.00	0.00	0.00	26	25	0.00
B. flexus	0.00	22	0.00	0.00	0.00	0.00	0.00	0.00	24	0.00
B. sp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E. sp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Amx, Amoxycillin; Ofl, Ofloxacin; Str, Streptomycin; Chl, Chloramphenicol; Cfx, Ceftazidime; Gen, Gentamycin; Pef, Pefloxacin; Cot, Cotrimoxazole; Cpx, Ciprofloxacin; Ery, Erythromycin. >11 mm = sensitive; 7–10 mm = moderately sensitive; 2–6 mm = resistant.

Conclusions

Three new divalent transition metal complexes containing fum dianion, fumaric acid, and nia have been prepared and characterized by elemental analysis, IR, UV-vis, TGA, and XRPD. The structure of $[Ni(H_2O)_4(nia)_2](fum).(H_2fum)$ (**3**) was confirmed by single-crystal X-ray diffraction analysis. The IR spectra and XRPD showed that the three complexes are isostructural. The presence of a non-coordinated fum dianion and a fumaric acid molecule in these compounds represent one of the rare occurrences in coordination chemistry. The antimicrobial screening data revealed that complex **3** exhibits more efficient biological activity than the free ligands.

Acknowledgments

The authors are grateful to Dr. Michael Worle from ETH, Zurich, for help with structure determination of compound **3** during the 2013 Zurich School of Crystallography, Institute of Organic Chemistry, University of Zurich.

References

1. Kose, D. A.; Zumreoglu-Karan, B.; Unaleroglu, C.; Sahin, O.; Buyukgungor, O. *J. Coord. Chem.* **2006**, *59*, 2125.
2. Krauth-Siegel, R. L.; Bauer, H.; Schirmer, R. H. *Angew. Chem. Int. Ed.* **2005**, *44*, 690.
3. (a) Abdelhamid, H. N.; Wu, H.-F. *Anal. Chim. Acta.* **2012**, *751*, 94. (b) Ott, I.; Gust, R. *Arch. Pharm.* **2007**, *340*, 117. (c) Farrell, N. P. Antitumour Activity of Metal Complexes. In *Transition Metal Complexes as Drugs and Chemotherapeutic Agents*; James, B. R.; Ugo, R.; Eds.; Reidel-Kluwer Academic Press: Dordrecht, **1989**, vol. 11. (d) Farrell, N. P. *The Uses of Inorganic Chemistry in Medicine*; The Royal Society of Chemistry: Cambridge, **1999**. (e) Warra, A. A. *J. Chem. Pharm. Res.* **2011**, *3*, 951.(f) Rafique, S.; Idrees, M.; Nasim, A.; Akbar, H.; Athar, A. *Biotechnol. Mol. Biol. Rev.* **2010**, *5*, 38.
4. Eliseeva, S. V.; Pleshkov, D. N.; Lyssenko, K. A.; Lepnev, L. S.; Buenzli, J. C. G.; Kuzminat, N. P. *Inorg. Chem.* **2010**, *49*, 9300.
5. Kim, Y. J.; Lee, E. W.; Jung, D. Y. *Chem. Mater.* **2001**, *13*, 2684.
6. Seki, K.; Mori, W. *J. Phys. Chem. B* **2002**, *106*, 1380.
7. Mohamed, A. Y. A. *J. Coord. Chem.* **1993**, *29*, 233.
8. Coyle, B.; Kavanagh, K.; McCann, M.; Devereux, M.; Geraghty, M. *Biometals* **2003**, *16*, 321.
9. Reza, M. Y.; Hossain, M. B.; Islam, M. S.; Alam, S. *Pak. J. Biol. Sci.* **2003**, *6*, 1314.
10. Kitagawa, S.; Kitaura, R.; Noro, S. I. *Angew. Chem. Int. Ed.* **2004**, *43*, 2334.
11. (a) Cañadillas-Delgado, L.; Fabelo, O.; Cano, J.; Pasán, J.; Delgado, F. S.; Lloret, F.; Julve, M.; Ruiz-Pérez, C. *CrystEngComm* **2009**, *11*, 2131. (b) Chen, H.; Tang, T.; Wang, J.; Liu, P.; Zhuo, Z. *Acta Crystallogr. Sect. E* **2011**, *E67*, m1717.
12. (a) Guillou, N.; Livage, C.; Ferey, G. *Eur. J. Inorg. Chem.* **2006**, 4963. (b) Rao, C. N. R.; Natarajan, S.; Vaidhyanathan, R. *Angew. Chem. Int. Ed.* **2004**, *43*, 1466.
13. Demir, S.; Yilmaz, V. T.; Sariboga, B.; Buyukgungor, O.; Mrozinski, J. *J. Inorg. Organomet. Polym.* **2010**, *20*, 220.
14. Demir, S.; Yilmaz, V. T.; Mrozinski, J.; Lis, T.; Holynska, M. *Z. Naturforsch* **2010**, *65b*, 695.

15. Williams, C. J.; Morris, H.; Svorec, J.; Valkova, M.; Valko, M.; Moncol, J.; Mazur, M.; Valach, F.; Melnik, M. *J. Mol. Struct.* **2003**, *659*, 53.
16. Andersen, F. A. *Int. J. Toxicol.* **2005**, *24*, 1.
17. Geraghty, M.; Cronin, J. F.; Devereux, M.; McCann, M. *Biometals* **2000**, *13*, 1.
18. Truelove, J.; Bawarshi-Nassar, R.; Chen, N. R.; Hussain, A. *Int. J. Pharm.* **1984**, *19*, 17.
19. Boh, A. W. *Curr. Sep.* **1999**, *18*, 47.
20. Anderson, O.; Aaseth, J. *Environ. Health* **2002**, *110*, 887.
21. Orvig, C.; Abrams, M. J. *Chem. Rev.* **1999**, *99*, 2201.
22. Obaleye, J. A.; Caira, A. C.; Tella, *Struct. Chem.* **2009**, *20*, 859.
23. (a) Tella, A. C.; Obaleye, J. A.; Eke, U. B.; Isaac, A. Y.; Ameen, O. M. *Res. Chem. Intermed.* **2014**, *40*, 1441.(b) Tella, A. C.; Obaleye, J. A. *J. Nepal Chem. Soc.* **2010**, *25*, 19.
24. (a) Tella, A. C.; Obaleye, J. A. *Bull. Chem. Soc. Ethiop.* **2011**, *25*, 371. (b) Obaleye, J. A.; Caira, M. R.; Tella, A. C. *J. Chem. Crystallogr.* **2007**, *37*, 707.
25. CLSI. Performance Standards for Antimicrobial Susceptibility. Seventeenth Informational Supplement.M100-S17.27:1, **2007**.
26. Superflip, D. *J. Appl. Crystallogr.* **2007**, *40*, 786.
27. Sheldrick, G. M. *Acta Crystallogr.* **2008**, *A64*, 112.
28. Dolomanor, O. V.; Bourhus, L. J.; Gildea, R. J.; Howard, J. A. K.; Puschmann, H. *Appl. Crystallogr.* **2009**, *42*, 339.
29. Borba, A.; Albrecht, M.; Gómez-Zavaglia, A.; Lapinski, L.; Nowak, M. J.; Suhm, M. A.; Fausto, R. *Phys. Chem. Chem. Phys.* **2008**, *10*, 7010.
30. Ramalingam, S.; Periandy, S.; Govindarajan, M.; Mohan, S. *Spectrochim. Acta* **2010**, *A75*, 1552.
31. Nakamoto, K. *Infrared and Raman Spectra of Inorganic and Coordination Compounds*; Wiley: New York, **1978**.
32. Zelenak, V.; Gyoryova, K.; Mlynarcik, D. *Metal Based Drugs* **2002**, *8*, 269.
33. Fan, Z.; Wu, X.; Ding, B.; Yang, P.; Liu, Y. Y.; Du, G. X. *Synth. React. Inorg. Met. Org. Chem.* **2014**, *44*, 371.
34. Köse, D. Ä.; Kaya, Ä.; Necefoglu, H. *Russ. J. Coord. Chem.* **2007**, *33*, 422.
35. Delgado, G. E.; Mora, A. J.; Guillén-Guillén, M.; Ramírez, J. W.; Contreras, J. E. *Cryst. Struct. Theor. Appl.* **2012**, *1*, 30.
36. Hokelek, T.; Dal, H.; Tercan, B.; Aybirdi, O.; Necefoglu, H. *Acta Cryst.* **2009**, *E65*, m605.
37. Brown, C. J. *Acta Cryst.* **1966**, *21*, 1.
38. Obaleye, J. A.; Tella, A. C.; Osunniran, W. A.; Simon, N.; Omojasola, P. F. *J Inorg. Organomet. Polym.* **2014**, *24*, 665.
39. Adetitun, D. O.; Araoye, H. K.; Akinyanju, J. A.; Anibijuwon, I. I. *Agrosearch* **2013**, *13*, 95.