Bioavailability of Organic Forms of the Microminerals

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Introduction

Diets for animals consisting of natural feed ingredients are frequently deficient in one or more mineral elements. These elements must be provided to the animal in a supplemental form either mixed with other dietary ingredients or, when necessary, as a separate mineral mixture. To accomplish this most effectively, it is important to know the bioavailability of mineral elements both in dietary ingredients and in dietary supplements. Considerably more information exists at present on the utilization of minerals used as supplements, than on those present in typical dietary ingredients. In recent years, organically-bound mineral compounds of various types have been introduced into the marketplace as sources of supplemental minerals for livestock. It is the purpose of this paper to present information on the utilization of supplemental micromineral elements by domestic animals with an emphasis on those studies in which comparisons have been made between inorganic and organic forms of a particular element. In addition, the concept of bioavailability will be discussed.

Definition of Organically-Bound Minerals

The Association of American Feed Control Officials (AAFCO, 1997) gives the following definitions for mineral products to be sold in the United States as organically-bound mineral compounds:

1) Metal Amino Acid Chelate (57.142) is the product resulting from the reaction of a soluble metal salt with amino acids with a mole ratio of one mole of metal to one to three (preferably two) moles of amino acids to form coordinate covalent bonds. The average weight of the hydrolyzed amino acids must be approximately 150 and the resulting molecular weight of the chelate must not exceed 800.

2) Metal Amino Acid Complex (57.150) is the product resulting from complexing of a soluble metal salt with an amino acid(s).

3) Metal (Specific amino acid) Complex (57.151) is the product resulting from complexing a soluble metal salt with a specific amino acid.

4) Metal Proteinate (57.23) is the product resulting from the chelation of a soluble salt with amino acids and/or partially hydrolyzed protein.

5) Metal Polysaccharide Complex (57.29) is the product resulting from complexing of a soluble salt with a polysaccharide solution declared as an ingredient as the specific metal complex.

Simple, easily used methodology for verification of the speciation and degree of binding strength of organic mineral compounds has not been available and this has hindered progress in research with these products. The authors' description of products tested has been used in this review.

Definition of Bioavailability

Terms relating to mineral utilization or the "bioavailability" of nutrients in general include

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"biological availability," "biopotency," "bioefficiency," and "bioefficacy." These terms are frequently used interchangeably but, on occasion, certain ones have been used to imply some unique function or unique pathway of absorption or utilization of the mineral element and suggested to be beyond the usual scope of "bioavailability." It seems, however, that most nutritionists accept the premise that several terms are being used to describe a single concept.

The term "bioavailability" has been defined as the degree to which an ingested nutrient (mineral in the present paper) is absorbed in a form that can be utilized in metabolism by the normal animal (Ammerman *et al.*, 1995). Thus, the mineral element is "available" at the tissue level as well as at the dietary level. Other investigators (Fox *et al.*, 1981; O'Dell, 1984) have stressed that utilization of the nutrient within normal metabolic processes of the animal must be demonstrated to establish bioavailability. With regard to certain minerals, actual measurement of utilization of the element is difficult and researchers have frequently relied on techniques which do not meet the strictest definition of bioavailability.

The absolute absorption of many of the orally administered essential mineral elements is small regardless of the form in which they are provided. This is particularly true for the micromineral elements. Relative bioavailability values are calculated for many of the mineral elements by relating their response to that of a standard source of the element with an assigned bioavailability value of "100." The resulting relative bioavailability values are useful in diet formulation and cost comparisons.

Bioavailability of Supplemental Micromineral Sources

Portions of the following material are taken from Ammerman *et al.* (1995). References for some of the earlier results including data summarized in the tables presented in this paper are found in that publication. An earlier review on the bioavailability of the micromineral elements was prepared by Ammerman and Miller (1972).

Cobalt

Elemental cobalt is of practical significance for the ruminant only and few critical studies have been made on the utilization of various sources. The sulfate ($CoSO_4 \cdot 7H_2O$), carbonate ($CoCO_3$), chloride ($CoCl_2$), and nitrate [$Co(NO_3)_2 \cdot 6H_2O$] forms have been indicated to be highly available (Ammerman and Miller, 1972). The oxide compounds (Co_3O_4 or CoO) in the form of heavy pellets which remain in the reticulorumen for several months, have been effective in supplying cobalt to sheep and cattle.

Based on research conducted at the University of Florida, Ammerman *et al.* (1982) suggested liver accumulation of cobalt as an indicator of its solubility in the rumen and, thus, its availability to ruminal microorganisms for vitamin B_{12} synthesis. This research along with that conducted in association with the Rowett Research Institute has been published in a series of papers (Henry *et al.* 1997; Kawashima *et al.*, 1997a, b). Cobaltous sulfate, cobaltous carbonate, and cobalt glucoheptonate were essentially equal in utilization when based on liver and kidney accumulation of cobalt in sheep fed dietary levels of 40 to 60 ppm cobalt for 16 to 20 days (table 1). The oxide forms were less well utilized. Serum and liver vitamin B_{12} concentrations increased with increasing dietary cobalt, but were not useful in separating the supplemental sources. Relative bioavailability values for cobalt sources based on production of vitamin B_{12} in ruminal effluent in a semicontinous *in vitro* culture system were similar to those

obtained with tissue cobalt accumulation.

Table 1. Relative bioavailability of supplemental cobalt for which comparative data are available[a]

Source	In vivo[b]	In vitro[c]
Cobaltous sulfate	100	100
Cobalt glucoheptonate	85 (1)	85 (1)
Cobaltic-cobaltous oxide (Co_3O_4)	10 (4)	0 (1)
Cobaltous carbonate	100 (4)	90 (1)
Cobaltous oxide (CoO)	50 (2)	-

[a]From Ammerman *et al.* (1995) with data added. Average values rounded to nearest "5" and expressed relative to response obtained with cobaltous sulfate. Number of studies or samples involved indicated within parentheses.

[b]Based on cobalt accumulation in liver and kidney of sheep fed high dietary intakes of the element.

[c]Based on production of vitamin B_{12} during semicontinuous ruminal culture.

Copper

Bioavailability values summarized in 1995 for several supplemental copper sources are presented in table 2. In early studies, cupric sulfate ($CuSO_4 \cdot 5H_2O$) was found to be well utilized as a source of copper for both rats and swine. Cupric sulfide (CuS) was less available than the sulfate form for both species. Although cupric oxide (CuO) continued to be used as a supplemental source of copper, there was evidence as early as the 1960's that it was of low bioavailability.

Baker *et al.* (1991) fed 0, 75, and 150 ppm copper to chicks for 2 wk and used liver copper accumulation to evaluate copper sources relative to cupric sulfate as the standard. Cuprous oxide (Cu_2O) and copper-lysine complex were equal to the standard as a source of the element, but cupric oxide provided no utilizable copper for chicks. In further research from the same laboratory (Aoyagi and Baker, 1993b), the bioavailability of copper in copper-methionine complex was estimated as 96 by a bile copper assay at low dietary intakes and 88 by a liver copper assay at elevated dietary intakes when compared relative to 100 for the copper in cupric sulfate. Copper bioavailability from copper-lysine was 114 relative to 100 for cupric sulfate when tested with the liver copper assay at elevated dietary intakes of the element.

In studies with swine, Apgar *et al.* (1995) fed weanling pigs 100, 150, or 200 ppm copper as either cupric sulfate or copper-lysine complex for 35 days. Average daily gain increased with supplemental copper, but did not differ between sources. Liver copper concentrations were similar for the two copper sources at 100 and 150 ppm supplemental copper. At 200 ppm added copper, liver copper was much greater for copper-lysine than for cupric sulfate suggesting greater absorption from the organic form. Further research from the

same laboratory (Apgar and Kornegay, 1996), however, found that absorption and retention of copper was similar for pigs fed growth-stimulating levels of the element from either cupric sulfate or copper-lysine complex.

Table 2. Relative bioavailability of selected supplemental copper sources[a]

Source	Poultry	Swine	Cattle	Sheep
Cupric sulfate	100	100	100	100
Copper EDTA	-	-	95 (2)	120 (1)
Copper-lysine	105 (2)	-	100 (1)	-
Copper-methionine	90 (2)	110 (1)	-	-
Copper-proteinate	-	-	-	130 (1)
Cupric acetate	100 (3)	-	-	-
Cupric basic carbonate	115 (1)	-	-	-
Cupric carbonate	65 (2)	85 (2)	-	-
Cupric chloride	110 (2)	-	115 (2)	115 (1)
Cupric chloride, tribasic	105 (2)	-	-	-
Cupric oxide[b]	0 (4)	30 (4)	15 (2)	-
Cuprous oxide	100 (1)	-	-	-

[a]From Ammerman *et al.* (1995). Average values rounded to nearest "5" and expressed relative to response obtained with cupric sulfate. Number of studies or samples involved indicated within parentheses.

[b]Cupric oxide needles which are retained for extended periods within the intestinal tract of ruminants have been shown to be an effective source of copper.

Supplemental copper is of special importance for the ruminant and especially so for the grazing animal. In a balance study with calves, DeBonis and Nockels (1992) observed that copper as copper-lysine was retained better than copper provided in the form of cupric sulfate. Ward *et al.* (1993), however, based their observations on feed intake, growth rate, feed efficiency, plasma copper, ceruloplasmin activity, and immune response as indicators of copper status and concluded that copper-lysine and copper sulfate were equal as sources of copper for steers. The study was 98 days in length and 0 on 5 ppm copper as either source was added to a corn silage-based diet. One-half of the animals was supplemented with 5 ppm molybdenum and 2 g/kg sulfur.

Luo *et al.* (1996) fed sheep 180 ppm supplemental copper either as cupric sulfate or as a copper-lysine complex once daily or every 4 hr for an equal daily intake during a 10-day period. Lambs fed once daily accumulated more copper in their livers than those fed every 4 hr with no copper by feeding regimen interaction. Based on slope ratios of final liver copper

concentration on total intake of copper with the initial biopsy copper concentration as a covariate, bioavailability of copper from copper-lysine relative to 100 for cupric sulfate was 93 for combined feeding regimens. Attaelmannan and Reid (1996) suggested that copper-lysine "chelate" fed to a ruminant will dissociate quickly in saliva and exist mainly as carbonate and phosphate compounds in the gastrointestinal tract.

In further studies with organic copper sources, supplemental dietary copper concentrations of 5 or 80 ppm as either copper-proteinate or cupric sulfate were fed to Holstein and Jersey cows and heifers for a period of 60 days (Du *et al.* 1996). Based on increased liver copper, bioavailability of the element in the two sources was similar. Ward *et al.* (1996b) conducted a study in which cupric sulfate, cupric carbonate, and copper-proteinate were compared as sources of copper for cattle when 0 or 5 ppm molybdenum were added to the diet. Based on plasma and liver copper concentrations, copper-proteinate and cupric sulfate were equal as sources of copper in the presence of low dietary molybdenum. The proteinate form appeared to have greater bioavailability than the sulfate in the presence of added molybdenum. Kincaid *et al.* (1986) had reported similar findings with cattle but a lack of uniformity in initial copper stores among animals may have confounded the results.

It has been proposed that organic forms of certain microminerals may be more effective than inorganic forms to enhance immune response of an animal. Engle *et al.* (1997) supplied 50% of the supplemental dietary copper and manganese and 66% of the zinc to growing calves which were challenged with an intranasal inoculation of infectious bovine rhinotracheitis virus. Replacing the inorganic microminerals with organic proteinate forms resulted in little effect on immunity or performance of the animals.

Iodine

Very little research has been conducted in recent years on the bioavailability of supplemental sources of iodine. Studies presented by Ammerman *et al.* (1995) indicated that most sources of supplemental iodine were well utilized by animals. These sources included potassium iodide (KI), potassium iodate (KIO_3), sodium iodide (NaI), calcium iodate [$Ca(IO_3)_2 \cdot H_2O$], ethylenediamine dihydriodide (EDDI; $C_2H_8N_2 \cdot 2HI$) and pentacalcium orthoperiodate [$Ca_5(IO_6)_2$]. The exception to this list of compounds was diiodosalicylic acid (DIS; $C_7H_4I_2O_3$) . Research revealed that DIS was absorbed intact and cleared rapidly from the body of cattle without iodine ever being released from the compound. Rats apparently have a considerably greater capacity to remove iodine from the DIS compound.

Iron

Relative bioavailability values for selected iron sources are shown in table 3. In general, the utilization of iron from organic sources including the citrate, fumarate, and gluconate forms was essentially equal to that of ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$). Ferric iron as ferric oxide was very poorly utilized. Considerable differences have been observed in bioavailability of iron in the form of ferrous carbonates, without any obvious explanation.

Apparently, few studies have been conducted with protein- or amino acid-bound organic forms of iron. In a study with swine, Spears *et al.* (1992) compared iron-methionine

with ferrous sulfate as a source of supplemental iron for the nursing pig. The authors concluded that, based on hemoglobin concentrations, the relative bioavailability of iron as iron-methionine was 180% when compared to that from ferrous sulfate. Lewis *et al.* (1995), however, reported relative bioavailability values of 81% and 68% for the iron in iron-methionine based on weight gain and hemoglobin, respectively, when compared with responses from ferrous sulfate for the weanling pig. In another study, Cao *et al.* (1996) fed either iron-methionine complex or reagent grade ferrous sulfate heptahydrate at supplemental dietary levels of 400 to 800 ppm iron to 6-day-old chicks for a period of 14 days. Slope ratio comparisons of liver iron concentrations yielded relative bioavailability estimates for the iron-methionine of 88% when based on dietary iron concentration and 83% when based on total iron intake.

Table 3. Relative bioavailability of selected supplemental iron sources[a]

Source	Poultry	Swine	Cattle	Sheep	Rats
Ferrous sulfate heptahydrate	100	100	100	100	100
Ferric citrate	75 (1)	150 (4)	110 (1)	-	100 (3)
Ferric oxide	10 (2)	10 (1)	-	5 (1)	5 (1)
Ferric sulfate	85 (2)	-	-	-	100 (1)
Ferrous carbonate-low[b]	5 (11)	15 (2)	10 (2)	-	5 (7)
Ferrous carbonate-high[b]	90 (1)	95 (3)	-	85 (1)	-
Ferrous chloride	100 (2)	-	-	-	-
Ferrous fumarate	100 (2)	-	-	-	-
Ferrous gluconate	100 (2)	-	-	-	-
Ferrous sulfate, anhydrous	100 (1)	-	-	-	-
Ferrous sulfate monohydrate	100 (3)	85 (1)	-	-	-
Iron-methionine	-	185 (1)	-	-	-
Iron-proteinate	-	125 (1)	-	-	-
Iron, reduced	50 (24)	45 (2)	-	-	40 (30)

[a]From Ammerman *et al.* (1995). Average values rounded to nearest "5" and expressed relative to response obtained with ferrous sulfate heptahydrate. Number of studies or samples involved indicated within parentheses.

[b]Most ferrous carbonates have been reported to be low in iron bioavailability, however, several were found to be of high availability and they are listed separately.

Manganese

Bioavailability research with manganese has been limited. A summary of relative values published in 1995 is shown in table 4. Manganese sulfate has been used as the standard in most studies and sources including the monoxide, carbonate, and dioxide forms, listed in declining order of bioavailability, have been tested. Studies with manganese-

methionine and manganese proteinate have yielded values above those obtained with the sulfate form.

In research not summarized in the table, Smith *et al.* (1995) conducted studies to evaluate relative bioavailability of manganese in the sulfate, monoxide, and proteinate forms in broilers reared at two environmental temperatures. Day-old chicks were fed 0, 1000, 2000, or 3000 ppm manganese from each source for 21 days. From day 22 to 47, birds from each treatment were continued under thermoneutral (temperature cycled between 18 and 23.9 C) or heat distress (temperature cycled between 23.9 and 35 C) conditions. Based on bone manganese regressed on manganese intake, bioavailabilities were 100, 91, and 120 for sulfate, monoxide, and proteinate forms at 21 days, respectively. These values were 100, 83, and 125, for 7-wk-old birds under thermoneutral conditions and 100, 82, and 145, respectively, for those under heat distress. Heat distress appeared to magnify the difference in bioavailability between manganese sulfate and manganese-proteinate.

Lambs were fed natural diets supplemented with 900, 1800, or 2700 ppm manganese from various sources for 21 days (Henry *et al.*, 1992). The overall estimated bioavailabilities based on bone, kidney, and liver manganese deposition were 100, 121, 70, and 53 for manganese sulfate, manganese-methionine complex, and the two feed grade manganese monoxides, respectively.

Table 4. Relative bioavailability of supplemental manganese sources[a]

Source	Poultry	Sheep
Manganese sulfate	100	100
Manganese carbonate, ppt.	55 (2)	30 (1)
Manganese dioxide	30 (3)	35 (1)
Manganese-methionine	120 (1)	125 (2)
Manganese monoxide	75 (8)	60 (3)
Manganese-proteinate	110 (2)	-
Manganous chloride	100 (1)	-

[a]From Ammerman *et al.* (1995). Average values rounded to nearest "5" and expressed relative to response obtained with manganese sulfate. Number of studies or samples involved indicated within parentheses.

Selenium

Sodium selenite (Na_2SeO_3) is well utilized by animals and has generally been used as the standard to which other selenium sources have been compared. The relative bioavailability values obtained for several supplemental selenium sources are presented in table 5. Earlier research reviewed by Ammerman *et al.* (1995) indicated that plant sources of selenium ranged in relative bioavailability from about 60 to 90% compared with sodium selenite. Average bioavailability for selenium in animal products in similar comparisons was

25% or less. Organic forms of selenium including selenocystine, selenomethionine, and a selenoyeast product were about equal to sodium selenite when compared on the basis of glutathione peroxidase (GSH-Px) activity or incidence of exudative diathesis. When tissue deposition or body retention was used as the response, inflated relative bioavailability values were obtained, no doubt due to the metabolism and deposition of the selenium as an integral part of the amino acid.

In recent research, Mahan and Parrett (1996) conducted a series of three experiments with grower and finisher swine in which supplemental selenium at concentrations of .1, .3, and .5 ppm was added to control diets containing .038 to .058 ppm of the element. Sodium selenite and selenium-enriched yeast (minimum content of 1000 ppm selenium) were used to provide supplemental selenium. Feed intake, body weight gain, and gain: feed ratio were not influenced in these studies. In general, pigs fed sodium selenite had serum selenium concentration and serum GSH-Px activity that reached a plateau at .1 ppm supplemental selenium and at .3 ppm when selenium-enriched yeast was fed. Selenium concentrations in loin, liver, and pancreas were greater when selenoyeast was fed and lower in kidney tissue than when the selenite form was fed. These observations are in keeping with those that selenium excretion via both feces and urine was less for selenoyeast, resulting in greater retention of selenium from this supplemental form. The responses observed with serum selenium concentration and GSH-Px activity led the authors to state that sodium selenite may be more biologically available for GSH-Px activity than selenium-enriched yeast. Because a control diet was fed in these studies, the reviewers could apply a three-point analysis to the serum data reported in the paper for dietary supplemental levels of 0 and .1 ppm. When based on serum GSH-Px activity and serum selenium concentration, estimated relative bioavailability values were 79 and 68%, respectively, for the selenium-enriched yeast compared with sodium selenite as the standard. These values are lower than those estimated for selenomethionine and unenriched selenoyeast products tested in other studies (table 5). Pehrson *et al.* (1989), for example, found with heifers in a 12 wk study that selenomethionine and selenoyeast were approximately twice as available as inorganic selenium based on red blood cell GSH-Px.

Table 5. Relative bioavailability of selected supplemental selenium sources[a]

Source	Poultry	Swine	Cattle	Sheep	Rats
Sodium selenite	100	100	100	100	100
Selenium, elemental	5 (1)[b]	-	-	0 (2)	0 (1)
Selenocystine	110 (9)	-	-	-	95 (6)
Selenomethionine[c]	80 (12)	120 (2)	-	-	105 (12)
Selenomethionine[d]	115 (17)	150 (1)	245 (1)	-	202 (2)
Selenoyeast	-	-	290 (1)	100 (1)	135 (3)

[a]From Ammerman *et al.* (1995). Average values rounded to nearest "5" and expressed relative to response obtained with sodium selenite. Number of studies or samples involved indicated within parentheses.

[b]One study with liver or kidney selenium accumulation from surfeit dietary levels reported relative values of 95 and 50, respectively, for the two tissues.

[c]From studies in which GSH-Px activity or incidence of exudative diathesis was the response variable.

[d]From studies in which whole body or tissue selenium retention or incidence of pancreatic fibrosis was the response variable.

Mahan and Kim (1996) conducted further studies in which two sources of selenium, sodium selenite or the selenium-enriched yeast were added at .1 and .3 ppm selenium to diets of first-parity gilts and their progeny. GSH-Px activity for the weanling pig was similar regardless of dietary selenium concentration or source but serum selenium concentrations were greater in pigs nursing dams fed selenoyeast. Milk selenium concentrations were greater in those sows receiving selenoyeast compared with inorganic selenium and concentrations of the element were generally greater in loins and livers of pigs from the same sows.

In balance studies with sheep in which selenium stable isotopes (enriched [^{77}Se]-yeast; enriched [^{82}Se]-selenite) were administered simultaneously into the rumen, Koenig *et al.* (1997) found that [^{82}Se]-selenite was more available for absorption and retention than [^{77}Se]-yeast. The authors interpreted this to mean that inorganic chemical forms of selenium are as available to the ruminant as are the organic forms of the element commonly found in feedstuffs.

Zinc

Relative bioavailability values for selected supplemental zinc sources are shown in table 6. Zinc acetate [$Zn(C_2H_3O_2)_2$], chloride ($ZnCl_2$), and sulfate ($ZnSO_4 \cdot 7H_2O$) have been used as standards in bioavailability research, and all three forms of the element are well utilized by animals. Other forms of zinc except for perhaps zinc carbonate ($ZnCO_3$) and zinc oxide (ZnO) appear to be equal in bioavailability to the sources used as standards.

The earliest experiments with organic zinc sources go back almost forty years. Pensack *et al.* (1958) compared a zinc-proteinate with inorganic zinc carbonate, oxide, and chloride to maximize growth of chicks fed zinc-deficient diets. The deficiency was corrected with 20 or 40 ppm zinc from any of the sources tested. There was no difference in bone zinc concentration of chicks fed zinc-deficient semipurified diets supplemented with from 8 to 58 ppm zinc as reagent-grade zinc oxide or feed grade zinc-methionine complex for 5 wk (Pimentel *et al.*, 1991). Liver zinc also was not influenced by zinc source, but pancreas zinc concentration was greater in chicks given zinc-methionine.

The work of Wedekind *et al.* (1992) with chicks demonstrated an effect of diet on relative bioavailability of zinc. Absolute bioavailability of a source is affected by many dietary and animal factors, but to have the broadest applicability, relative bioavailability estimates should not be influenced in a similar manner. However, bioavailability of zinc-methionine complex compared to feed grade zinc sulfate set at 100 was calculated at 117 in a zinc-deficient crystalline amino acid diet, 177 in a zinc-deficient soy isolate semipurified diet, and

206 in a corn-soybean meal diet, when bone zinc was the dependent variable. Aoyagi and Baker (1993a) added graded levels up to 8 ppm zinc from either feed grade zinc sulfate or zinc-lysine to a semipurified basal diet containing 13 ppm zinc. These authors reported that relative bioavailability of zinc-lysine complex was 111% based on bone zinc accumulation for the chick. The bioavailability of zinc as either zinc-methionine complex or zinc sulfate as affected by dietary calcium concentration was studied by Wedekind *et al.* (1994). Chick diets were supplemented with 0, 5, or 10 ppm zinc in the presence of .60 or .74% calcium. Based on slope ratio comparisons of tibia zinc concentration, bioavailability of zinc-methionine was 166 relative to 100 for zinc sulfate when the dietary calcium concentration was .60% and 292 when the dietary calcium concentration was .74%.

Cao *et al.* (1997) fed 0, 200, 400, or 600 ppm added zinc to chicks as reagent grade zinc sulfate, zinc-amino acid chelate, or zinc-proteinate. Based on mucosal zinc concentration at 3 wk, relative bioavailability of sulfate, zinc-amino acid chelate and zinc-proteinate was 100, 76, and 133, respectively.

In one of the earliest experiments with organic sources for swine, Swinkels *et al.* (1991) reported no difference in bioavailability of reagent grade zinc sulfate or zinc-amino acid chelate for zinc-depleted pigs. Supplementation with either source at 45 ppm in a semipurified diet (20 ppm zinc) resulted in similar growth and liver and kidney zinc concentrations. An overall mean ratio of 98% for zinc chelate was calculated from the above three criteria. Kornegay *et al.* (1993) reported further work from the above experiments in which chromic oxide was used as a marker to determine apparent absorption of zinc from the two sources. In general, on this semipurified diet, apparent zinc absorption was lower from zinc sulfate, however, data were not consistent between their two experiments.

Wedekind *et al.* (1993) fed pigs a corn-soybean meal diet (approximately 40 ppm zinc) with 0, 7.5, or 15 ppm added zinc as feed grade zinc sulfate, zinc-methionine, zinc-lysine or zinc oxide. Multiple regression slope ratios of bone zinc on supplemental zinc intake estimated bioavailability values of 100, 84, 24, and 70, respectively. Zinc-lysine complex was compared to feed grade zinc sulfate in an experiment in which pharmacological concentrations (1500 to 3000 ppm) were fed in practical diets to swine (Hahn and Baker, 1993). Based on plasma zinc concentration, a slope ratio comparison valued zinc-lysine at 110% of sulfate. In another experiment, the same authors compared addition of 3000 ppm zinc as feed grade zinc sulfate or zinc-methionine complex. Bioavailability estimate for zinc-methionine compared to the sulfate was 116% based on plasma zinc concentrations.

Supplementation of a corn-soy diet containing 80 ppm zinc as sulfate with an additional 80 ppm from zinc-lysine or zinc-methionine complexes did not improve performance or enhance immune function of weanling pigs (van Heugten *et al.*, 1995). Cheng and Kornegay (1995) reported no difference in performance, immune response or bone, kidney, and liver zinc concentrations in weanling pigs supplemented with 100 ppm zinc as either zinc sulfate or zinc-lysine complex. In a similar experiment, addition of 100 ppm zinc as zinc sulfate or zinc-lysine to a diet for weanling pigs resulted in no difference in serum, liver, kidney, or rib zinc concentrations between zinc sources (Cheng *et al.*, 1995).

Matsui *et al.* (1996) partitioned a zinc-amino acid chelate on a Sephadex column and reported that the compound remained chelated at a pH of 4.0, but completely dissociated at a pH of 2.0. In a study with swine supplemented with 100 ppm zinc as the above zinc-amino

acid chelate or zinc sulfate, the same authors reported greater concentration of zinc in femurs of weanling pigs fed 30 d with the organic form of zinc. A three point calculation gave a relative value of 286% for the organic form. A simple mean ratio calculation valued the organic form at 111% of the inorganic compound (Matsui *et al.*, 1996).

Schell and Kornegay (1996) reported zinc bioavailability estimated from mean ratio calculations of bone zinc concentrations of pigs fed plethoric (2000-3000 ppm) doses of zinc as zinc oxide, zinc-methionine, zinc-lysine, and zinc sulfate of 83, 93, 92, and 100, respectively. Ward *et al.* (1996a) reported similar performance in weaned pigs supplemented with plethoric amounts of zinc-methionine complex (150 to 750 ppm zinc) or zinc oxide (2000 ppm zinc). Results were variable, but some performance measurements were improved by the high zinc supplementation compared to controls given 160 ppm zinc in the inorganic sulfate form.

In pigs given 100 ppm added zinc as either zinc sulfate or zinc-lysine in conjunction with chromic oxide as a marker, apparent absorption coefficients were greater in the stomach for pigs given the inorganic form (32%) than the organic (24%), but absorption in the intestine and lower colon was similar for the organic complex (27% and 28%) and zinc sulfate (30% and 35%), respectively (Kornegay *et al.*, 1996).

Pigs were fed various combinations of two forms of organic zinc (250 ppm added) and copper during phase 1 (up to 13 days post weaning) and phase 2 (13 to 33 days postweaning) by Hoover *et al.* (1997). Zinc-methionine complex increased gain in phase 1, but did not affect gain or feed intake in stage 2 or the overall experiment. This organic source did, however, increase gain/feed for the overall experiment. The zinc-amino acid complex increased feed intake and gain during both production phases, but did not affect gain/feed compared with the control given only zinc sulfate.

Table 6. Relative bioavailability of selected supplemental zinc sources[a]

Source	Poultry	Swine	Cattle	Sheep	Rats
Zinc acetate	-	-	-	-	100
Zinc chloride	100	100	-	-	-
Zinc sulfate	100	-	100	100	100
Zinc carbonate	105 (5)	-	60 (1)	-	-
Zinc, chelated				110 (2)	-
Zinc citrate	-	-	-	-	100 (7)
Zinc, elemental	100 (1)	130 (1)	-	-	-
Zinc-lysine	-	100 (1)	-	-	-
Zinc-methionine	125 (3)	100 (2)	-	100 (2)	-
Zinc oxide[b]	100 (5)	-	100 (4)	70 (1)	-

Zinc oxide[b]	55 (2)	50 (1)	-	-	-
Zinc picolinate	-	-	-	-	105 (9)
Zinc-proteinate	100 (1)	-	-	-	-
Zinc, sequestered	-	-	-	105 (2)	-

[a]From Ammerman et *al.* (1995). Average values rounded to nearest "5" and expressed relative to response with sulfate, chloride, or acetate forms of zinc. Number of studies or samples involved indicated within parentheses. Terminology for sources is that of the author(s).

[b]Some recent studies have indicated zinc oxide to be less bioavailable than that observed in earlier research.

An early research report (Johnson *et al.*, 1988) indicated no significant improvement in performance of new stocker cattle supplemented with zinc-methionine complex compared with an untreated control. If animals arriving sick were removed from the analysis, zinc supplemented animals had faster gains and required fewer medical treatments.

Zinc-methionine was compared to zinc oxide for finishing steers (Greene *et al.*, 1988). When zinc sources were added to the basal diet (81 ppm zinc) at 360 mg zinc/day there was no difference in live performance. Quality grade, marbling score, and kidney, heart and pelvic fat were greater in steers given zinc-methionine than those given zinc oxide or the control diet. Zinc oxide and two zinc-proteinate sources were supplemented to diets for feedlot steers at 25 ppm added zinc (Spears and Kegley, 1994). Performance and carcass characteristics were improved by supplementation with zinc either in the organic or inorganic form. Spears (1989) reported no difference in performance of growing crossbred heifers supplemented with 25 ppm zinc as either zinc-methionine or zinc oxide.

Chirase *et al.* (1991) studied the effect of supplementation with zinc-methionine complex (60 ppm zinc) on feed intake and rectal temperature of feedlot steers challenged with infectious bovine rhinotracheitis. By day 5 after the challenge, feed intake of steers fed the control diet dropped to 50% of initial intake, whereas those fed zinc-methionine only decreased to 40%. Steers feed zinc-methionine recovered to about 90% of initial intake by day 6, while those fed the control diet didn't recover until 12 days. In a second experiment, the dry matter intake dropped even lower for steers fed both sources, but again, those given zinc-methionine recovered appetite more rapidly.

Nockels *et al.* (1993) reported no difference in absorption or retention of zinc in stressed calves given zinc sulfate or zinc-methionine. Incidence of footrot during a 3 yr study decreased from 5.4 to 2.5% in grazing steers supplemented with additional zinc-methionine (2.5%) in a free-choice mineral mixture already containing zinc in an inorganic form (Brazle, 1994). Reiling *et al.* (1992) reported a trend toward stronger hooves in heifers supplemented with 180 mg/head/day zinc as zinc-proteinate compared to zinc sulfate.

Rojas *et al.* (1996) reported no difference in tissue zinc concentrations of beef heifers supplemented with 360 mg/head/day zinc as zinc-methionine complex, zinc oxide, or zinc sulfate compared with controls. Kincaid *et al.* (1997) recently reported an increase in liver zinc concentrations of Holstein heifer calves given 300 ppm zinc as a combination of zinc-

methionine and zinc-lysine compared to heifers given a similar amount of zinc oxide or those fed a control diet (60 ppm). There was no effect of treatment on mitogen-induced lymphocyte blastogenesis, interleukin-2 production, lymphocyte cytotoxicity, or phagocytic and intracellular killing ability of blood neutrophils.

Kerley and Ledoux (1992) reported similar absorption of zinc in sheep given 60 ppm zinc as either zinc oxide or a chelated zinc-proteinate, however, more zinc was retained by sheep given the organic form. Similar results were reported by Spears (1989) in an experiment in which lambs were supplemented with 5 ppm zinc as zinc-methionine complex or zinc oxide. It is not clear whether the organic zinc were absorbed and transported to the bloodstream for redistribution and subsequent use or if it were sequestered by metallothionein in the intestinal tissue where it could be later lost in the sloughing of intestinal cells.

Summary

The micromineral elements represent an essential group of nutrients for all animals and must be provided in appropriate dietary amounts and in biologically available forms to assure normal health and optimal animal performance. The bioavailability of the mineral elements in supplemental sources must be known to make effective use of various products in diet formulation. In general, the soluble forms of the microminerals including the sulfates and chlorides are well utilized by animals. The carbonate and oxide forms tend to be less well utilized, but this varies with element. Sodium selenite and sodium selenate, the only forms of selenium approved for supplemental use in the United States, are both well utilized. Biologically available forms of iodine include sodium or potassium iodide, calcium iodate, pentacalcium orthoperiodate, and ethylenediamine dihydriodide. The organic complexes which have been developed for several of the micromineral elements have been demonstrated to be equal to or somewhat greater in bioavailability than the same element in the sulfate or chloride form. In certain studies, there has also been the suggestion that there may be less interference from other dietary components on the absorption of micromineral elements when they are provided to the animal in organic form.

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