Studies on metal complex formation of environmentally friendly aminopolycarboxylate chelating agents

Helena Hyvönen

Laboratory of Inorganic Chemistry
Department of Chemistry
Faculty of Science
University of Helsinki
Finland

Academic dissertation

To be presented with the permission of the Faculty of Science of the University of Helsinki for public criticism in Auditorium A110 of the Department of Chemistry, A.I. Virtasen aukio 1, on June 25th 2008 at 12 o'clock noon

Helsinki 2008

Supervisor

Professor Heikki Saarinen
Department of Chemistry
University of Helsinki
Finland

Reviewers

Professor Konstantin Popov
Physical and Colloid Chemistry Department
Moscow State University of Food Production
Russia

Professor Mika Sillanpää
Department of Environmental Sciences
University of Kuopio
Finland

Opponent

Professor Lauri Lajunen
Department of Chemistry
University of Oulu
Finland

ISBN 978-952-92-4005-0 (paperback)
ISBN 978-952-10-4741-1 (PDF)
http://ethesis.helsinki.fi

Yliopistopaino
Helsinki 2008

Abstract

For decades, ethylenediaminetetraacetic acid (EDTA) and other aminopolycarboxylates with similar complexation properties and applicability have been widely used as chelating agents in various branches of industry. Recently, the low biodegradability of these ligands and their accumulation in the environment has become cause for concern, because of the persistence of these ligands and their metal complexes in nature. Ethylenediaminedisuccinic acid (EDDS), iminodisuccinic acid (ISA), N-bis[2-(1,2-dicarboxyethoxy)ethyl]aspartic acid (BCA6), N-bis[2-(1,2-dicarboxyethoxy)ethyl]-glycine (BCA5), N-bis[2-(1,2-dicarboxyethoxy)ethyl]methylglycine (MBCA5) and N-tris[(1,2-dicarboxy-ethoxy)ethyl]amine (TCA6) are more environmentally benign and potential candidates to replace EDTA, and also diethylenetriaminepentaacetic acid (DTPA), in several applications. The protonation of these ligands and their complex formation equilibria with selected metal ions were studied in aqueous solution by potentiometric titration. Models of the complexation and stability constants of the different complex species were determined with the computer program SUPERQUAD. The metals tested were Mg(II), Ca(II), Mn(II), Fe(III), Cu(II), Zn(II), Cd(II), Hg(II), Pb(II) and La(III), the selection varying somewhat with the ligand. The formation of species ML was dominant in all systems. Besides the main species, hydroxo and acidic complexes often complemented the complexation models. In some cases, additions of binuclear or bis complexes to models significantly improved the fit. According to the results of the complexation studies, the stability constants of the new ligands are somewhat lower than the corresponding values of EDTA and DTPA. The complexation capability of the new ligands is nevertheless high enough for them to be used in several applications. The new ligands also have other environmental advantages, including low nitrogen content. In the case of the BCA ligands, less chemical and fewer process steps are required in pulp bleaching due to the inertness of their Mn(II) complexes. The lower stability of Cd(II), Hg(II) and Pb(II) complexes of BCA6 is an environmentally advantageous because, in conjunction with the better biodegradability, it probably reduces the capability of BCA6 to remobilize toxic heavy metal ions from sediments.

Preface

This study was carried out in the Laboratory of Inorganic Chemistry, University of Helsinki. I am most grateful to my supervisor, Professor Heikki Saarinen, for his advice, encouragement and valuable comments on the manuscript. I also wish to express my sincere thanks to the head of the laboratory, Professor Markku Leskelä, for his support and for giving me the opportunity to work in the field of solution chemistry. I am indebted to Dr. Marjatta Orama for her collaboration in the early period of the project when most of the measurements were done. Her great professional skill and experience were invaluable when this project was being launched. Dr. Pirkko Tilus is warmly thanked for introducing me to potentiometric titration and for her collaboration over several years in various projects related to teaching as well as to research in solution chemistry. The reviewers of the manuscript, Professor Konstantin Popov and Professor Mika Sillanpää, provided valuable comments and suggestions for improvements.

I am most grateful to all those involved in the chelating agent project, the co-authors from Kemira, and especially Dr. Reijo Aksela, for good cooperation and always a positive and an encouraging attitude to my work. Dr. Sirpa Metsärinne was a valued source of information and advice in regard to the biodegradability of the studied ligands.

All those students who did laboratory work within the project are warmly thanked for their fine contribution as well as their welcome company. Markku Salonen is thanked for the many ideas he shared in the field of solution chemistry, Vasilij Kozlov for his patient help with reference articles written in Russian and Kathleen Ahonen for revising the language of this manuscript.

During this project I have worked as part-time researcher and part-time teacher. Thus, it is impossible to think of the research without the yearly periods in the teaching laboratories. All co-workers are thanked for their good company and cooperation, especially those long-time colleagues who have created a welcoming and fair working team during this project and many years before it. Teaching is one of the best ways to appreciate the limitations of one's own knowledge, and thus I express my gratitude as well to those countless students who year by year have tried to educate me.

Finally I would like to thank my children, husband, parents, other relatives and friends, who have been with me in spirit, listening to my complaining, offering encouragement during difficult times and reinvigorating me with thoughts and activities outside the project.

Järvenpää, June 2008
Helena Hyvönen

List of original publications

This thesis is based on the following publications, which are referred to in the text by Roman numerals I-VII.

I M. Orama, H. Hyvönen, H. Saarinen H. and R. Aksela, *J. Chem. Soc. Dalton Trans.*, 2002, 4644-4648. Complexation of [S,S] and mixed stereoisomers of N,N′-ethylenediaminedisuccinic acid (EDDS) with Fe(III), Cu(II), Zn(II) and Mn(II) ions in aqueous solution.

II H. Hyvönen, M. Orama, H. Saarinen and R. Aksela, *Green Chem.*, 2003, **5**, 410-414. Studies on biodegradable chelating ligands: complexation of iminodisuccinic acid (ISA) with Cu(II), Zn(II), Mn(II) and Fe(III) ions in aqueous solution.

III H. Hyvönen, M. Orama, P. Alén, H. Saarinen, R. Aksela and A. Parén, *J. Coord. Chem.*, 2005, **58**(13), 1115-1125. Complexation of N-tris[(1,2-dicarboxyethoxy) ethyl]amine with Ca(II), Mn(II), Cu(II) and Zn(II) ions in aqueous solution.

IV H. Hyvönen, M. Orama, R. Arvela, K. Henriksson, H. Saarinen, R. Aksela, A. Parén, J. Jäkärä and I. Renvall, *Appita Journal*, 2006, **59**(2), 142-149. Studies on three new environmentally friendly chelating ligands.

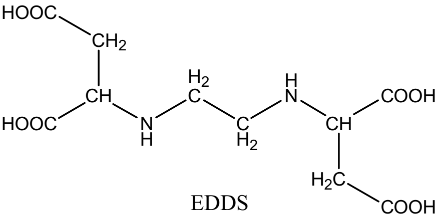
V H. Hyvönen, R. Aksela, *J. Coord. Chem.*, 2007, **60,** 901-910. The complexation of novel amino acid derivatives with La(III) ion in aqueous solution.

VI H. Hyvönen, P. Lehtinen, R. Aksela, *J. Coord. Chem.*, 2008, **61**, 984-996. Complexation of N-bis[2-(1,2-dicarboxyethoxy)ethyl]aspartic acid with Cd(II), Hg(II) and Pb(II) ions in aqueous solution.

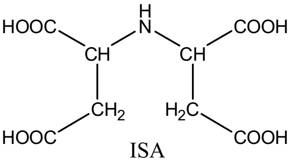
VII H. Hyvönen, R. Aksela, *J. Coord. Chem.*, accepted. Complexation of [S,S,S]- and [R,S,R]-isomers of N-bis[2-(1,2-dicarboxyethoxy)ethyl]aspartic acid with Mg(II), Ca(II), Mn(II), Fe(III), Cu(II) and Zn(II) ions in aqueous solution.

Table of contents

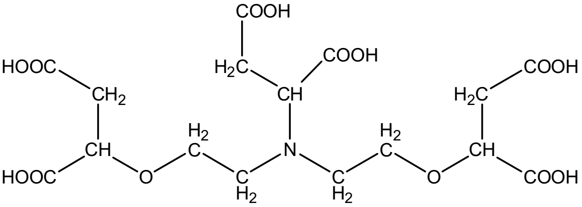
Studied ligands



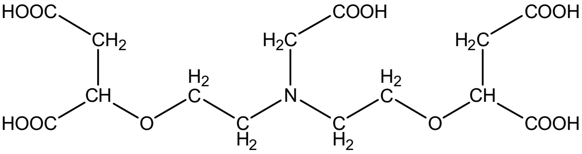
EDDS



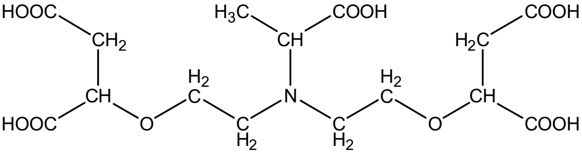
ISA



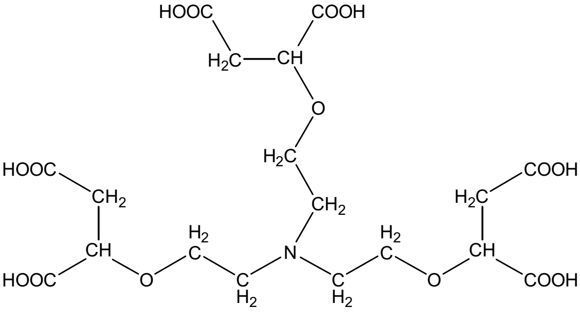
BCA6



BCA5

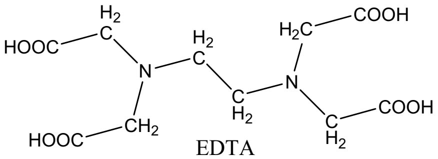


MBCA5

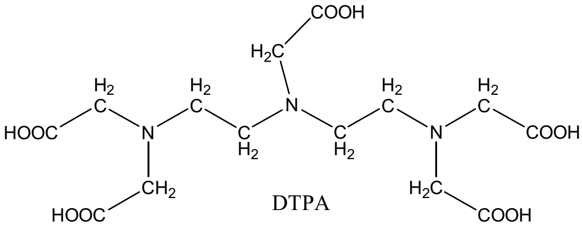


TCA6

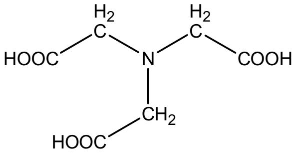
Reference ligands



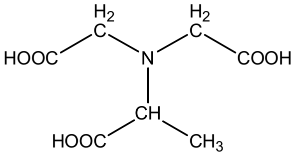
EDTA



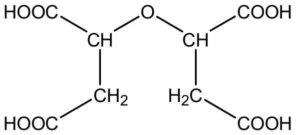
DTPA



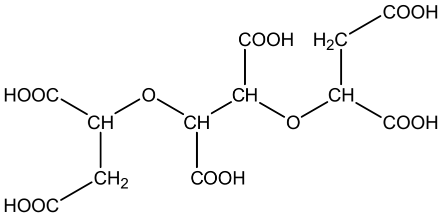
NTA



MGDA



ODS



TDS

Abbreviations

BCA5	N-bis[2-(1,2-dicarboxyethoxy)ethyl]glycine
BCA6 (AES)	N-bis[2-(1,2-dicarboxyethoxy)ethyl]aspartic acid
CMOS	carboxymethyloxysuccinic acid
DTPA	diethylenetriaminepentaacetic acid
EDDA	ethylenediaminediacetic acid
EDDHA	ethylenediiminobis(2-hydroxyphenyl)acetic acid
EDDS	ethylenediaminedisuccinic acid
EDTA	ethylenediaminetetraacetic acid
EEDTA	oxybis(ethylenenitrilo)tetraacetic acid
EGDA	ethyleneglycoldiacetate / 2,5-dioxa-1,1,6-hexanedicarboxylic acid
ISA	iminodisuccinic acid
MBCA5	N-bis[2-(1,2-dicarboxyethoxy)ethyl]methylglycine
MGDA	methylglycinediacetic acid
NTA	nitrilotriacetic acid
ODA	oxydiacetate
ODS	oxydisuccinic acid
TCA6	N-tris[(1,2-dicarboxyethoxy)ethyl]amine
TDS	3,6-dioxaoctane-1,2,4,5,7,8-hexacarboxylic acid
TEA	triethanolamine
TMS	1-hydroxy-3-oxapentane-1,2,4,5-tetracarboxylic acid

1 Introduction

The ability of aminopolycarboxylates such as ethylenediaminetetraacetic acid (EDTA) and diethylenetriaminepentaacetic acid (DTPA) to form stable metal complexes has been widely exploited in analytical chemistry and industrial applications. For decades, both ligands have extensively been used as effective chelating agents in a variety of large-scale industrial applications from detergents to agrochemicals. Recently, however, the nonbiodegradability of these ligands and their metal complexes and their accumulation in the environment has become cause for concern. [1-6] Further, EDTA and DTPA may be capable of remobilizing toxic heavy metal ions from sediments,[7, 8] and they form strong complexes with iron and may increase eutrophication through release of phosphates. The high nitrogen content of EDTA and DTPA is an environmental disadvantage. EDTA has been found in drinking water and is present in almost all anthropogenically influenced surface waters in industrialized countries.[2, 4] Replacement of EDTA and DTPA by more environmentally friendly chelating agents would be highly desirable.

Because of their industrial importance, chelating agents are produced and used in large and increasing quantities. EDTA was patented in Germany in 1935 and has been in constant production since then. Figure 1 shows the development of EDTA sales (calculated as H_4EDTA) in Western Europe between 1989 and 1999. According to data supplied by industry, currently 53900 tonnes EDTA per year are produced in the European Union. The sales of EDTA in 1999 were 34546 tonnes in Western Europe and 1192 tonnes in Finland. [9] EDTA is used as a complexing agent in many branches of industry. The estimated percentage EDTA use in Western Europe [9], Sweden [9] and the World [1] is shown in Figure 2. As in Sweden, the major user of complexing agents in Finland is the pulp and paper industry. [10] The quantity of DTPA sold in Western Europe in 1999 was 14357 tonnes. Sales in Sweden, Finland and Germany comprised two-thirds of the total. [2]

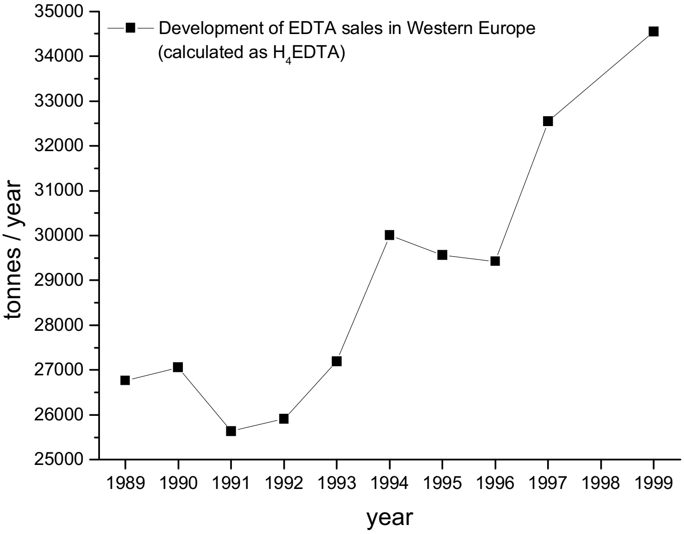


Figure 1. Development of EDTA sales in Western Europe 1989-1999 (calculated as H_4EDTA). [9]

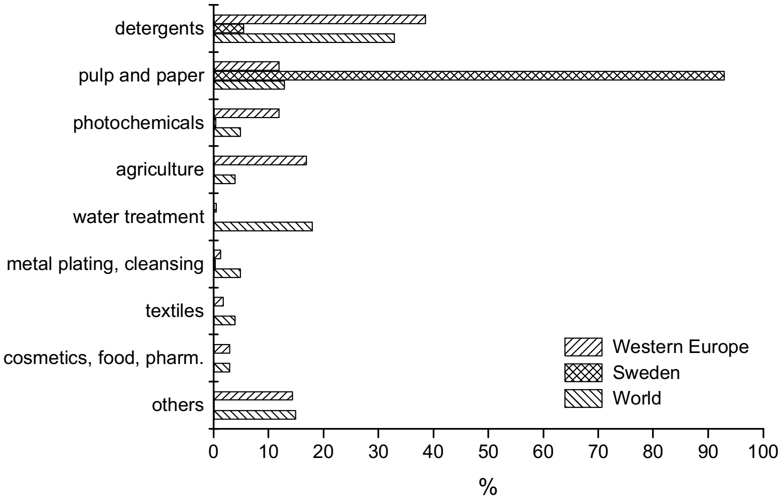


Figure 2. Percentage EDTA use in different branches industry in Western Europe [9], Sweden [9] and the World [1].

EDTA is on the EU priority list of substances for risk assessment. The EU Risk Assessment Report stresses the need to limit the risks that EDTA continues to pose to the environment. This conclusion was reached in view of the high levels of EDTA released to the environment through its use in industrial detergents, by paper mills, by circuit board manufacturers and during the recovery of EDTA-containing wastes. Investigations of these release scenarios have demonstrated a risk to aquatic organisms. [9]

Although EDTA is the main chemical of concern and was the chief motivation for our search for alternative ligands, other ligands with the same kind of biodegradability and the same complexation properties or applicability are discussed where appropriate. DTPA, for example, is heavily consumed in pulp bleaching.

Alternative chelating agents should fulfil the following three criteria: their complex forming properties should be sufficient for the application, the nitrogen content should be as low as possible to reduce the loading of nitrogen, for example, in the effluents of a pulp mill, and they should be readily or at least inherently biodegradable.

The present complexation studies were part of a wider research project coordinated by Kemira Oyj. The complexation data are currently being utilized in various practical studies with the aim of developing new environmentally friendly products.

The protonation of six candidate ligands to replace EDTA, and their complex formation equilibria with selected metal ions, were studied in aqueous solution by potentiometric titration. Models of the complexation and stability constants of the different complex species were determined with the computer program SUPERQUAD. The selection of metals varied somewhat depending on the ligand and included Mg(II), Ca(II), Mn(II), Fe(III), Cu(II), Zn(II), Cd(II), Hg(II), Pb(II) and La(III).

2 Features of studied ligands, metal ions and complexation

2.1 The chelate effect

Chelation is a process in which a metal ion coordinates with two or more donor atoms of the same ligand resulting in the formation of one or more rings. The word chelate, originally proposed in 1920 by Morgan and Drew [11], is derived from the Greek word χηλή (chelé), meaning claw, while ligand comes from the Latin word ligare, to bind. Chelating agents are typically organic molecules with several atoms (polydentate or multidentate ligands) capable of forming chelate rings by coordination bonds with metal cations by donating electron pairs of ligand (Lewis base) to metal ions (Lewis acid). [12] Five- or six-membered chelate rings are usually the most stable.

The chelate effect refers to the preference of metal ions to form complexes with chelating ligand rather than non-chelating ligands where the two types of ligands can form bonds of similar strength. The chelating effect is affected by enthalpy and entropy contributions.[13-22] In general, for any stability constant as well as for their differences, the following thermodynamic relationship can be expressed as

$$\Delta G^0 = -RT \ln \beta = \Delta H^0 - T\Delta S^0 \qquad [1]$$

With increasing β, ΔG^0 becomes more negative, due to more negative enthalpy term ΔH^0 or more positive entropy term ΔS^0. Factors ΔH^0 and ΔS^0 can operate in the same or different directions, the sum effect being decisive.

The following enthalpy contribution can be considered: ligand repulsion, ligand distortion and crystal field stabilization energy. [13-15] When two ligands approach a metal ion they repel one another, with unfavourable enthalpy change upon complex formation, but in the case of a chelating ligand some of this repulsion has already been built into the ligand. Some distortion of the ideal bond angles within the ligand almost always occurs in chelate formation. This can be unfavourable as compared with monodentate complex formation if the distances of the donor atoms are not ideally suited to the metal. Bond distortions are generally lowest in five- and six-membered rings, and these ring sizes are usually favoured. Besides these effects, a chelate ligand generates a larger crystal field splitting than do otherwise similar monodentate ligands, and this enables the formation of stronger complexes.

There are also several entropy contributions to the chelate effect. [13, 16-20] Although the complexation of chelating ligands may be disfavoured relative to monodentate ligands due to the unfavourable position of the other end of a chelating ligand when one end is bound to metal, there are also some favouring entropy terms in chelate formation. The activity factor means that the chance of coordination of the other end of the ligand is proportional to its effective local concentration around the metal ion. In dilute solution, this is much higher than the average ligand concentration because the other end is located in a relatively small volume immediately surrounding the metal ion. The activity factor also provides an explanation of the decreasing magnitude of the chelate effect as the ring size increases beyond the most favoured size, and of the strengthening of the chelate effect with increase in the number of chelate rings. Much of the internal entropy of the ligand is lost upon coordination. The internal entropy of the ligand is less for a rigid chelating ligand than for corresponding monodentate ligand. The internal entropy losses will disfavour complex formation of the monodentate ligand more than that of the chelating ligand. The gain in translational entropy when several monodentate ligands are replaced by one polydentate ligand is also considered as an important source of the chelate effect.

2.2 Ligands investigated

In this work, the metal complexation ability was studied for a series of chelating agents regarded as candidates to replace EDTA and DTPA in several applications. All the ligands contain basic amino nitrogen donors with an electron pair capable of interacting with metal ion, and acidic carboxylic acid groups, capable of losing proton and coordinating to metal ion through oxygen donors. Containing both hard metal ion-favouring carboxylic acid groups and one or two soft metal ion-favouring amino groups, these ligands can be expected to complex both hard and soft metal ions. These same donors are present in EDTA and DTPA. Some of the ligands studied here (BCA6, BCA5, MBCA5, TCA6) also have neutral ether oxygen atoms, which enhance the effect of the stronger donor atoms and, in some cases, enable the formation of chelate rings of adequate size. It can be assumed that rings formed through ether oxygens are less stable than rings consisting solely of stronger donors. On the other hand, the stability of a chelate is expected to grow with increasing number of donor atoms. Although nitrogen is usually a strong donor, forming stable complexes, high nitrogen content in a chelating agent is environmentally undesirable. Thus, it is reasonable to seek ligands with the number of oxygen donors increased at the expense of nitrogen donors.

Ethylenediaminedisuccinic acid (EDDS) is a structural isomer of EDTA. With two chiral carbon atoms it has three stereoisomeric forms [S,S], [S,R/R,S] and [R,R]. In the present work, EDDS was used as [S,S] form and as a mixture consisting of 25% [S,S], 50% [R,S] and 25% [R,R] forms. [S,S]-EDDS was prepared using 1,2-dibromoethane and L-aspartic acid [23] and the isomeric mixture of EDDS was synthesised from ethylenediamine and maleic anhydride. [23-26] The iminodisuccinic acid (ISA) was an isomeric mixture consisting of 50% [S,S] and 50% [R,S] forms synthesised by Michael addition of aspartic acid to maleic acid. [24] While EDDS and ISA are not new compounds, they are used in this project in new applications.

In the context of the project, a series of novel chelating agents was designed by Kemira. These were N-bis[2-(1,2-dicarboxyethoxy)ethyl]aspartic acid (BCA6), N-bis[2-(1,2-dicarboxyethoxy)ethyl]glycine (BCA5), N-bis[2-(1,2-dicarboxyethoxy)ethyl]methyl-glycine (MBCA5) and N-tris[2-(1,2-dicarboxyethoxy)ethyl]amine (TCA6), synthesised, respectively, via a lanthanide-catalysed Michael addition of diethanolamine, bis-N-(2-hydroxyethyl)aspartic acid, bis-N-(2-hydroxyethyl)-D-L-alanine or triethanolamine to maleic acid. [27-29]

All new ligands were studied as isomeric mixtures, and in addition BCA6, which appears as six conformational isomers, [S,S,S], [S,S,R], [S,R,R], [S,R,S], [R,S,R] and [R,R,R], was studied as its pure isomers [S,S,S] and [R,S,R]. These were produced using stereo centres from L- and D-malic and aspartic acid. [30] All ligands were produced by Kemira.

2.3 Metal ions investigated

Metal ions for the study were selected with a view to the intended applications. In pulp bleaching, Mn(II) and Fe(III) should be sequestered, while Mg(II) and Ca(II) ions, which have a positive effect on peroxide bleaching, should not. The complexation of Ca(II) is essential in detergent applications, and the complex formation with Zn(II), Cu(II) and Fe(III) is beneficial in applications to plant growth.

The complexation of La(III) was studied in an attempt to discover the reason for the disappearance of the lanthanum catalyst used in the synthesis of most of the ligands. The complexation of BCA5, BCA6 and TCA6 with La(III) was studied while searching for the lost lanthanum, and the reason for the disappearance was discovered: these ligands are good chelators for La(III). The problem of loss was solved by recycling the catalyst by ion exchange. [31]

When application tests showed BCA6 to be the most suitable of the new ligand for pulp bleaching, some additional studies were done with BCA6. Concern over its possible ability to mobilize heavy metals led to widening of the studies to include the complexation of BCA6 with Cd(II), Hg(II) and Pb(II) ions.

The isomers of EDDS are known to exhibit different degrees of biodegradability and it was of interest to study their possibly different behaviour in complexation. These comparisons were first done for EDDS with Fe(III), Mn(II), Cu(II) and Zn(II) – the metal ions that were measured with almost all ligands here – and then for BCA6 with these ions and also with Ca(II) and Mg(II).

2.4 Properties of the metal ions

Several properties of the metal ion affect chelate formation. These include electronic structure, acceptor character, size, oxidation state and coordination number of metal ion. The nature of the bond between metal and ligand may vary from essentially electrostatic to almost purely covalent. [12]

Metal ions can be classified according to their electronic structure as set out in Table 1. Types i-iv have filled subshells and types v and vi incompletely filled subshells. The effect of variable oxidation states is present in the latter two cases. The complexes of transition metals and the lanthanides (and actinides) are generally highly stable compared with those of non-transition elements. [12]

Two classifications of metals divide them according to their nature of acceptor character towards different ligands in aqueous solution: the **a**/**b** and the hard/soft classification. Most metals in their common oxidation states are class **a** acceptors and form their most stable complexes with more electronegative ligands containing nitrogen, oxygen and fluorine. The bonding is predominately electrostatic, and these metal ions have weak polarizing power. Class **b** acceptors form their most stable complexes with elements like phosphorus, sulphur and chlorine and elements below these in the periodic table. The greater polarizing power of the class **b** metal ions results in covalent forces in their complexes, which contribute significantly to the metal-ligand bonding. Class **b** metals can form more stable complexes than class **a** metals with neutral ligands such as ethylenediamine, while class **a** metals prefer ligands containing acidic functional groups such as polycarboxylic acids. The division into the different classes is not sharp, and there are several borderline ions. Metal ions of type i and ii with 2 or 8 electrons in their outermost shells belong to class **a**. When d-subshells are completely filled (type iii), class **b** character changes to class **a** with increasing charge of the ion, and in type iv ("inert" pair of s-electrons) class **b** behaviour predominates. When the number of electrons in the d-shell increases (in type v), the class **a** character changes to class **b**. It must be emphasized that the **a**/**b** classification is purely empirical, and the **a**/**b** character of metal ions is exhibited as described only in highly polar solvents like water. [12, 13, 32]

Since metal ions behave as Lewis acids (electron pair acceptor) and ligands as Lewis bases (electron pair donor), the hardness/softness of metal ions and ligands offers another way to classify them. Stable complexes result from interactions between hard acids and hard bases or between soft acids and soft bases. Ligands containing highly electronegative donor atoms, which are difficult to polarize, are classified as hard bases (e.g. the carboxylic acid donors as in the ligands studied here). Like class **a** ions, hard metal ions retains their valence electrons strongly and are not easily polarized. Ions that are small in size and possess high charge are classified as hard. Soft metal ions in turn, like class **b** ions, are relatively large, do not retain their valence electrons firmly and are easily polarized. [12, 13, 33-36] According to the hardness parameter derived from electronegativity by Parr and Pearson, [36] the hardness order of the studied metal ions is $Mg^{2+} > Ca^{2+} > La^{3+} > Fe^{3+} > Zn^{2+} > Cd^{2+} > Mn^{2+} > Pb^{2+} > Cu^{2+} > Hg^{2+}$. A hardness order similar to this, expressed by Hancock and Marsicano [37-39] as relative ionicity versus covalence in the M-L bond, gives the series $Ca^{2+} > Mg^{2+} > La^{3+} > Fe^{3+} > Mn^{2+} > Pb^{2+} > Zn^{2+} > Cd^{2+} > Cu^{2+} > Hg^{2+}$.

Besides the ionic contribution and strength of covalence of Lewis acid and base, [40] steric hindrance may affect the formation of the M-L bond. When sizes of the metal ion and donor atom are disparate, steric effects increase. [37-39] The relative sizes of metal ion and ligand are reported to affect the hardness of the metal ion and thereby the strength of complexation. [39, 41, 42] Although nitrogen is classified as a class **a** or hard donor atom, it is considered to be more suitable than oxygen for soft acids. Its lower electronegativity (3) as compared with oxygen (3.5) and its neutral character in the studied ligands make it more suitable than oxygen for complexation with softer acids. On the other hand both oxygen and nitrogen donors bond well with the large Hg^{2+} ion, and Hg^{2+} benefits from the addition of neutral oxygen donors to the ligand as is discussed later.

The size of a metal ion is not invariant, but is affected by several factors, including coordination number, nature of the linked molecules and bonding, and in the case of transition metals, spin state (high/low spin). Ionic radii can be estimated by applying different assumptions. The effective ionic radii given by Shannon and Prewitt, [43] often considered most useful, are shown for the present metal ions for coordination number six in Table 1. Progressing to the right in a periodic series should mean a decrease in the ionic size. If the ionic charge remains constant, the decrease in size is smooth and moderate, but if the charge increases there will be a precipitous drop in the ionic radii. Increase in the oxidation state causes a shrinkage in size for certain metal ions. The ion becomes smaller because of loss of electron density and because the increasing cationic charge pulls the negatively charged ligands closer to the metal. In the case of transition metals, also the spin state affects the effective ionic radii. Increasing coordination number has an increasing effect on the ionic radii because of repulsions among the coordinating ions.[44]

If the studied metal ions are considered with respect to the hard/soft and **a**/**b** criteria together, it can be seen that Mg(II), Ca(II) and La(III) can be classified as hard, class **a** ions, while Hg(II) is a soft, class **b** ion. Its small size and high charge put Fe(III) in the hard, class **a** category, while Mn(II), Cu(II), Zn(II), Cd(II) and Pb(II) lie in the borderline area.

Table 1. Electronic structures, acceptor nature and hardness/softness of the metal ions of the study.[12, 13, 32, 33] Effective radii of metal ions in octahedral coordination (*spin state: high spin).[43]

studied metal ion	type i-vi	outermost electrons	class a / b / borderline	hard / soft / borderline	ionic radii r / pm
-	i	ns^2	(**a**)	(hard)	-
Mg(II)	ii	ns^{2}np^6	**a**	hard	72
Ca(II)			**a**	hard	100
Zn(II)	iii	(n-1)d^{10}	**a**	hard-soft	74
Cd(II)			**a-b**	soft	95
Hg(II)			**b**	soft	102
Pb(II)	iv	(n-1)d^{10}ns^2	**a-b**	hard-soft	118
Mn(II)	v	(n-1)d^1 $\rightarrow$ (n-1)d^9	**a-b**	hard-soft	82 *
Fe(III)		transition metals	**a**	hard	64 *
Cu(II)			**a-b**	hard-soft	73
La(III)	vi	(n-1)(f^1 $\rightarrow$ f^{13})ns^{2}np^6 lanthanides n=5 actinides n=6	**a**	hard	106

Alkaline earth metals (type ii) Mg(II) and Ca(II) are hard acids, favour oxygen donor, are not easily polarized and show predominately electrostatic bonding in complexes.

Type iii ions with d^{10} subshell electrons are relatively easily polarized and tend to have significant covalent bonding character. Coordination number 4 is common for the group 12 metals, Zn(II), Cd(II) and Hg(II) and also coordination number six for Zn(II) and Cd(II). In addition, coordination numbers 5 and 8 are reported for Hg(II).[12] In the case of multidentate ligands like EDTA, the lower coordination number 4 of metal ions usually increases due to chelation. As a borderline ion, Zn(II) forms stable complexes with both oxygen and nitrogen. Cd(II) is also a borderline ion, but class **b** behaviour predominates; Hg(II) is in class **b**.

Pb(II) ion (type iv) has an oxidation state two units lower than the group valence because the pair of s-electrons outside the completed electronic shell do not usually participate in bonding. Pb(II) shows class **b** behaviour, and covalent bonding is important in chelates. Coordination numbers 4, 5 and 6 are common.[12]

In the case of transition metals (type v), the d-subshell is progressively filled as the atomic number increases. Metals with few d-electrons outside the shielding noble gas configuration ns^2np^6 have relatively low ionization energies, like the alkaline and alkaline-earth metals. They prefer oxygen donors and have large ion size and high coordination numbers, e.g. 7 or 8. As the number of d-electrons is increased across the transition metal series, the electron affinity increases with the decreasing shielding of the configuration ns^2np^6 and increasing effective nuclear charge. Ionic radii and maximum coordination numbers are decreased (to 6), and polarizing power and covalent character of the bonding are increased. As a consequence, with increasing atomic number and d-electrons the character of the transition metals changes from class **a** to class **b**. The stability of complexes of divalent ions in the transition metal series with chelators containing oxygen or nitrogen donors often follows the Irving-Williams order: $Mn^{2+} < Fe^{2+} < Co^{2+} < Ni^{2+} < Cu^{2+} > Zn^{2+}$. [45] In octahedral coordination the radius of high spin divalent ions follows the same sequence for all ions except Cu^{2+}. The Cu^{2+} ion is exceptional because of its distortion from regular octahedral environment by the Jahn-Teller effect. In the sequence of octahedrally coordinated ions from Mn^{2+} to Zn^{2+}, the crystal-field stabilization energy (CFSE) is zero for Mn^{2+} (d^5) and Zn^{2+} (d^{10}) but rises for intermediate ions, giving a further increase to stability constants, estimated to be as much as 5-10%.[12]

An example of type vi ions among the studied metals is La(III), which shows class **a** behaviour. In interaction with ligands it shows electrostatic character, preferring oxygen donors, and coordination with nitrogen is usually in association with oxygen donors, as in EDTA, DTPA and the studied ligands. The large size of La(III) allows high coordination numbers of 8, 9 or even 10 as, for example, in $La(H_2O)_4(H\text{-}EDTA)$. [12]

The basicity of neutral oxygen donors increases slightly in the series $H_2O < CH_3OH < (CH_3)_2O$, and this affects the complex stabilities because of the greater electron density of the lone pairs of the ethers than of water. [46-51] Several studies report that the addition to ligands of groups containing neutral oxygen donors, such as ether oxygen, alters the selectivity in favour of larger ions. [46, 48, 52, 53] This preference for larger ions has been reported in connection with the common practice of adding neutral oxygen donors to ligands in such positions that five-membered chelate rings are formed on complex formation. Five- and six-membered chelate rings are commonly considered to form the most stable complexes, with the five-membered rings rated more stable than the six. However, it is pointed out that five-membered chelate rings are better preorganized for coordinating with large metal ions, and six-membered chelate rings for coordinating with small metal ions. Although this different tendency has been extensively studied for macrocyclic compounds, it does not appear to depend on the presence of a macrocyclic ring. Rather, it is related to the presence of five-membered vs. six-membered chelate rings in the formed complex, since similar size-selectivity patterns are observed in the open-chain analogues. This tendency is valid irrespective of the hard or soft character of the metal ion because it is related to donor-metal-donor angles and to steric strain with different metal ion and chelate ring sizes. [39, 48, 54-60]

3 Biodegradation and photodegradation properties

EDTA and DTPA have shown virtually no biodegradability in various tests. [1-6, 61-64] Biodegradability of complexing agents based on ethylene(propylene)di(tri)amine is reported to depend on the character and number of substituents and nitrogen atoms in the molecule. Tetra(penta)-substituted derivatives with two or more tertiary nitrogen atoms and carboxymethyl groups (EDTA, DTPA) are highly stable, while disubstituted derivatives with two secondary nitrogen atoms (e.g. EDDA, ethylenediaminediacetic acid) are potentially degradable. [65] EDTA and DTPA are reported to be photodegradable only as their Fe(III) complexes. Although Fe(III) complexes would be rapidly photodegraded in summer in shallow rivers, the rate may be lower in lakes because of the greater light attenuation. Photodegradation is also pH dependent; degradation is faster under acidic conditions. Under typical freshwater conditions at neutral pH, the free Fe(III) concentration is very low due to the insolubility of iron oxides, and the metal ion is not available for complexation. [66-70]

In the case of EDDS, the biodegradability depends significantly on the isomeric form of the compound: the [S,S]-isomer is rapidly and completely biodegradable, the mixture of isomers degrades partially, and the [R,R]-isomer is resistant in the standard Sturm test (OECD 301B). [25] Similar results have been found in ISO 9439 tests, where [S,S]-EDDS degraded significantly better than the EDDS mixture both as the sodium salt and as iron complex. [71] Both the OECD 301B and ISO 9439 tests are classified as CO_2 evolution tests. [72, 73] In a study of the biodegradation of several metal complexes of [S,S]-EDDS,[74] the Na, Mg, Ca, Cr, Fe, Zn, Cd, Al, and Pb complexes were found to biodegrade readily, whereas the Cu, Ni, Co and Hg complexes remained undegraded. In the case of Hg-EDDS, the lack of biodegradation was due to metal toxicity. [74] Besides biodegradation, the low toxicity of EDDS to fish and algae has been reported. [75]

EDDS is reported to photodegrade markedly faster than EDTA, both in the laboratory and in field experiments. [70] This is because the photodegradation of EDDS is independent of its speciation, whereas the photodegradation of EDTA depends on its existence as Fe(III)-EDTA species.

Chelating agents have sometimes been applied to solubilize heavy metals in polluted soils. Although most of the chelating agent would be removed from the soil before return of the soil to the field, some amount is always left. The formation of metal complexes with this residual complexing agent is possible and must be taken into consideration. EDTA is persistent in the environment and its metal complexes may be leached deep into the soil and contaminate groundwater. Investigation of the degradation of residual EDDS from washing of polluted soil has shown that the EDDS degrades in the soil. [76] Recently, the readily biodegradable isomer [S,S]-EDDS has been used as a replacement for EDTA in soil washing and phytoextraction. [77-80] Phytoextraction through the use of high biomass plants has been proposed as an alternative method to remove metals from contaminated soil. Because the process is generally conceived as being very slow, EDTA and EDDS have been investigated and compared for chemically enhanced phytoextraction. Heavy metals were strongly mobilized by both chelators, EDDS being more effective for Cu and Zn and EDTA for Cd and Pb. Again, however, the persistence of EDTA is considered to make it unsuitable for use in phytoextraction under normal field conditions. [80-83]

An ISA mixture containing 50% [S,S]- and 50% [R,S]-isomers is more biodegradable than a mixture containing 25% [S,S]-, 25% [R,R]- and 50% [R,S]-isomers in the ISO9439 test. [71] All isomers of ISA are biodegradable in some degree in the OECD 301F test. [84] In the same test, but with a different strain isolated from activated sludge, the cleavage of the [S,S]-isomer is twice as high as that of the [R,S]-isomer, and the [R,R]-isomer is not transformed at all. [85] ISA has also been tested as a biodegradable alternative to EDTA in soil washing tests, but it proved to be less effective than EDDS. [79]

TCA6 shows weaker biodegradability in the ISO9439 test than does EDDS, ISA or BCA6, but slightly better biodegradability than DTPA, both as Na salt and as Fe complex. [71] Only preliminary tests have been done on the biodegradability of MBCA5, [86] but it seems to be less biodegradable than EDDS, ISA and the other compounds in the BCA series. In the OECD standardized biodegradation tests (301B and 301F), BCA5 is noticeably more biodegradable than EDTA and DTPA. The degradation of BCA6 is improved in prolonged tests. [87] Also, enhanced biodegradation of BCA6 in a prolonged ISO9439 test is reported. [71] BCA5 and BCA6 appear to be partially biodegradable and more degradable than EDTA and DTPA in OECD tests. If the complexing agents studied in the above-mentioned OECD tests are arranged from least to most biodegradable, the order is DTPA ≤ EDTA < BCA6 < BCA5 < [S,S]-EDDS. [87, 88] Additionally, BCA6 and BCA5 have demonstrated their superior degradability to EDTA in Fenton's process. [89]

In photodegradation tests carried out on the same series of chelating agents, the isomeric mixture of EDDS was used instead of the [S,S] isomer used in biodegradation tests. Since total elimination was achieved, it was concluded that all three isomers of EDDS are photodegradable. All other ligands showed photodegradability, and they can be arranged from least to most photodegradable when exposed to sunlight in lake water as follows: EDTA < BCA5 < DTPA < BCA6 < EDDS. [69, 70, 88, 90] In both biodegradability and photodegradability comparisons, EDDS appears as the most degradable. One disadvantage of EDDS in real applications is that its nitrogen content is not lower than that of EDTA. The degradability of different isomers of BCA6 has not been studied because of poor availability of the pure isomers.

4 Experimental

4.1 Preparation of compounds

4.1.1 Preparation of stock solutions of metal ions

Metal salts were p.a. grade from different producers. Aqueous Cu(II), Mn(II), Mg(II), Zn(II) and Ca(II) chloride solutions were prepared by dissolving $CuCl_2$, $MnCl_2$ and $MgCl_2$ hydrates in distilled water and ZnO and CaO in aqueous hydrochloric acid. Fe(III) chloride solution was prepared from a Fixanal ampoule (Riedel-de Haën). Aqueous Cd(II) and Hg(II) nitrate solutions were prepared by dissolving $Cd(NO_3)_2$ in distilled water and $Hg(NO_3)_2$ in aqueous nitric acid. Pb(II) nitrate solution was prepared from a Titrisol ampoule (Merck). Aqueous La(III) solutions were prepared by dissolving $La(NO_3)_3$ hydrate in distilled water. The metal contents of the stock solutions were standardized by EDTA titration. The Cu(II) concentration was also determined electrogravimetrically. The acid contents of the metal solutions were determined by titration with 0.1 M NaOH solution after liberation of the H^+ ions by cation exchange.

4.1.2 Preparation of ligands

All ligands were produced by Kemira as described in section 2.2. The purity of the ligands was checked by ^{13}C-NMR and ^{1}H-NMR techniques at Kemira. The products were usually in the form of sodium salts containing sodium hydroxide, sodium chloride and water. The base contents of the products were checked by potentiometric titration. Some products contained organic impurities (0.5-2.9 % w/w depending on product, impurity and batch). Where necessary, the complexation of impurities was included as known parameters in the calculations.

4.1.3 Titration solutions

Aqueous 0.1 M NaOH, 0.1 M HCl and 0.1 M HNO_3 were prepared from Titrisol ampoules (Merck). Water used in the dilutions and titration solutions was purified with a Milli-RO and Milli-Q water purification system (Millipore).

4.2 Potentiometric measurements

The protonation and complex formation equilibria were studied in aqueous 0.1 M NaCl (or in 0.1 M $NaNO_3$ where the metal ion was Cd(II), Hg(II) or Pb(II)) at atmospheric pressure, in a nitrogen atmosphere and in a water–thermostated vessel with jacket at 25.0 °C through a series of potentiometric emf (electromotoric force) titrations. The titrations were carried out with a Schott-Geräte GmbH titrator TPC2000 and utilizing titration software TR600 version 5.00. The cell arrangement for the measurement of the hydrogen ion concentration, $[H^+]$ was the following:

$$-\text{RE} \mid \text{equilibrium solution} \mid \text{GE}+ \qquad [2]$$

where GE denotes a glass electrode, Schott N2680, and RE is Hg, Hg_2Cl_2 || 0.1 M NaCl (or 0.01 M NaCl, 0.09 M $NaNO_3$). Assuming the activity coefficients to be constant, expression [3] is valid at 25.0 °C.

$$E = E_0 + 59.157\log[H^+] + j_H[H^+] + j_{OH}[OH^-] \qquad [3]$$

The cell parameter E_0 and the liquid junction coefficient j_H, valid in acidic solutions, were determined for each titration by adding a known amount of HCl (or HNO_3) to the background electrolyte. The value of the liquid junction coefficient j_{OH}, valid in basic solutions, was determined periodically by adding a known amount of NaOH to the background electrolyte. The value of the coefficient j_H varied slightly in different runs, and was in 0.1 M background about -500 mV M^{-1} on average, and the value of the coefficient j_{OH} was 230 mV M^{-1}. The repeatability of these values was good and the values correspond to those in earlier studies made in our laboratory and elsewhere. [91] The ionic product of water, the pK_w value, used when measurements were done in 0.1 M NaCl (13.78) was determined in earlier work done in the same background in this laboratory and corresponds to values determined elsewhere. [91, 92] For measurements done in 0.1 M $NaNO_3$, the pK_w value (13.75) was calculated from E_0 values [93-98] and again corresponds to values reported elsewhere [92]. Although most titrations were carried out under conditions where the liquid junction potential was negligible, the liquid junction correction was made to all emf values.

For measurements of the metal complex equilibria, aqueous NaOH or HCl (or HNO_3) was added to the solution. The ratio of the total concentrations of metal, C_M, to ligand, C_L, was usually held constant. The initial concentrations were varied within the limits $0.0002\ M \leq C_M \leq 0.0065\ M$ and $0.0002\ M \leq C_L \leq 0.0063\ M$, covering the metal-to-ligand ratios from 3:1 to 1:4 depending on the system. In some runs, aqueous metal chloride was used as the titrant. Three to nine independent titrations were carried out for each system. The number of data points used in the calculation of the stability constants varied between 145 and 467 in the pH (= $-\log[H^+]$) ranges 1.9–11.2 depending on the metal ion and ligand. In some of the titrations, the upper pH values were limited by the appearance of a precipitate or very slow attainment of equilibrium. Only stable emf readings (0.2 mV / 2-3 min) were used in the calculations. The reproducibility and reversibility of the equilibria were tested by performing forward (increasing pH) and backward (decreasing pH) titrations.

5 Calculations

5.1 Z_H, zero level and calculation equations

When an alkaline ligand solution was titrated with aqueous HCl (or HNO_3) or an acidic ligand solution was titrated with aqueous NaOH, there was an easily detected inflection point at about pH 7. The data was usually analysed by using HL as the zero level of the ligand.

Protonation/deprotonation of the ligand was controlled with addition of HCl (or HNO_3) / NaOH. Curves of Z_H versus pH were drawn to visualize the experimental data sets. Z_H describes the average number of protons added or liberated per mole of ligand and is given by the relation

$$Z_H = (C_H - [H^+] + K_w[H^+]^{-1})/C_L \qquad [4]$$

where C_H denotes the total concentration of protons calculated over the zero level HL^{1-x}, H_2O and M^{n+}, where x = 6 for BCA6 and TCA6, x = 5 for BCA5 and MBCA5 and x = 4 for ISA, and n^+ is the oxidation number of each metal ion.

In evaluating the equilibrium constants, the following two-component equilibria were considered for TCA6, BCA6, BCA5, MBCA5 and ISA:

$$HL^{1-x} \leftrightharpoons L^{x-} + pH^+ \text{ , } p = 1;\ \beta_{-p01} \qquad [5]$$

(where x = 6 for BCA6 and TCA6, x = 5 for BCA5 and MBCA5 and x = 4 for ISA)

$$pH^+ + HL^{1-x} \leftrightharpoons H_{p+1}L^{p-x+1},\ p = 1\text{-x};\ \beta_{p01} \qquad [6]$$

(where x = 6 for BCA6 and TCA6, x = 5 for BCA5 and MBCA5 and x = 4 for ISA).

In the evaluation of H^+ - M^{n+} - HL^{1-x} systems, the complexation can be characterized by the general three-component equilibrium

$$pH^+ + qM^{n+} + r(HL^{1-x}) \leftrightharpoons (H^+)_p(M^{n+})_q(HL^{1-x})_r \ ; \ \beta_{pqr} \qquad [7]$$

(where x = 6 for BCA6 and TCA6, x = 5 for BCA5 and MBCA5 and x = 4 for ISA).

The hydrolysis of metal ions can be written

$$pH^+ + qM^{n+} \leftrightharpoons (H^+)_p(M^{n+})_q \ ; \ \beta_{pq0} \qquad [8]$$

The zero level was chosen differently for EDDS: in that case C_H denotes the total concentration of protons calculated over the zero level H_4L, H_2O and M^{n+}, and Z_H curves were drawn to the other direction:

$$Z_H = ([H^+] - C_H - K_w[H^+]^{-1})/C_L \qquad [9]$$

For EDDS, the following two-component equilibria were considered:

$$H_4L \leftrightharpoons H_{4-p}L^{p-} + pH^+ \ , \ p = 1\text{-}4; \ \beta_{-p01} \qquad [10]$$

$$pH^+ + H_4L \leftrightharpoons H_{4+p}L^{p+}, \ p = 1, 2; \ \beta_{p01} \qquad [11]$$

and the metal complexation for EDDS was characterized by the three-component equilibrium expressed as follows:

$$pH^+ + qM^{n+} + r(H_4L) \leftrightharpoons (H^+)_p(M^{n+})_q(H_4L)_r \ ; \ \beta_{pqr} \qquad [12]$$

The protonation constants of the ligand and the hydrolysis constants of the metal ions were considered as known parameters in the evaluation of the three-component system (equation [7] or [12]). The hydrolysis constants calculated from data presented by Baes and Mesmer [99] are shown in Table 2. These were taken into consideration in the calculations to the appropriate extent.

Table 2. Hydrolysis constants of the metal ions in ionic strength 0.1, at 25 °C. [99]

metal ion	***pqr*** (equation [8])	**log β_{pqr}**	**formula**
Mg(II)	-110	-11.69	$MgOH^+$
Ca(II)	-110	-13.06	$CaOH^+$
Mn(II)	-110	-10.79	$MnOH^+$
	-210	-22.42	$Mn(OH)_2$
	-310	-34.81	$Mn(OH)_3^-$
	-410	-47.81	$Mn(OH)_4^{2-}$
	-120	-10.31	$Mn_2(OH)^{3+}$
	-320	-24.39	$Mn_2(OH)_3^+$
Fe(III)	-110	-2.56	$FeOH^{2+}$
	-210	-6.21	$Fe(OH)_2^+$
	-310	-12.50	$Fe(OH)_3$
	-410	-21.88	$Fe(OH)_4^-$
	-220	-2.84	$Fe_2(OH)_2^{4+}$
	-430	-6.05	$Fe_3(OH)_4^{5+}$
Cu(II)	-110	-8.22	$CuOH^+$
	-210	-17.53	$Cu(OH)_2$
	-310	-27.80	$Cu(OH)_3^-$
	-410	-39.12	$Cu(OH)_4^{2-}$
	-220	-10.60	$Cu_2(OH)_2^{2+}$
Zn(II)	-110	-9.15	$ZnOH^+$
	-210	-17.10	$Zn(OH)_2$
	-310	-28.39	$Zn(OH)_3^-$
	-410	-40.71	$Zn(OH)_4^{2-}$
	-120	-8.89	$Zn_2(OH)^{3+}$
	-620	-57.53	$Zn_2(OH)_6^{2-}$
Cd(II)	-110	-10.31	$CdOH^+$
	-210	-20.59	$Cd(OH)_2$
	-410	-46.91	$Cd(OH)_4^{2-}$
	-120	-9.16	$Cd_2(OH)^{3+}$
	-440	-32.36	$Cd_4(OH)_4^{4+}$
Hg(II)	-110	-3.60	$HgOH^+$
	-210	-6.34	$Hg(OH)_2$
	-310	-21.10	$Hg(OH)_3^-$
	-120	-3.08	$Hg_2(OH)^{3+}$
	-330	-6.42	$Hg_3(OH)_3^{3+}$
Pb(II)	-110	-7.86	$PbOH^+$
	-210	-17.27	$Pb(OH)_2$
	-310	-28.06	$Pb(OH)_3^-$
	-120	-6.16	$Pb_2(OH)^{3+}$
	-430	-23.95	$Pb_3(OH)_4^{2+}$
	-440	-20.30	$Pb_4(OH)_4^{4+}$
	-860	-43.61	$Pb_6(OH)_8^{4+}$
La(III)	-110	-8.90	$LaOH^{2+}$

5.2 Calculation program SUPERQUAD

Mathematical analysis of the systems involves a search for the complex models (*pqr* triplets) and the corresponding equilibrium constants of the complexes (β_{pqr}) that best describe the experimental data.

The calculations were carried out with the computer program SUPERQUAD [100], which determines the best fit to the experimental data by minimizing the error sum

$$U = \Sigma w_\mathrm{i}(E_\mathrm{i}^\mathrm{obs} - E_\mathrm{i}^\mathrm{calc})^2 \qquad [13]$$

where $E_\mathrm{i}^\mathrm{obs}$ are the observed quantities, $E_\mathrm{i}^\mathrm{calc}$ are the corresponding calculated values, and w_i are the weights of each observation.

In SUPERQUAD the titre volume is chosen as the independent variable (predictor) and the measured potential (emf value) as the dependent variable (response). Electrode readings in the unbuffered parts of the titration curve (in the region of end-points) are unreliable because there even small titre errors can have a significant effect. Weighting is necessary therefore. The standard error propagation formula

$$\sigma^2 = \sigma_\mathrm{E}^2 + (\delta E/\delta V)^2\sigma_\mathrm{V}^2 \qquad [14]$$

is used to calculate the error in measured potential, where σ^2 is the calculated variance of the measurement, σ_E^2 and σ_V^2 are the estimated variances of the electrode and volume readings (depending on the instrumental precision of the potentiometer and burette, usually 0.1 mV and 0.02 ml) and $\delta E/\delta V$ is the slope of the titration curve. The weight for each observed titration point is inversely proportional to the variance at that point,

$$w_\mathrm{i} = 1/(\sigma^2)_\mathrm{i}. \qquad [15]$$

The data near the end-point, where $\delta E/\delta V$ is large, have less weight than the other data.

As experimental input data, SUPERQUAD uses the titration curves (series of titre volumes and electrode readings), the reaction temperature, total number of millimoles of each reactant initially present in the titration vessel, concentration of the titrant in the burette, initial volume in the titration vessel, standard potential of the electrode, and the electrode and volume reading errors. As well, a suggested complexation model with estimated initial log β values is given to the program. Additionally, the maximum number of refinement cycles, selection of output data and choice of weighting scheme can be selected. The output data consists, among others, of the results (log β values with their standard deviation and reaction stoichiometry, sample standard deviation s and the χ^2 statistics), plots of residuals, table of concentrations and percentage distribution curves. The maximum number of data points in the calculation is 600, the maximum number of reactants is four and the maximum number of reactions is 18.

The main task and challenge is to find a complexation model that gives a satisfactory fit to the experimental data and is chemically reasonable. Some model selection criteria are incorporated in SUPERQUAD. As input data, the program reads the proposed set of formation constants associated with the stoichiometric coefficients and the refinement key that tells if the constant is held constant, refined or ignored. The sample standard deviation s and the χ^2 statistics are used as criteria in selection of the complex models. The sample standard deviation should be about one, but models with an s value less than three can be considered acceptable. During the calculations the model with the lowest sample standard deviation and χ^2 and no ill-defined formation constants is taken as the best. A formation constant is ill-defined if its calculated standard deviation is excessive (more than 33% of its value) or if its value is negative. If after refinement a formation constant is found to be ill-defined, a new model, from which the corresponding species has been rejected, is automatically generated. Negative constants are not rejected during the refinement, but at the end of it if they remain negative. Each successive model uses as initial estimates the constants stored for the previous model before the new refinement is started. Finally, if no ill-defined formation constant is found, the output routine gives a full range of diagnostics, including plots of residuals and species distributions. Residual plots are useful in giving the possibility to detect anomalous titration points, large deviations of unbuffered parts of the titrations and lack of agreement between different titration curves.

The initial amount of reactant, the concentration of reactant and the standard electrode potential can also be treated as variables and be refined. However, such a procedure is clearly questionable if their values can be established with sufficient accuracy by a known chemical method. This refinement possibility is designed for circumstances where substances cannot be obtained in a state of high purity, for example because they are of biological origin or extremely difficult to synthesise, in which case the quantity available is small and purification difficult. The designers of the program call these variables dangerous parameters and warn against their use except in unusual situations because changes in concentrations can mask or mimic other systematic errors in the data, leading to an erroneous model or incorrect values of stability constants. This kind of refinement was not used in the determination of stability constants in this study.

Sometimes, for example in the study of protonation or simple binary complex equilibria, especially from calculations of only one titration curve, it is possible to obtain standard deviations for the logarithm of the constant with a third or even fourth decimal digit. This implies higher accuracy in the determination than is reasonable. Even if all other sources of error had been completely eliminated, the response of the electrode would still be at the level of 0.1 mV. Thus, usually only the first two significant decimals digits of stability constants can be considered reliable. As a means to improve the confidence level, the error limits for log β values determined in this study are reported as three times the standard deviation given by the program.

In comparisons of computer programs (MINIQUAD, SCOGS, LETAGROP, ESTA), SUPERQUAD has proved to be an excellent tool for the potentiometric determination of stability constants. [101, 102] SUPERQUAD reaches the correct solution almost regardless of the errors in the starting log β values, and the automatic elimination is highly useful when the suggested model includes spurious components. However, the conclusion may be wrong if the initial model is incomplete.

5.3 Calculation procedure

After the liquid junction correction to the titration data (with coefficients obtained from E_0 titration [3]), the data analysis was always started by drawing curves of Z_H versus pH (equation[4]). Comparison of Z_H curves of protonation and complexation data (zero level of the ligand being HL, for example; charges omitted here for clarity) gave an estimate of the pH range where complexation occurs and sometimes rough estimates of the species likely to be present. In all systems, Z_H for complexation titration obtained the value -1 (compared to zero level of the Z_H protonation curve) when the pH was increased, indicating the coordination of ligand to metal in the form L. The formation of species ML was dominant in all systems. This is logical because the aqueous complexation of a polydentate ligand is expected to be characterized by the formation of a stable mononuclear 1:1 metal to ligand complex as the major species. In such cases, a Z_H value lower than -1 for the complexation indicates the presence of hydroxo complex species, M(OH)L. Besides the major species ML, hydroxo or acidic complexes (when Z_H curves of complexation diverge from Z_H curves of protonation in acidic pH range before ML complexes) often complemented the complexation models. In some cases, additions of binuclear or bis complexes to models significantly improved the fit. These species may significantly broaden the pH range of applications or they may be of only marginal relevance to applications. Usually, SUPERQUAD succeeds well in finding the right model and in rejecting species that are not present. A “wrong” model is usually rejected without error, but the absence of an existing species in the calculations could cause the rejection of another existing species or even ruin the calculation. In these cases, extra care must be taken that all possible “right” species have been taken into account. Often Z_H curves gave only crude trend estimations, and the choice of the complexation model given to SUPERQUAD was guided more by experience about similar kinds of ligands. The prerequisite to accept additions to models was that they give significant improvement to the fit.

6 Results

6.1 Protonation and stability constants

The results were obtained from SUPERQUAD as overall stability constants (log β), following the chosen zero level described in section 5. The log β_{pqr} results with error limits (± 3σ), number of points / titrations and χ^2 / s statistics are shown in Tables 3-8. All results were recalculated to the form used in the Critical Stability Constants Database [92] (i.e., stepwise stability constants, log K) to allow comparison with EDTA, DTPA and some other reference ligands.[92, 103-107] The results are collected in Tables 9 and 10. The reactions are included in the tables, but charges are omitted for clarity.

EDTA and DTPA were of particular interest for comparisons because they are currently used in large quantities in the pulp and paper industry. Nitrilotriacetic acid (NTA) and methylglycinediacetic acid (MGDA) were included as references for the chelating agents used in detergents, while oxydisuccinic acid (ODS) and 3,6-dioxaoctane-1,2,4,5,7,8-hexacarboxylic acid (TDS) were examples of ligands with only oxygen donors and with similar functional groups to those of the studied ligands. Examination of the main species, ML, which is dominant in wide pH area, showed that, in all cases, EDTA and DTPA clearly form the most stable complexes. However, the complexes of the studied ligands are strong enough that they can be applied for several purposes, as described in section 8.

Besides the main species, ML, the complexation models were complemented by some other species, which significantly improved the fit. M(OH)L was found in the basic pH region of most of the studied ligand-metal systems, as for many of the reference systems. It was not found in systems Hg(II)-BCA6, Fe(III)-BCA5 or Mn(II)-EDDS. For Hg(II)-BCA6 and Fe(III)-BCA5, the strong hydrolysis of the metal ions overcame the formation of the M(OH)L species. Hydrolysis also significantly limited the pH range suitable for complex formation in the basic area in the case of Fe(III) for ISA and BCA5 and in the Hg(II)-BCA6 system.

The metal ions formed acidic complexes with most of the studied ligands, as with most of the reference ligands. The number of acidic species was greater for the BCA series and TCA6 than for ISA or EDDS and much greater than for EDTA or DTPA, but similar to the models found for ODS and TDS. The carboxylic acid groups are more acidic in EDTA and DTPA than in the BCA series and TCA6. The ligands with ether oxygen groups have a wider pH area where acidic groups can exist. For example, ISA and ODS are otherwise similar, but the nitrogen donor in ISA is replaced by ether oxygen in ODS, and less acidic carboxylic acid groups and a greater number of acidic complex species are found for ODS than for ISA. Probably the electron-withdrawing effect of the ether oxygen in ODS isolates the two succinic acid groups more effectively than occurs in ISA. Thus, the succinic groups in ligands containing ether oxygen act more independently, producing more acidic species. Selected protonation profiles are compared in Figure 3, where the similarity of BCA6, TCA6 and TDS can be seen. It is also noteworthy that only mono- and triprotonated species were found in the EDDS-Zn(II) system. Probably a change of complex geometry associated with the simultaneous dissociation of two protons occurs when the pH is changed. The greatest number of acidic complexes was found for ligands with highest negative charge, L^{6-}, i.e. BCA6 and TCA6. The trivalent ions Fe(III) and La(III) usually formed less protonated species than did divalent metal ions.

The complexation model was completed with binuclear species for all ligands except the smallest one, ISA. More binuclear species were found for the ligands with several carboxylic acid substituents located apart from one another, especially for TCA6 (Ca, Mn, Cu, Zn, La) and BCA6 (Ca, Cu, Zn, La), but also for BCA5 (Cu, Zn, La), MBCA5 (Cu) and EDDS (Cu). The same trend was seen with the larger reference ligands DTPA (Mg, Mn, Cu, Zn, Cd, Pb) and TDS (Mg, Ca, Mn, Cu, Zn, Hg, Pb). As expected, bis complexes were found only for the smaller ligands EDDS (Mn, Cu, Zn) and ISA (Pb)[92] and for the reference ligands of similar size NTA (Ca, Mn, Fe, Cu, Zn, Cd, Pb, La) and MGDA (La). As a curiosity, the trinuclear Ca_3L species was found for TCA6.

When the work with ISA was done, reference values were available only for Mg^{2+} and Ca^{2+}.[108] The compatibility of the present results with values published later [92] for ISA, as well as for EDDS, can be seen in Table 9. The complexation of ISA with some divalent ions has recently been investigated by voltammetric method. [109] The results published in article II are in good agreement with the values of the stability constants for ML complexes of ISA with Cu^{2+} and Zn^{2+} obtained by voltammetry.

Table 3. Protonation and complexation of ISA with Mn(II), Fe(III), Cu(II), and Zn(II) in aqueous 0.1 M NaCl at 25 °C. [II]

	$p\ q\ r$	$\log(\beta_{pqr} \pm 3\sigma)$	proposed formula
	eq. [5,6,7]	ISA HL^{3-}	
H^+			
	-1 0 1	-10.52 ± 0.03	L^{4-}
	1 0 1	4.55 ± 0.02	H_2L^{2-}
	2 0 1	8.08 ± 0.02	H_3L^-
	3 0 1	10.51 ± 0.04	H_4L
	4 0 1	12.02 ± 0.15	H_5L^+
χ^2 / s	142.53 / 1.41		
points / titrations	286 / 4		
Mn^{2+}			
	-2 1 1	-14.52 ± 0.34	$Mn(OH)L^{3-}$
	-1 1 1	-3.26 ± 0.04	MnL^{2-}
χ^2 / s	53.50 / 1.46		
points / titrations	226 / 6		
Fe^{3+}			
	-2 1 1	-1.96 ± 0.14	$Fe(OH)L^{2-}$
	-1 1 1	3.34 ± 0.11	FeL^-
	0 1 1	7.23 ± 0.11	$FeHL$
χ^2 / s	70.55 / 2.28		
points / titrations	255 / 7		
Cu^{2+}			
	-2 1 1	-8.04 ± 0.12	$Cu(OH)L^{3-}$
	-1 1 1	2.36 ± 0.10	CuL^{2-}
	0 1 1	6.75 ± 0.07	$CuHL^-$
	1 1 1	9.88 ± 0.10	CuH_2L
χ^2 / s	73.25 / 2.98		
points / titrations	266 / 4		
Zn^{2+}			
	-2 1 1	-11.63 ± 0.18	$Zn(OH)L^{3-}$
	-1 1 1	-0.37 ± 0.03	ZnL^{2-}
	0 1 1	4.04 ± 0.03	$ZnHL^-$
χ^2 / s	82.20 / 1.45		
points / titrations	345 / 7		

Table 4. Protonation and complexation of [S,S]-EDDS and EDDS mixture with Mn(II), Fe(III), Cu(II) and Zn(II) in aqueous 0.1 M NaCl at 25 °C.[I]

p q r	log(β_{pqr} ± 3σ)	log(β_{pqr} ± 3σ)	proposed formula
eq. [10,11,12]	[S,S]-EDDS, H_4L	EDDS-mix, H_4L	
H^+			
-4 0 1	-23.91 ± 0.02	-23.99 ± 0.01	L^{4-}
-3 0 1	-13.80 ± 0.02	-13.87 ± 0.01	HL^{3-}
-2 0 1	-6.89 ± 0.02	-6.93 ± 0.01	H_2L^{2-}
-1 0 1	-3.05 ± 0.02	-3.08 ± 0.01	H_3L^-
1 0 1	1.37 ± 0.19	1.59 ± 0.07	H_5L^+
2 0 1	3.48 ± 0.09	3.20 ± 0.20	H_6L^{2+}
χ^2 / s	59.84 / 0.82	78.03 / 0.76	
points / titrations	287 / 4	321 / 4	
Mn^{2+}			
-4 1 1	-14.94 ± 0.02	-15.30 ± 0.02	MnL^{2-}
-3 1 1	-10.24 ± 0.12	-10.29 ± 0.11	$MnHL^-$
-6 2 1	-20.02 ± 0.33	-20.16 ± 0.19	$Mn(HL)_2{}^{4-}$
χ^2 / s	11.64 / 1.63	20.53 / 1.35	
points / titrations	180 / 5	173 / 5	
Fe^{3+}			
-6 1 1	-20.87 ± 0.42	-20.91 ± 0.31	$Fe(OH)_2L^{3-}$
-5 1 1	-11.03 ± 0.37	-11.18 ± 0.25	$Fe(OH)L^{2-}$
-4 0 1	-3.06 ± 0.38	-3.95 ± 0.16	FeL^-
χ^2 / s	80.51 / 0.94	86.50 / 1.02	
points / titrations	283 / 9	325 / 8	
Cu^{2+}			
-5 1 1	-16.27 ± 0.16	-16.68 ± 0.17	$Cu(OH)L^{3-}$
-4 1 1	-5.21 ± 0.13	-5.65 ± 0.12	CuL^{2-}
-3 1 1	-1.62 ± 0.13	-1.90 ± 0.11	$CuHL^-$
-2 1 1	0.66 ± 0.15	0.64 ± 0.13	CuH_2L
-4 2 1	-2.84 ± 0.25	-3.44 ± 0.31	Cu_2L
-7 1 2	-16.52 ± 0.19	-17.16 ± 0.23	$CuL(HL)^{5-}$
-6 1 2	-9.42 ± 0.17	-9.77 ± 0.15	$Cu(HL)_2{}^{4-}$
-5 1 2	-5.69 ± 0.23	-5.78 ± 0.16	$Cu(HL)(H_2L)^{3-}$
-4 1 2	-2.18 ± 0.26	-2.50 ± 0.23	$Cu(H_2L)_2{}^{2-}$
χ^2 / s	22.20 / 1.08	15.97 / 1.08	
points / titrations	303 / 5	345 / 5	
Zn^{2+}			
-5 1 1	-21.63 ± 0.10	-21.89 ± 0.09	$Zn(OH)L^{3-}$
-4 1 1	-10.32 ± 0.02	-10.84 ± 0.03	ZnL^{2-}
-3 1 1	-6.64 ± 0.03	-6.66 ± 0.02	$ZnHL^-$
-1 1 1	-0.72 ± 0.14	-0.70 ± 0.12	ZnH_3L^+
-6 1 2	-14.97 ± 0.11	-15.14 ± 0.09	$Zn(HL)_2{}^{4-}$
χ^2 / s	42.38 / 1.13	18.40 / 1.67	
points / titrations	276 / 5	378 / 5	

Table 5. Protonation and complexation of BCA5 and MBCA5 with Mg(II), Ca(II), Mn(II), Fe(III), Cu(II) and Zn(II) in aqueous 0.1 M NaCl at 25 °C. [IV,V]

p q r eq. [5,6,7]	$\log(\beta_{pqr} \pm 3\sigma)$ BCA5, HL^{4-}	$\log(\beta_{pqr} \pm 3\sigma)$ MBCA5, HL^{4-}	proposed formula
H^+			
-1 0 1	-9.30 ± 0.04	-9.56 ± 0.03	L^{5-}
1 0 1	5.22 ± 0.04	5.32 ± 0.03	H_2L^{3-}
2 0 1	9.68 ± 0.04	9.87 ± 0.02	H_3L^{2-}
3 0 1	13.24 ± 0.05	13.83 ± 0.03	H_4L^-
4 0 1	16.00 ± 0.07	16.88 ± 0.03	H_5L
5 0 1	18.33 ± 0.07	19.74 ± 0.03	H_6L^+
χ^2 / s	72.03 / 1.83	17.38 / 0.58	
points / titrations	460 / 4	251 / 3	
Mg^{2+}			
-2 1 1	-13.94 ± 0.14	-14.91 ± 0.11	$Mg(OH)L^{4-}$
-1 1 1	-3.38 ± 0.04	-4.47 ± 0.06	MgL^{3-}
0 1 1	2.99 ± 0.05		$MgHL^{2-}$
χ^2 / s	39.13 / 1.84	22.98 / 1.77	
points / titrations	226 / 3	95 / 3	
Ca^{2+}			
-2 1 1	-12.73 ± 0.14	-13.45 ± 0.08	$Ca(OH)L^{4-}$
-1 1 1	-1.90 ± 0.02	-2.79 ± 0.04	CaL^{3-}
0 1 1	3.32 ± 0.03	2.67 ± 0.08	$CaHL^{2-}$
χ^2 / s	21.17 / 1.46	47.32 / 1.49	
points / titrations	222 / 3	219 / 4	
Mn^{2+}			
-2 1 1	-12.52 ± 0.10	-11.18 ± 0.05	$Mn(OH)L^{4-}$
-1 1 1	-1.80 ± 0.04	-0.51 ± 0.05	MnL^{3-}
0 1 1	3.82 ± 0.03	4.66 ± 0.03	$MnHL^{2-}$
1 1 1		8.59 ± 0.05	MnH_2L^-
χ^2 / s	29.62 / 1.36	21.08 / 1.24	
points / titrations	148 / 3	208 / 4	
Fe^{3+}			
-2 1 1		1.11 ± 0.15	$Fe(OH)L^{3-}$
-1 1 1	3.33 ± 0.10	7.39 ± 0.12	FeL^{2-}
0 1 1	8.40 ± 0.08	11.85 ± 0.13	$FeHL^-$
1 1 1	12.38 ± 0.10	15.60 ± 0.12	FeH_2L
2 1 1	15.21 ± 0.15	18.13 ± 0.15	FeH_3L^+
0 2 1	13.46 ± 0.28		Fe_2HL^+
χ^2 / s	22.20 / 1.58	15.90 / 0.87	
points / titrations	204 / 4	171 / 3	
Cu^{2+}			
-2 1 1	-9.99 ± 0.18	-7.15 ± 0.17	$Cu(OH)L^{4-}$
-1 1 1	0.27 ± 0.07	3.13 ± 0.04	CuL^{3-}
0 1 1	5.86 ± 0.07	8.25 ± 0.03	$CuHL^{2-}$
1 1 1	10.13 ± 0.10	12.31 ± 0.04	CuH_2L^-
2 1 1	13.81 ± 0.06	15.71 ± 0.02	CuH_3L
3 1 1	16.46 ± 0.18	18.24 ± 0.07	CuH_4L^+

-1 2 1	4.36 ± 0.15	7.34 ± 0.12	Cu_2L^-
0 2 1	9.38 ± 0.14	11.68 ± 0.18	Cu_2HL
χ^2 / s	21.93 / 1.69	42.20 / 0.69	
points / titrations	232 / 3	296 / 4	
Zn^{2+}			
-2 1 1	-11.67 ± 0.13	-9.99 ± 0.09	$Zn(OH)L^{4-}$
-1 1 1	1.21 ± 0.05	1.04 ± 0.03	ZnL^{3-}
0 1 1	4.33 ± 0.07	6.22 ± 0.03	$ZnHL^{2-}$
1 1 1	8.64 ± 0.08	10.39 ± 0.02	ZnH_2L^-
2 1 1		13.88 ± 0.04	ZnH_3L
-1 2 1	1.78 ± 0.19		Zn_2L^-
0 2 1	7.44 ± 0.13		Zn_2HL
χ^2 / s	17.02 / 1.50	39.63 / 0.79	
points / titrations	187 / 3	288 / 4	
La^{3+}			
-2 1 1	-7.10 ± 0.16		$La(OH)L^{3-}$
-1 1 1	2.06 ± 0.10		LaL^{2-}
0 1 1	6.26 ± 0.12		$LaHL^-$
χ^2 / s	11.10 / 1.47		
points / titrations	307 / 4		

Table 6. Protonation and complexation of TCA6 with Ca(II), Mn(II), Cu(II), Zn(II) and La(III) in aqueous 0.1 M NaCl at 25 °C. [III,V]

	p q r eq. [5,6,7]	log ($\beta_{pqr} \pm 3\sigma$) TCA6, HL^{5-}	proposed formula
H^+			
	-1 0 1	-9.87 ± 0.05	L^{6-}
	1 0 1	5.40 ± 0.03	H_2L^{4-}
	2 0 1	10.08 ± 0.02	H_3L^{3-}
	3 0 1	14.25 ± 0.03	H_4L^{2-}
	4 0 1	17.87 ± 0.03	H_5L^-
	5 0 1	20.81 ± 0.05	H_6L
	6 0 1	23.56 ± 0.05	H_7L^+
χ^2 / s	148.81 / 0.46		
points / titrations	364 / 3		
Ca^{2+}			
	-2 1 1	-15.27 ± 0.17	$Ca(OH)L^{5-}$
	-1 1 1	-3.72 ± 0.05	CaL^{4-}
	0 1 1	2.02 ± 0.49	$CaHL^{3-}$
	1 1 1	7.58 ± 0.30	CaH_2L^{2-}
	-1 2 1	-0.97 ± 0.13	Ca_2L^{2-}
	0 2 1	4.81 ± 0.17	Ca_2HL^-
	-1 3 1	1.65 ± 0.19	Ca_3L
χ^2 / s	10.22 / 0.58		
points / titrations	240 / 5		
Mn^{2+}			
	-2 1 1	-13.74 ± 0.28	$Mn(OH)L^{5-}$
	-1 1 1	-2.40 ± 0.03	MnL^{4-}
	0 1 1	2.99 ± 0.07	$MnHL^{3-}$
	-1 2 1	0.51 ± 0.06	Mn_2L^{2-}
	0 2 1	5.76 ± 0.11	Mn_2HL^-
χ^2 / s	19.37 / 0.87		
points / titrations	263 / 4		
Cu^{2+}			
	-2 1 1	-9.44 ± 0.10	$Cu(OH)L^{5-}$
	-1 1 1	0.39 ± 0.05	CuL^{4-}
	0 1 1	5.68 ± 0.06	$CuHL^{3-}$
	1 1 1	10.08 ± 0.10	CuH_2L^{2-}
	2 1 1	14.22 ± 0.05	CuH_3L^-
	3 1 1	17.36 ± 0.10	CuH_4L
	-3 2 1	-10.53 ± 0.24	$Cu_2(OH)_2L^{4-}$
	-2 2 1	-2.30 ± 0.31	$Cu_2(OH)L^{3-}$
	-1 2 1	5.02 ± 0.07	Cu_2L^{2-}
	0 2 1	9.40 ± 0.12	Cu_2HL^-
χ^2 / s	48.38 / 1.60		
points / titrations	367 / 4		

Zn^{2+}			
	-2 1 1	-11.70 ± 0.25	$Zn(OH)L^{5-}$
	-1 1 1	-1.15 ± 0.02	ZnL^{4-}
	0 1 1	4.19 ± 0.02	$ZnHL^{3-}$
	1 1 1	8.68 ± 0.05	ZnH_2L^{2-}
	2 1 1	12.81 ± 0.03	ZnH_3L^{-}
	3 1 1	15.94 ± 0.39	ZnH_4L
	-2 2 1	-4.97 ± 0.46	$Zn_2(OH)L^{3-}$
	-1 2 1	1.79 ± 0.07	Zn_2L^{2-}
χ^2 / s	28.80 / 0.56		
points / titrations	342 / 4		
La^{3+}			
	-2 1 1	-7.88 ± 0.14	$La(OH)L^{4-}$
	-1 1 1	3.15 ± 0.03	LaL^{3-}
	0 1 1	7.86 ± 0.02	$LaHL^{2-}$
	1 1 1	11.09 ± 0.09	LaH_2L^{-}
	2 1 1	14.63 ± 0.07	LaH_3L
	-1 2 1	7.26 ± 0.03	La_2L
	0 2 1	10.99 ± 0.05	La_2HL^{+}
	1 2 1	14.22 ± 0.09	$La_2H_2L^{2+}$
χ^2 / s	42.53 / 1.02		
points / titrations	374 / 4		

Table 7. Protonation and complexation of [S,S,S]-BCA6, [R,S,R]-BCA6 and BCA6-mixture with Mg(II), Ca(II), Mn(II), Fe(III), Cu(II), Zn(II) and La(III) in aqueous 0.1 M NaCl at 25 °C. (*when $C_L \leq C_M$, χ^2/S 47.08/1.06, points/titrations 289/3) ^{IV,V,VII}

p q r eq. [5,6,7]	log ($\beta_{pqr} \pm 3\sigma$) [S,S,S]-BCA6 HL^{5-}	log ($\beta_{pqr} \pm 3\sigma$) [R,S,R]-BCA6 HL^{5-}	log ($\beta_{pqr} \pm 3\sigma$) BCA6-mixture HL^{5-}	proposed formula
H^+				
-1 0 1	-9.38 ± 0.05	-8.99 ± 0.04	-8.98 ± 0.03	L^{6-}
1 0 1	5.58 ± 0.04	5.58 ± 0.04	5.47 ± 0.03	H_2L^{4-}
2 0 1	10.30 ± 0.03	10.29 ± 0.04	10.20 ± 0.02	H_3L^{3-}
3 0 1	14.32 ± 0.04	14.08 ± 0.05	14.16 ± 0.03	H_4L^{2-}
4 0 1	17.49 ± 0.04	17.09 ± 0.04	17.36 ± 0.03	H_5L^-
5 0 1	19.86 ± 0.05	19.31 ± 0.06	19.92 ± 0.05	H_6L
6 0 1	21.05 ± 0.18	20.48 ± 0.26	21.89 ± 0.06	H_7L^+
χ^2 / s	11.90 / 0.82	9.62 / 0.82	51.19 / 0.85	
points / titrations	168 / 4	251 / 5	313 / 3	
Mg^{2+}				
-2 1 1	-14.30 ± 0.18	-13.64 ± 0.17	-14.07 ± 0.12	$Mg(OH)L^{5-}$
-1 1 1	-2.56 ± 0.11	-2.46 ± 0.13	-3.00 ± 0.06	MgL^{4-}
0 1 1	4.13 ± 0.09	4.00 ± 0.10	3.07 ± 0.08	$MgHL^{3-}$
1 1 1	9.22 ± 0.12	9.14 ± 0.13	7.99 ± 0.17	MgH_2L^{2-}
2 1 1	13.87 ± 0.09	13.58 ± 0.10	12.49 ± 0.14	MgH_3L^-
3 1 1	17.41 ± 0.18	17.06 ± 0.15	16.11 ± 0.50	MgH_4L
χ^2 / s	24.00 / 1.60	25.50 / 2.10	35.78 / 1.25	
points / titrations	312 / 4	351 / 4	283 / 4	
Ca^{2+}				
-2 1 1	-11.91 ± 0.13	-11.26 ± 0.09	-11.27 ± 0.11	$Ca(OH)L^{5-}$
-1 1 1	-1.22 ± 0.10	-0.62 ± 0.08	-1.27 ± 0.03	CaL^{4-}
0 1 1	4.20 ± 0.11	4.51 ± 0.14	4.06 ± 0.04	$CaHL^{3-}$
1 1 1	8.97 ± 0.16	9.08 ± 0.19	8.47 ± 0.10	CaH_2L^{2-}
2 1 1	13.26 ± 0.15	13.33 ± 0.11	12.61 ± 0.10	CaH_3L^-
3 1 1	17.06 ± 0.16	16.98 ± 0.13	16.11 ± 0.32	CaH_4L
0 2 1		7.54 ± 0.30	6.03 ± 0.35	Ca_2HL^-
χ^2 / s	15.38 / 1.81	27.79 / 1.03	12.10 / 0.92	
points / titrations	261 / 4	179 / 3	265 / 4	
Mn^{2+}				
-2 1 1	-10.25 ± 0.16	-8.48 ± 0.18	-10.79 ± 0.52	$Mn(OH)L^{5-}$
-1 1 1	0.72 ± 0.11	2.32 ± 0.13	0.30 ± 0.09	MnL^{4-}
0 1 1	5.59 ± 0.13	6.91 ± 0.12	5.56 ± 0.07	$MnHL^{3-}$
1 1 1	10.24 ± 0.15	10.87 ± 0.21	10.04 ± 0.08	MnH_2L^{2-}
2 1 1	14.01 ± 0.17	14.22 ± 0.17	13.56 ± 0.15	MnH_3L^-
3 1 1	17.58 ± 0.21	17.36 ± 0.40	16.52 ± 0.48	MnH_4L
χ^2 / s	35.43 / 2.03	20.94 / 1.59	27.61 / 2.61	
points / titrations	263 / 4	215 / 4	372 / 4	

Fe^{3+}				
-2 1 1	0.10 ± 0.31	0.18 ± 0.33	2.66 ± 0.28	$Fe(OH)L^{4-}$
-1 1 1	7.79 ± 0.26	7.73 ± 0.26	8.32 ± 0.26	FeL^{3-}
0 1 1	12.85 ± 0.28	12.24 ± 0.29	12.65 ± 0.28	$FeHL^{2-}$
1 1 1	17.11 ± 0.27	16.27 ± 0.27	16.36 ± 0.26	FeH_2L^-
2 1 1	20.11 ± 0.28	18.44 ± 0.30	18.58 ± 0.30	FeH_3L
χ^2 / s	20.37 / 1.57	12.01 / 1.08	18.67 / 0.96	
points / titrations	205 / 3	261 / 4	228 / 3	
Cu^{2+}				
-2 1 1	-5.18 ± 0.20	-5.61 ± 0.23	-5.91 ± 0.18	$Cu(OH)L^{5-}$
-1 1 1	5.21 ± 0.14	4.93 ± 0.20	4.10 ± 0.11	CuL^{4-}
0 1 1	9.44 ± 0.15	9.63 ± 0.19	8.90 ± 0.11	$CuHL^{3-}$
1 1 1	13.53 ± 0.15	13.79 ± 0.21	13.01 ± 0.12	CuH_2L^{2-}
2 1 1	16.53 ± 0.11	17.11 ± 0.17	16.34 ± 0.10	CuH_3L^-
3 1 1	19.47 ± 0.16	19.25 ± 0.27	18.99 ± 0.16	CuH_4L
-1 2 1		(7.84 ± 0.20)*	7.87 ± 0.12	Cu_2L^{2-}
0 2 1		(12.16 ± 0.49)*	11.89 ± 0.17	Cu_2HL^-
χ^2 / s	36.62 / 2.48	28.09 / 1.77	46.42 / 1.77	
points / titrations	467 / 6	402 / 6	285 / 4	
Zn^{2+}				
-2 1 1	-6.81 ± 0.14	-6.57 ± 0.09	-7.53 ± 0.39	$Zn(OH)L^{5-}$
-1 1 1	2.99 ± 0.07	3.53 ± 0.06	2.36 ± 0.05	ZnL^{4-}
0 1 1	7.31 ± 0.06	8.12 ± 0.07	7.25 ± 0.04	$ZnHL^{3-}$
1 1 1	11.09 ± 0.12	12.29 ± 0.06	11.42 ± 0.05	ZnH_2L^{2-}
2 1 1	14.28 ± 0.11	15.53 ± 0.03	14.92 ± 0.04	ZnH_3L^-
3 1 1	17.42 ± 0.26	17.68 ± 0.19	17.62 ± 0.12	ZnH_4L
-1 2 1			4.92 ± 0.30	Zn_2L^{2-}
0 2 1			9.62 ± 0.43	Zn_2HL^-
χ^2 / s	18.42 / 1.81	47.20 / 1.66	81.10 / 2.04	
points / titrations	367 / 5	420 / 5	349 / 4	
La^{3+}				
-2 1 1			-6.60 ± 0.19	$La(OH)L^{4-}$
-1 1 1			4.44 ± 0.05	LaL^{3-}
0 1 1			9.19 ± 0.03	$LaHL^{2-}$
1 1 1			12.67 ± 0.02	LaH_2L^-
2 1 1			15.34 ± 0.05	LaH_3L
-1 2 1			7.87 ± 0.08	La_2L
0 2 1			11.61 ± 0.21	La_2HL^+
χ^2 / s			49.36 / 1.08	
points / titrations			326 / 4	

Table 8. Protonation and complexation of BCA6 with Cd(II), Hg(II) and Pb(II) in 0.1 M $NaNO_3$ aqueous solution at 25 °C. [VI]

	p q r eq. [5,6,7]	log(β_{pqr} ± 3σ) BCA6, HL^{5-}	proposed formula
H^+			
	-1 0 1	-8.84 ± 0.03	L^{6-}
	1 0 1	5.50 ± 0.05	H_2L^{4-}
	2 0 1	10.29 ± 0.04	H_3L^{3-}
	3 0 1	14.30 ± 0.05	H_4L^{2-}
	4 0 1	17.55 ± 0.05	H_5L^-
	5 0 1	20.19 ± 0.05	H_6L
	6 0 1	21.79 ± 0.09	H_7L^+
χ^2 / s	49.79 / 0.86		
points / titrations	349 / 4		
Cd^{2+}			
	-2 1 1	-7.37 ± 0.10	$Cd(OH)L^{5-}$
	-1 1 1	2.25 ± 0.05	CdL^{4-}
	0 1 1	7.33 ± 0.05	$CdHL^{3-}$
	1 1 1	11.69 ± 0.04	CdH_2L^{2-}
	2 1 1	15.26 ± 0.03	CdH_3L^-
	3 1 1	17.74 ± 0.09	CdH_4L
χ^2 / s	16.64 / 0.80		
points / titrations	400 / 4		
Hg^{2+}			
	-1 1 1	6.01 ± 0.06	HgL^{4-}
	0 1 1	11.29 ± 0.09	$HgHL^{3-}$
	1 1 1	15.79 ± 0.08	HgH_2L^{2-}
	2 1 1	19.95 ± 0.09	HgH_3L^-
	3 1 1	23.25 ± 0.08	HgH_4L
	4 1 1	25.80 ± 0.08	HgH_5L^+
χ^2 / s	37.99 / 0.75		
points / titrations	355 / 4		
Pb^{2+}			
	-2 1 1	-7.90 ± 0.11	$Pb(OH)L^{5-}$
	-1 1 1	1.98 ± 0.08	PbL^{4-}
	0 1 1	7.22 ± 0.07	$PbHL^{3-}$
	1 1 1	11.58 ± 0.08	PbH_2L^{2-}
	2 1 1	15.32 ± 0.07	PbH_3L^-
	3 1 1	18.07 ± 0.12	PbH_4L
	-1 2 1	6.76 ± 0.16	Pb_2L^{2-}
	0 2 1	11.52 ± 0.13	Pb_2HL^-
	1 2 1	15.20 ± 0.21	Pb_2H_2L
χ^2 / s	23.16 / 1.25		
points / titrations	343 / 5		

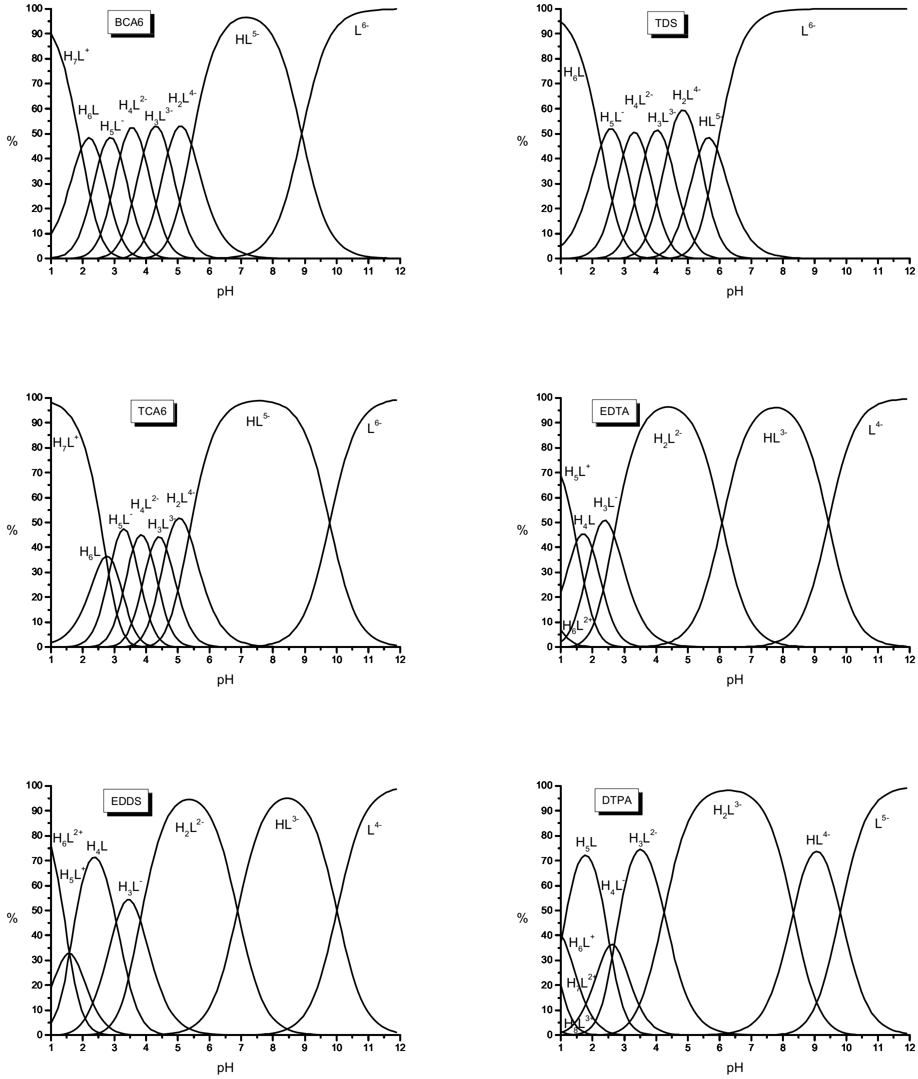


Figure 3. Percentage distribution of different protonation stages of BCA6, TCA6, EDDS, TDS, EDTA and DTPA.

Table 9. Protonation and complexation of TCA6, BCA6, BCA5, MBCA5, EDDS and ISA, [I-VII, 92] log *K* values at 25 °C, in μ = 0.1 (^{b} at 20 °C, ^{c} in μ = 1.0), *ref. 92.

reaction	TCA6 H_6L III,V	[SSS]-BCA6 H_6L^{VII}	[RSR]-BCA6 H_6L^{VII}	BCA6-mix H_6L IV,V,VI	BCA5 $H_5L^{IV,V}$	MBCA5 H_5L^{IV}	[SS]-EDDS H_4L^{I}	EDDS-mix H_4L^{I}	ISA H_4L^{II}
$L + H \rightleftharpoons HL$	9.87	9.38	8.99	8.98	9.30	9.56	10.11	10.12/ 10.01*	10.52/ 10.00*
$HL + H \rightleftharpoons H_2L$	5.40	5.58	5.58	5.47	5.22	5.32	6.91	6.94/6.84*	4.55/4.24*
$H_2L + H \rightleftharpoons H_3L$	4.68	4.72	4.71	4.73	4.46	4.55	3.84	3.85/3.86*	3.53/3.24*
$H_3L + H \rightleftharpoons H_4L$	4.17	4.02	3.79	3.96	3.56	3.96	3.05	3.08/2.95*	2.43/1.97*
$H_4L + H \rightleftharpoons H_5L$	3.62	3.17	3.01	3.20	2.76	3.06	2.11	1.61	1.52
$H_5L + H \rightleftharpoons H_6L$	2.94	2.37	2.22	2.56	2.33	2.86	1.37	1.59	
$H_6L + H \rightleftharpoons H_7L$	2.75	1.19	1.17	1.97					
Mg(II)									
$M(OH)L + H \rightleftharpoons ML$		11.74	11.18	11.07	10.56	10.44			
$M + L \rightleftharpoons ML$		6.82	6.53	5.98	5.92	5.09		6.01*	5.45*
$ML + H \rightleftharpoons MHL$		6.69	6.46	6.07	6.37			5.8^{c*}	
$MHL + H \rightleftharpoons MH_2L$		5.09	5.14	4.92					
$MH_2L + H \rightleftharpoons MH_3L$		4.65	4.44	4.50					
$MH_3L + H \rightleftharpoons MH_4L$		3.54	3.48	3.62					
Ca(II)									
$M(OH)L + H \rightleftharpoons ML$	11.55	10.69	10.64	10.00	10.83	10.67			
$M + L \rightleftharpoons ML$	6.15	8.16	8.37	7.71	7.40	6.77		4.58*	4.3 *
$ML + H \rightleftharpoons MHL$	5.74	5.42	5.13	5.33	5.22	5.46		6.8 *	
$MHL + H \rightleftharpoons MH_2L$	5.56	4.77	4.57	4.41					
$MH_2L + H \rightleftharpoons MH_3L$		4.29	4.25	4.14					
$MH_3L + H \rightleftharpoons MH_4L$		3.80	3.65	3.50					
$ML + M \rightleftharpoons M_2L$	2.75								
$MHL + M \rightleftharpoons M_2HL$	2.79		3.03	1.97					
$M_2L + H \rightleftharpoons M_2HL$	5.78								
$M_2L + M \rightleftharpoons M_3L$	2.62								
Mn(II)									
$M(OH)L + H \rightleftharpoons ML$	11.34	10.97	10.80	11.09	10.72	10.67			11.26
$M + L \rightleftharpoons ML$	7.47	10.10	11.31	9.28	7.50	9.05	8.97	8.69/8.57*	7.26
$ML + H \rightleftharpoons MHL$	5.39	4.87	4.59	5.26	5.62	5.17	4.73	5.01/4.91*	
$MHL + H \rightleftharpoons MH_2L$		4.65	3.96	4.48		3.93			
$MH_2L + H \rightleftharpoons MH_3L$		3.77	3.35	3.52					
$MH_3L + H \rightleftharpoons MH_4L$		3.57	3.14	2.96					
$ML + M \rightleftharpoons M_2L$	2.91								
$MHL + M \rightleftharpoons M_2HL$	2.77								
$M_2L + H \rightleftharpoons M_2HL$	5.25								
$MHL+ HL \rightleftharpoons M(HL)_2$							4.02	4.00	
Fe(III)									
$M(OH)L + H \rightleftharpoons ML$		7.69	7.55	5.66		6.28	7.97	7.23	5.30
$M(OH)_2L + H \rightleftharpoons M(OH)L$							9.84	9.73	
$M + L \rightleftharpoons ML$		17.17	16.72	17.30	12.63	16.95	20.85	20.04/22.0 *	13.86
$ML + H \rightleftharpoons MHL$		5.06	4.51	4.33	5.07	4.46			3.89
$MHL + H \rightleftharpoons MH_2L$		4.26	4.03	3.71	3.98	3.75			
$MH_2L + H \rightleftharpoons MH_3L$		3.00	2.17	2.22	2.83	2.53			
$MHL + M \rightleftharpoons M_2HL$					5.1				
Cu(II)									
$M(OH)L + H \rightleftharpoons ML$	9.83	10.39	10.54	10.01	10.26	10.28	11.06	11.03/ 11.38*	10.40
$M + L \rightleftharpoons ML$	10.26	14.59	13.87	13.08	9.57	12.69	18.70	18.34/ 18.4*	12.88/ 12.69*
$ML + H \rightleftharpoons MHL$	5.29	4.23	4.70	4.80	5.59	5.12	3.59	3.75/3.61*	4.39/4.01*
$MHL + H \rightleftharpoons MH_2L$	4.40	4.09	4.15	4.11	4.27	4.06	2.28	2.54	3.13/2.95*
$MH_2L + H \rightleftharpoons MH_3L$	4.14	3.00	3.33	3.33	3.68	3.40			
$MH_3L + H \rightleftharpoons MH_4L$	3.14	2.94	2.14	2.65	2.65	2.53			
$M_2(OH)_2L + H \rightleftharpoons M_2(OH)L$	8.23								

$M_2(OH)L + H \leftrightharpoons M_2L$	7.32								
$ML + M \leftrightharpoons M_2L$	4.63		(3.52)	3.77	4.09	4.21	2.37	2.21	
$MHL + M \leftrightharpoons M_2HL$	3.72		(2.61)	2.99	3.52	3.43			
$M_2L + H \leftrightharpoons M_2HL$	4.38		(4.32)	4.02	5.02	4.34			
$ML + HL \leftrightharpoons ML(HL)$							2.49	2.36	
$ML(HL) + H \leftrightharpoons M(HL)_2$							7.10	7.39	
$M(HL)_2 + H \leftrightharpoons M(HL)(H_2L)$							3.73	4.00	
$M(HL)(H_2L) + H \leftrightharpoons M(H_2L)_2$							3.51	3.28	
Zn(II)									
$M(OH)L + H \leftrightharpoons ML$	10.54	9.80	10.10	9.89	10.46	11.03	11.31	11.05	11.26
$M + L \leftrightharpoons ML$	8.72	12.37	12.52	11.34	8.09	10.60	13.58	13.15/ 13.4*	10.15/ 9.88*
$ML + H \leftrightharpoons MHL$	5.34	4.32	4.59	4.89	5.54	5.18	3.68	4.18/3.29*	4.41/4.29*
$MHL + H \leftrightharpoons MH_2L$	4.49	3.78	4.17	4.17	4.31	4.17		/2.64*	
$MH_2L + H \leftrightharpoons MH_3L$	4.13	3.19	3.24	3.50		3.49			
$MHL + 2\,H \leftrightharpoons MH_3L$							5.92	5.96	
$MH_3L + H \leftrightharpoons MH_4L$	3.13	3.14	2.15	2.70					
$M_2(OH)L + H \leftrightharpoons M_2L$	6.76								
$ML + M \leftrightharpoons M_2L$	2.94			2.56	2.99				
$MHL + M \leftrightharpoons M_2HL$				2.37	3.11				
$M_2L + H \leftrightharpoons M_2HL$				4.70	5.66				
$MHL+ HL \leftrightharpoons M(HL)_2$							5.47	5.39	
Cd(II)									
$M(OH)L + H \leftrightharpoons ML$				9.62					
$M + L \leftrightharpoons ML$				11.09				10.9^{*,b}	8.33*
$ML + H \leftrightharpoons MHL$				5.08				3.6*	4.68*
$MHL + H \leftrightharpoons MH_2L$				4.36					3.28*
$MH_2L + H \leftrightharpoons MH_3L$				3.57					
$MH_3L + H \leftrightharpoons MH_4L$				2.48					
Hg(II)									
$M(OH)L + H \leftrightharpoons ML$								6.6*	
$M + L \leftrightharpoons ML$				14.85				(17.5) *	
$ML + H \leftrightharpoons MHL$				5.28				(5.0) *	
$MHL + H \leftrightharpoons MH_2L$				4.50					
$MH_2L + H \leftrightharpoons MH_3L$				4.16					
$MH_3L + H \leftrightharpoons MH_4L$				3.30					
$MH_4L + H \leftrightharpoons MH_5L$				2.55					
Pb(II)									
$M(OH)L + H \leftrightharpoons ML$				9.88					
$M + L \leftrightharpoons ML$				10.82				12.7^{*,b}	9.75*
$ML + H \leftrightharpoons MHL$				5.24				3.2*	
$MHL + H \leftrightharpoons MH_2L$				4.36					
$MH_2L + H \leftrightharpoons MH_3L$				3.74					
$MH_3L + H \leftrightharpoons MH_4L$				2.75					
$ML + M \leftrightharpoons M_2L$				4.78					
$MHL + M \leftrightharpoons M_2HL$				4.30					
$M_2L + H \leftrightharpoons M_2HL$				4.76					
$MH_2L + M \leftrightharpoons M_2H_2L$				3.62					
$M_2HL + H \leftrightharpoons M_2H_2L$				3.86					
$M + 2\,L \leftrightharpoons ML_2$									16.27*
La(III)									
$M(OH)L + H \leftrightharpoons ML$	11.03			11.04	9.16				
$M + L \leftrightharpoons ML$	13.02			13.42	11.36			11.98*	
$ML + H \leftrightharpoons MHL$	4.71			4.75	4.20				
$MHL + H \leftrightharpoons MH_2L$	3.24			3.48					
$MH_2L + H \leftrightharpoons MH_3L$	3.54			2.67					
$ML + L \leftrightharpoons M_2L$	4.11			3.43					
$MHL + M \leftrightharpoons M_2HL$	3.13			2.42					
$M_2L + H \leftrightharpoons M_2HL$	3.73			3.74					
$M_2HL + H \leftrightharpoons M_2H_2L$	3.23								

Table 10. Protonation and complex formation of EDTA, DTPA, NTA, MGDA, ODS and TDS,[92, 103-107] log *K* values at 25 °C, in μ = 0.1 ([a] at 37 °C, in μ = 0.15, [b] at 20 °C, [c] in μ = 1.0, [d] in μ = 0.5 [e] in μ = 1.25).

reaction	**EDTA** **H_4L** [92, 103]	**DTPA** **H_5L** [92, 104]	**NTA** **H_3L** [92, 105]	**MGDA** **H_3L** [92]	**[SR]-ODS** **H_4L** [92, 106]	**[SS]-ODS** **H_4L** [92, 106]	**TDS** **H_6L** [92, 107]
$L + H \leftrightharpoons HL$	9.52–10.37	9.90–10.79	9.46–9.95	(9.85)	5.97	5.97	5.97
$HL + H \leftrightharpoons H_2L$	6.13-6.24	8.40–8.60	2.38-2.95	(2.58)	4.85	4.79	5.40
$H_2L + H \leftrightharpoons H_3L$	2.69-2.79	4.28-4.30	(1.81)	(1.5) [b]	3.98	3.40	4.40
$H_3L + H \leftrightharpoons H_4L$	2.00-2.2	2.70-2.77	(1.0)-1.68		2.07	2.57	3.69
$H_4L + H \leftrightharpoons H_5L$	1.34[b]-(1.5)	2.0					2.99
$H_5L + H \leftrightharpoons H_6L$	(0.0)-0.12[b,c]	(1.6)-1.7[d]					2.28
$H_6L + H \leftrightharpoons H_7L$		(0.7)-0.9[d]					
$H_7L + H \leftrightharpoons H_8L$		(-0.1)					
Mg(II)							
$M + L \leftrightharpoons ML$	8.79-8.9	9.27-9.3	5.50	5.84[c]	5.09	4.44	4.40
$ML + H \leftrightharpoons MHL$	4.0	6.85-6.9			4.05	4.18	5.41
$MHL + H \leftrightharpoons MH_2L$					3.44	4.11	
$MH_2L + H \leftrightharpoons MH_3L$		3.74[a]			3.30	2.77	
$ML + M \leftrightharpoons M_2L$		2.07[a]					1.59
Ca(II)							
$M + L \leftrightharpoons ML$	10.65-10.73	10.7-10.75	6.3–6.64	6.97 [b]	5.82	5.42	6.86
$ML + H \leftrightharpoons MHL$	3.1	6.10-6.11			4.43	4.35	5.33
$MHL + H \leftrightharpoons MH_2L$		3.7[a]			3.53	3.53	4.31
$MH_2L + H \leftrightharpoons MH_3L$					3.41	2.72	2.91
$MH_3L + H \leftrightharpoons MH_4L$							2.36
$ML + M \leftrightharpoons M_2L$		1.6-2.0[b]					2.63
$M + 2\ L \leftrightharpoons ML_2$			8.8–9.27				
Mn(II)							
$M + L \leftrightharpoons ML$	13.8-13.89	15.2-15.5	7.27–7.46		5.69	5.40	7.00
$ML + H \leftrightharpoons MHL$	3.1	4.3[b] -4.45			4.23	4.02	
$ML + 2\ H \leftrightharpoons MH_2L$							4.67
$MHL + H \leftrightharpoons MH_2L$					(2.4)	3.72	
$MH_2L + H \leftrightharpoons MH_3L$					(4.25)	3.13	4.03
$MH_3L + H \leftrightharpoons MH_4L$							3.54
$ML + M \leftrightharpoons M_2L$		2.09[b]					2.57
$M + 2\ L \leftrightharpoons ML_2$			10.44-10.94				
Fe(III)							
$M(OH)L + H \leftrightharpoons ML$	7.39	9.66	(4.36)		3.96	3.87	7.01
$M(OH)_2L + H \leftrightharpoons M(OH)L$			(7.58)		5.49	5.37	
$M(OH)_3L + H \leftrightharpoons M(OH)_2L$			10.72				
$M + L \leftrightharpoons ML$	25.1	27.8-28.0	15.9-16.26[b]		12.01	11.43	20.96
$ML + H \leftrightharpoons MHL$	(1.3)	3.56	(1.0)[d]		2.37	2.49	
$ML + 2\ H \leftrightharpoons MH_2L$							7.78
$2\ M + L \leftrightharpoons M_2(OH)L + H$							22.98
$M_2(OH)_2L + H \leftrightharpoons M_2(OH)L$							2.72
$M_2(OH)_3L + H \leftrightharpoons M_2(OH)_2L$							4.04
$M_2(OH)_4L + H \leftrightharpoons M_2(OH)_3L$							5.20
$M_2(OH)_5L + H \leftrightharpoons M_2(OH)_4L$							5.96
$M + L \leftrightharpoons ML_2$			24.0-24.76[b]				
$2\ M(OH)L \leftrightharpoons M_2(OH)_2L_2$	2.8[c]		(9.14)[d]				
$2\ M + 2\ L \leftrightharpoons M_2L_2$			30.9[d]				

Cu(II)							
$M(OH)L + H \rightleftharpoons ML$	(11.4)-11.71		9.14-9.2				
$M + L \rightleftharpoons ML$	18.78	21.2-21.5	12.7–13.3	13.88[b]	8.38	7.65	9.24
$ML + H \rightleftharpoons MHL$	3.1	4.79-4.80	1.6		3.91	3.11	4.40
$MHL + H \rightleftharpoons MH_2L$	2.0	2.88-2.96			2.44	2.87	2.52
$MH_2L + H \rightleftharpoons MH_3L$						2.29	
$MH_2L + 2\ H \rightleftharpoons MH_4L$							3.78
$ML + M \rightleftharpoons M_2L$	1.3[e]	5.5[b] -6.79					3.57
$M + 2\ L \rightleftharpoons ML_2$			17.4				
Zn(II)							
$M(OH)L + H \rightleftharpoons ML$	(11.6)		10.06–10.1				
$M + L \rightleftharpoons ML$	16.5-16.68[b]	18.2-18.6[b]	10.45–10.66	10.98[b]	7.60	6.62	8.09
$ML + H \rightleftharpoons MHL$	3.0	5.43[b] -5.60			3.95	3.64	4.45
$MHL + H \rightleftharpoons MH_2L$	(1.2)[e]	2.35[a]			2.24	2.96	3.60
$MH_2L + H \rightleftharpoons MH_3L$					1.6	2.49	2.81
$ML + M \rightleftharpoons M_2L$		4.4[b] -4.48					3.22
$M + 2\ L \rightleftharpoons ML_2$			14.24-14.28[b]				
Cd(II)							
$M(OH)L + H \rightleftharpoons ML$	(13.2)[e]		11.25				
$M + L \rightleftharpoons ML$	16.4-16.5	19.0-19.3[b]	9.76-9.80[b]	10.61[b]	5.38	4.94	7.02
$ML + H \rightleftharpoons MHL$	2.9	4.06[b] -4.17			4.32	4.28	4.79
$MHL + H \rightleftharpoons MH_2L$	(1.6)[e]	2.79[a]			3.41	3.74	4.11
$MH_2L + H \rightleftharpoons MH_3L$					(3.49)	3.05	3.17
$ML + M \rightleftharpoons M_2L$		2.3-3.0[b]					2.52
$M + 2\ L \rightleftharpoons ML_2$			14.47				
Hg(II)							
$M(OH)L + H \rightleftharpoons ML$	8.9-9.3						8.26
$M + L \rightleftharpoons ML$	21.5-21.65	26.4-26.7[b]	14.3-14.6		14.37	13.82	15.49
$ML + H \rightleftharpoons MHL$	3.2	4.24[b]			5.72	5.89	5.48
$MHL + H \rightleftharpoons MH_2L$	2.1[e]				4.70	4.62	5.20
$MH_2L + H \rightleftharpoons MH_3L$					3.72	3.16	4.04
$2\ M + L \rightleftharpoons M_2(OH)L + H$							22.33
$M_2(OH)_3L + 2\ H \rightleftharpoons M_2(OH)L$							17.17
$M_2(OH)_5L + 2\ H \rightleftharpoons M_2(OH)_3L$							18.34
Pb(II)							
$M + L \rightleftharpoons ML$	18.0-18.3[b]	18.8-18.9[b]	11.48	12.07[b]	7.71	7.44	8.66
$ML + H \rightleftharpoons MHL$	2.4[e]-2.8[b]	4.52[b]	2.3[d]		3.98	3.74	4.80
$MHL + H \rightleftharpoons MH_2L$	(1.7)[e]				2.84	2.64	4.05
$MH_2L + H \rightleftharpoons MH_3L$	(1.2)[e]				1.7	2.04	3.18
$ML + M \rightleftharpoons M_2L$		3.41[b]					5.93
$M + 2\ L \rightleftharpoons ML_2$			12.8[b]				
La(III)							
$M(OH)L + H \rightleftharpoons ML$			(7.9)				
$M + L \rightleftharpoons ML$	15.36	19.49	10.36-10.47	11.02[b]			
$ML + H \rightleftharpoons MHL$	2.24	2.60 [b]					
$M + 2\ L \rightleftharpoons ML_2$			17.6-17.84	(18.24)[b]			

6.2 Estimation of chelating efficiency

The complexation efficiency of ligands can be estimated by calculating the distribution of metal among different species for the conditions of interest. In this study, the percentage distribution curves of the complexes were drawn in concentration areas used in the measurements (1 mM solutions). The efficiency limit was defined as over 80% of the metal ion bound to ligand. The pH ranges where such efficiency is achieved for the metal to ligand ratio 1:1 are shown in Table 11. The effective chelation is restricted to the acidic pH area in the case of Fe(III)-ISA, Fe(III)-EDDS and Hg(II)-BCA6 because of strong hydrolysis of the metal ions. The scarcity or weakness of acidic species restricted the effective chelation to the basic region for Mg(II) with all studied ligands and in systems Ca(II)-BCA5, Ca(II)-TCA6, Mn(II)-EDDS, Mn(II)-ISA and Mn(II)-TCA6.

As an example, Figure 4 shows the percentage distribution curves drawn for Cu(II) complexes of the studied ligands and of EDTA and DTPA. Dilution of the solution, e.g. to micromolar concentration, raises the lower pH limit of the effective chelation region to more basic direction. In the case of Fe(III) and Hg(II) ions, the competitive binary hydrolysis of metal ions is so dominant in the micromolar concentration area that it overcomes the complex formation, or the complexation is markedly limited to very narrow pH range.

Table11. Chelation efficiency derived from percentage distribution curves: pH ranges where over 80% of metal ions are bound to ligands, 1 mM solutions, M:L=1:1
(* calculated from values in ref. 92).

metal ion	**EDTA ***	**DTPA ***	**EDDS**	**ISA**	**BCA6**	**BCA5**	**MBCA5**	**TCA6**
Ca^{2+}	5-12	6-12	10-12*	11-12*	6-12	6-12	7-12	8-12
Mg^{2+}	6-12	7-12	8-12*	9-12*	7-12	8-12	9-12	-
Mn^{2+}	3-12	4-12	7-12	7-11	5-12	6-12	5-12	7-11
Fe^{3+}	1-11	1-12	2-10	3-6	2-9	3-5	2-9	-
Cu^{2+}	1-12	2-12	2-12	3-12	3-12	4-11	3-12	5-11
Zn^{2+}	2-12	3-12	4-12	5-11	4-12	6-10	4-12	6-11
Cd^{2+}	2-12	3-12	6-12*	7-12*	4-12	-	-	-
Hg^{2+}	1-12	1-12	2-12*	-	1-8	-	-	-
Pb^{2+}	2-12	3-12	5-12*	5-11*	4-12	-	-	-
La^{3+}	3-12	3-12	5-12*	-	4-12	5-12	-	5-12

Another way to estimate the chelation efficiency is to calculate the conditional stability constants of the complexes.[110] Such values are often used as the criterion when estimating the complexation efficiency for industrial applications. The conditional stability constant, log K'_{ML}, for the major complex species $\mathrm{ML}^{\mathrm{n-x}}$ is given by the equation [16]:

$$K'_{\mathrm{ML}} = \frac{\alpha_{\mathrm{ML}}}{\alpha_{\mathrm{M}} \cdot \alpha_{\mathrm{L}}} \cdot K_{\mathrm{ML}} \qquad [16]$$

where the side reaction coefficients $_{\mathrm{M}}$, $_{\mathrm{L}}$ and $_{\mathrm{ML}}$ are defined as in equations [17], [18] and [19] and K_{ML} is as in equation [20]:

$$\alpha_{\mathrm{M}} = \frac{\Sigma(\mathrm{H}^{+})_{\mathrm{p}}(\mathrm{M}^{\mathrm{n+}})_{\mathrm{q}}}{[\mathrm{M}^{\mathrm{n+}}]} \qquad [17]$$

$$\alpha_{\mathrm{L}} = \frac{\Sigma(\mathrm{H}^{+})_{\mathrm{p}}(\mathrm{L}^{\mathrm{x-}})}{[\mathrm{L}^{\mathrm{x-}}]} \qquad [18]$$

$$\alpha_{\mathrm{ML}} = \frac{\Sigma(\mathrm{H}^{+})_{\mathrm{p}}(\mathrm{M}^{\mathrm{n+}})(\mathrm{L}^{\mathrm{x-}})_{\mathrm{r}}}{[\mathrm{ML}^{\mathrm{n-x}}]} \qquad [19]$$

$$K_{\mathrm{ML}} = K(\mathrm{M}^{\mathrm{n+}} + \mathrm{L}^{\mathrm{x-}} \rightleftharpoons \mathrm{ML}^{\mathrm{n-x}}) \qquad [20]$$

As an example, the values of conditional stability constants for CaL, FeL, CuL and MnL complexes of the studied ligands are calculated with the aid of the equilibrium constants and protonation constants determined in this study and the binary hydrolysis constants of the metal ions [99]. The conditional stability constants, as also the corresponding values for EDTA and DTPA, vary as a function of pH, as shown in Figure 5. In this analysis, values log $K'_{\mathrm{ML}} \geq 6$ are often considered as the criterion for an efficient complexation. Defined on this basis, the approximate pH ranges suitable for use of the present ligands are about the same or 1-2 pH units narrower than the ranges estimated above from the percentage distribution curves.

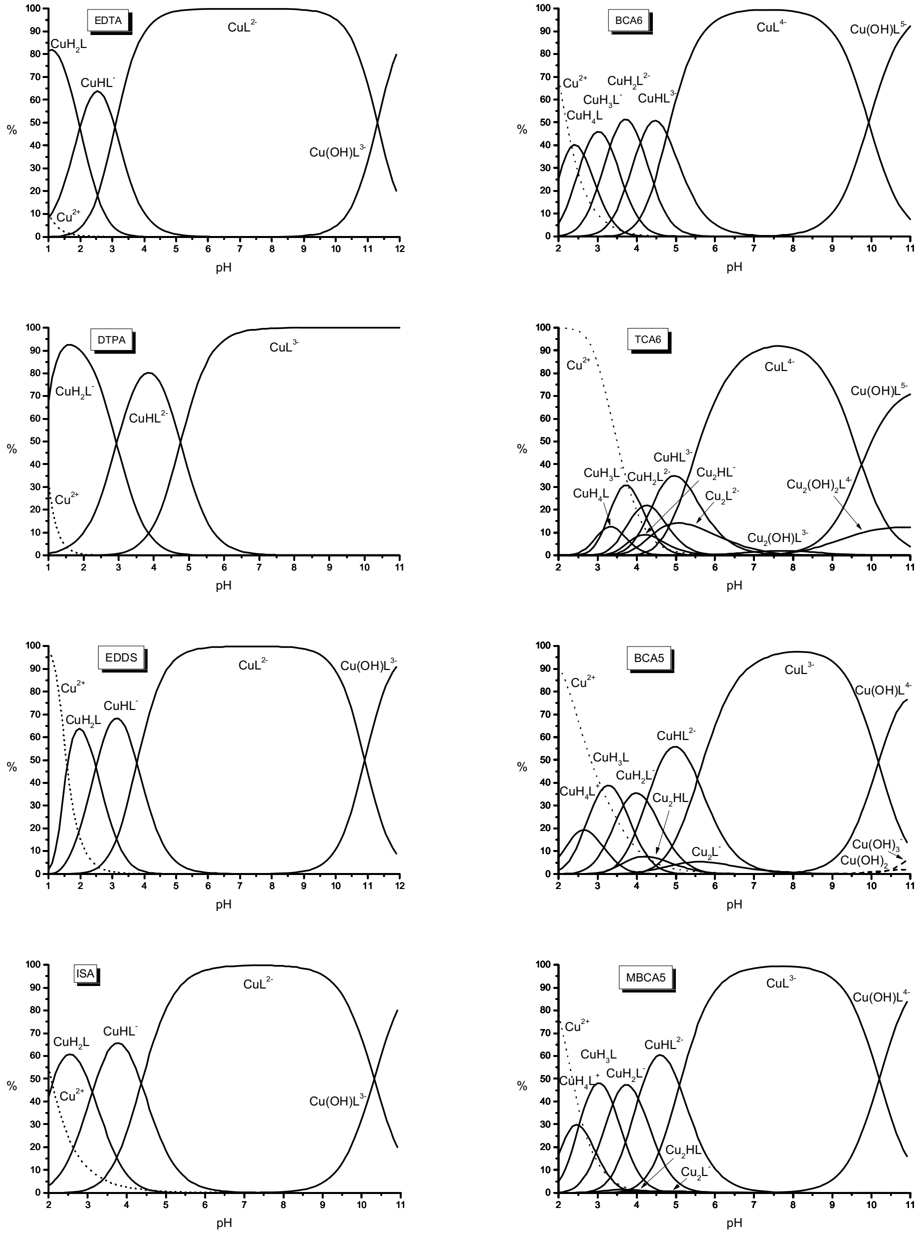


Figure 4. Percentage distribution of Cu(II) complexes of EDTA, DTPA, EDDS, ISA, BCA6, TCA6, BCA5 and MBCA6 *versus* pH ($C_M = C_L = 1$ mM).

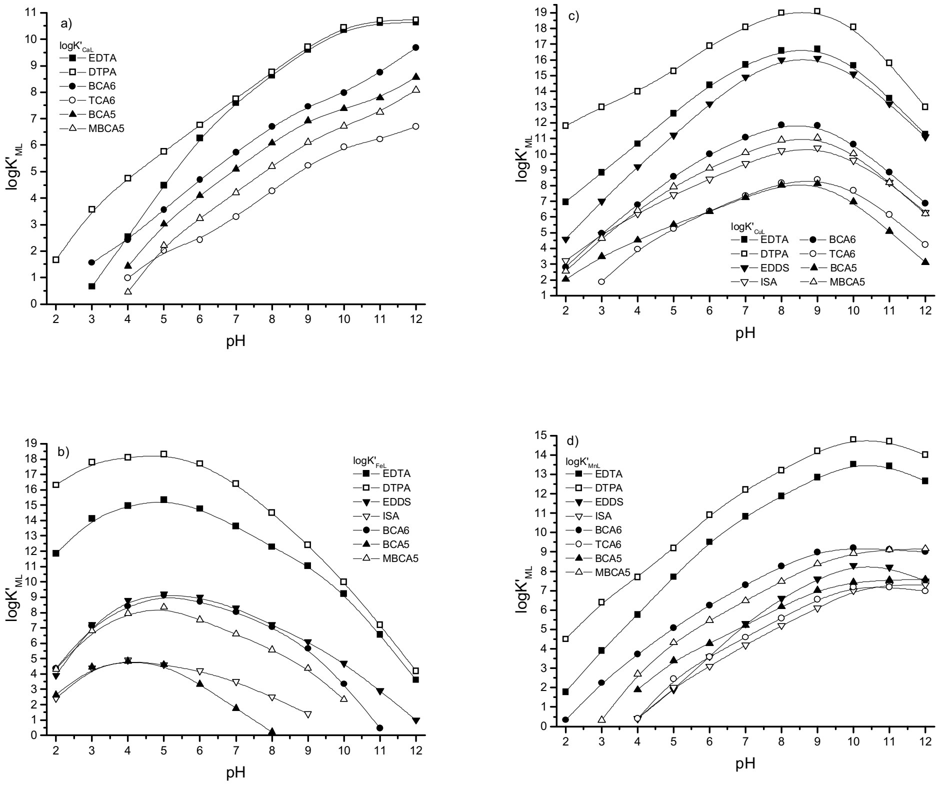


Figure 5. Conditional stability constants for a) CaL, b) FeL, c) CuL and d) MnL complexes of EDTA, DTPA, EDDS, ISA, BCA6, BCA5, MBCA5 and TCA6 as a function of pH.

6.3 Order of protonation constants and stability order of ML complexes

6.3.1 Order of protonation sites

Although potentiometric data does not give any information about the protonation order of the different carboxylate groups, estimations can still be made. The order of the protonation steps suggested [111] for ISA is as follows:

$^-OOC-CH_2-CH(COO^-)-NH-CH(COO^-)-CH_2-COO^-$	log *K*[II]
$^-OOC-CH_2-CH(COO^-)-NH_2^+-CH(COO^-)-CH_2-COO^-$	10.52
$HOOC-CH_2-CH(COO^-)-NH_2^+-CH(COO^-)-CH_2-COO^-$	4.55
$HOOC-CH_2-CH(COO^-)-NH_2^+-CH(COO^-)-CH_2-COOH$	3.53
$HOOC-CH_2-CH(COOH)-NH_2^+-CH(COO^-)-CH_2-COOH$	2.43
$HOOC-CH_2-CH(COOH)-NH_2^+-CH(COOH)-CH_2-COOH$	1.52

and the order suggested [112] for carboxymethyloxysuccinic acid (CMOS) is

$^-OOC-CH_2-CH(COO^-)-O-CH_2-COO^-$	log *K*[112]
$HOOC-CH_2-CH(COO^-)-O-CH_2-COO^-$	5.0
$HOOC-CH_2-CH(COO^-)-O-CH_2-COOH$	3.8
$HOOC-CH_2-CH(COOH)-O-CH_2-COOH$	2.5

Similar trends have been suggested for oxydisuccinic acid (ODS), 1-hydroxy-3-oxapentane-1,2,4,5-tetracarboxylic acid (TMS) and 3,6-dioxaoctane-1,2,4,5,7,8-hexa-carboxylic acid (TDS) by comparison with acetic acid (log *K* 4.56), succinic acid (5.24, 4.00), malic acid (4.68, 3.24) and tartaric acid (3.95, 2.82). Higher protonation constants are estimated for carboxylates lacking electron-withdrawing substituents, that is to say, where the carboxylate is at the end of the "longer arm" of the succinate group. The protonation constants of carboxylates in "shorter arms" near the ether oxygen would have smaller values.[106, 107]

This same reasoning could be applied for the carboxylate groups of BCA6, BCA5, MBCA5 and TCA6. The ether oxygens may also decrease the basicity of nitrogen in these ligands relative the basicity of nitrogen in ISA (log *K* values for the protonation of nitrogen are ISA 10.52, BCA6 8.98, BCA5 9.30, MBCA5 9.56, TCA6 9.87) in analogy to the relationship between nitrilotriacetic acid (NTA, log K 9.46-9.84) and triethanolamine (TEA, log K 7.85).[92]

6.3.2 Trends in stability orders of ML complexes

A number of trends became evident when stabilities of the different ML complexes were compared for each ligand. Tables 12 and 13 show the ascending orders of complexation strengths for the ligands with different metals and the metals with different ligands respectively.

6.3.2.1 Irving-Williams order for transition metal ions Mn^{2+}, Cu^{2+} and Zn^{2+}

The stability of the ML complexes of the ligands studied here and the reference ligands follows the Irving-Williams order for divalent transition metal ions ($Mn^{2+} < Fe^{2+} < Co^{2+} < Ni^{2+} < Cu^{2+} > Zn^{2+}$).[45]

EDDS: $\log K_{MnL}$ (8.69) < $\log K_{CoL}$ (14.0)[92] < $\log K_{NiL}$ (16.7)[92] < $\log K_{CuL}$ (18.3) > $\log K_{ZnL}$ (13.15)

ISA: $\log K_{MnL}$ (7.26) < $\log K_{Fe(II)L}$ (9.00)[113] < $\log K_{CoL}$ (9.96)[114] < $\log K_{NiL}$ (11.68)[115] < $\log K_{CuL}$ (12.88) > $\log K_{ZnL}$ (10.15)

TCA6: $\log K_{MnL}$ (7.47) < $\log K_{CuL}$ (10.26) > $\log K_{ZnL}$ (8.72)

BCA6: $\log K_{MnL}$ (9.28) < $\log K_{Fe(II)L}$ (9.8)[116] < $\log K_{CuL}$ (13.08) > $\log K_{ZnL}$ (11.34)

BCA5: $\log K_{MnL}$ (7.50) < $\log K_{CuL}$ (9.57) > $\log K_{ZnL}$ (8.09)

MBCA5: $\log K_{MnL}$ (9.05) < $\log K_{CuL}$ (12.69) > $\log K_{ZnL}$ (10.60)

6.3.2.2 Trends for alkaline earth metal ions Mg^{2+} and Ca^{2+}

The lowest stabilities of the ML complexes were found with Mg^{2+} and Ca^{2+} for both studied and reference ligands (Table 12). The order of the stability constants of alkaline-earth metal complexes varies with the nature of the ligand. The following three orders are reported:[117] a) Mg > Ca > Sr > Ba for small or highly charged anions and some mono- or bidentate ligands, b) Mg < Ca < Sr < Ba for anions of inorganic oxoacids, such as iodate, nitrate, sulfate, and thiosulfate and c) Mg < Ca > Sr > Ba for hydroxycarboxylic, polycarboxylic and polyaminopolycarboxylic ligands. Only Mg^{2+} and Ca^{2+} ions were studied here and only for some of the ligands. Comparison of measured values for these two ions indicate the order c) (for hydroxycarboxylic, polycarboxylic and polyaminopolycarboxylic ligands, Mg < Ca) for ligands in the BCA series, while the literature values for ISA and EDDS [92] follow the order Mg > Ca. The complexes of the small Mg^{2+} ion are destabilized by the presence of neutral oxygen donors. The stabilities of the Ca^{2+} ion complexes increase with the number of carboxylate groups, and Ca^{2+} is stated to benefit greatly from the introduction of a single neutral oxygen donor. [39] This can be seen for ODS.

BCA6: $\log K_{\mathrm{MgL}}$ (5.98) < $\log K_{\mathrm{CaL}}$ (7.71)
BCA5: $\log K_{\mathrm{MgL}}$ (5.92) < $\log K_{\mathrm{CaL}}$ (7.40)
MBCA5: $\log K_{\mathrm{MgL}}$ (5.09) < $\log K_{\mathrm{CaL}}$ (6.77)
EDDS: $\log K_{\mathrm{MgL}}$ (6.01) [92] > $\log K_{\mathrm{CaL}}$ (4.58) [92]
ISA: $\log K_{\mathrm{MgL}}$ (5.45) [92] > $\log K_{\mathrm{CaL}}$ (4.30) [92]

6.3.2.3 Trends for Cd^{2+}, Hg^{2+}, Pb^{2+}, La^{3+} and Fe^{3+}

Ions Cd^{2+}, Hg^{2+} and Pb^{2+} were studied here only for BCA6. The $\log K_{\mathrm{ML}}$ values for Cd^{2+} and Pb^{2+} are located near the $\log K_{\mathrm{ML}}$ value for Zn^{2+} for both studied and reference ligands, except for the ligands that contain only oxygen donors (Table 12). In these cases the $\log K_{\mathrm{ML}}$ values for nitrogen-favouring Cd^{2+} are smaller than those for oxygen-favouring Ca^{2+}, which has an ionic radius close to that of Cd^{2+}. Another oxygen-favouring metal ion, La^{3+}, appears to benefit from the presence of ether oxygens in TCA6, BCA6 and BCA5. This can be seen in the higher $\log K_{\mathrm{ML}}$ values than those obtained for nitrogen-favouring Cu^{2+}. The $\log K_{\mathrm{ML}}$ values for the Fe^{3+} ion are the highest in the series followed by those of Hg^{2+} for all ligands discussed here except ODS, which favours Hg^{2+} at the expense of Fe^{3+}. [92, 106, 107] It is not surprising that the hard Fe^{3+} ion forms stable complexes with ligands that have several hard carboxylic acid donors. The strength of the complexes of the soft Hg^{2+} ion, even with ligands containing only oxygen donors, is apparently due to the capability of Hg^{2+} to bond well to both nitrogen and oxygen, the presence of neutral ether oxygen donors and the suitable size of the Hg^{2+} ion. The complex stability of large ions, such as Hg^{2+}, La^{3+}, Ca^{2+} and Pb^{2+}, is reported to increase with the addition of a neutral oxygen donor to the ligand, but for small metal ions the benefit of the addition is reduced by the increase in steric strain. This correlation appears to be mainly with ionic size rather than with e.g. hard/soft acid character. [46, 53, 55]

Although the addition of neutral oxygen donors is reported to increase the stability of large ions, the Pb^{2+} ion may behave exceptionally. When nitrogen donors are added to neutral oxygen-containing ligands, the stability of Pb^{2+} complexes is found to decrease. The decrease is attributed to the change from inactive lone pair ($6s^2$ electrons) to active lone pair which is generally accompanied by shortening of the Pb-N bond lengths by about 0.3 Å. The Pb^{2+} ion then behaves as a smaller and more covalent ion and gains no benefit from neutral oxygen donors. Such behaviour is reported for ligands with three or more nitrogen donors. [39, 48, 57, 118-120] This type of effect is also said to be possible with ligands containing less than three nitrogen donors, when a large number of acetate groups are present. Thus, the Pb^{2+} complex of ether-oxygen-containing oxybis(ethylenenitrilo)tetraacetic acid (EEDTA) is less stable than the corresponding EDTA complex, whereas the complexes of other large ions (Sr^{2+}, Hg^{2+} and La^{3+}) with EEDTA are more stable than the corresponding EDTA complexes. [39, 92] For BCA6, note that the stability of the Pb^{2+} complex is lower than that of the Zn^{2+} and Cd^{2+} complexes, while for TDS the order is the opposite.

Table 12. Strength of ML complexes in ascending order according to metal.

ligand	**log K_{ML}**											
TCA6		Ca^{2+}		Mn^{2+}	Zn^{2+}				Cu^{2+}	La^{3+}		
BCA6	Mg^{2+}	Ca^{2+}		Mn^{2+}	Pb^{2+}	Cd^{2+}	Zn^{2+}		Cu^{2+}	La^{3+}	Hg^{2+}	Fe^{3+}
BCA5	Mg^{2+}	Ca^{2+}		Mn^{2+}	Zn^{2+}				Cu^{2+}	La^{3+}		Fe^{3+}
MBCA5	Mg^{2+}	Ca^{2+}		Mn^{2+}	Zn^{2+}				Cu^{2+}			Fe^{3+}
NTA	Mg^{2+}	Ca^{2+}		Mn^{2+}	Cd^{2+}	Zn^{2+}	La^{3+}	Pb^{2+}	Cu^{2+}		Hg^{2+}	Fe^{3+}
ISA	Ca^{2+}	Mg^{2+}		Mn^{2+}	Cd^{2+}	Pb^{2+}	Zn^{2+}		Cu^{2+}			Fe^{3+}
EDDS	Ca^{2+}	Mg^{2+}		Mn^{2+}	Cd^{2+}	Zn^{2+}	La^{3+}	Pb^{2+}	Cu^{2+}			Fe^{3+}
EDTA	Mg^{2+}	Ca^{2+}		Mn^{2+}	La^{3+}	Cd^{2+}	Zn^{2+}	Pb^{2+}	Cu^{2+}		Hg^{2+}	Fe^{3+}
DTPA	Mg^{2+}	Ca^{2+}		Mn^{2+}	Zn^{2+}	Pb^{2+}	Cd^{2+}	La^{3+}	Cu^{2+}		Hg^{2+}	Fe^{3+}
ODS	Mg^{2+}	Cd^{2+}		Mn^{2+}	Ca^{2+}	Zn^{2+}	Pb^{2+}		Cu^{2+}		Fe^{3+}	Hg^{2+}
TDS	Mg^{2+}	Cd^{2+}	Ca^{2+}	Mn^{2+}	Zn^{2+}	Pb^{2+}			Cu^{2+}		Hg^{2+}	Fe^{3+}

Table 13. Strength of ML complexes in ascending order according to ligand.

metal ion	log K_{ML}											
Mg^{2+}		TDS	MBCA5=	ODS	ISA	NTA	MGDA	BCA5	BCA6	EDDS	EDTA	DTPA
Ca^{2+}	ISA	EDDS	ODS	TCA6	NTA	MBCA5	TDS	MGDA	BCA5	BCA6	EDTA	DTPA
Mn^{2+}		ODS	TDS	ISA	NTA	TCA6	BCA5	EDDS	MBCA5	BCA6	EDTA	DTPA
Fe^{3+}			ODS	BCA5	ISA	NTA	MBCA5	BCA6	EDDS	TDS	EDTA	DTPA
Cu^{2+}	ODS	TDS	BCA5	TCA6	MBCA5	ISA	BCA6	NTA	MGDA	EDDS	EDTA	DTPA
Zn^{2+}	ODS	TDS=	BCA5	TCA6	ISA	MBCA5	NTA	MGDA	BCA6	EDDS	EDTA	DTPA
Cd^{2+}				ODS	TDS	ISA	NTA	MGDA	EDDS	BCA6	EDTA	DTPA
Hg^{2+}							ODS	BCA6	TDS	EDDS	EDTA	DTPA
Pb^{2+}				ODS	TDS	ISA	BCA6	NTA	MGDA	EDDS	EDTA	DTPA
La^{3+}					NTA	MGDA	BCA5	EDDS	TCA6	BCA6	EDTA	DTPA

6.4 Effect of adding ether oxygen to amines or carboxylic acids

Besides containing succinic acid groups rather than acetic acid arms and different numbers of nitrogens and carboxylate groups, BCA6, BCA5, MBCA5 and TCA6 differ from EDTA and DTPA in the presence of ether oxygens. The effect of ether oxygen added to amines or carboxylic acids is discussed here in the light of some examples. In the “middle arm” of BCA6, BCA5 and MBCA5, five- or six-membered rings can be formed through nitrogen and carboxylic acid group, but all other possibilities for the formation of such rings are through ether oxygen separated from nitrogen and carboxylate donor groups by methylene or ethylene groups. In TCA6, only the latter is possible.

6.4.1 Amines with ether oxygen

A study of diamine compounds from ethylenediamine to pentamethylenediamine showed the protonation constants of these compounds to be closely similar, as presented in Table 14 (log K_H^n values for ligands 1-4). [92] Note, however, that the ionic strength was not always the same in the different measurements, so that the values in Tables 14 and 15 are not always completely comparable. Taking the CuL complex as a reference, it can be seen that the complex species is found only for ethylenediamine (five-ring, log K_{CuL} 10.49, Table 14, ligand 1) and trimethylenediamine (six-ring, log K_{CuL} 9.70, ligand 2). In tetra- and pentamethylenediamine (ligands 3 and 4), the nitrogen donor atoms are located too far from each other to allow stable ring formation. If the methylene group in the middle of pentamethylenediamine is replaced by amine producing

$NH_2CH_2CH_2NHCH_2CH_2NH_2$ (diethylenetriamine, ligand 5 in Table 14) or by ether oxygen producing $NH_2CH_2CH_2OCH_2CH_2NH_2$ (oxybis(ethyleneamine), ligand 6), the length of the molecule chains does not change, but the nitrogen or oxygen donors at the centre of the compounds enable the formation of two five-membered rings. The situation with diethylenetriamine resembles that with ethylenediamine; with an extra five-membered ring the complex formation is strengthened (log K_{CuL} 16.2). With oxybis(ethyleneamine) the oxygen donor allows the formation of two five-membered chelate rings. Because of the weaker donor atom, however, the stability constant of the complex is lower (log K_{CuL} 8.97). [92]

If two further ethyleneamine groups are added to ligands 5 and 6 so as to produce $NH_2CH_2CH_2NHCH_2CH_2NHCH_2CH_2NHCH_2CH_2NH_2$ (tetraethylenepentaamine, ligand 8) and $NH_2CH_2CH_2NHCH_2CH_2OCH_2CH_2NHCH_2CH_2NH_2$ (oxybis(diethylenediamine), ligand 9), the number of chelate rings is increased to four and the stability of the complexes is increased, to log K_{CuL} 22.8 for ligand 8 and log K_{CuL} 17.96 for ligand 9. No data were available for the complexation of 1,4,10,13-tetraazatridecane (ligand 7) with Cu(II) or Ca(II). [92] The effect of ether oxygen is twofold: it is a weaker donor than amine nitrogen and it decreases the basicity of the adjacent amine nitrogens owing to its electron-withdrawing effects. The oxygen atom is not, however, expected to influence the terminal basic nitrogens six atoms away. [121] These ligands (8 and 9) are still viable chelating agents, as is true for TCA6, BCA6, BCA5 and MBCA5. Both oxybis(ethyleneamine) and oxybis(diethylenediamine) (ligands 6 and 9) are reported to coordinate through all their donor atoms and to form two and four five-membered chelate rings. [121, 122] Part of the ligands of the BCA series resemble mono- and diethanolamine, and TCA6 is akin to triethanolamine (ligands 10-12 in Table 14), which are also reported to form stable five-membered chelate rings through N and O atoms with copper(II) ion. [123, 124]

6.4.2 Carboxylic acids with ether oxygen

The protonation constants of simple compounds with one carboxylic acid group are closely similar, as reported in Table 15. [92] The addition of a hydroxyl or ether group does not significantly change the value, so long as this is not located close to the acid group. The same is true for compounds with two or more acid groups. When hydroxyl group or ether oxygen is located near the carboxylic acid group, the protonation constants are decreased to some extent. Chelate formation is not possible for compounds a-d, and the stability constants of the complexes are very low. The formation of chelate rings increases the stability constants of the complexes if the chelate ring is five- or six-membered. In ligands BCA6, BCA5, MBCA5 and TCA6, the succinic acid group is separated from the ether oxygen by the methylene group. Succinic acid as such (ligand k in Table 15) can form only a seven-membered ring, which is not very stable in comparison with the complex formed with ligand j (six-membered ring). In the studied ligands, five- or six-membered chelate rings can be formed through ether oxygens. For ligands o-t in Table 15 (which resemble the studied ligands), the possibility to form five- or six-membered rings through the ether oxygen appears to promote the complexation. In the BCA series, some of the rings can be formed through nitrogen and carboxylate groups, but in TCA6 the formation of five- or six-membered rings can occur only through ether oxygen, as in the small ligands (o,p,r,s,t). In TCA6, the polydentation serves to enhance the complexation, as is also seen with ligands s and t. Oxydiacetic acid (ligand o) coordinates tridentately with several metal ions. [125-127] Both oxydiacetic acid and carboxymethoxybutanedioic acid (ligand s) are biodegradable ligands and have been studied for detergent applications, but their Ca-binding capability is not adequate. [128]

Table 14. Protonation and complexation of selected ligands containing nitrogen and ether oxygen. [92] $H^+ + H_{n-1}L \rightleftharpoons H_nL$, $\log K_H^n$ and $M + L \rightleftharpoons ML$, $\log K_{ML}$

	ligand	**log K_H^1**	**log K_H^2**	**log K_H^3**	**log K_H^4**	**log K_H^5**	**log K_{CuL}**	**log K_{CaL}**
1	$H_2N\text{-}CH_2CH_2\text{-}NH_2$, ethylenediamine	9.92	9.61				10.49	0.11
2	$H_2N\text{-}CH_2CH_2CH_2\text{-}NH_2$, trimethylenediamine	10.59	8.78				9.70	
3	$H_2N\text{-}CH_2CH_2CH_2CH_2\text{-}NH_2$, tetramethylenediamine	10.72	9.46					
4	$H_2N\text{-}CH_2CH_2CH_2CH_2CH_2\text{-}NH$, pentamethylenediamine	10.99	10.05					
5	$H_2N\text{-}CH_2CH_2\text{-}NH\text{-}CH_2CH_2\text{-}NH_2$, diethylenetriamine	9.99	9.26	4.64			16.2	0.2
6	$H_2N\text{-}CH_2CH_2\text{-}O\text{-}CH_2CH_2\text{-}NH_2$, oxybis(ethyleneamine)	9.89	9.16				8.97	
7	$CH_2(CH_2CH_2\text{-}NH\text{-}CH_2CH_2\text{-}NH_2)_2$, 1,4,10,13-tetraazatridecane	10.6	9.9	7.74	7.03			
8	$NH\text{-}(CH_2CH_2\text{-}NH\text{-}CH_2CH_2\text{-}NH_2)_2$, tetraethylepentaamine	9.85	9.27	8.19	4.45	2.97	22.8	1.8
9	$O\text{-}(CH_2CH_2\text{-}NH\text{-}CH_2CH_2\text{-}NH_2)_2$, oxybis(diethylenediamine)	9.81	9.24	6.89	5.98		17.96	
10	$H_2N\text{-}CH_2CH_2\text{-}OH$, ethanolamine	9.52					4.50	
11	$HN\text{-}(CH_2CH_2\text{-}OH)_2$, diethanolamine	9.02					4.20	
12	$N\text{-}(CH_2CH_2\text{-}OH)_3$, triethanolamine	7.85					4.07	0.78

Table 15. Protonation and complexation of selected ligands containing carboxylate and ether oxygen. [92] $H^+ + H_{n-1}L \rightleftharpoons H_nL$, $\log K_H^n$ and $M + L \rightleftharpoons ML$, $\log K_{ML}$

	ligand	**log K_H^1**	**log K_H^2**	**log K_H^3**	**log K_H^4**	**log K_{CuL}**	**log K_{CaL}**
a	$H\text{-}COOH$, formic acid	3.57				1.61	0.27
b	$CH_3\text{-}COOH$, acetic acid	4.56				1.79	0.55
c	$CH_3CH_2\text{-}COOH$, propanoic acid	4.69				1.91	0.50
d	$CH_3CH_2CH_2\text{-}COOH$, butanoic acid	4.62				1.7	0.51
e	$HO\text{-}CH_2\text{-}COOH$, hydroxyacetic acid	3.62				2.40	1.11
f	$CH_3\text{-}O\text{-}CH_2\text{-}COOH$, methoxyacetic acid	3.32				1.38	1.12
g	$HO\text{-}CH_2CH_2\text{-}COOH$, 3-hydroxypropanoic acid	4.40				2.05	
h	$HO\text{-}CH_2CH_2CH_2\text{-}COOH$, 4-hydroxybutanoic acid	4.54				1.82	
i	$HOOC\text{-}COOH$, oxalic acid	3.80	1.2			4.85	2.46
j	$HOOC\text{-}CH_2\text{-}COOH$, malonic acid	5.27	2.65			5.04	1.50
k	$HOOC\text{-}CH_2CH_2\text{-}COOH$, succinic acid	5.24	3.99			2.70	1.24
l	$HOOC\text{-}CH_2CH_2CH_2\text{-}COOH$, glutaric acid	5.06	4.19			2.37	1.18
m	$HOOC\text{-}CH_2CH_2CH_2CH_2\text{-}COOH$, adipic acid	5.04	4.26			2.3	2.19
n	$HOOC\text{-}CH_2CH_2CH_2CH_2CH_2\text{-}COOH$, pimelic acid	5.08	4.31			2.2	
o	$HOOC\text{-}CH_2\text{-}O\text{-}CH_2\text{-}COOH$, oxydiacetic acid	3.94	2.02			3.95	3.38
p	$HOOC\text{-}CH_2CH_2\text{-}O\text{-}CH_2CH_2\text{-}COOH$, 3,3'-oxydipropanoic acid	4.62	3.77			2.52	
q	$HO\text{-}CH\text{-}(COOH)_2$, hydroxymalonic acid	4.24	2.02			5.34	2.27
r	$HO\text{-}CH\text{-}COOH(CH_2COOH)$, malic acid	4.68	3.24			3.63	1.95
s	$HOOC\text{-}CH_2\text{-}O\text{-}CH\text{-}COOH(CH_2COOH)$, carboxymethoxybutanedioic acid	5.00	3.77	2.52			4.06
t	$O\text{-}(CH\text{-}COOH(CH_2COOH))_2$, oxybisbutanedioic acid	5.97	4.85	3.98	2.07	8.38	5.82

In summary, although ether oxygen is a weak donor, it appears to strengthen the stabilities of complexes where it makes chelate formation possible. In the ligands of this study, the location of the ether oxygen between N and carboxylate groups enables multidentate chelation and adequate ring sizes, so that the stability constants of the complexes are higher than those of complexes with the smaller reference ligands, which are unable to form as many rings.

6.5 Comparison of stabilities of ML complexes of the studied and reference ligands

Since all ligands of the study form ML complexes as main species, it was reasonable to employ values of the respective stability constants as a measure of the complexation efficiency. Different factors may affect the strength of the complexation, as discussed in general in section 2.4. Some of them were noted in section 6.3 as well. These factors include the affinities of different metal ions to different donor atoms, not only to the strongly coordinating nitrogen and carboxylate oxygens but also to ether oxygens. Open-chain ligands containing neutral oxygen donor atoms tend to be poor ligands, but when the neutral oxygen is a part of a ligand that contains more strongly coordinating groups it may enhance the overall strength of complexation. The strength of complexation is also affected by the size of chelate rings formed in complexes, by the ionic radii of metal ions and by the basicity of N-donor atoms. The basicity of N-donor atoms would be expected to have a clearer effect on metal ions like Cu^{2+}, which favour N-donors, than on metal ions like Ca^{2+} and La^{3+}, which favour O-donors. Another factor to be considered is the size of the chelate ring relative to the size of the coordinating metal ion: for steric reasons, large metal ions prefer five-membered chelate rings, while small metal ions favour six-membered rings (see section 2.4).[39, 46-48, 52-60, 129, 130] When some or all of these factors are operating at the same time and sometimes in different directions, it may be impossible to distinguish their contributions to the strength of complexation. Some trends can nevertheless be detected as illustrated in the comparisons of the complexation tendencies of the ligands that follow.

The only difference between EDTA and EDDS is the size of chelate ring. With EDTA, only five-membered rings are formed between metal ion and N- and/or O-donors, whereas with EDDS two of the chelate rings are six-membered. Comparison of log K_{ML} values (Figure 6 a) shows that increase in the size of some of the rings from EDTA to EDDS causes a slighter decrease in the log K_{ML} values for complexes with smaller ions like Mg^{2+}, Cu^{2+}, Zn^{2+} than for complexes with larger ions like Hg^{2+}, Pb^{2+}, Cd^{2+}, Ca^{2+} (and Mn^{2+} as "medium"-size ion). This trend logically follows from the differences in ring size selectivity and ionic radii discussed above. The effect is not seen for trivalent Fe^{3+} and La^{3+}.

The same kind of comparison can be made between NTA and ISA, although in addition to the size of the ring there is a difference here in the number of carboxylate groups (NTA: five-membered rings and three carboxylates, ISA: five- and six-membered rings and four carboxylates). The log K_{ML} values of complexes with smaller ions, Mg^{2+}, Cu^{2+}, Zn^{2+} and Mn^{2+}, are closely similar for the two ligands, while those of complexes with larger ions, Pb^{2+}, Cd^{2+} and Ca^{2+}, are smaller for the ligand with larger size of some of the rings (ISA). Here, ring size appears to be the dominant factor for the O-donor-favouring Ca^{2+} ion, but Fe^{3+} does not appear to gain any benefit from the fourth carboxylate group (Figure 6 b).

It is also interesting to compare ISA with ODS. The two ligands are similar except for the replacement of the nitrogen donor in ISA by the ether oxygen in ODS. The large O-donor- favouring Ca^{2+} ion prefers ODS to ISA, but all other metal ions (Mg^{2+}, Mn^{2+}, Zn^{2+}, Cd^{2+}, Pb^{2+}, Fe^{3+} and especially Cu^{2+}) prefer ISA with its stronger N-donor group (Figure 6 c).

The following observations can be made when TCA6, which has six carboxylate groups and three ether oxygens, is compared with EDDS and ISA, which have four carboxylates and do not contain ether oxygens. All three ligands have the potential to form both five- and six-membered chelate rings, but in TCA6 the rings can be formed only through ether oxygens. This does not create any disadvantage for the large O-donor favouring Ca^{2+} and La^{3+} ions, which form stronger complexes with TCA6 than with EDDS or ISA. On the other hand, Mn^{2+}, Zn^{2+} and Cu^{2+} ions, which favour N-donors, form stronger complexes with EDDS and ISA, and this tendency is clearly strengthened when the number of N-donors increases from ISA to EDDS (Figure 6 d).

There are only O-donors in TDS, and both five- and six-membered chelate rings can be formed only through ether oxygens. Comparison of TDS, TCA6 and BCA6 shows that, in most cases, BCA6 with its six carboxylate groups, and the ability to form five- and six-membered rings also without ether oxygens, forms the strongest complexes. TDS is a stronger chelating agent than TCA6 for Ca^{2+} and a stronger chelating agent than BCA6 for Hg^{2+} and Fe^{3+} (Figure 6 e).

In many practical applications, BCA6 appeared to be the most suitable of the new ligands. Thus it is reasonable to compare its performance with that of the other ligands studied here. Figure 6 f shows that BCA6 is the strongest chelating agent excluding two N-donor containing EDDS for Pb^{2+}, Zn^{2+}, Hg^{2+}, Fe^{3+} and especially Cu^{2+}.

In addition to the comparison of ISA and ODS above, the general benefit of nitrogen donor to the complexation can be seen in a comparison of DTPA, BCA5 and MBCA5. All these ligands have five carboxylate groups, but the three nitrogens of DTPA give it a substantial advantage over BCA5 and MBCA5 with their one nitrogen and two ether oxygens.

The ligand MGDA is derived from NTA by addition of one CH_3 group. The protonation constants of the nitrogen atom and one of the carboxylic acid groups are closely similar for the two compounds, but the acidity of the two other COOH-groups is greater in MGDA, which forms more stable complexes than NTA (Tables 10 and 13) with all metal ions tested here. The same kind of structural difference is present in BCA5 and MBCA5, but the additional methyl group in MBCA5 does not have an increasing effect on the acidities of the carboxylic acid groups, which are located apart from each other. The stronger basicity of nitrogen in MBCA5, however, allows more stable complexes than BCA5 with Mn^{2+}, Fe^{3+}, Cu^{2+} and Zn^{2+}. With Mg^{2+} and Ca^{2+}, the order is the reverse.

ISA and ODS can also be compared by plotting log K_{ML}(ISA)-log K_{ML}(ODS) as a function of log $K_{\mathrm{ML}}(NH_3)$. Figure 7 shows the greater basicity of the secondary nitrogen than of nitrogen in ammonia. The preference of the Ca^{2+} ion for oxygen over nitrogen donor can also be seen. Although Fe^{3+} forms stronger complexes with ISA than with ODS, its strong affinity to oxygen donors makes the difference between the ligands smaller than the value of the ammine complex. Note, however, that the log K_{ML} value of the ammine complex of Fe^{3+} is an estimated value [131], while stabilities for the other metal ions are experimental values. [92]

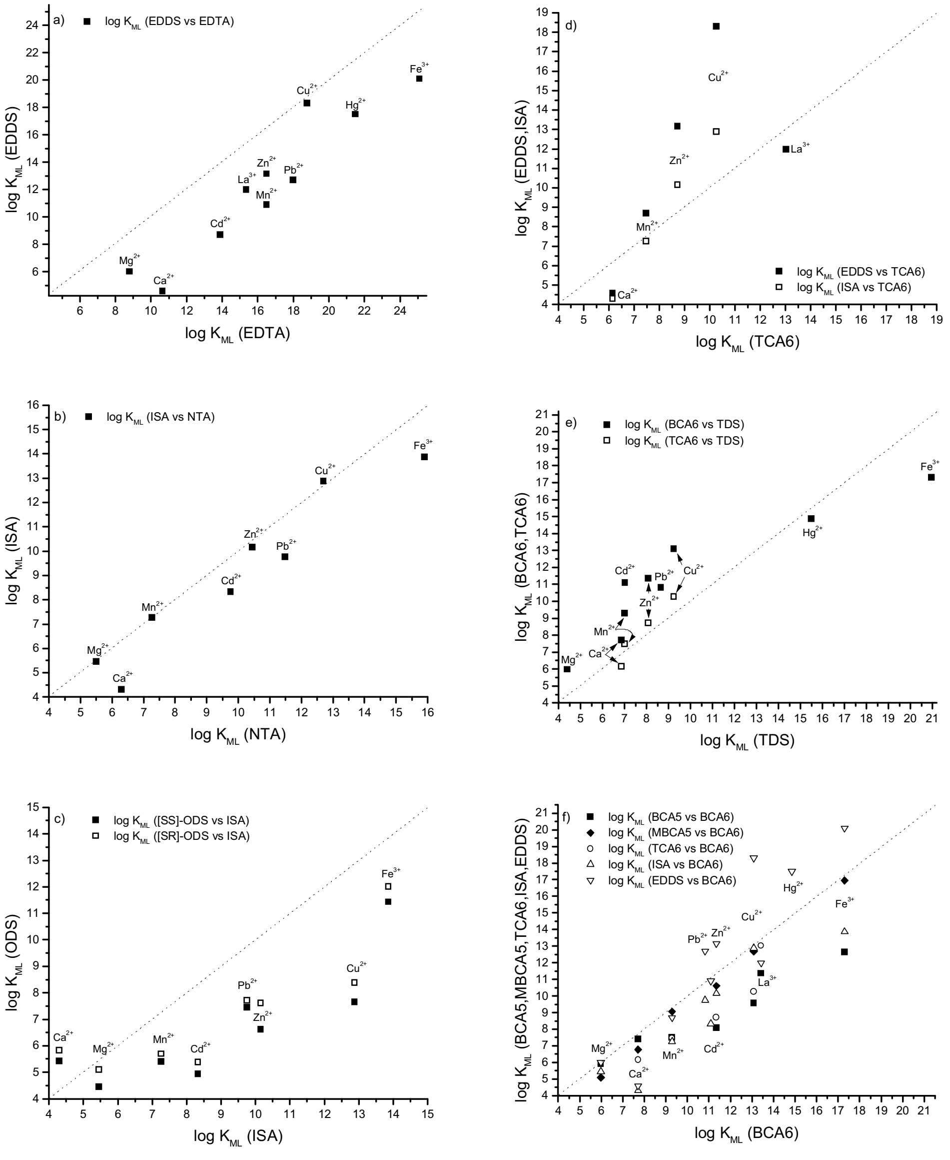


Figure 6. Comparison of the strength of ML complexes (dotted line shows the unit slope).

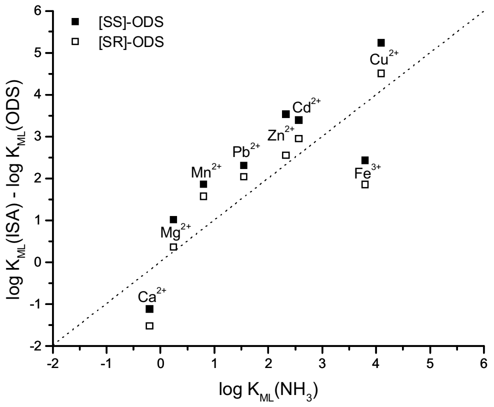
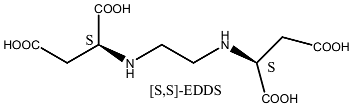
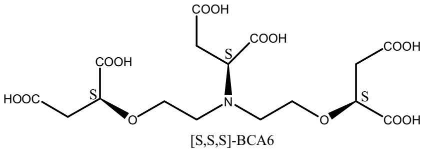


Figure 7. Relationship between log K_{ML}(ISA)-log K_{ML}(ODS) and log K_{ML}(NH_3) for the different metal ions (dotted line shows the unit slope).

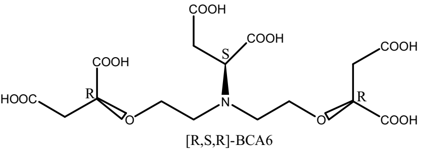
6.6 Differences between isomers



[S,S]-EDDS



[S,S,S]-BCA6



[R,S,R]-BCA6

Two ligands, EDDS and BCA6, were studied as isomeric mixtures and as selected pure isomers: [S,S]-EDDS, [S,S,S]-BCA6 and [R,S,R]-BCA6 (Tables 4, 7 and 9). Interest in studying the complexation of isomers was sparked by the significant difference in the biodegradability of EDDS isomers. One would expect differences in stability constants or complexation models of the isomers to be relevant to the applicability of those forms. In the case of EDDS, close dependence has been demonstrated between the biodegradability and the isomeric form of the compound: the [S,S]-isomer is completely biodegraded while the [R,R]-isomer is only marginally degraded in the standard Sturm test (OECD 301B). [25] Poor availability has so far prevented biodegradability studies on the pure isomers of BCA6.

In the case of EDDS, differences in the strength of complexes of the [S,S]-form and the EDDS mixture were small. The complexation models obtained were the same, and most of the differences in the values of stability constants were within experimental error. For all metal ions studied with EDDS (Mn^{2+}, Zn^{2+}, Cu^{2+} and Fe^{3+}), the stability of the major species $ML^{(4-n)-}$ was 0.3-0.8 log units higher for the [S,S]-isomer than for the isomeric mixture. While this indicates a slight difference in stereospecificity, the difference is immaterial as regards practical applications of EDDS.

For BCA6, two stereoisomers, [S,S,S]- and [R,S,R]-forms, were compared with each other and with a BCA6 mixture containing all isomers of the ligand. Again, the complexation model was closely similar for the two isomers, but some differences appeared in the binuclear species. Binuclear species were found in complexes of the BCA6 mixture with Ca^{2+}, Cu^{2+} and Zn^{2+}. The species Ca_2HL^-, found for the BCA6 mixture, could not be calculated for the [S,S,S]-isomer but was found for the [R,S,R]-isomer and with clearly higher stability than for the isomeric mixture. Binuclear species M_2L^{2-} and M_2HL^- were found for Cu^{2+} and Zn^{2+} with the BCA6 mixture but neither species could be calculated for either metal ion with the [S,S,S]-isomer nor for the Zn^{2+}-[R,S,R]-system. With the [R,S,R]-isomer, Cu_2L^{2-} and Cu_2HL^- could be calculated only from data where $C_L \leq C_M$. The differences between the values of stability constants for these species and the corresponding values for the BCA6 mixture were within experimental errors.

In the case of mononuclear species, the complexation models were the same for the pure isomers and the isomeric mixture, and for most species the differences in the corresponding stability constants were close to or within experimental errors. It is noteworthy, however, that for MnL^{4-} the value of the stability constant is over one logarithm unit higher with the [R,S,R]-isomer, and for CuL^{4-} it is about one logarithm unit higher with the [S,S,S]-isomer. For ZnL^{4-} and $Fe(OH)L^{4-}$ the differences between the values for the isomers and the BCA6 mixture, which has the lowest values, is about logarithm unit. Evidently, the stabilities of these species are even lower for some unmeasured isomer than for the isomeric mixture.

Figure 8 illustrates the differences between the major (ML) species of EDDS and BCA6. A similar comparison for ODS is included. [106] The effect of stereoselectivity in the millimolar concentration area ($C_M = C_L = 1$ mM, where C_L consists of equal amounts of [S,S]-EDDS and EDDS mixture or [S,S,S]-BCA6 and BCA6 mixture) is illustrated in Figure 9, where the percentage distribution of the different Cu(II) and Fe(III) complex species is presented as a function of pH. Increase in ligand-to-metal ratios increases the difference in the distributions of species for the isomer and mixture.

Instead of in terms of proton association reactions, the values of the stability constants of acidic complexes, MH_iL^{n-6+i}, can also be compared by rewriting the formation reactions so that the ligands contain the same number of protons as the complexes, as described in equations [21]-[24] (charges omitted for clarity).

$$M + HL \leftrightharpoons MHL \qquad K_{MHL} = \frac{[MHL]}{[M] \cdot [HL]} \tag{21}$$

$$M + H_2L \leftrightharpoons MH_2L \qquad K_{MH_2L} = \frac{[MH_2L]}{[M] \cdot [H_2L]} \tag{22}$$

$$M + H_3L \leftrightharpoons MH_3L \qquad K_{MH_3L} = \frac{[MH_3L]}{[M] \cdot [H_3L]} \tag{23}$$

$$M + H_4L \leftrightharpoons MH_4L \qquad K_{MH_4L} = \frac{[MH_4L]}{[M] \cdot [H_4L]} \tag{24}$$

This presentation allows a direct comparison of the tendencies of the protonated forms of the ligands to form the corresponding protonated metal complexes. Although the differences are generally small, some trends can be seen, as shown for ligand BCA6 in

Table 16 and Figure 10. The log K_{MHiL} values of all protonated complexes of Mg^{2+} and Fe^{3+} are somewhat higher for the [S,S,S]-isomer than the [R,S,R]-isomer. With Ca^{2+}, Mn^{2+}, Cu^{2+} and Zn^{2+}, however, the values are higher for the [R,S,R]-isomer. The difference suggests that there could be some structural factor related to the ion size, which makes the [S,S,S]-isomer more favourable for the smaller ions and the [R,S,R]-isomer for the larger ions. Another interesting observation is that the order of magnitudes of the log K_{MHiL} values for Ca^{2+} and Mg^{2+} ions changes with the degree of protonation. This trend is strongest for the [S,S,S]-isomer, somewhat weaker for the [R,S,R]-isomer and least for the BCA6 mixture. The trend may be explained by the order of protonation of the carboxylic acid groups: when only some of the carboxylates take part in the complex formation the effect of their positions will be expressed more clearly in the stability constants.

It can be concluded from the above that there is a small degree of stereospecificity for BCA6, but, again, this is insignificant for any practical applications of the ligand. From the environmental perspective, it would be of interest to know if the different isomers of BCA6, like those of EDDS, biodegrade at significantly different rates. This would be an important question for the future.

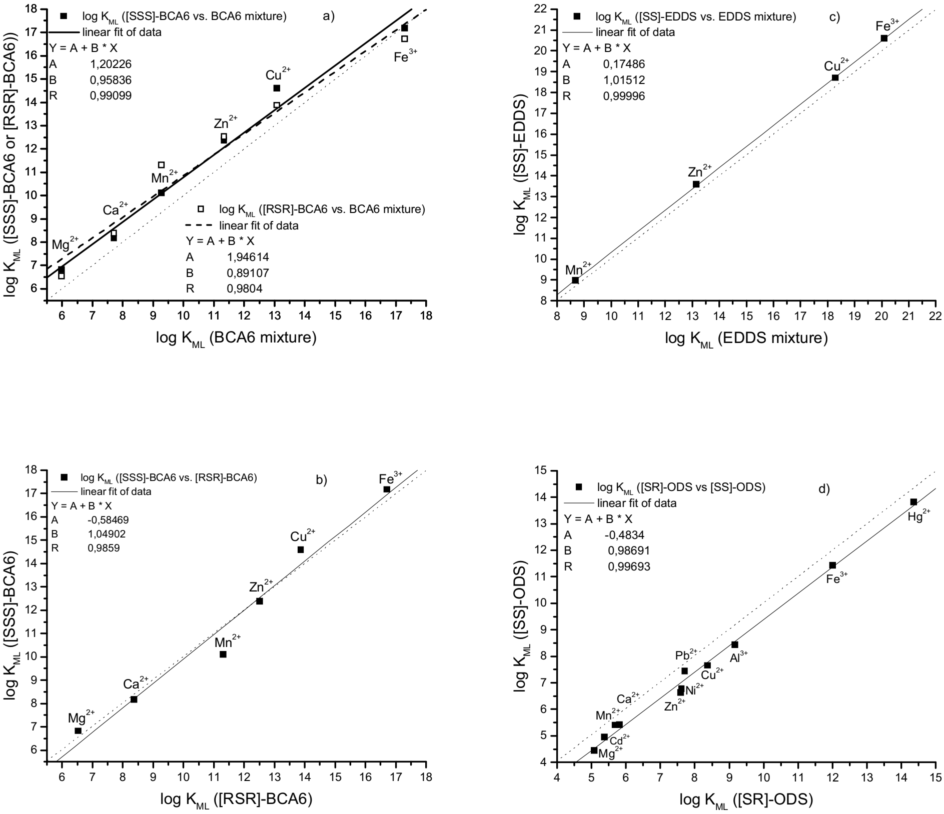


Figure 8. Comparison of log K_{ML} values for forms of BCA6, EDDS and ODS (dotted line shows the unit slope).

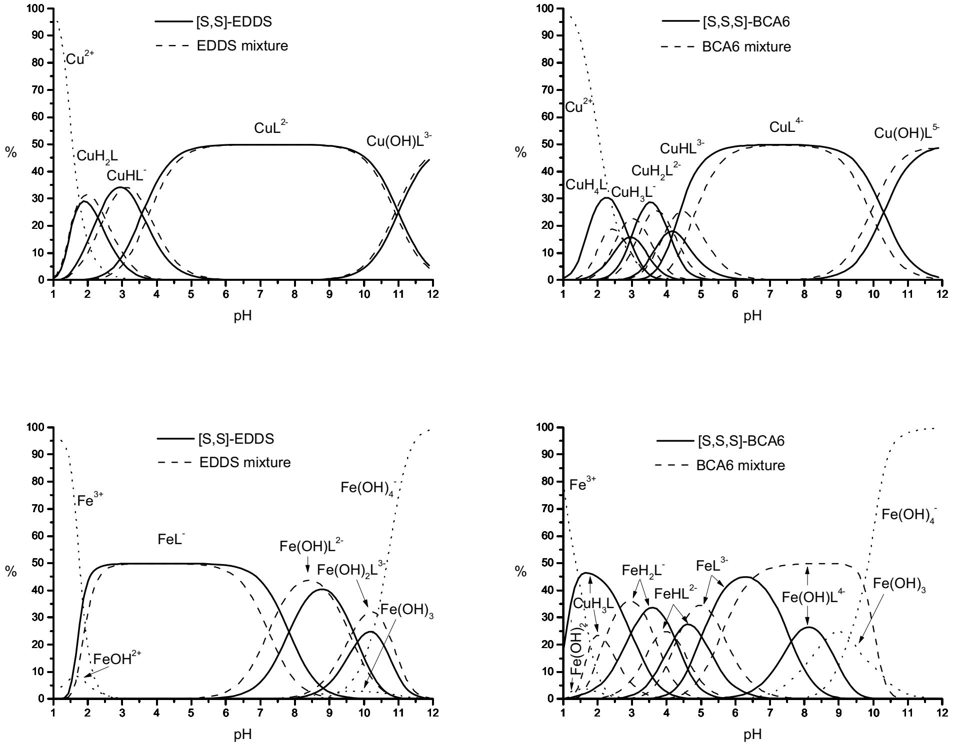


Figure 9. Percentage distribution of the Cu(II) and Fe(III) complexes of [S,S]-EDDS, EDDS mixture, [S,S,S]-BCA6 and BCA6 mixture as a function of pH.

Table 16. Comparison of $\log K_{\mathrm{MHiL}}$ values expressed as addition of the metal ion to H_iL (as defined in equations [21]-[24]).

	[SSS]-BCA6 $\log K_{\mathrm{MHiL}}$			
M^{n+}	MHL	MH_2L	MH_3L	MH_4L
Mg^{2+}	4.13	3.64	3.57	3.09
Fe^{3+}	12.85	11.53	9.81	
Ca^{2+}	4.20	3.39	2.96	2.74
Mn^{2+}	5.59	4.66	3.71	3.26
Cu^{2+}	9.44	7.95	6.23	5.15
Zn^{2+}	7.31	5.51	3.98	3.10
	[RSR]-BCA6 $\log K_{\mathrm{MHiL}}$			
M^{n+}	MHL	MH_2L	MH_3L	MH_4L
Mg^{2+}	4.00	3.56	3.29	2.98
Fe^{3+}	12.24	10.69	8.15	
Ca^{2+}	4.51	3.50	3.04	2.90
Mn^{2+}	6.91	5.29	3.93	3.28
Cu^{2+}	9.63	8.21	6.82	5.17
Zn^{2+}	8.12	6.71	5.24	3.60
	BCA6 mixture $\log K_{\mathrm{MHiL}}$			
M^{n+}	MHL	MH_2L	MH_3L	MH_4L
Mg^{2+}	3.07	2.52	2.29	1.95
Fe^{3+}	12.65	10.89	8.38	
Ca^{2+}	4.06	3.00	2.41	1.95
Mn^{2+}	5.56	4.57	3.36	2.36
Cu^{2+}	8.90	7.54	6.14	4.83
Zn^{2+}	7.25	5.95	4.72	3.46

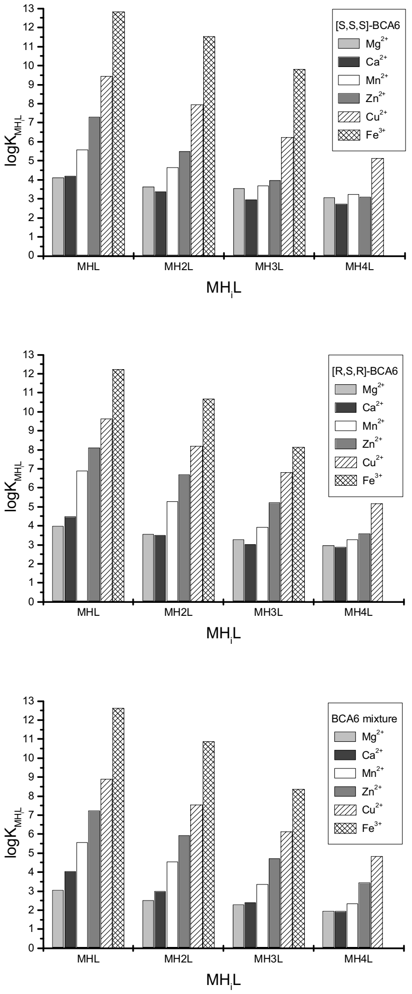


Figure 10. Comparison of $\log K_{\mathrm{MHiL}}$ values of BCA6 products.

7 Structure estimations

No solid-state data was available for the BCA series and TCA6, but computational density functional methods (geometry optimizations, continuum-solvation model, mixed cluster-continuum model and Car-Parillo molecular dynamics simulation) have been used in estimating coordination geometries for BCA6, EDDS, ISA, ODS, EDTA and DTPA complexes with Mg^{2+}, Ca^{2+}, Mn^{2+}, $Fe^{3+}$and Zn^{2+}.[132] Six-coordinated complex geometries were found for BCA6 and all these metals. At higher coordination numbers, the strain on the ligand backbone forces at least one coordinating atom much further away from the metal. Fe^{3+} favours six-coordination over eight-coordination to BCA6 by 50 $kJmol^{-1}$. The coordination environment of Fe^{3+} involves five-membered rings from ether oxygens to shorter arms of the succinate group and a six-membered ring from nitrogen to the longer carboxylate arm. Although the complexation energies primarily support five-membered rings over six-membered rings, in the case of Fe(III)-BCA6 the structure where the carboxylate arm from the central nitrogen atom forms a six-membered ring is more stable than the five-membered ring by 10 $kJmol^{-1}$. For $[Ca\text{-}BCA6]^{4-}$ an eight-coordinate structure where the carboxylate arm from nitrogen forms a five-membered ring with metal is about 20 $kJmol^{-1}$ more stable than the structure with comparable six-membered ring. Potential sources of error are the assumption that only 1:1 complexes are formed, the ligands are completely deprotonated and possible dimers, polymers, ML_2 or M_2L complexes were not taken into consideration in the calculations. The 1:1 approximation is reasonable, however. The EDTA complex geometries obtained in the calculations were reported not to correspond directly to the available X-ray data, but the agreement was generally good. [132]

The coordination geometries of the [S,S] or [R,S] forms of EDDS with Fe^{3+}, Co^{2+}, Cu^{2+} and Ni^{2+} are known in the solid state from X-ray diffraction studies. [133-137] In all these complexes the central metal atom is coordinated by two nitrogen atoms and by one oxygen atom from each of the four carboxylate groups. There is virtually no doubt that the basic structures of the solid complexes of Mn^{2+} and Zn^{2+} are similar. Computational methods have shown the geometry of minimum energy to be a corresponding model involving both nitrogen donors and all four carboxylate oxygens. [132] Hexadentate coordination has also been concluded from investigations by infrared (IR), proton magnetic resonance (PMR), electronic absorption and circular dichroism (CD) for [S,S]-EDDS with trivalent ions Cr^{3+}, Co^{3+} and Rh^{3+}. [138-140] In the case of Cr^{3+} and Rh^{3+}, EDTA has been reported [139, 141] to form pentadentate complexes with one free acetate arm. Binding of one aqua molecule to metal gives the coordination number six. Thus, it seems that hexadentate complexes of EDDS, with its two longer carboxylate chains, will have less strain in chelate rings.

Although EDTA can act as a hexadentate ligand, the coordination number of the metal ion is often greater than six. X-ray studies have demonstrated hexadentate coordination for Co^{2+}, Co^{3+} and Mn^{3+}. [142-145] The addition of one aqua molecule raises the coordination number to seven, e.g., with Mg^{2+} and Mn^{2+}. [146-148] Six coordination can also be achieved by pentadentate coordination of EDTA and further coordination of one aqua molecule, as reported for Rh^{3+}, Cr^{3+}, Ru^{3+}, Ru^{3+} and Ni^{2+}. [139, 141, 149, 150] EDTA has been proposed to coordinate hexadentately or pentadentately with Fe^{3+}, with aqua ligand raising the coordination number to seven and six, respectively. [151] Coordination numbers 9 and 10 with three and four aqua molecules have been found for EDTA complexes with La^{3+} ion. [152, 153] It has been suggested that if the ionic radius of the metal ion is larger than 0.79 Å and the d-electron configuration is other than d^0, d^5 or d^{10}, EDTA may be pentadentate with a monodentate ligand occupying the sixth position. The coordination number may increase from 6 to 7 or 8 in the case of a metal ion with 0, 5 or 10 d-electrons and ionic radius greater than 0.79 Å. [154] This suggestion seems to describe the above-mentioned cases.

According to with some structural studies on ISA and its metal complexes, the $[Fe(III)L]^-$ anion of ISA has the same structure as the corresponding EDTA and EDDS complexes. [155] For Ni^{2+}, a structure has been found where coordination is through nitrogen and three oxygen atoms, two from the shorter and one from the longer arms, and one aqua molecule. [156] A similar structure is reported for Co^{2+}, but instead of an aqua molecule, the ethylenediamine molecule is coordinated to the metal by both its nitrogens, one of these forming a hydrogen bond with the uncoordinated carboxylate oxygen in ISA. [157] In IR studies of acidic complexes of ISA (H_2ML) with several transition metal ions, nitrogen and two carboxylate groups were found to be coordinated, but it was not clear from which of the four possible groups they were derived. [158] Computational studies of complexation geometries suggest that ISA is coordinated with Fe^{3+} by nitrogen and all four carboxylate groups in minimum energy geometry. In the case of Ca^{2+}, one carboxylate group is detached and the metal is coordinated on average by three water molecules. [132]

8 Applications of the ligands

Stability constants of the complexes studied here were somewhat lower than those of complexes formed by EDTA and DTPA. The complexation capability of these new ligands is nevertheless sufficient for several practical applications. Moreover, the somewhat lower chelation efficiency of BCA6 than of EDTA and DTPA for Cd(II), Hg(II) and Pb(II) is an environmental advantage because, in conjunction with the better biodegradability, it probably lowers the capability of BCA6 to remobilize toxic heavy metal ions from sediment. The results obtained from complexation studies of EDDS, ISA, BCA6, BCA5, MBCA5 and TCA6 have been utilized in several application tests and further research. Some examples of applications and other related studies of these ligands are described in the following.

8.1 Method to determine BCA6 and BCA5

EDTA and DTPA have been quantified in pulp and paper mill process and waste waters by liquid chromatographic method as their Fe(III) complexes, which are highly stable in aqueous solutions. [159] Fe(III) complexes have also been used in determinations of EDTA, EDDS and ISA in cosmetic products by high performance liquid chromatography (HPLC) and capillary electrophoresis (CE). [160] As well CE method has been utilized for the determination of Fe(III) and Cu(II) complexes of EDDS in wood pulp. [161] On the basis of the complexation data of BCA6 and BCA5 produced in this work, a method for the determination of these ligands relying on reversed-phase HPLC with UV detection was developed for lake water and for a pulp and paper mill effluent leaving wastewater treatment. [162] Cu(II) complexes were chosen for the determination of BCA6 and BCA5 because they are the most stable complexes over a broad pH range and also in the μM concentration area where hydrolysis of Fe(III) would cause problems. Moreover, no interference of other metal ions was observed when Cu(II) chelates were applied. [162]

8.2 Pulp bleaching applications

Pulp bleaching methods based on oxygen chemicals have been developed with the aim of reducing the consumption of chlorine-based chemicals. Oxygen, ozone, hydrogen peroxide and peracetic acid are the common replacements for chlorine chemicals. Pulp usually contains traces of transition metal ions, such as iron and manganese, which catalyse the decomposition of hydrogen peroxide and peracids during bleaching. [163] The presence of these metals results in excess chemical consumption, poorer pulp strength and reduced whiteness. Their removal by chelation is an essential step, therefore, when bleaching is carried out with oxygen-based chemicals. EDTA and DTPA are common complexing agents for the chelation, but both are virtually nonbiodegradable in the conditions of waste water treatment plants [61-63] and are difficult to remove from bleaching effluents.

Results obtained in pulp bleaching tests with ISA and EDDS showed EDDS to be a realistic alternative to EDTA and DTPA as a chelating agent for totally chlorine free (TCF) bleaching of chemical pulp. ISA is a competitive biodegradable alternative particularly in the bleaching of high yield pulp. Successful full-scale mill trials with ISA as chelating agent have also been carried out with thermomechanical pulp (TMP). [164]

The performance of BCA6, BCA5 and MBCA5 was studied in TCF bleaching of eucalyptus pulp (*E. Globulus*). Although the stabilities of chelates of these ligands with Mn(II) and Fe(III) are somewhat lower than those of EDTA and DTPA, they appear to be sufficient for pulp bleaching applications. As chelating agents the new ligands showed equal performance to EDTA and DTPA. The somewhat lower chelation efficiency of the new ligands than of EDTA and DTPA for Mg(II) and Ca(II) is an advantage in fact, because alkaline earth metal ions have a stabilizing effect in peroxide bleaching. [165, 166] More importantly, the Mn complexes of BCA6, BCA5 and MBCA5 appear to be inert in peracetic acid solution, in contrast to Mn-EDTA and Mn-DTPA complexes, which are capable of decomposing peracetic acid. This would also be an environmental advantage due to the savings in chemicals and process steps with these new ligands. EDDS and ISA do not have this advantage; like the Mn complexes of EDTA and DTPA they decompose peroxy compounds. Overall, BCA6 proved to be the most effective of these new chelating agents in pulp bleaching. [IV, 165-168]

8.3 Modelling

As mentioned above, computational methods have been used to estimate the coordination geometries for BCA6, EDDS, ISA, ODS, EDTA and DTPA with several metal ions. [132] Metal ion complexation with polymeric ligands has also been studied, using functional methods and a continuum-solvation model (COSMO). In these studies the most effective poly(carboxylic acid) ligand, poly(epoxy succinic acid) (PESA), was compared with EDTA, DTPA, BCA6, EDDS and ISA in regard to (uncorrected) complexation energies for Mn(II) and Fe(III). For Mn(II), PESA seemed to perform better than ISA or EDDS, but worse than DTPA, EDTA or BCA6. In the case of Fe(III), all the compared ligands performed clearly better than PESA. [169]

The chemical speciation simulation program JESS (Joint Expert Speciation System)[170-172] has been used to assess the efficiency of EDTA, [S,S]-EDDS, ISA and NTA for use in the pulp and paper industry. [173] Calculations of the Speciation Efficiency Index (SEI) showed EDDS to be superior to the other three ligands. The SEI value takes into account the efficiency to sequester undesired transition metals, Mn, Fe and Cu, but also the sequestration of desired Mg and Ca as a decrease in the SEI value. An extra advantage of [S,S]-EDDS is that it is readily biodegradable.

EDTA, BCA6 and nitric acid have been studied in modelling of metal removal from hardwood (birch) kraft pulp by displacement chelation and acid displacement. Fe and Cu were better removed by EDTA and BCA6 than by acid. [174]

The complexation properties of BCA6 have also been utilized to model the chemical effects of cumulating metal in closed loop bleaching. BCA6 was compared with DTPA in regard to metal complexing abilities as well as to cost efficiency. Washing effluents cannot be cycled when DTPA is used for chelation because of the lowered bleaching performance due to the reactions of DTPA with other bleaching chemicals. Such effects do not interfere in the case of BCA6 and the water in the D/Q sequence can be cycled. [175]

8.4 Detergent applications

Many compounds have been examined in the search for substitutes for sodium triphosphate in detergent applications because sodium triphosphate is considered to accelerate eutrophication. Only a few compounds have been found to be both ecologically acceptable and commercially viable. To be acceptable, a complexing agent should have a log K_{CaL} value at least between 4 and 5. [128, 130] At first, NTA was considered a promising substitute, but it is no longer generally accepted because of the possible carcinogenic effects. When attention was subsequently focused on ligands containing only carbon, hydrogen and oxygen, it was found that polymeric materials (e.g. polymaleates, copolymers of maleic acid and ethylene or vinyl ethers, polyacrylates and oxidized starch), which have excellent washing performance, are not sufficiently biodegradable. Lower molecular weight compounds (e.g. CMOS or citric acid), in turn may have good biodegradability but weak calcium binding ability.

The features needed for high calcium binding capacity are reported to be as follows. [128] The sequestrant should have at least five chelating groups for each calcium ion, and the chelating groups should form six- or preferably five-membered rings. Particularly suitable chelating groups for calcium are carboxylate groups, tertiary nitrogen atom, and, to a lesser extent, ether or alcohol oxygen atoms. In oxydiacetate (ODA) and ethyleneglycoldiacetate (EGDA) complexes of calcium, for example, the weaker complexing ether oxygens are present together with stronger carboxylate groups, making the formation of five-membered rings possible. [126, 176] Both ligands are readily biodegradable, but K_{CaL} is rather low for effective calcium binding. [128] In the attempt to avoid nitrogen, test has been made of several nitrogen-free compounds with acetate, malonate or succinate groups. Unfortunately, it seems that good biodegradability and sufficient calcium binding strength are not found in the same compounds. [128, 130]

Evidently, at least one tertiary nitrogen group is needed to raise the stability constant of calcium (K_{CaL}) to sufficient level. In any event, it seems that compounds that are readily biodegradable will contain groups like –CH_2-O-CH(COOH)-CH_2COOH or –CH_2-O-CH_2COOH rather than –CH_2-O-CH(COOH)-COOH. [128] Succinic acid groups appear to be more favourable to biodegradation than are malonic acid groups. Succinic acid groups were included in the ligands studied here. It is also stated that biodegradability depends on the nature and number of nitrogen atoms. Complexing agents with a single nitrogen atom in the molecule biodegrade relatively easily, whereas compounds with two or more tertiary amino groups are biologically highly stable. [6] This relationship was also observed for most of the chelating agents studied here.

In study III, the calcium binding ability of TCA6 was measured in NH_4Cl-NH_3 buffer at pH 9.5 at hardness level of 1000 ppm (calculated as $CaCO_3$) with comparison made to EDTA, DTPA, MGDA, NTA, EDDS and ISA. Each chelating agent was added to buffered calcium solution until the molar ratio Ca:ligand was 1:1, and the free calcium concentration was measured with an ion selective electrode. The performance of BCA6 was only slightly poorer than that of TCA6 (Figure 11). [177]

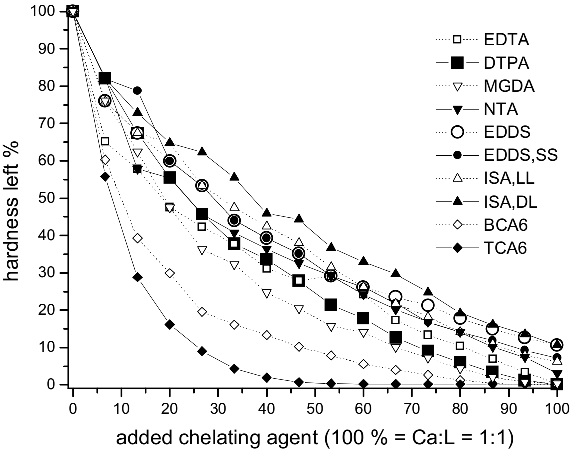


Figure 11. Chelation of Ca(II) at hardness level of 1000 ppm.

8.5 Applications to plant growth

The results of the complexation studies have also been utilized in research on nutrient uptake by plants. The uptake of iron was compared for different compounds of iron: $FeSO_4$, Fe-EDTA, Fe-EDDS and Fe-EDDHA (ethylenediimino-bis(2-hydroxyphenyl) acetic acid). The iron complexes of [S,S]-EDDS and an isomeric mixture of EDDS were also compared. These studies showed EDDS to be as effective as the more resistant ligands EDTA and EDDHA in providing iron to plants in sand media. The use of biodegradable ligands like [S,S]-EDDS to sustain iron availability may be especially valuable in drip irrigation, where ligand accumulations may pose a threat to groundwater quality. [178, 179]

A new invention that uses biodegradable compounds ISA and EDDS as fixing agents for coating seeds provides strong adherence to trace metals and nutrient salts. Detachment of the nutrients from the seeds is reduced, “burns” caused by salts are eliminated, the initial development of the seed is intensified and a more flexible addition of nutrients through the seed coating is facilitated. [180]

9 Conclusions

Potentiometric determinations of protonation and stability constants of EDDS, ISA, BCA6, BCA5, MBCA5 and TCA6 with Mg(II), Ca(II), Mn(II), Fe(III), Cu(II), Zn(II), La(III), Cd(II), Hg(II) and Pb(II) ions were carried out as part of a broad project investigating the suitability of these chelating agents to replace EDTA and DTPA. Kemira Oyj coordinated the project and, in addition to the complexation studies, several research groups at Kemira and at different universities took part in investigations dealing with biodegradability, modelling, and pulp and paper, detergent and plant growth applications. During the investigations it emerged that some of these ligands are suitable candidates to replace EDTA and/or DTPA, not only because of their chemical behaviour in applications but also for their cost effectiveness. The research on complex formation of the ligands was an essential part of the project on the way from ideas to applications. The ligands were confirmed to form complexes strong enough for practical use. The information on complexation ability obtained in the potentiometric studies was sufficient for planning of the applications. For the future it would be of value to study the structures of the metal complexes of these ligands by X-ray diffraction, though the preparation of crystals for solid-state studies has turned out to be very difficult. This work is in progress and will hopefully give additional information about the behaviour of the ligands. It would also be useful to widen the selection of metal ions, especially for BCA6, the most promising of the new chelating agents. This would be of interest not only to increase understanding of the complexation behaviour of the new ligand but also to obtain information relevant to other potential applications of this environmentally friendly chelator.

References

(1) Williams, D. *Chem. Br.* **1998**, *34*, 48-50.

(2) Knepper, T. P. *Trend. Anal. Chem.* **2003**, *22*, 708-724.

(3) Nowack, B. *Environ. Sci. Technol.* **2002**, *36*, 4009-4016.

(4) Fuerhacker, M.; Lorbeer, G.; Haberl, R. *Chemoshphere* **2003**, *52*, 253-257.

(5) Allard, A. S.; Renberg, L.; Neilson, A. H. *Chemosphere* **1996**, *33*, 577-583.

(6) Sýkora, V.; Pitter, P.; Bittnerová, I.; Lederer, T. *Wat. res.* **2001**, *35*, 2010-2016.

(7) Hornburg, V.; Brümmer, G. W. *Z. Pflanzenernähr. Bodenk.* **1993**, *156*, 467-477.

(8) Nowack, B.; Kari, F. G.; Krüger, H. G. *Water, Air, Soil Poll.* **2001**, *125*, 243-257.

(9) ECB, European Chemical Bureau *European Union risk assessment report, tetrasodiumethylenediaminetetraacetate* **2004**, *51*.

(10) Sillanpää, M. *Analysis and environmental fate of EDTA and DTPA*. Helsinki university of technology, laboratory of inorganic and analytical chemistry, Espoo, Finland, 1997.

(11) Morgan, G. T.; Drew, H. D. K. *J. Chem. Soc.* **1920**, *117*, 1456-1465.

(12) Bell, C. F. *Principles and applications of metal chelation;* Oxford Chemistry Series; Clarendon Press: Oxford, 1977, pp 149.

(13) Hartley, F. R.; Burgess, C.; Alcock, R. *Solution equilibria;* Ellis Horwood publishers: Chichester, 1980, pp 361.

(14) Williams, R. J. P. *J. Phys. Chem.* **1954**, *58*, 121-126.

(15) Atkinson, G.; Bauman, J. E. J. *Inorg. Chem.* **1963**, *2*, 64-67.

(16) Pryde, A. J.; Shaw, B. L.; Weeks, B. *J. C. S. Chem. Comm.* **1973**, 947-948.

(17) DeStefano, N. J.; Johnson, D. K.; Venanzi, L. M. *Angew. Chem.* **1974**, *86*, 133.

(18) Hartley, F. R. *Chem. Soc. Rev.* **1973**, *2*, 163-179.

(19) Schwarzenbach, G. *Helv. Chim. Acta* **1952**, *35*, 2344-2359.

(20) Adamson, A. W. *J. Am. Chem. Soc.* **1954**, *76*, 1578-1579.

(21) Myers, R. T. *Inorg. Chem.* **1978**, *17*, 952-958.

(22) Hancock, R. D.; Marsicano, F. *J. Chem. Soc., Dalton Trans.* **1976**, 1096-1098.

(23) Neal, J. A.; Rose, N. J. *Inorg. Chem.* **1968**, *7*, 2405-2412.

(24) Pavelčik, F.; Majer, J. *Chem. Zvesti* **1978**, *32*, 37-41.

(25) Schowanek, D.; Feijtel, T.; Perkins, C.; Hartman, F.; Federle, T.; Larson, R. *Chemosphere* **1997**, *34*, 2375.

(26) Ramsey-Downey, W. M.; Kerzerian, C. USA Patent US Pat., 3,077,487, 1963.

(27) van Westrenen, J.; Roggen, R. M.; Hoefnagel, M. A.; Peters, A. J.; Kieboom, A. P. G.; Bekkum, H. *Tetrahedron* **1990**, *46*, 5741-5758.

(28) Aksela, R.; Renvall, I.; Parén, A. WO 9745396, 1997.

(29) Aksela, R.; Renvall, I.; Parén, A. WO 9946234, 1999.

(30) Pihko, P. M.; Rissa, T. K.; Aksela, R. *Tetrahedron* **2004**, *60*, 10949-10954.

(31) Lahtinen, M.; Walavaara, I.; Aksela, R.; Tonteri, V.; Jokela, R. .

(32) Ahrland, S.; Chatt, J.; Davies, N. R. *Quart. Rev.* **1958**, *12*, 265-276.

(33) Pearson, R. G. *J. Am. Chem. Soc.* **1963**, *85*, 3533-3539.

(34) Pearson, R. G. *J. Chem. Educ.* **1968**, *45*, 581-587.

(35) Pearson, R. G. *J. Chem. Educ.* **1968**, *45*, 643-648.

(36) Parr, R. G.; Pearson, R. G. *J. Am. Chem. Soc.* **1983**, *105*, 7512-7516.

(37) Hancock, R. D.; Marsicano, F. *Inorg. Chem.* **1978**, *17*, 560-564.

(38) Hancock, R. D.; Marsicano, F. *Inorg. Chem.* **1980**, *19*, 2709-2714.

(39) Hancock, R. D.; Martell, A. E. *Chem. Rev.* **1989**, *89*, 1875-1914.

(40) Drago, R. S.; Vogel, G. C.; Needham, T. E. *J. Am. Chem. Soc.,* **1971**, *93*, 6014-6026.

(41) Hancock, R. D.; Darling, E. A.; Hodgson, R. H.; Ganesh, K. *Inorg. Chim. Acta* **1984**, *90*, L83-L84.

(42) Wu, S. Y.; Lee, C. S.; Chung, C. S. *Inorg. Chem.* **1984**, *23*, 2548-2550.

(43) Shannon, R. D.; Prewitt, C. T. *Acta Cryst.* **1969**, *B25*, 925-946.

(44) Huheey, J. E.; Keiter, E. A.; Keiter, R. L. *Inorganic chemistry, principles of structure and reactivity;* Harper Collins college publishers: New York, 1993.

(45) Irving, H. M.; Williams, R. J. P. *J. Chem. Soc.* **1953**, 3192-3210.

(46) Hancock, R. D.; Nakani, B. S. *J. Coord. Chem.* **1984***, 13*, 309-314.

(47) Hancock, R. D.; McDougall, G. J. *J. Am. Chem. Soc.* **1980***, 102*, 6551-6553.

(48) Hancock, R. D.; Bhavan, R.; Wade, P. W.; Boeyens, J. C. A.; Dobson, S. M. *Inorg. Chem.* **1989***, 28*, 187-194.

(49) Munson, M. S. B. *J. Am. Chem. Soc.* **1965***, 87*, 2332-2336.

(50) Taft, R. W.; Wolf, J. F.; Beauchamp, J. L.; Scorrano, G.; Arnett, E. M. *J. Am. Chem. Soc.* **1978***, 100*, 1240-1249.

(51) Kappes, M. M.; Staley, R. H. *J. Am. Chem. Soc.* **1982***, 104*, 1819-1823.

(52) Damu, K. V.; Shaikjee, M. S.; Michael, J. P.; Howard, A. S.; Hancock, R. D. *Inorg. Chem.* **1986***, 25*, 3879-3883.

(53) Hancock, R. D.; Bhavan, R.; Shaikjee, M. S.; Wade, P. W.; Hearn, A. *Inorg. Chim. Acta* **1986***, 112*, L23-L25.

(54) Thöm, V. J.; Hosken, G. D.; Hancock, R. D. *Inorg. Chem.* **1985***, 24*, 3378-3381.

(55) Thöm, V. J.; Shaikjee, M. S.; Hancock, R. D. *Inorg. Chem.* **1986***, 25*, 2992-3000.

(56) Hancock, R. D. *Pure Appl. Chem.* **1986***, 58*, 1445-1452.

(57) Hancock, R. D. *Pure Appl. Chem.* **1993***, 65*, 941-946.

(58) Maumela, H.; Hancock, R. D.; Carlton, L.; Reipenspies, J. H.; Wainwright, K. P. *J. Am. Chem. Soc.* **1995***, 117*, 6698-6707.

(59) Clapp, L. A.; Siddons, C. J.; VanDerveer, D. G.; Reibenspies, J. H.; Jones, S. B.; Hancock, R. D. *J. Chem. Soc. Dalton Trans.* **2006**, 2001-2007.

(60) Bartsch, R. A.; Czech, B. P.; Kang, S. I.; Stewart, L. E.; Walkowiak, W.; Charewicz, W. A.; Heo, G. S.; Son, B. *J. Am. Chem. Soc.* **1985***, 107*, 4997-4998.

(61) Means, J. L.; Kucak, T.; Crerar, D. A. *Environ. Poll. (Ser. B)* **1980***, 1*, 45-60.

(62) Sillanpää, M. *Rev. Environ. Contam. Toxicol.* **1997***, 152*, 85-111.

(63) Kari, F. G.; Giger, W. *Wat. Res.* **1996***, 30*, 122-134.

(64) Bucheli-Witschel, M.; Egli, T. *FEMS Microbiol. Rev.* **2001***, 25*, 69-106.

(65) Pitter, P.; Sýkora, V. *Chemosphere* **2001***, 44*, 823-826.

(66) Lockhart, H. B.; Blakeley, R. V. *Environ. Sci. Technol.* **1975**, *9*, 1035-1038.

(67) Kari, F. G.; Giger, W. *Environ. Sci. Technol.* **1995**, *29*, 2814-2827.

(68) Kari, F. G.; Hilger, S.; Canonica, S. *Environ. Sci. Technol.* **1995**, *29*, 1008-1017.

(69) Metsärinne, S.; Rantanen, P.; Aksela, R.; Tuhkanen, T. *Chemosphere* **2004**, *55*, 379-388.

(70) Metsärinne, S.; Tuhkanen, T.; Aksela, R. *Chemosphere* **2001**, *45*, 949-955.

(71) Itävaara, M.; Vikman, M. **1997**, *Technical Research Centre of Finland, Research Report no. BEL 235/97.*

(72) OECD guideline for testing of chemicals. Proposal for revised introduction to the OECD guidelines for testing of chemicals, section 3. Part 1: Principles and strategies related to the testing of degradation of organic chemicals. *http://www.oecd.org/dataoecd/55/12/34898616.pdf* (accessed april, 2005).

(73) Pagga, U. *Chemosphere* **1997**, *35*, 2953-2972.

(74) Vandevivere, P. C.; Saveyn, H.; Verstraete, W.; Feijtel, T. C. J.; Schowanek, D. R. *Environ. Sci. Technol.* **2001**, *35*, 1765-1770.

(75) Jaworska, J. S.; Schowanek, D.; Feijtel, T. C. J. *Chemosphere* **1999**, *38*, 3597-3625.

(76) Tandy, S.; Ammann, A.; Schulin, R.; Nowack, B. *Environ. Pollut.* **2006**, *142*, 191-199.

(77) Vandevivere, P.; Hammes, F.; Verstraete, W.; Feijtel, T.; Schowanek, D. *J. Environ. Eng.* **2001**, *127*, 802-811.

(78) Kos, B.; Leštan, D. *Plant Soil* **2003**, *253*, 403-411.

(79) Tandy, S.; Bossart, K.; Mueller, R.; Ritschel, J.; Hauser, L.; Schulin, R.; Nowack, B. *Environ. Sci. Technol.* **2004**, *38*, 937-944.

(80) Meers, E.; Ruttens, A.; Hopgood, M. J.; Samson, D.; Tack, F. M. G. *Chemosphere* **2005**, *58*, 1011-1022.

(81) Luo, C.; Shen, Z.; Li, X. *Chemosphere* **2005**, *59*, 1-11.

(82) Luo, C.; Shen, Z.; Li, X.; Baker, A. J. M. *Chemosphere* **2006**, *63*, 1773-1784.

(83) Komárek, M.; Tlustoš, P.; Száková, J.; Chrastný, V.; Ettler, V. *Chemosphere* **2007**, *67*, 640-651.

(84) Cokesa, Ž; Knackmuss, H. J.; Rieger, P. G. *Appl. Environ. Microbiol.* **2004**, *70*, 3941-3947.

(85) Cokesa, Ž; Lakner, S.; Knackmuss, H. J.; Rieger, P. G. *Biodegradation* **2004***, 15*, 229-239.

(86) Metsärinne, S., personal communication, preliminary unpublished results.

(87) Metsärinne, S.; Ronkainen, E.; Tuhkanen, T.; Aksela, R.; Sillanpää, M. *Sci. Total Environ.* **2007***, 377*, 45-51.

(88) Metsärinne, S. *Degradation of novel and conventional complexing agents*, University of Kuopio, Department of environmental sciences, Kuopio, Finland, Kuopio, Finland, 2006.

(89) Pirkanniemi, K.; Metsärinne, S.; Sillanpää, M. *J. Hazard. Mater.* **2007***, 147*, 556-561.

(90) Metsärinne, S.; Peltonen, P.; Aksela, R.; Tuhkanen, T. *Chemosphere* **2004***, 56*, 1077-1084.

(91) Sjöberg, S.; Hägglund, Y.; Nordin, A.; Ingri, N. *Mar. Chem.* **1983***, 13*, 35-44.

(92) Martell, A. E.; Smith, R. M. *NIST Standard Reference Database 46. Critically Selected Stability Constants of Metal Complexes Database, version 7.0* **2003**.

(93) Rossotti, H. S. *Talanta* **1974***, 21*, 809-829.

(94) Rossotti, F. J. C.; Rossotti, H. *The determination of stability constants;* McGraw-Hill: New York, 1961, pp 425.

(95) Sillén, L. G.; Ekedahl, E. *Arkiv Kemi, Mineral. Geol.* **1946***, 22A*, no. 16. (1-12).

(96) Dyrssen, D. *Svensk Kem. Tidskr.* **1952***, 64*, 213-224.

(97) Ingri, N.; Lagerström, G.; Frydman, M.; Sillén, L. G. *Acta Chem. Scand.* **1957***, 11*, 1034-1058.

(98) Maslarska, V.; Tencheva, J.; Budevsky, O. *Anal. Bioanal. Chem.* **2003***, 375*, 217-222.

(99) Baes, C. F.; Mesmer, R. E. *The Hydrolysis of Cations;* Wiley: New York, 1976, pp 489.

(100) Gans, P.; Sabatini, A.; Vacca, A. *J. Chem. Soc. Dalton Trans.* **1985**, 1195-1200.

(101) Casassas, E.; Tauler, R.; Filella, M. *Anal. Chim. Acta* **1986***, 191*, 399-411.

(102) Lomozik, L.; Jaskólski, M.; Gasowska, A. *J. Chem. Educ.* **1995***, 72*, 27-30.

(103) Anderegg, G. *Critical survey of stability constants of EDTA complexes.* IUPAC chemical data series. No. 14; Pergamon Press: Oxford, UK, 1977, pp 42.

(104) Anderegg, G.; Arnaud-Neu, F.; Delgado, R.; Felcman, J.; Popov, K. *Pure Appl. Chem.* **2005***, 77*, 1445-1495.

(105) Anderegg, G. *Pure Appl. Chem.* **1982***, 54*, 2693-2758.

(106) Motekaitis, R. J.; Martell, A. E. *Inorg. Chem.* **1992***, 31*, 11-15.

(107) Motekaitis, R. M.; Martell, A. E. *Inorg. Chem.* **1989***, 28*, 3499-3503.

(108) Martell, A. E.; Smith, R. M. *NIST Standard Reference Database 46. Critically Selected Stability Constants of Metal Complexes Database, version 4.0* **1997**.

(109) Polhuis, M.; Katata, L. M.; Crouch, A. M. *Chem. Speciation Bioavailability* **2006***, 18*, 85-93.

(110) Ringbom, A. *J. Chem. Educ.* **1958***, 35*, 282-288.

(111) Malahaev, E. D.; Nikolskii, V. M.; Gorelov, I. P. *Zh. Obshch. Khim.* **1978***, 48*, 2601-2604.

(112) Rodriguez, C. E.; Devine, C. D. *Talanta* **1974***, 21*, 1313-1315.

(113) Knyazeva, N. E.; Nikolskii, V. M.; Alekseev, V. G.; Ryasenskii, S. S.; Gorelov, I. P. *Zh. Neorg. Khim.* **2002***, 47*, 262-265.

(114) Vasilev, V. P.; Katrovtseva, A. V.; Bychkova, S. A.; Tukumova, N. V. *Zh. Neorg. Khim.* **1998***, 43*, 808-809.

(115) Vasilev, V. P.; Katrovtseva, A. V.; Gorelov, I. P.; Tukumova, N. V. *Zh. Neorg. Khim.* **1996***, 41*, 1320-1323.

(116) Hyvönen, H., preliminary unpublished results.

(117) Aruga, R. *Inorg. Chem.* **1980***, 19*, 2895-2896.

(118) Hancock, R. D.; Shaikjee, M. S.; Dobson, S. M.; Boeyens, J. C. A. *Inorg. Chim. Acta* **1988***, 154*, 229-238.

(119) Hancock, R. D.; Reibenspies, J. H.; Maumela, H. *Inorg. Chem.* **2004***, 43*, 2981-2987.

(120) Shimoni-Livny, L.; Glusker, J. P.; Bock, C. W. *Inorg. Chem.* **1998***, 37*, 1853-1867.

(121) Bedell, S. A.; Timmons, J. H.; Martell, A. E.; Murace, I. *Inorg. Chem.* **1982***, 21*, 874-878.

(122) Barbucci, R.; Vacca, A. *J. Chem. Soc. Dalton Trans.* **1974**, 2363-2367.

(123) Tauler, R.; Casassas, E. *Inorg. Chim. Acta* **1986***, 114*, 203-209.

(124) Casassas, E.; Gustems, L. L.; Tauler, R. *J. Chem. Soc. Dalton Trans.* **1989**, 569-573.

(125) Aruga, R. *J. Inorg. Nucl. Chem.* **1978**, *40*, 1077-1080.

(126) Uchtman, V. A.; Oertel, R. P. *J. Am. Chem. Soc.* **1973**, *95*, 1802-1811.

(127) Motekaitis, R. J.; Martell, A. E. *J. Coord. Chem.* **1984**, *13*, 265-271.

(128) Kemper, H. C.; Martens, R. J.; Nooi, J. R.; Stubbs, C. E. *Tenside Deterg.* **1975**, *12*, 47-51.

(129) Bannochie, C. J.; Martell, A. E. *Inorg. Chem.* **1991**, *30*, 1385-1392.

(130) Nieuwenhuizen, M. S.; Kieboom, A. P. G.; van Bekkum, H. *Tenside Detergents* **1985**, *22*, 247-251.

(131) Mulla, F.; Marsicano, F.; Nakani, B. S.; Hancock, R. D. *Inorg. Chem.* **1985**, *24*, 3076-3080.

(132) Sillanpää, A. J.; Aksela, R.; Laasonen, K. *Phys. Chem. Chem. Phys.* **2003**, *5*, 3382-3393.

(133) Pavelčik, F.; Kettmann, V. *Collect. Czech. Chem. Commun.* **1983**, *48*, 1376-1389.

(134) Pavelčik, F.; Majer, J. *Acta Cryst.* **1978**, *B34*, 3582-3585.

(135) Pavelčik, F.; Kettmann, V.; Majer, J. *Collect. Czech. Chem. Commun.* **1979**, *44*, 1070-1079.

(136) Pavelčik, F.; Majer, J. *Z. Naturforsch.* **1977**, *32B*, 1089-1090.

(137) Soldánová, J.; Pavelčik, F.; Majer, J. *Acta Cryst.* **1981**, *B37*, 921-923.

(138) Neal, J. A.; Rose, N. J. *Inorg. Chem.* **1973**, *12*, 1226-1232.

(139) Radanovic, D. J.; Gailey, K. D.; Djuran, M. I.; Douglas, B. E. *J. Coord. Chem.* **1980**, *10*, 115-123.

(140) Radanovic, D. J.; Douglas, B. E. *J. Coord. Chem.* **1975**, *4*, 191-198.

(141) Gerdom, L. E.; Baenziger, N. A.; Goff, H. M. *Inorg. Chem.* **1981**, *20*, 1606-1609.

(142) McCandlish, E. F. K.; Michael, T. K.; Neal, J. A.; Lingafelter, E. C.; Rose, N. J. *Inorg. Chem.* **1978**, *17*, 1383-1394.

(143) Weakliem, H. A.; Hoard, J. L. *J. Am. Chem. Soc.* **1959**, *81*, 549-555.

(144) Okamoto, K.; Tsukihara, T.; Hidaka, J.; Shimura, Y. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 3534-3539.

(145) Stein, J.; Fackler, J. P.; McClune, G. J.; Fee, J. A.; Chan, L. T. *Inorg. Chem.* **1979**, *18*, 3511-3519.

(146) Stezowski, J. J.; Countryman, R.; Hoard, J. L. *Inorg. Chem.* **1973**, *12*, 1749-1754.

(147) Richards, S.; Pedersen, B.; Silverton, J. V.; Hoard, J. L. *Inorg. Chem.* **1964**, *3*, 27-33.

(148) Zetter, M. S.; Grant, M. W.; Wood, E. J.; Dodgen, H. W.; Hunt, J. P. *Inorg. Chem.* **1972**, *11*, 2701-2706.

(149) Matsubara, T.; Creutz, C. *Inorg. Chem.* **1979**, *18*, 1956-1966.

(150) Smith, G. S.; Hoard, J. L. *J. Am. Chem. Soc.* **1959**, *81*, 556-561.

(151) Hoard, J. L.; Kennard, C. H. L.; Smith, G. S. *Inorg. Chem.* **1963**, *2*, 1316-1317.

(152) Lind, M. D.; Lee, B.; Hoard, J. L. *J. Am. Chem. Soc.* **1965**, *87*, 1611-1612.

(153) Hoard, J. L.; Lee, B.; Lind, M. D. *J. Am. Chem. Soc.* **1965**, *87*, 1612-1613.

(154) Prelesnik, B. V.; Radanović, D. D.; Tomić, Z. D.; Djurdjević, P. T.; Radanović, D. J.; Veselinović, D. S. *Polyhedron* **1996**, *15*, 3761-3770.

(155) Kovaleva, I. B.; Mitrofanova, N. D.; Martynenko, L. I.; Kazin, P. E. *Zh. Neorg. Khim.* **1989**, *34*, 898-901.

(156) Poznyak, A. L.; Antsyshkina, A. S.; Sadikov, G. G.; Sergienko, V. S. *Zh. Neorg. Khim.* **1998**, *43*, 236-240.

(157) Polynova, T. N.; Chuklanova, E. B.; Porai-Koshits, M. A. *Dokl. Akad. Nauk SSSR* **1985**, *283*, 673-677.

(158) Kovaleva, I. B.; Mitrofanova, N. D.; Martynenko, L. I.; Spitsyn, V. I.; Felin, M. G. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1988**, *7*, 1468-1472.

(159) Sillanpää, M.; Kokkonen, R.; Sihvonen, M. *Anal. Chim. Acta* **1995**, *303*, 187-192.

(160) Katata, L.; Nagaraju, V.; Crouch, A. M. *Anal. Chim. Acta* **2006**, *579*, 177-184.

(161) Nagaraju, V.; Goje, T.; Crouch, A. M. *Anal. Sci.* **2007**, *23*, 493-496.

(162) Metsärinne, S.; Ronkainen, E.; Aksela, R.; Tuhkanen, T.; Sillanpää, M. *J. Chromatogr. A* **2005**, *1094*, 56-59.

(163) Yuan, Z.; d'Entremont, M.; Ni, Y.; van Heiningen, A. R. P. *Pulp Paper Canada* **1997**, *98*, T408-T413 (24-29).

(164) Aksela, R.; Parén, A.; Jäkärä, J.; Renvall, I. *Application of Ethylenediamine Disuccinic Acid and Iminodisuccinic acid as Biodegradable Chelating Agents in Pulp Bleaching;* 4th International Conference on Environmental Impacts of the Pulp and Paper Industry; Helsinki, Finland, 2000, pp 340-344.

(165) Jäkärä, J.; Parén, A.; Renvall, I.; Aksela, R. *Peracetic acid in low AOX and high brightness pulp production;* Japan Tappi Annual Meeting; Nagoya, Japan, 1997.

(166) Parén, A.; Aksela, R.; Jäkärä, J.; Renvall, I. *Study of the effect of new alternative complexing agents on peroxide and peracetic acid bleaching;* Sixth European Workshop on Lignocellulosics and Pulp; Bordeaux, France, 2000, pp 503-506.

(167) Aksela, R.; Parén, A.; Jäkärä, J.; Renvall, I. *The overall performance of new diethanolamine derivatives as complexing agents in peroxide and peracetic acid bleaching of TCF pulp;* 11th ISWPC International Symposium on Wood and Pulping Chemistry; Nice, France, 2001, pp 481-484, P127.

(168) Jäkärä, J.; Aksela, R. *PPI* **2006**, *48*, 28-31.

(169) Pesonen, H.; Sillanpää, A.; Aksela, R.; Laasonen, K. *Polymer* **2005**, *46*, 12653-12661.

(170) May, P. M.; Murray, K. *Talanta* **1991**, *38*, 1409-1417.

(171) May, P. M.; Murray, K. *Talanta* **1991**, *38*, 1419-1426.

(172) May, P. M.; Murray, K. *J. Chem. Eng. Data* **2001**, *46*, 1035-1040.

(173) Jones, P. W.; Williams, D. R. *Inorg. Chim. Acta* **2002**, *339*, 41-50.

(174) Räsänen, E.; van Heiningen, A. R. P.; Koukkari, P.; Pajarre, R.; Aksela, R. *Pap. Puu* **2004**, *86*, 279-282, 284-288.

(175) Sundquist, A.; Jäkärä, J.; Aksela, R.; Kaijaluoto, S.; Pajarre, R.; Penttilä, K. *Modelling the chemical effects of cumulating metal content in bleaching plants with closed water circulation.* Pulpaper; Helsinki, Finland, 2004.

(176) Ancillotti, F.; Boschi, G.; Perego, G.; Zazzetta, A. *J. Chem. Soc. Dalton Trans.* **1977**, 901-905.

(177) Parén, A., Kemira, personal communication, unpublished data.

(178) Ylivainio, K.; Jaakkola, A.; Aksela, R. *J. Plant. Nutr. Soil Sci.* **2004**, *167*, 602-608.

(179) Ylivainio, K.; Jaakkola, A.; Aksela, R. *J. Plant. Nutr. Soil Sci.* **2006**, *169*, 523-528.

(180) Aksela, R.; Peltonen, J.; Weckman, A. WO 2004110961, 2004.