ISSN 1070-3284, Russian Journal of Coordination Chemistry, 2023, Vol. 49, No. 12, pp. 862–885. © Pleiades Publishing, Ltd., 2023.

A Review of the Synthesis, Spectral Aspects, and Biological Evaluation of Silicon(IV) Complexes with N, O, and S Donor Ligands

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Received February 3, 2023; revised September 9, 2023; accepted September 9, 2023

Abstract—The chemical and biological applications of silicon(IV) complexes of N, O, and S donor ligands discovered in past few years are the main topics of this comprehensive review (>100 references). The review mainly covers the synthesis and biological activity of the complexes. The structure of these complexes are discussed on the basis of electronic, infrared, multinuclear (^{1}H NMR, ^{13}C NMR and ^{29}Si NMR) spectral and X-ray crystallographic studies. These silicon complexes exhibited significant activity against all the tested microorganisms.

Keywords: silicon, synthesis, solubility, spectroscopic studies, X-ray crystallography, biological activities

DOI: 10.1134/S1070328423601292

INTRODUCTION

Ligands having N, O, and S donor atoms are a distinct family of ligands that shows an attractive coordination style towards a variety of metal ions [1–5]. Over the past few year, these ligands have grown in importance because they are extremely useful in a variety of disciplines such as medicine, agriculture, cosmetics, coordination chemistry and so on [6–13]. Additionally, it has been reported that these ligands have a wide range of biological properties, such as anticonvulsant, antimalarial, antiproliferative, anticancer, antibacterial, antifungal, antitubercular, anti-inflammatory, antimicrobial, antiviral, insecticidal, antitumor and antipyretic properties [6, 14–32].

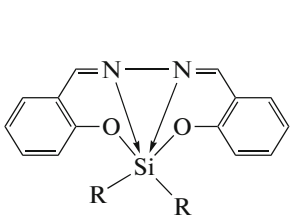
Silicon(IV) complexes of N, O, and S donor ligands are attracting attention from many researchers because of their unique coordination numbers, synthetic flexibility, diversified stereochemistry, important industrial [33–35], environmental applications [36–39] and also due to their many uses in the pharmaceutical and chemical sectors [40–42]. These complexes are well known for their anticarcinogenic, antibacterial, tuberculostatic, antifungal, insecticidal, antitumor and acaricidal activities [43–51]. Some silicon(IV) complexes have been widely employed in organic transformation processes, such as chemical vapour deposition and deoxygenation. In addition, they are useful synthons for a wide range of important chemicals [52]. The primary focus of our review is the synthesis and structural elucidation and biological applications of numerous novel silicon(IV) complexes with a variety of N, O, and S donor ligands.

Most of the silicon(IV) complexes discussed in this review have been synthesized either by silicon chlorides, silicon acetates or silicon alkoxides with several forms of N, O, and S donor ligands.

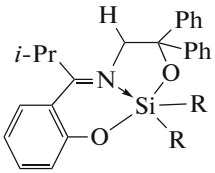
SYNTHESIS OF SILICON(IV) COMPLEXES WITH N^O DONOR LIGANDS (**1a**–**4f**)

By the reaction of silicon(IV) chloride with ligands. Silicon(IV) complexes are formed by chelating with N^O donor ligand. Various silicon complexes R_2SiL (where R = alkyl or aryl) **1a**–**1e** have been prepared by refluxing dichlorodiorganosilane with different N^O donor ligands in the presence of triethylamine as a base and THF as solvent (see Eq. (1)).

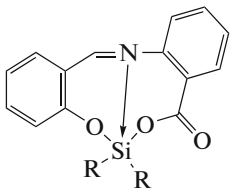
$$R_2SiCl_2 + H_2L + 2Et_3N \xrightarrow{THF} R_2SiL + 2Et_3N{\cdot}HCl \quad (1)$$



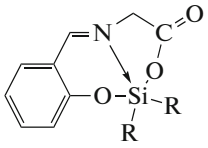
1a [53]



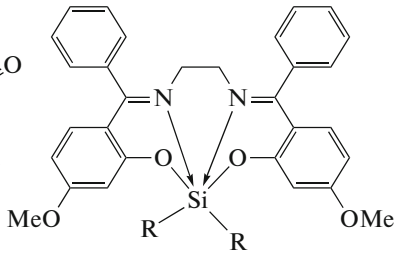
1b [54]



1c [55]

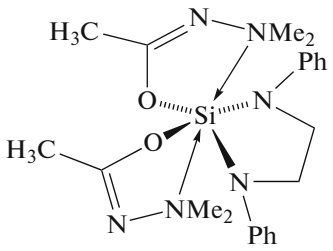


1d [55]

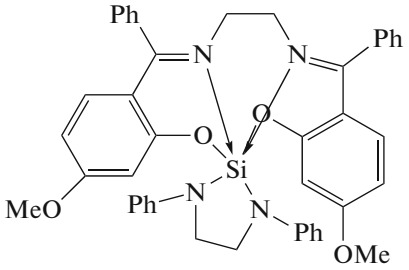


1e [56]

Banchik et al. and Wagler et al. have synthesized hexa-coordinate silicon compounds **1f, 1g** from monocyclic dichlorosilane with trimethylsilyl-imidates [57] and tetradentate salen-type ligand [58, 59].



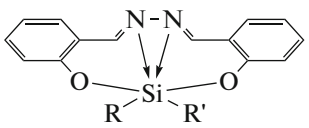
1f [57]



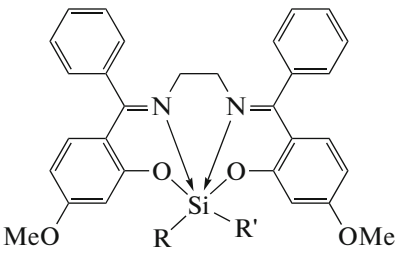
1g [58, 59]

Wagler et al. and Singh has also synthesized RR'SiL (where R = aryl, alkyl; R' = alkyl, vinyl) and PhSiClL complexes **1h**–**1k.** On the other hand, Puri et al. have reported hypercoordinate silicon(IV) complex RSiL **1l** of O,N,N,O-donor salen type ligand [53, 56, 60, 61]. The triethylamine base was required in excess amount for the formation of salt as triethylammonium chloride (Eq. (2)).

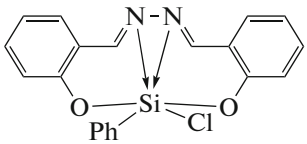
$$RR'SiCl_2/RSiCl_3 + LH_2/LH_3 + nEt_3N \xrightarrow[\text{Stirring}]{\text{THF}} RR'SiL/RSiL/PhSiClL + nEt_3N{\cdot}HCl \quad (2)$$



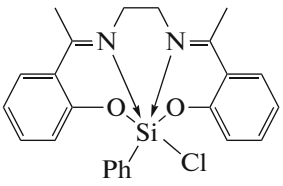
1h [53]



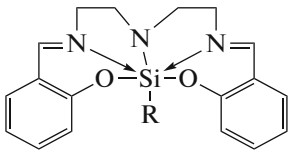
1i [56, 60]



1j [53]



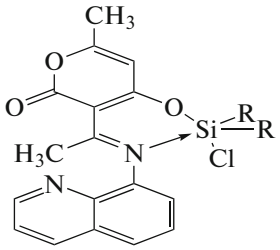
1k [60]



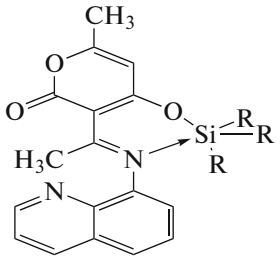
1l [61]

Devi et al. [62] synthesized complexes of silicon(IV) **1m**–**1p** having the general formula R_2SiClL or R_3SiL by the reaction of diorganodichlorosilane(IV) or chlorotriorganosilane(IV) with Schiff base ligands (L) in dry toluene/benzene as solvent and excess amount of triethylamine as a base (Eq. (3)).

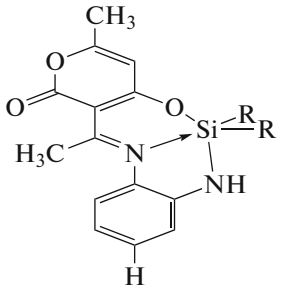
$$R_2SiCl_2/R_3SiCl + HL/H_2L + nEt_3N \xrightarrow{\text{Toluene/benzene}} R_2SiCl{\cdot}L/R_3SiL + nEt_3N{\cdot}HCl \quad (3)$$



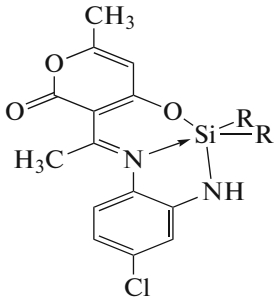
1m [62]



1n [62]



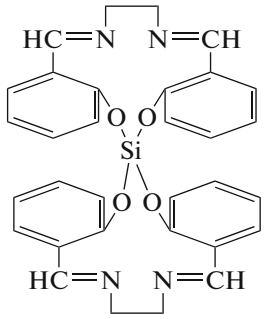
1o [62]



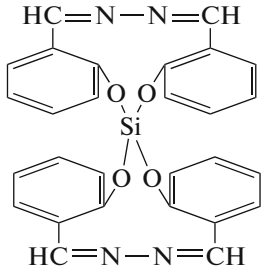
1p [62]

By the reaction of silicon tetrachloride(IV) with ligands. The interaction of silicon tetrachloride(IV) with N^O ligands in acetonitrile/benzene leads to some new complexes of organosilicon(IV) **2a**–**2c** (Eq. (4)) [52]. Bohme et al. synthesized a chiral hexacoordinate silicon complex **2d** in a 1 : 2 ratio of silicon to the ligand in the presence of THF and excess triethylamine (Eq. (4)) [54]. Similarly, the reaction of $SiCl_4$ with *N*-(salicylidene)-D-phenyl glycine methyl ester in with Et_3N (Eq. (4)) also leads to the preparation of new silicon(IV) complexes **2e** of amino acid ester derivatives [63, 64]. Kampfe et al. synthesized a hexacoordinate dichlorosilicon complex **2f** by the reaction of $SiCl_4$ with two chelating 2-acylpyrrolide ligands (Eq. (4)) [65].

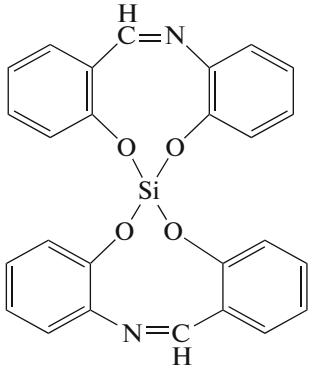
$$SiCl_4 + 2H_2L + 4NEt_3 \xrightarrow[Et_3N]{CH_3CN/benzene/toluene/THF} SiL_2/SiL_2Cl_2 + 4NEt_3{\cdot}HCl/2HCl \quad (4)$$



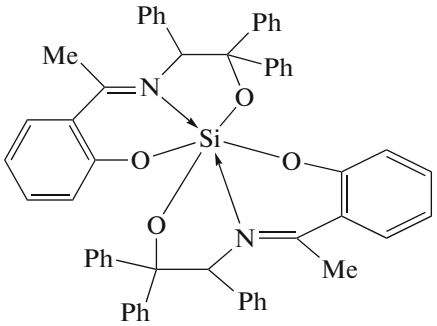
2a [52]



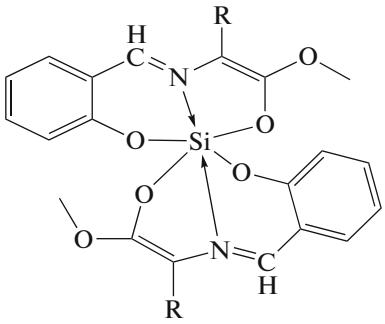
2b [52]



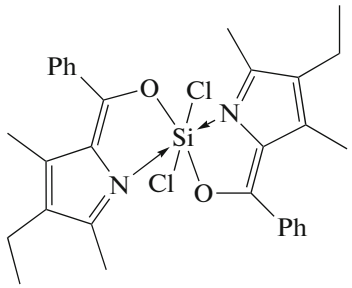
2c [52]



2d [54]



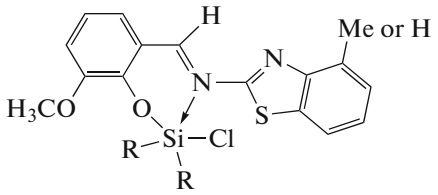
2e [63, 64]



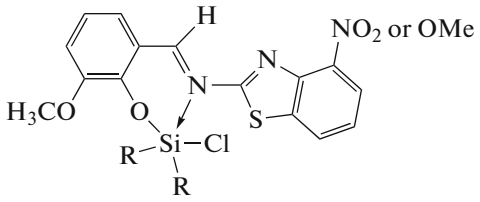
2f [65]

By the reaction of mono, di and tri-organosilicon(IV) chloride with the sodium salt of ligands. Devi et al. and Nath et al. reported a series of new organosilicon(IV) complexes **3a**–**3e** $R_3SiL/R_2SiL_2/R_2SiLCl/R_2SiL$ with R_3SiCl/R_2SiCl_2 (where R = aryl, alkyl) and a variety of sodium salt of ligands in 1 : 1 as well as in a 1 : 2 ratio of metal to the ligand in methanol/ethanol (Eq. (5)) (Scheme 1) [66–70].

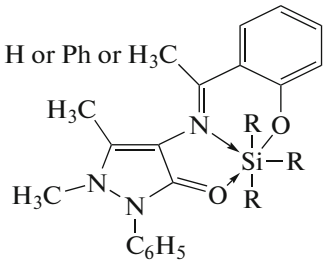
$$R_3SiCl/R_2SiCl_2 + nNaL \xrightarrow{\text{Methanol/ethanol}} R_3SiL/R_2SiL_2/R_2SiLCl + nNaCl \quad (5)$$



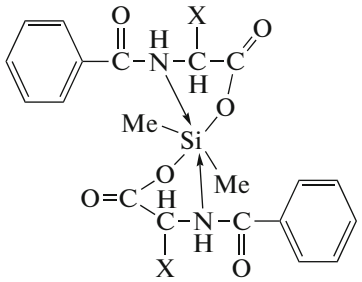
3a [66]



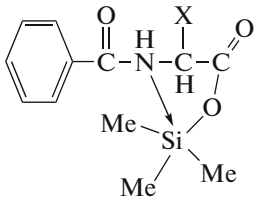
3b [66]



3c [67]

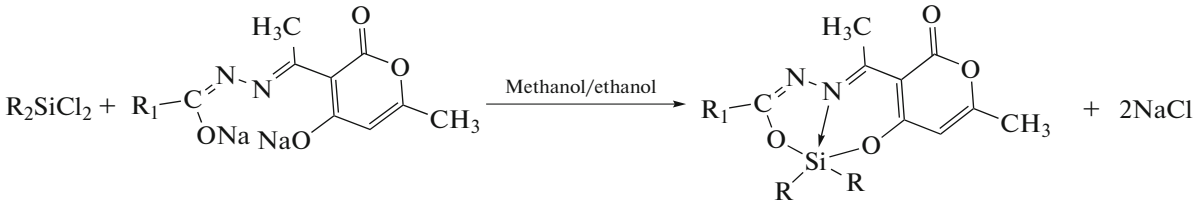


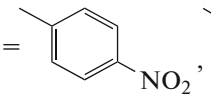
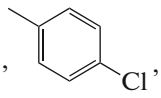
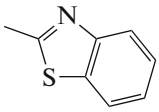
3d [68]

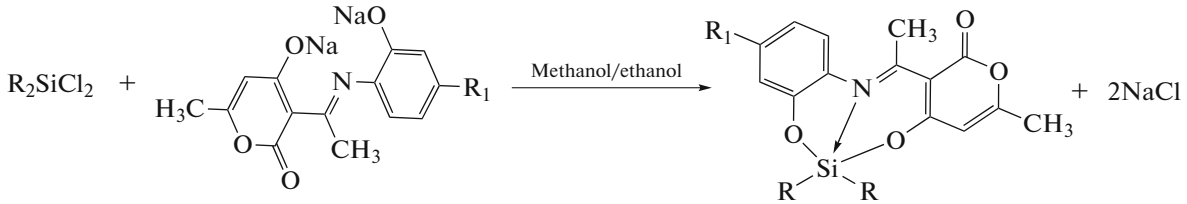


3e [68]

(X = H, CH_3, $CH(CH_3)_2$, $CH_2CH(CH_3)_2$)



(R1 =  ,  , ) [69]

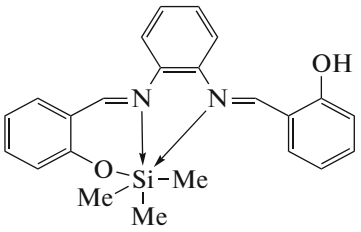


(R_1 = H, Me, NO_2, Cl [70])

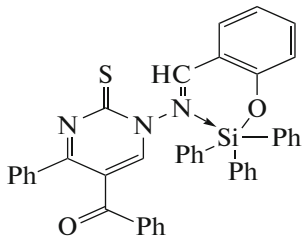
Scheme 1.

The organosilicon(IV) complexes of the types R_2SiClL, R_3SiL, $RSiCl_2L$, $RSiClL$ and R_2SiL **3f**–**3p** have been prepared by the replacement reactions of R_2SiCl_2, R_3SiCl, and $RSiCl_3$ (where R = Me, Et, Ph, Vi, Cy, *n*-Pr , *n*-Bu and $CH_2{=}CH_2$), respectively, with the sodium salts of ligands (Eqs. (6) and (7)) [71–75].

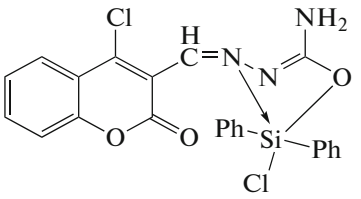
$$R_3SiCl/R_2SiCl_2 + Na_nL \xrightarrow{\text{Methanol/benzene/toluene}} R_3SiL/R_2Si{\cdot}LCl + n\,NaCl \quad (6)$$



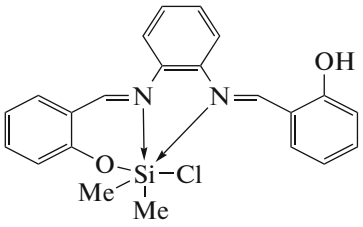
3f [71]



3g [72]

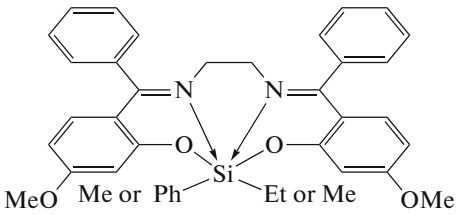


3h [75]

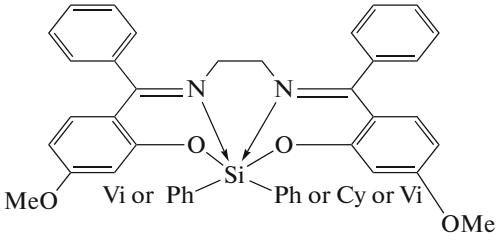


3i [71]

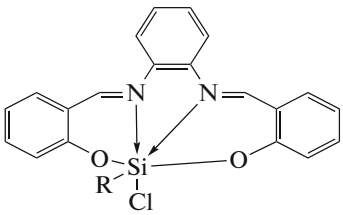
$$R_2SiCl_2/RSiCl_3 + Na_nL \xrightarrow{\text{Methanol/benzene}} RSiCl_2{\cdot}L/RSiCl{\cdot}L/R_2SiL + NaCl \quad (7)$$



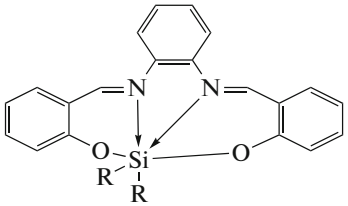
3j [74]



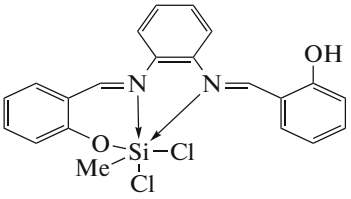
3k [74]



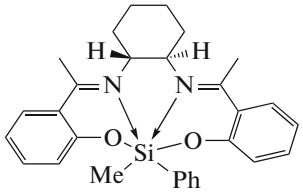
3l [71]



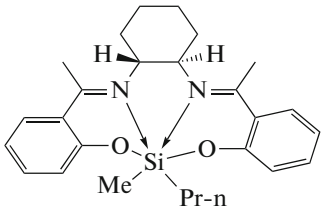
3m [71]



3n [71]

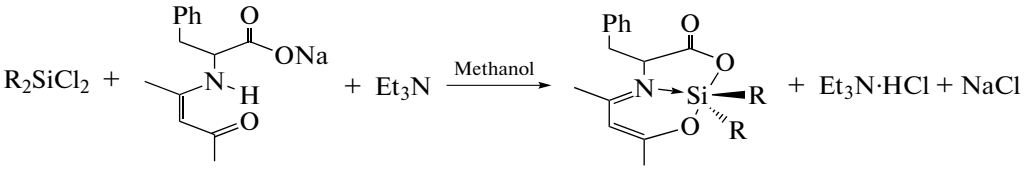


3o [73]



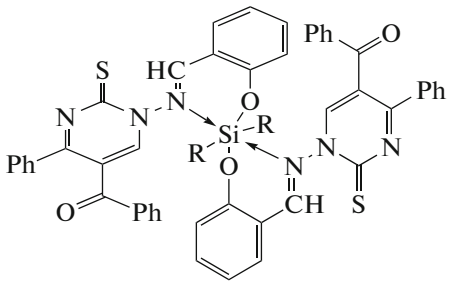
3p [73]

Bohme and Fels [64] synthesized organosilicon(IV) complexes with the removal of triethylammonium hydrochloride and sodium chloride (Scheme 2).

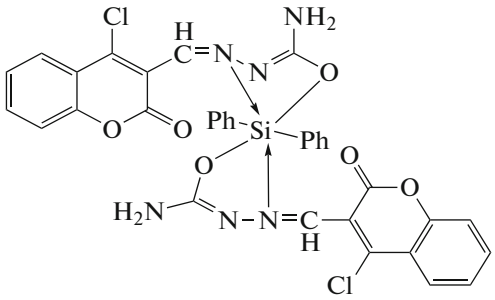


Scheme 2.

Several silicon complexes have been reported with the sodium salt of ligands. Raju [72] and Watt et al. [75] also synthesized organosilicon(IV) complexes R_2SiL_2 **3q, 3r** (where R = alkyl, aryl) by one-step reaction of diorganodichlorosilicon and the corresponding sodium salt of ligands in benzene/methanol (1 : 2) mixture.

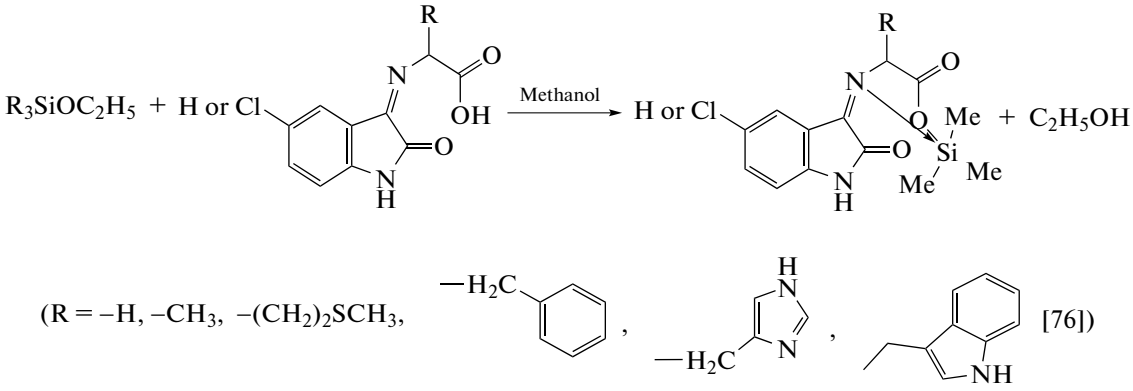


3q [72]

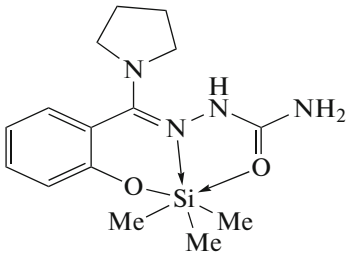


3r [75]

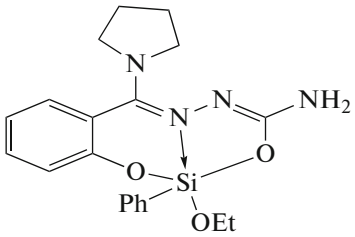
By the reaction of mono, di and trialkyl/arylsilicon (IV) alkoxides with ligands. The organosilicon derivatives Me_3SiL and $PhSiOC_2H_5L$ **4a, 4b** were synthesized by refluxing organosilicon(IV) alkoxides with the ligand in dry methanol [76, 77]. The alcohol liberated during the reaction is removed azeotropically with methanol and n-hexane, and the complexes were purified by distillation under reduced pressure (Scheme 3).



Scheme 3.



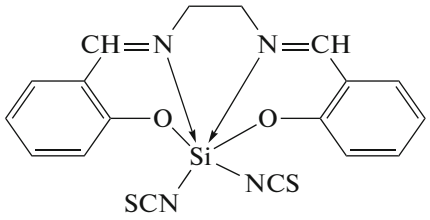
4a [77]



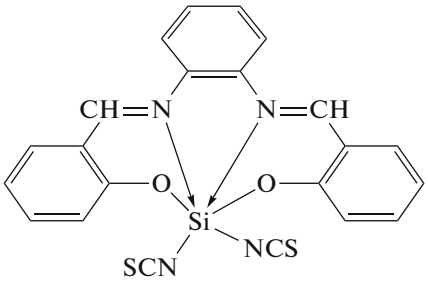
4b [77]

Refluxing diorganosilicon(IV) alkoxides with O,N,N,O-donor salen-type ligand in benzene/dry acetonitrile results in the formation of diorganosilicon(IV) R_2SiL **4c**–**4f** chelates and the liberation of ethyl alcohol which is removed as an azeotrope with benzene (Eq. (8)) [53, 78, 79].

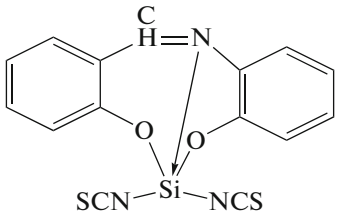
$$R_2Si(OC_2H_5)_2 + LH_2 \xrightarrow{CH_3CN/benzene} R_2SiL + 2C_2H_5OH \quad (8)$$



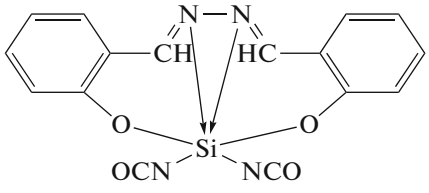
4c [78]



4d [78, 79]

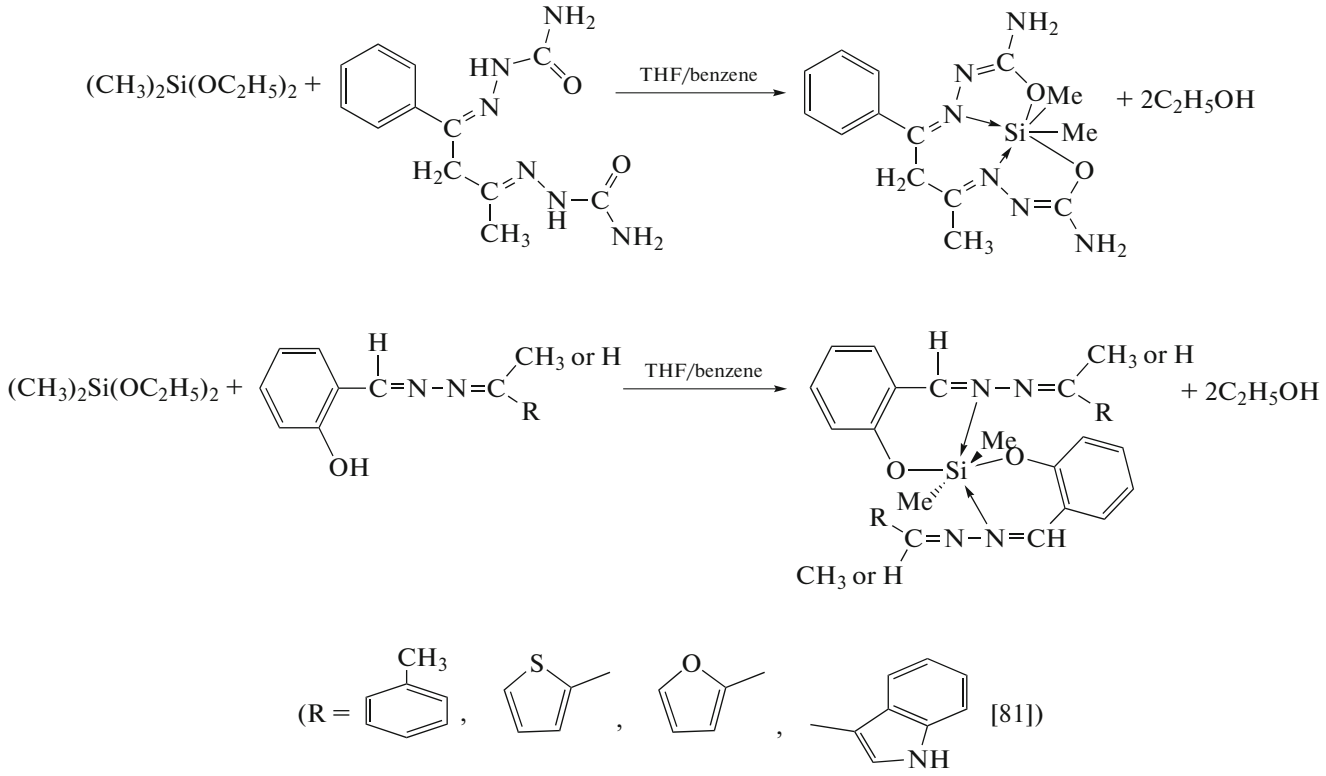


4e [78]



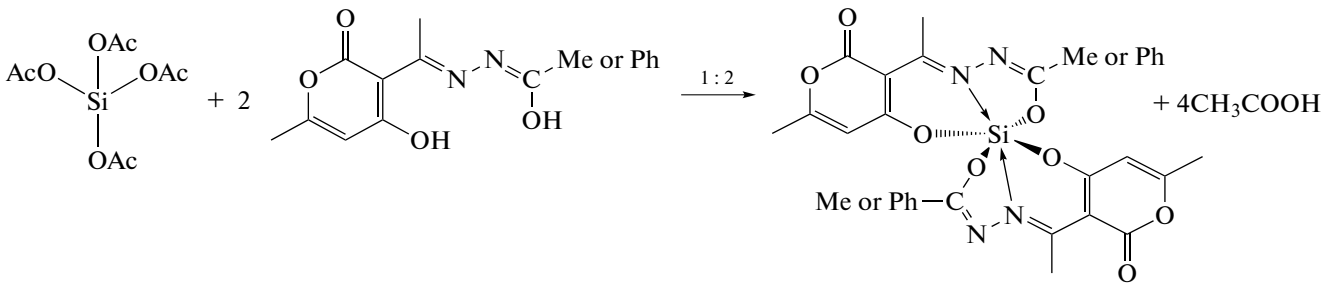
4f [53]

Similarly, dimethylsilicon(IV) chelates of semicarbazones, thiosemicarbazones [80] and amino acids with mixed azines [81] have been prepared (Scheme 4).



Scheme 4.

By the reaction of silicon tetra acetate with ligands. New silicon(IV) complexes have been prepared by reacting the silicon tetraacetate with hydrazones in 1 : 2 molar ratios, respectively, in THF (Scheme 5) [82].

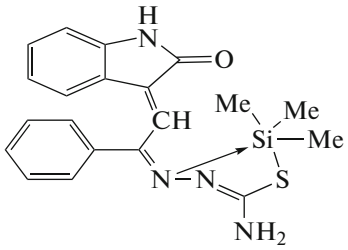


Scheme 5.

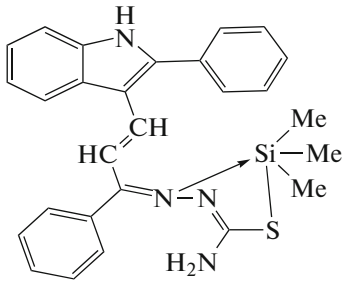
SYNTHESIS OF SILICON(IV) COMPLEXES WITH N^S DONOR LIGANDS (**5a–5m**)

By the reaction of organosilicon (IV) chlorides and sodium salt of ligands. Many organosilicon(IV) complexes of the types R_3SiL, R_2SiLCl and R_2SiL_2 **5a–5i** have been reported with the sodium salt of ligands. Belwal and Singh have synthesized silicon complexes with hydrazine carbothioamide ligands in dry methanol in a 1 : 1 molar ratio [33]. Diorganosilicon(IV) derivatives of the Schiff bases derived from pyrrole-2-carboxaldehyde have also been reported [45]. Watts et al. have synthesized organosilicon(IV) complexes by the condensation of organosilicon(IV) chlorides with the sodium salts of 1-(4-chloro-2-oxo-2H-chromen-3-yl)-methylene)-thiosemicarbazide and 1-(4-chloro-2-oxo-2H-chromen-3-yl)-methylene)-semicarbazide in 1 : 1 and 1 : 2 molar ratios [75]. Similarly, Singh and Nagpal have synthesized the diorganosilicon(IV) complexes of indole-2,3-dione derivatives (Eq. (9)) [83].

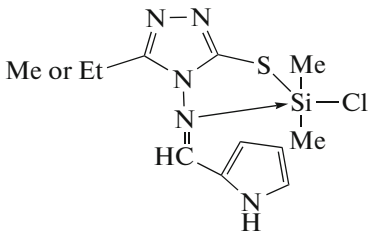
$$R_3SiCl/R_2SiCl_2 + NaL/2NaL \xrightarrow{1:1,\ 1:2} R_3SiL/R_2SiLCl/R_2SiL_2 + NaCl/2NaCl \quad (9)$$



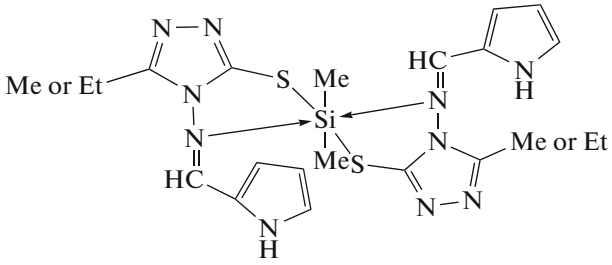
5a [33]



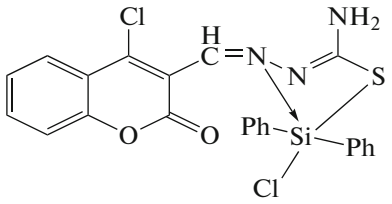
5b [33]



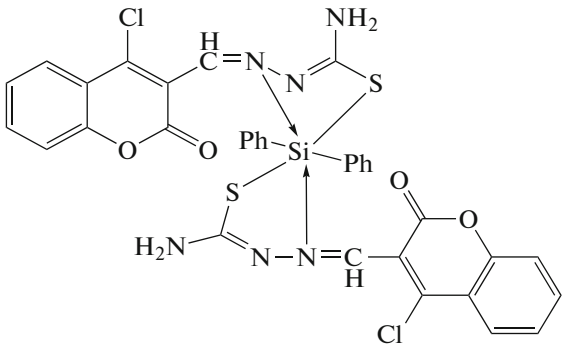
5c [45]



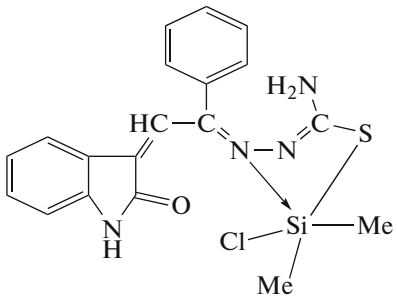
5d [45]



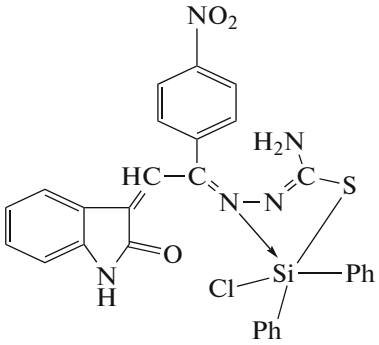
5e [75]



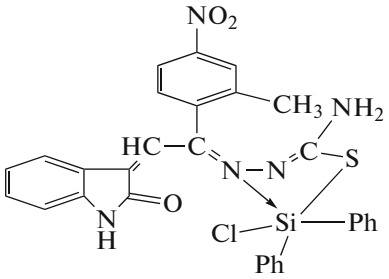
5f [75]



5g [83]

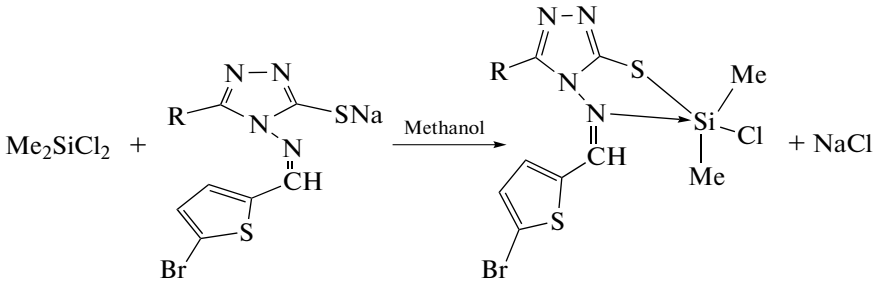


5h [83]

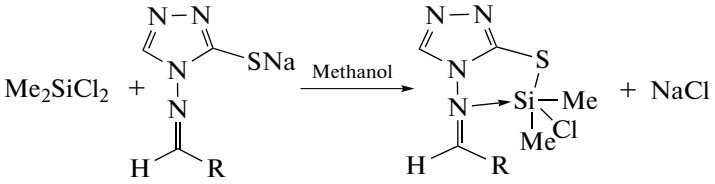


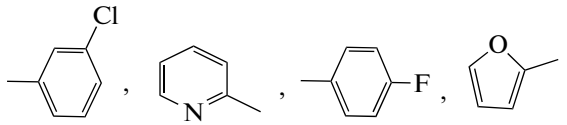
5i [83]

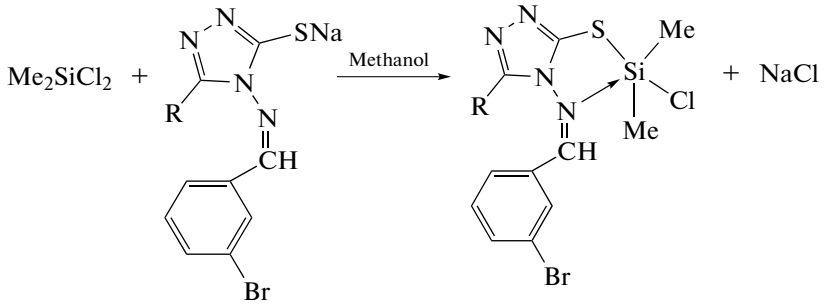
Singh and his co-workers have synthesized the diorganosilicon(IV) complexes of the sodium salt of ligands in dry methanol with the removal of sodium chloride (Scheme 6) [84–86].



(R = –CH_3, –$CH_2CH_2CH_3$, –$CH(CH_3)_2$) [84])



(R =  [85])

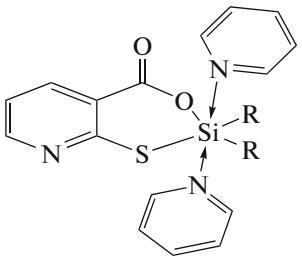


(R = –CH_2CH_3, –$CH_2CH_2CH_3$) [86])

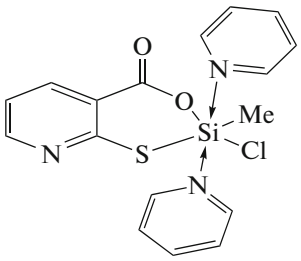
Scheme 6.

From organosilicon(IV) chlorides and mercapto pyridine carboxylic acid ligands. By the reaction of $R_2SiCl_2/RSiCl_3$ (where R = alkyl, aryl) with pyridine in the presence of chloroform reacted with a methanolic solution of mercapto pyridine carboxylic acid in the presence of triethylamine to prepare new organosilicon(IV) complexes $R_2Si(Py)_2L/RSi(Py)_2LCl$ **5j, 5k** (Eq. (10)) [87].

$$R_2SiCl_2/RSiCl_3 + 2Py + H_2L \xrightarrow[Et_3N]{\text{Chloroform/methanol}} R_2Si(Py)_2L/RSi(Py)_2LCl + 2Et_3NH^+Cl^- \quad (10)$$

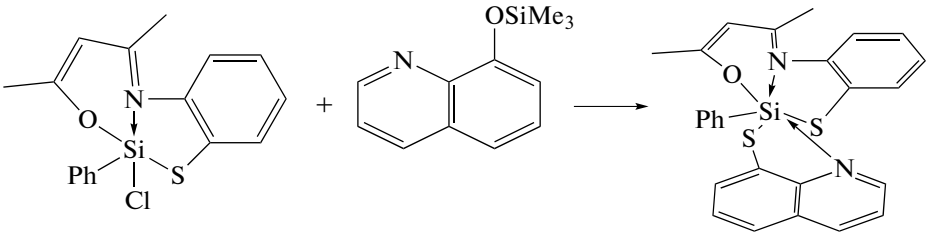


5j [87]



5k [87]

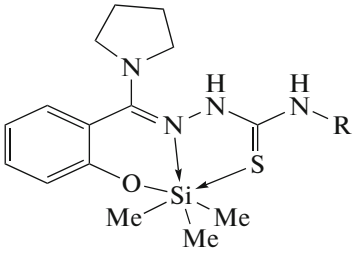
Weiss et al. has reported hexacoordinate silicon complexes by the reaction of penta-coordinate chlorosilane with thioquinolate ligand (Scheme 7) [88, 89].



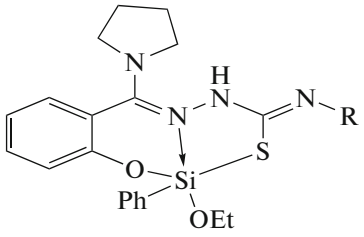
Scheme 7.

By the reaction of mono and trialkyl/arylsilicon(IV) alkoxides with ligands. Singh et al. has synthesized organosilicon(IV) complexes by the condensation of trimethylethoxysilane and triethoxyphenylsilane (Eq. (11)) [77].

$$PhSi(OC_2H_5)_3/(CH_3)_3Si(OC_2H_5) + LH \xrightarrow{MeOH} PhSi(OC_2H_5)\cdot L/(CH_3)_3SiL + C_2H_5OH \quad (11)$$



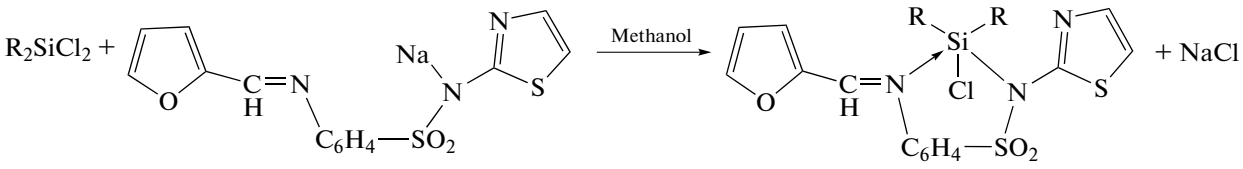
5l [77]

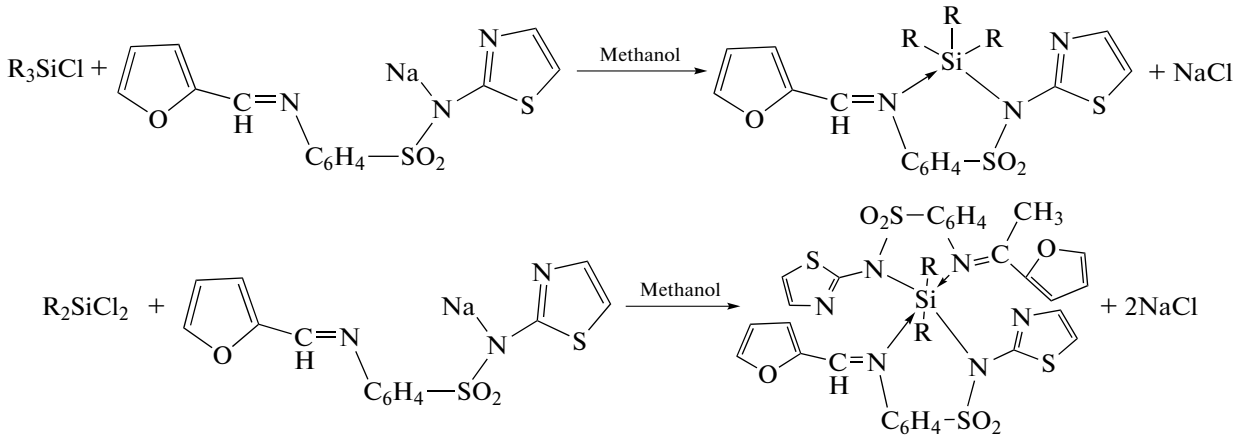


5m [77]

SYNTHESIS OF ORGANOSILICON(IV) COMPLEXES WITH N^N DONOR LIGANDS

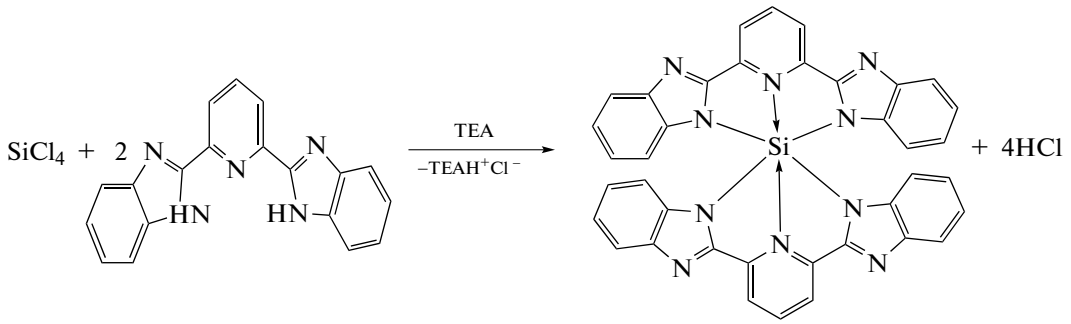
By the reaction of organosilicon chlorides with sulphonamide imine ligands. The organosilicon(IV) complexes of the types R_3SiL, R_2SiLCl and R_2SiL_2 (where R = alkyl, aryl) have been synthesized by replacement reactions of R_3SiCl and R_2SiCl_2, respectively, with the corresponding sodium salt of the ligand in methanol in 1 : 1 and 1 : 2 molar ratio (Scheme 8) [43].





Scheme 8.

Kocherga et al. have synthesized a neutral hexacoordinate silicon complex by adding $SiCl_4$ to a chloroform solution containing two equivalents of the 2,6-bis(benzimidazol-2'-yl)pyridine ligand (scheme 9) [90].



Scheme 9.

PHYSICAL PROPERTIES: SOLUBILITY AND MOLAR CONDUCTIVITY OF SILICON(IV) COMPLEXES

Some silicon(IV) complexes are semi-solids [68, 87] and other ones are hygroscopic solids that are moisture sensitive and hydrolyse easily when exposed to the atmosphere [55, 68, 78, 81, 83, 91]. Many of them are exist in the form of powdered [56, 77, 92] and oil [59, 92, 93]. Molecular weight determination of R_nSiL_n (where $n = 1$ or 2) [61, 81, 83], R_nSiL (where $n = 2$ or 3) [62, 94], R_2SiClL [62, 83], SiL_2 [82] shows monomeric nature of these complexes.

Mostly silicon(IV) complexes with different ligands are non-volatile and coloured solids soluble in DMSO, DMF and methanol [55, 62, 68, 72, 75–78, 87, 95]. These complexes are insoluble in common organic solvents but a few of them have good solubility in common organic solvents [71, 77, 83], and some are soluble/sparingly soluble in chloroform [60, 62, 68, 96].

The low molar conductivity data represents the non-electrolyte nature of these complexes. Even after having non-electrolyte nature of R_2SiL_2 [68], R_2SiLCl [66, 86] and R_nSiL (where $n = 2$ or 3) [67–69], the possibility of partial hydrolysis cannot be ignored. All the physical properties which are available from the research paper published after 2010 are described in Table 1.

SPECTROSCOPIC STUDIES OF SILICON(IV) COMPLEXES WITH N, O, AND S DONOR LIGANDS

To determine the structural features of silicon(IV) complexes in solutions, their multinuclear (^1H, ^{13}C and ^{29}Si NMR) measurements have been carried out in appropriate solvents. In addition, infrared data is used to predict the structures of the complexes in the solid state. A summary of the conclusion drawn from these studies is discussed below.

Electronic spectral studies of silicon(IV) complexes with N, O, and S donor ligands. Electronic spectra of silicon(IV) complexes with different ligands suggest ($n–\pi^*$) transition of azomethine, showed with blue

Table 1. Physical properties of silicon(IV) complexes with N, O, and S donor ligands

Compound (Empirical formula)	Yield, %	M.P., °C	Colour	Solubility	Elemental analysis				Reference
					C	H	N	Si	
$C_{26}H_{20}N_2O_2Si$ (**1a**; R = Ph)	62	266–268	Yellow	DMSO	74.26 (74.18)	4.79 (4.68)	6.66 (6.58)		[53]
$C_{16}H_{15}NO_3Si$ (**1c**; R = Me)	73.7			DMF and DMSO	64.64 (63.95)	5.05 (4.45)	4.71 (4.56)	9.42 (9.38)	[55]
$C_{26}H_{19}NO_3Si$ (**1c**; R = Ph)	67			DMF and DMSO	74.10 (73.32)	4.51 (3.85)	3.32 (2.01)	6.65 (6.57)	[55]
$C_{11}H_{13}NO_3Si$ (**1d**)	54.2			DMF and DMSO	56.17 (55.69)	5.53 (5.50)	5.95 (5.57)	11.90 (11.74)	[55]
$C_{43}H_{37}N_2O_4SiCl_3$ (**1e**; R = Ph)	74	249	Light yellow	$CDCl_3$	66.20 (66.20)	4.78 (4.83)	3.59 (3.78)		[56]
$C_{33}H_{33}N_2O_4SiCl_3$ (**1e**; R = Me)	53	165	Colourless	$CDCl_3$	60.41 (60.31)	5.07 (5.19)	4.27 (4.43)		[56]
$C_{22}H_{32}N_6O_2Si$ (**1f**)	97	149			59.97 (59.13)	7.32 (7.18)	19.07 (18.68)		[57]
$C_{52}H_{56}N_4O_8Si$ (**1g**)	49		Orange-red		69.93 (69.68)	6.32 (6.33)	6.27 (6.15)		[58]
$C_{21}H_{18}N_2O_2Si$ (**1h**; R = Ph, R' = Me)	71	260–262		$CDCl_3$ and DMSO	70.36 (70.16)	5.06 (4.98)	7.81 (7.67)		[53]
$C_{39}H_{36}N_2O_4SiCl_6$ (**1i**; R = Ph; R' = Et)	85.6				55.93 (56.14)	4.33 (4.20)	3.34 (3.18)		[56, 60]
$C_{40}H_{38}N_2O_4SiCl_6$ (**1i**; R = Ph, R' = Et)	63.8				56.42 (57.03)	4.50 (4.57)	3.29 (3.55)		[56, 60]
$C_{43}H_{43}N_2O_4SiCl_3$ (**1i**; R = Ph, R' = Cy)	21	161	Yellow		65.69 (65.66)	5.51 (5.52)	3.56 (3.56)		[56]
$C_{26}H_{18}N_2O_4Si$ (**2c**)	78	258–263	Brown	DMSO	69.33 (69.03)	4.00 (3.91)	6.22 (5.99)	6.22 (6.03)	[52]
$C_{42}H_{31}N_3O_2SSi$ (**3g**)	70	240		DMF and DMSO	75.31 (75.31)	4.66 (4.66)	6.27 (6.27)	4.19 (4.19)	[72]
$C_{50}H_{38}N_6O_4S_2Si$ (**3q**; R = Me)	77	280		DMF and DMSO	68.31 (68.31)	4.36 (4.36)	3.19 (3.19)	9.56 (9.56)	[72]
$C_{15}H_{24}N_4O_2Si$ (**4a**)	80.14	98	Light grey	DMF, DMSO and MeOH	56.22 (55.10)	7.55 (7.50)	14.48 (17.35)	8.76 (8.68)	[77]
$C_{20}H_{24}N_4O_3Si$ (**4b**)	75	94	White creamy	DMF, DMSO and MeOH	60.58 (60.65)	6.10 (6.02)	14.13 (14.19)	7.08 (7.0)	[77]
$C_{20}H_{22}N_4OSSi$ (**5a**)		160–162	Red		60.63 (63.34)	5.45 (5.62)	13.85 (14.2)	7.00 (7.12)	[33]
$C_{27}H_{28}N_4SSi$ (**5b**)		162–164	Red		69.02 (69.19)	5.78 (6.02)	11.84 (11.95)	5.85 (5.99)	[33]
$C_{20}H_{23}O_2N_3SSi$ (**5j**; R = Et)	61		Light green	DMF and DMSO	56.57 (56.42)	5.72 (5.64)	8.82 (8.77)	9.11 (9.09)	[87]

shift [62, 76, 80, 81] caused by polarization within the C=N-chromophore group suggesting metal–ligand interaction through azomethine nitrogen [76, 80, 81]. A red shift in the K band is also visible in the π–π* transition due to the overlap of the central metal *d*-orbital with the donor atoms *p*-orbital, resulting in an increase in conjugation, while the B-band exhibited a hypsochromic shift in the complexes [33, 76]. In Schiff bases and their silicon complexes, two bands may be seen in the region 192–262 and 224–380 nm which might be assigned to π–π* transitions of the benzenoid and to the C=N-chromophore, respectively [33, 62, 68, 76].

Infrared spectral studies of silicon(IV) complexes with N, O, and S donor ligands. To identify the functional group present in ligands and silicon(IV) complexes, FT-IR spectra were reported. In this review, we study and compare the IR spectra of ligands and their silicon(IV) complexes which provide important information on the solid-state structures of the complexes and also give us an idea about the coordination of metal with the donor group N, O, and S of the ligand.

Watts et al. [75] identify a strong band of ν(C=O) in region 1750–1710 cm^{-1} in spectra of ligands which remains unchanged in the spectra of silicon complexes indicating non-involvement of the group. ν(C=O) band appears at 1690 and 1685 cm^{-1} in hydrazine carboxamide [33] and semicarbazones [94], respectively, which disappear on silicon(IV) complex spectra due to the formation of a covalent bond between ligand and the silicon metal through the oxygen atom [33]. The stretching vibration of ν(C=N), which appears in the region 1672–1570 cm^{-1} [53, 55, 61, 62, 66, 67, 69–72, 75–78, 80, 81, 83, 86, 94, 95, 97] in the spectra of free ligands, generally have a negative shift in the spectra of complexes by ~10–35 cm^{-1}, leading to the conclusion that the ligands coordinate with the silicon atom through the azomethine nitrogen atom [33, 55, 61, 62, 66, 67, 69, 70, 72, 75–77, 80, 83, 97]. But according to Jai et al. the coordination of pyridyl N to the silicon atom is confirmed by the ν(C=N) peaks at 1423 and 1597 cm^{-1} that was shifted to a lower value in the IR spectra of complexes [87]. The phenolic ν(C–O) shifts to a higher wave number in the spectra of silicon complexes, indicating that the ligand is coordinated to silicon via azomethine nitrogen and phenolic oxygen [52, 77, 81, 98].

The IR spectra of silicon(IV) derivatives show no band in the region 3530–3090 cm^{-1} which could be assigned to ν(N–H) or ν(O–H), suggesting that the proton of these ligands has been replaced during the process of complexation [33, 52, 55, 61, 62, 72, 77, 78, 83, 87, 96–98]. While in other cases, a strong absorption band in the region 3350–2850 cm^{-1} indicates intramolecular H-bonding in ligands which disappears in spectra of silicon complexes suggesting deprotonation of this functional group during complexation [81].

Two sharp bands are observed in the spectra of the silicon complexes at 1700–1604 and 1389–1320 cm^{-1} which have been assigned to $\nu_{as}(COO)$ and $\nu_s(COO)$, respectively [58, 59, 86]. In some research articles, the separation between $\nu_{as}(COO)$ and $\nu_s(COO)$ i.e., $\Delta\nu = \nu_{as}(COO) - \nu_s(COO)$ is 271–248 cm^{-1}, indicating the covalent nature of the Si–O bond and also suggesting that the COO group should bind to Si unidentically [76]. For monodentate bonding, values of carboxylate anions are expected to be more than 200 cm^{-1} whereas, for bridging or chelating carboxylates, Δν values of complexes are predicted below 200 cm^{-1} [76, 99].

The band between 850–830 and 650–633 cm^{-1} is assigned to $\nu_{as}(Si–O)$ and $\nu_s(Si–O)$, respectively [87], and the appearance of a new band in the region 760–710, 590–509, and 484–428 cm^{-1}, of ν(Si ← N) confirmed the formation of a coordination linkage between silicon and nitrogen [33, 52, 53, 55, 62, 66, 67, 69, 71, 76, 77, 80, 81, 83, 87, 94, 97, 98] and the band around 565–540 cm^{-1} indicating the ν(Si–S) which further confirms the silicon complex formation with S donor ligands [80, 87, 94, 97]. A cis form of complexes has two (Si–N) bands, therefore, in the spectra of silicon(IV) complexes, the presence of only one (Si–N) band explains that the complexes exist in the trans-form [76].

Bands around 3446–3450 ($\nu_{as}(NH_2)$), 3440–3400 ($\nu(NH_2)$), and 3350–3334 cm^{-1} ($\nu_s(NH_2)$) remains unchanged in the silicon(IV) complexes spectra showing no involvement in complex formation [33, 80, 94]. The disappearance of ν(N–H) at 3415–3150 cm^{-1} [61] in complex spectra indicates deprotonation of the functional group and on the other hand, the shift of ν(N–H) (3066–3064 cm^{-1}) to a slightly lower frequency suggests the involvement of imino group in complexation [62]. The peaks between 1641–1572 and 586–450 cm^{-1} are attributed to ν(C=N) and ν(Si ← N), respectively. Finally, the IR data available according to the papers published in the recent ten years are shown in Table 2.

Multinuclear (^1H, ^{13}C and ^{29}Si) magnetic resonance spectral studies of silicon (IV) complexes with N, O, and S donor ligands. In ^1H NMR spectra of silicon(IV) complexes of various N, O, and S donor ligands, there is a slight shift ranging between 9.90–8.16 ppm (either downfield or upfield) in chemical shift values for azomethine group [CH=N– or $C(CH_3)$=N–] [52, 53, 55, 66, 80, 81, 94]. The shift of the azomethine proton in the silicon complexes indicated shielding or deshielding, implying that the most likely binding of the ligands to the silicon was accomplished via the nitrogen atom of the azomethine group [52] shown in Table 3. Disappearance or shift in OH and NH signals of these ligands in the ^1H NMR of hexacoordinate silicon complexes indicates formation of covalent bonds between silicon and oxygen/nitrogen, respectively as a

Table 2. IR data of silicon(IV) complexes with N, O, and S donor ligands

Compound (Empirical formula)	ν(C=N)	ν(C–O)	ν(C=S)	ν(Si ← N)	ν(Si–O)	ν(Si–S)	Reference
$C_{26}H_{20}N_2O_2Si$ (**1a**; R = Ph)	1630			560	1040		[53]
$C_{16}H_{15}NO_3Si$ (**1c**; R = Me)	1607			578	890		[55]
$C_{26}H_{19}NO_3Si$ (**1c**; R = Ph)	1596			586	884		[55]
$C_{11}H_{13}NO_3Si$ (**1d**)	1617			575	872		[55]
$C_{21}H_{18}N_2O_2Si$ (**1h**; R = Ph, R' = Et)	1639			557	1036		[53]
$C_{28}H_{20}N_4O_4Si$ (**2b**)	1617	1264		563	1031		[52]
$C_{26}H_{18}N_2O_4Si$ (**2b**)	1625	1270		554	1119		[52]
$C_{42}H_{31}N_{31}O_2SSi$ (**3g**)	1640	1266	1020	550	1075	495	[72]
$C_{50}H_{38}N_6O_4S_2Si$ (**3q**; R = Me)	1610	1273	1030	550	1070	520	[72]
$C_{15}H_{24}N_4O_2Si$ (**4a**)	1635	1265	856	478	582		[77]
$C_{20}H_{24}N_4O_3Si$ (**4b**)	1630	1268	860	465	560		[77]
$C_{18}H_{19}O_2N_3SSi$ (**5j**; R = Me)	1580	1685	1132	535	873	478	[87]
$C_{20}H_{23}O_2N_3SSi$ (**5j**; R = Et)	1585	1683	1130	543	870	475	[87]
$C_{28}H_{23}O_2N_3SSi$ (**5j**; R = Ph)	1580	1681	1126	532	850	487	[87]
$C_{17}H_{16}O_2N_3SSiCl$ (**5k**; R = Me)	1580	1690	1127	543	842	480	[87]
$C_{18}H_{18}O_2N_3SSiCl$ (**5k**; R = Et)	1574	1682	1132	539	859	489	[87]
$C_{22}H_{18}O_2N_3SSiCl$ (**5k**; R = Ph)	1572	1682	1127	537	833	483	[87]

result of deprotonation [33, 52, 55, 61, 62, 68, 72, 73, 75–77, 80, 81, 83, 87, 94, 97]. In some cases, a shift in the aromatic peak of complexes ranging between 8.81–5.94 ppm is also observed in ^{1}H NMR of silicon(IV) complexes which may arise due to deshielding and represent coordination through N atom [33, 52, 75–77, 87]. And in other cases, same position of NH/NH_2 peak indicates no involvement of these group in complex formation [33, 76, 77, 80, 83, 94].

Nath et al. [68] have reported that the relative intensities in ^{1}H NMR spectra of Me_3SiL^{1-3} and $Me_2Si(L)_2^2$ (where L^1 = N-BenzGly, L^2 = N-Benz-DL-Ala and L^3 = N-Benz-DL-Val) agree with the formulation of the complexes in 1 : 1 and 1 : 2 molar ratio. When compared to the ethyl ester, the –NH (amido) resonances in di and trimethyl silicon(IV) derivatives have higher δ values. This is most likely due to the participation of amido carbonyl oxygen in coordination with silicon and hydrogen bonding involving O–CN—O=C–O/NHCO–H interactions. In ^{1}H NMR spectra of the complexes an additional peak in region 6.0–8.10, 1.54–2.43 and 0.35–1.85 ppm has been reported in $R_3Si(L)$ complexes is due to R_3Si, where R = Me, Et, Bu and Ph [62, 68, 72, 76, 77, 81, 83, 87].

Belwal et al. reported that the values of $^2J[^1H,^{29}Si]$ for several tri-organosilicon complexes reveal that the complexes are surrounded by a penta-coordinated environment [33]. The inception of ^{13}C NMR data proposed coordination in these complexes is supported by a substantial shift in the position of carbon atoms bonded to the azomethine nitrogen, thiolic sulfur and phenolic, carboxylic or amido oxygen atom [53, 55, 61, 71–73, 76–78, 80, 81, 83, 87, 93–95, 97]. All the ^{1}H NMR, ^{13}C and ^{29}Si NMR data available from the research paper published after 2010 concluded that the peak for (Si-R) in ^{1}H NMR is likely to be found between 1.08–1.32 ppm which further can be affected by the nature of ligands. In ^{13}C NMR spectra, the peak for (CH=N) is probably found between 152.4–172.0 ppm as listed in Tables 3 and 4. The ^{29}Si NMR spectra of several silicon(IV) complexes show only one sharp singlet indicating the formation of single silicon species [33, 62, 76–78, 80, 81, 91–95]. Hence it can be concluded that according to the spectroscopic studies the structure suggested by the researchers are mostly hexa and penta-coordinated structure [33, 55, 56, 59, 61, 62, 64, 71, 75–78, 81, 83, 87, 91, 93–97, 100–105], distorted trigonal bipyramidal [62, 68, 83, 97, 106] and distorted octahedral [68, 83, 87].

X-RAY CRYSTALLOGRAPHIC STUDIES OF SILICON(IV) COMPLEXES WITH N, O, AND S DONOR LIGANDS

The finding of X-ray crystallographic data of a number of silicon(IV) complexes of N, O, and S donor ligand implies that the coordination environment around these complexes exist either in distorted trigonal bipyramidal [106, 107], distorted octahedral [63, 108, 109], twisted octahedral [110], bicapped tetrahedral [57], and square pyramidal [111] geometry around silicon atom.

The single crystal X-ray diffraction of several silicon(IV) complexes have been reported by several researchers world wide. The interfacial angle of these complexes designated as α [63, 79, 96, 107, 108, 112–118], β [63, 79, 96, 100, 103, 106–108, 112–119] and γ [63, 79, 96, 107, 108, 112–118] forms belonging to the monoclinic [63, 79, 96, 100, 103, 106–108, 112–119], triclinic [63, 79, 108, 112, 113, 116–118], tetragonal [103] and orthorhombic [63, 100, 103, 106, 114–116, 119, 120] crystal system.

BIOLOGICAL STUDIES OF SILICON(IV) COMPLEXES WITH N, O, AND S DONOR LIGANDS

These complexes are unique among silicon-containing compounds and they have high biological activity in different fields. The silicon(IV) complexes with N, O, and S donor ligands have been shown to exhibit a broad range of biological activities including antimicrobial, nematicidal, insecticidal, anti-fertility, anticancer and antitumor activities.

Antimicrobial activity. The complexes of the types, $R_nSiL/R_{n'}SiL_2/R_{n''}SiAL$ ($n = 2, 3$, $n' = 2$, $n'' = 1, 2$, R = Me, Et, Bu, Ph, A = Cl, OEt, L = Schiff bases derived from amino acids [68, 76], semicarbazide, phenylthiosemicarbazide, thiosemicarbazide and cyanato-N or thiocyanato-N ligands [75, 77, 80, 101], hydrazine carbothioamide and hydrazine carboxamide [33, 83], dehydroacetic acid [62, 69, 70], pyridine dicarboxylic acid and Mercapto pyridine carboxylic acid [87], 1-phenyl-3-arylpyrazole-4-carboxaldehydes [94], 2-aminobenzothiazole derivatives and 2-hydroxy-3-methoxy benzaldehyde [66], sulphonamide imine [43], pyrrole-2-carboxaldehyde [45], 4-amino-5-mercapto-3-methyl/propyl/isopropyl-s-triazole [84], mixed azines [81] and 4-aminoantipyrine and 2-hydroxyacetophenone/2-hydro-xynapthaldehyde [67]). SiXYZL (X = OEt, Ph, Y = OEt, Cl, Ph, NCS, Z = OEt, Cl, NCS, quinoline moiety, L = Schiff base derived from 2-aminopyridine and salicylaldehyde [98]) showed a remarkable activity towards bacterial species, e.g. *Bacillus* spp. [45, 62, 66, 67, 69, 75–77, 84, 87, 94, 98] *Nocardia* spp. [76], *Enterobacter aerogenes* [76], *Escherichia coli* [33, 43, 45, 62, 66–70, 75–77, 80, 81, 84, 87, 94, 98], *Klebsiella* spp. [76, 77, 83], *Staphylococcus* spp. [43, 62, 66–70, 76, 77, 80, 81, 84,

Table 3. ^{1}H NMR data of silicon(IV) complexes with N, O, and S donor ligands

Compound (Empirical formula)	Solvent	Ligand proton shifts (ppm)	(Si-R) ppm	Coupling constant (J)	Reference
$C_{26}H_{20}N_2O_2Si$ (**1a**; R = Ph)	$CDCl_3$/DMSO d_6	9.20 (s, CH=N); 8.05–7.58 (m, H_{ar})			[53]
$C_{16}H_{15}NO_3Si$ (**1c**; R = Me)	$CDCl_3$/DMSO- d_6	8.36 (s, CH=N); 7.9–7.0 (m, H_{ar}); 1.3 (s, CH_3)			[55]
$C_{26}H_{19}NO_3Si$ (**1c**; R = Ph)	$CDCl_3$/DMSO d_6	8.58 (s, CH=N); 7.5–6.7 (m, H_{ar})			[55]
$C_{11}H_{13}NO_3Si$ (**1d**)	$CDCl_3$/DMSO d_6	8.66 (s, CH=N); 3.87 (s, N–CH_2); 0.9 (s, CH_3)			[55]
$C_{43}H_{37}N_2O_4SiCl_3$ (**1e**; R = Ph)	$CDCl_3$	3.31 (s, CH_2CH_2); 3.75 (s, OCH_3); 7.8–5.95 (dd/mm, H_{ar})		9.0, 2.4	[56]
$C_{33}H_{33}N_2O_4SiCl_3$ (**1e**; R = Me)	$CDCl_3$	3.39 (s, CH_2CH_2); 3.79 (s, OCH_3); 7.5–6.50 (dd, H_{ar})	0.40(s)	9.0, 2.4	[56]
$C_{22}H_{32}N_6O_2Si$ (**1f**)	$[D]_8$ toluene	1.69 (s, Me); 3.71–2.56 (m/br, NMe); 7.19 (m, Ph)			[57]
$C_{52}H_{56}N_4O_8Si$ (**1g**)	$CDCl_3$	3.35–2.3 (m, C=NCH_2CH_2N=C); 3.55–3.35 (m, PhNCH_2CH_2NPh); 5.94–5.75 (dd, H_{ar})		9.2, 2.4	[58]
$C_{21}H_{18}N_2O_2Si$ (**1h**; R = Ph, R' = Me)	$CDCl_3$/DMSO d_6	7.80 (s, CH=N); 7.45–6.65 (m, H_{ar}); 0.86 (s, CH_3)			[53]
$C_{16}H_{18}N_2O_3Si$ (**1o**)	DMSO d_6	7.43–6.50 (m, H_{ar}); 6.82 (s,CH); 6.37 (s, NH_2); 2.46–1.35 (s, CH_3); 2.02 (s, –N=C–CH_3)			[62]
$C_{25}H_{31}ClN_2O_3Si$ (**1p**)	DMSO d_6	8.81–7.67 (m, H_{ar}); 5.75 (s, CH); 2.52–2.17 (t, Bu); 2.50 (s, CH_3); 2.14 (s, –N=C–CH_3); 2.01–1.80 (m, Bu)			[62]
$C_{32}H_{28}N_4O_4Si$ (**2a**)	DMSO d_6	9.90 (s, CH=N); 7.51–6.89 (m, H_{ar}); 2.01 (t, N–CH_2)			[52]
$C_{26}H_{18}N_2O_4Si$ (**2b**)	DMSO d_6	8.50 (s,CH=N); 7.24–5.94 (d/dd, H_{ar})			[52]
$C_{42}H_{31}N_3O_2SSi$ (**3g**)		8.65–6.80 (m, H_{ar})			[72]
$C_{50}H_{38}N_6O_4S_2Si$ (**3q**; R = Me)		8.3–6.9 (m, H_{ar}); 1.5–0.6 (m, n-Bu); 1.1–0.5 (t, CH_3)			[72]
$C_{15}H_{24}N_2O_2Si$ (**4a**)	DMSO d_6	7.62–6.88 (d/m, H_{ar}); 3.74 (s, NH_2); 3.52–1.86 (m, pyrrolidine)	1.09(s)	8.2, 6.8	[77]
$C_{20}H_{24}N_4O_3Si$ (**4b**)	DMSO d_6	7.60–6.85 (m/d, H_{ar}); 3.50–1.78 (m, pyrrolidine); 3.66 (s, NH_2)		8.0, 6.9	[77]
$C_{16}H_{10}N_4O_4Si$ (**4f**)	DMSO d_6	9.20 (s, CH=N); 8.05–7.58 (m, H_{ar})			[53]
$C_{20}H_{22}N_4OSSi$ (**5a**)	DMSO d_6	12.96 (bs, NH); 8.84 (s, =CH–C=N); 7.98–7.64 (m, indole $ring_{ar}$); 7.58–7.22 (m, H_{ar}); 3.34 (bs, NH_2)	0.56	6.5	[33]

Table 4. ^{13}C and ^{29}Si–NMR data of silicon(IV) complexes with N, O, and S donor ligands

Compound (Empirical formula)	Solvent	^{13}C	(Si–R) ppm	^{29}Si	Reference
$C_{26}H_{20}N_2O_2Si$ (**1a**; R = Ph)	$CDCl_3$/DMSO d_6	145.8–114.8 (C_{ar}); 160.7 (CH=N)			[53]
$C_{16}H_{15}NO_3Si$ (**1c**; R = Me)	$CDCl_3$/DMSO d_6	164.1 (C=N); 144.2 (C–O); 170.8 (COO)		–94.7	[55]
$C_{26}H_{19}NO_3Si$ (**1c**; R = Ph)	$CDCl_3$/DMSO d_6	172.0 (COO); 166.1 (CH=N); 148.2 (C=O)		–114.0	[55]
$C_{11}H_{13}NO_3Si$ (**1d**)	$CDCl_3$/DMSO d_6	158 (CH=N); 169.1 (COO); 139 (C–O); 42.3 (NCH_2)		–80.0	[55]
$C_{43}H_{37}N_2O_4SiCl_3$ (**1e**; R = Ph)	$CDCl_3$	48.3 (CH_2CH_2); 55.3 (OCH_3); 161.0–104.2 (C_{ar}); 171.6 (C=N)		–177.6, –177.7	[56]
$C_{33}H_{33}N_2O_4SiCl_3$ (**1e**; R = Me)	$CDCl_3$	48.7 (CH_2CH_2); 55.3 (OCH_3); 135.4–104.3 (C_{ar}); 168.3 (C=N)	16.7		[56]
$C_{21}H_{18}N_2O_2Si$ (**1h**; R = Ph, R' = Et)	$CDCl_3$/DMSO d_6	160.7 (CH=N); 134.0–114.9 (C_{ar}); 5.38 (CH_3)			[53]
$C_{16}H_{18}N_2O_3Si$ (**1o**)	DMSO d_6	175.59–99.68 (C_{ar}); 34.67–19.10 (CH_3)			[62]
$C_{25}H_{31}ClN_2O_3Si$ (**1p**)	DMSO d_6	177.03–98.09 (C_{ar}); 29.56–20.29 (Bu); 19.74 (CH_3)			[62]
$C_{32}H_{28}N_4O_4Si$ (**2a**)	DMSO d_6	160.79 (CH=N); 136.54–117.54 (C_{ar}); 39.22 (N–CH_2)			[52]
$C_{42}H_{31}N_3O_2SSi$ (**3g**)		188.2 (C=O); 160.3 (C=N); 139.8–126.4 (C_{ar})	18.34, 11.44, 8.64	–45.46	[72]
$C_{50}H_{38}N_6O_4S_2Si$ (**3q**; R = Me)		8.3–6.9 (m, H_{ar}); 1.5–0.6 (m, n-Bu); 1.1–0.5 (t, CH_3)	19.93, 12.81, 9.63	–326.23	[72]
$C_{15}H_{24}N_2O_2Si$ (**4a**)	DMSO d_6	168.9 (C–O); 156.2 (C=N); 131.3–116.7 (C_{ar}); 45.6–23.7 (–CH_2–CH_2–, pyrrolidine)	9.11	–105.1	[77]
$C_{20}H_{24}N_4O_3Si$ (**4b**)	DMSO d_6	168.2 (C–O); 160.64 (C=N); 131.0–116.5 (C_{ar}); 45.6–23.8 (–CH_2–CH_2–, pyrrolidine)		–95.85	[77]
$C_{16}H_{10}N_4O_4Si$ (**4f**)	$CDCl_3$/DMSO d_6	166.1 (CH=N); 131.6–115.8 (C_{ar})			[53]
$C_{20}H_{22}N_4OSSi$ (**5a**)	Dry MeOH	166.16 (amido/thiolo); 165/04 (–NH–C=O/–NH–C–Ph); 156.04 (C=N); 150.01–125.68 (indole $ring_{ar}$); 138.90–128.5 (C_{ar})	16.38		[33]

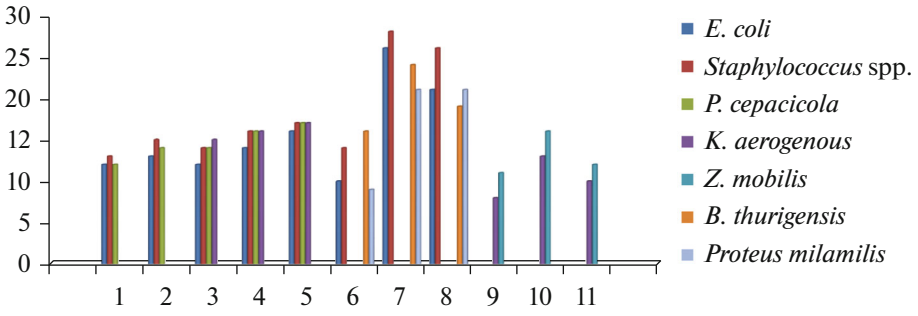


Fig. 1. Antibacterial activity of silicon(IV) complexes (diameter inhibition zone (mm), concentration in 1000 ppm). 1. $C_{20}H_{22}N_4OSSi$, 2. $C_{27}H_{28}N_4SSi$, 3. Me_2Si(2-Ac-F-St)Cl, 4. Ph_2Si(2-Ac-F-St)Cl, 5. Ph_3Si(2-Ac-F-St), 6. $C_9H_{18}N_6O_2Si$, 7. $C_{14}H_{20}N_6S_2Si$, 8. $C_6H_{12}N_6S_2Si$, 9. $C_{19}H_{19}N_4OSSiC1$, 10. $C_{29}H_{22}N_5O_3SSiC1$, 11. $C_{30}H_{24}N_5O_3SSiCl$.

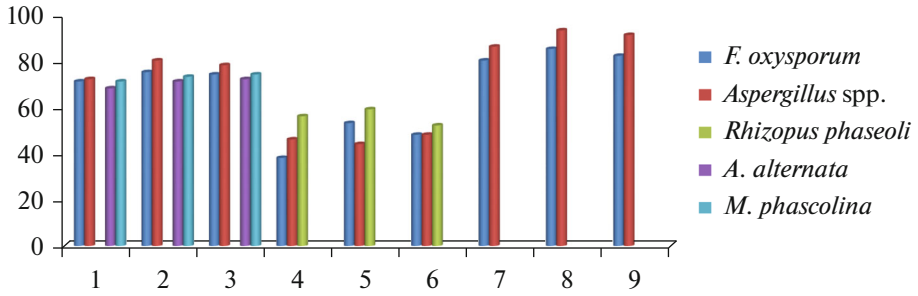


Fig. 2. Antifungal activity of silicon(IV) complexes (average percentage inhibition after 95–96 days, concentration in 100 ppm). 1. Me_2Si(2-Ac-F-St)Cl, 2. Ph_3Si(2-Ac-F-St), 3. Me_2Si(2-Ac-F-St)2, 4. $C_9H_{18}N_6O_2Si$, 5. $C_{14}H_{20}N_6S_2Si$, 6. $C_6H_{12}N_6S_2Si$, 7. $C_{19}H_{19}N_4OSSiC1$, 8. $C_{29}H_{22}N_5O_3SSiC1$, 9. $C_{30}H_{24}N_5O_3SSiCl$.

87, 94], *Pseudomonas* spp. [33, 43, 68, 84], *Aeromonas formicans* [68], *Proteus mirabilis* [80], *Zymomonas mobilis* [83], and *Vibrio cholera* [98].

On the other hand same compounds also showed antifungal activity towards fungi species, e.g. *Penicillium* spp. [68], *Aspergillus* spp. [43, 62, 66–70, 80, 81, 83, 87, 94], *Aureobasidium pullulans* [68], *Verticillium dahlia* [68], *Puccinia substriata* [33], *Fusarium oxyporum* [43, 75, 80, 83], *Rhizopus phaseoli* [75, 80, 81], *Candida albicans* [66, 67, 69, 70, 87], *Altemaria alternata* [43] and *Macrophomina phaseolina* [43].

The conclusion of the study states that silicon(IV) complexes mostly show antibacterial and antifungal activity. The highest antibacterial activity in diameter inhibition zone (mm), concentration in 1000 ppm is reported against *Staphylococcus aureus* and *Escherichia coli* whereas reports against *Pseudomonas cepacicola* and *Zymomonas mobilis* show lesser antibacterial activity as shown in Fig. 1. Similarly, in the case of MIC (in μg mL^{-1}) values shows greater antibacterial activity against *Staphylococcus aureus* and *Escherichia coli* whereas lesser antibacterial activity against *Klebsiella pneumonia* and *Bacillus cereus* is shown in Table 5. The antifungal activity in diameter inhibition zone (mm), concentration in 1000 ppm and MIC (in μg mL^{-1}) values reported in research papers are shown in Fig. 2 and Table 6.

Nematicidal and insecticidal activity. R_2SiL_2/R_3SiL (R = Me and Ph; L = sulphonamide imine and anion of 2-acetylnapthalene sulphapyridine) have also shown good nematicidal activity against *Meloidogyne incognita* [43] and insecticidal activity against *Trogoderma granarium* [43].

Anticancer and antitumor activity. Liu et al. have reported that silicon-containing diorganotin complexes with salicylaldehyde thiosemicarbazone have good anticancer activity on human breast cancer cells. The anticancer activity of all the complexes was tested by the Cell Counting K it-8(CCK-8) method in vitro. It has been observed that all the complexes exhibited better anticancer activity against MDA-MB-231 and MCF-7, overall, the biological activity of MDA-MB-231 is superior to that of MCF-7, and some of the complexes showed stronger activity than cisplatin [121].

Padrón et al. prepared a series of (2R,3S)-disubstituted tetrahydropyrans in a simple and direct way. With these derivatives they have demonstrated the possibility of silicon protecting groups, such as tert-butyl dimethyl silyl ethers, to be used in anticancer drug design. These types of groups can increase lipophilicity and may explain in part the antitumor activity of the compounds herein reported. A structure-activity link was discovered by in vitro screening of six rep-

Table 5. Antibacterial activity of silicon(IV) complexes (MIC in μg/mL)

Complexes1234567	Minimum inhibitory concentration (MIC) in (μg/mL) against bacteria							Reference
	1	2	3	4	5	6	7	
$C_{20}H_{20}XO_6N_2Si$ (**3d**; X = H)	100	12.5	25	50				[68]
$C_{20}H_{20}XO_6N_2Si$ (**3d**; X = CH_3)	100	50	50	50				[68]
$C_{20}H_{20}XO_6N_2Si$ (**3d**; X = $CH(CH_3)_2$)	6.25	12.5	50	50				[68]
$C_{20}H_{20}XO_6N_2Si$ (**3d**; X = $CH_2CH(CH_3)_2$)	50	50	12.5	6.25				[68]
$C_{12}H_{16}XO_3NSi$ (**3e**; X = H)	100	6.25	100	50				[68]
$C_{12}H_{16}XO_3NSi$ (**3e**; X = CH_3)	25	50	12.5	50				[68]
$C_{12}H_{16}XO_3NSi$ (**3e**; X = $CH(CH_3)_2$)	100	25	100	6.25				[68]
$C_{12}H_{16}XO_3NSi$ (**3e**; X = $CH_2CH(CH_3)_2$)	50	12.5	6.25	6.25				[68]
$C_{15}H_{23}RN_4OSSi$ (**5l**; R = H)	1.562	12.5			3.125		6.25	[77]
$C_{20}H_{23}RN_4O_2SSi$ (**5m**; R = H)	6.25	12.5			6.25		12.5	[77]
$C_{18}H_{19}O_2N_3SSi$ (**5j**; R = Me)	12.5	6.25				12.5		[87]
$C_{20}H_{23}O_2N_3SSi$ (**5j**; R = Et)	12.5	12.5				6.25		[87]
$C_{17}H_{16}O_2N_3SSiCl$ (**5k**)	6.25	6.25				12.5		[87]

1. *E. coli*, 2. *S. aureus*, 3. *P. putida*, 4. *A. formicans*, 5. *K. pneumonia*, 6. *B. subtilis*, 7. *B. cereus*, I = inactive, Nt = not tested.

resentative human solid tumour cell lines. Overall, silyl groups can be considered protection groups and a viable strategy to introduce lipophilicity into drugs [122].

Rui Zhao et al., created a novel class of silicon-containing compounds and assessed their anticancer properties and mode of action with the use of cellular and animal models of drug-resistant PCa. The NCI-60 panel and well-established drug-resistant PCa cell lines were used to test five organosilicon compounds for their anticancer properties. A variety of human cancer cells, including PCa cells resistant to ADT and chemotherapy, showed strong in vitro cytotoxicity when treated with GH1504 [123].

CONCLUSIONS

A concise survey of literature on the synthesis, coordination modes and biological activity of complexes are presented in this review article. Most of the silicon(IV) complexes discussed in this review article have been synthesized by silicon chlorides, silicon acetates and silicon alkoxides with several derivatives of N, O, and S donor ligands. From this review it is clear that mostly silicon(IV) complexes are non-volatile, colour solids, non-electrolyte and soluble in DMSO, DMF and methanol. Several modern spectroscopic techniques are successfully studied from a number of research papers to determine the wide variety of structural motifs of these complexes. The ^{29}Si NMR peak in the silicon(IV) complexes depends on the nature of the ligand. According to these studies, the structure suggested by the researchers are mostly hexa- and penta-coordinated structures, distorted trigonal bipyramidal and distorted octahedral. The spectral data of complexes are as per the suggested structures. These silicon complexes have been successfully screened

Table 6. Antifungal activity of silicon(IV) complexes (MIC in μg/mL)

Complexes	Minimum inhibitory concentration (MIC) in (μg/mL) against fungi					Reference
	A. niger	*P. notatum*	*A. pullulans*	*V. dahliae*	*C. albicans*	
$C_{20}H_{20}XO_6N_2Si$ (**3d**; X = H)	50	6.25	50	50		[68]
$C_{20}H_{20}XO_6N_2Si$ (**3d**; X = CH_3)	50	50	12.5	12.5		[68]
$C_{20}H_{20}XO_6N_2Si$ (**3d**; X = $CH(CH_3)_2$)	50	50	12.5	6.25		[68]
$C_{20}H_{20}XO_6N_2Si$ (**3d**; X = $CH_2CH(CH_3)_2$)	100	50	50	6.25		[68]
$C_{12}H_{16}XO_3NSi$ (**3e**; X = H)	100	25	12.5	25		[68]
$C_{12}H_{16}XO_3NSi$ (**3e**; X = CH_3)	100	50	12.5	6.25		[68]
$C_{12}H_{16}XO_3NSi$ (**3e**; X = $CH(CH_3)_2$)	50	100	100	100		[68]
$C_{12}H_{16}XO_3NSi$ (**3e**; X = $CH_2CH(CH_3)_2$)	100	12.5	6.25	100		[68]
$C_{18}H_{19}O_2N_3SSi$ (**5j**; R = Me)	12.5				6.25	[87]
$C_{20}H_{23}O_2N_3SSi$ (**5j**; R = Et)	6.25				6.25	[87]
$C_{17}H_{16}O_2N_3SSiCl$ (**5k**)	25				12.5	[87]

against different strains of microorganisms where they exhibited significant activity.

ABBREVIATIONS

Et_3N	Triethyl amine	Ala	Alanine
$EtiPr_2$	Ethyl isopropyl	Meth	Methionine
Me	Methyl	Val	Valine
Et	Ethyl	Phe	Phenylalanine
Bu	Butyl	Benz	Benzoyl
Ph	Phenyl	Ac	Acetate
Vi	Vinyl	Py	Pyridine
Cy	Cyclohexyl	$MeCl_2$	Methyl dichloride
Ar	Aromatic	Gly	Glycine

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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