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BIOLOGICAL AVAILABILITY OF NUTRIENTS IN FEEDS: AVAILABILITY OF MAJOR MINERAL IONS [1]

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IN the study of mineral metabolism, it is generally recognized that the total content of a mineral element in a particular compound or in a complete ration has little significance unless it is qualified by a factor indicating the biological availability of the element to animals. In other words, chemical analysis shows how much of a given mineral nutrient is present, but it does not indicate to what degree, if any, the nutrient is utilized when it is consumed by animals. No element is ever completely absorbed and utilized; some of it is always lost in the normal digestive and metabolic processes. Before a required nutrient can be of nutritional value, it must be in a form that can be digested, absorbed, and transported to the part of the body where it is utilized for its essential function.

In the literature there appears to be some confusion as to what constitutes "utilization" and "availability" of the major ions and how they should be expressed and applied in nutrition. As a result of biological availability studies of the major mineral ions over the years, a number of terms have been developed to define certain specific observations. These include percent utilization, percent apparent digestibility, percent true digestibility, percent absorption, percent net retention, percent apparent availability, percent true availability, biological availabilty, and others. It should be pointed out that obviously these terms do not necessarily mean the same thing and should not be used interchangeably. They should be considered only in the context suggested by the researcher.

In this particular presentation, the term *biological availability* will be used as a measure of the ability of the element or ion under consideration to support some physiological process. And, in this regard, where it has been possible to do so, biological availability data are reported in relative numerical terms in comparison with a previously selected reference standard. In most research, where nutritional requirements for the major metal ions have been studied experimentally, relatively pure chemical salts, recognized for their nutritional value have been used, and subsequently these salts have become useful to others as reference standards.

Because of the large volume of research reported in the literature, information presented here will be confined primarily to the inorganic sources of mineral ions most commonly encountered in practical feed formulation, and except in certain cases the contribution of these elements from natural sources will be disregarded.

Phosphorus

There is a tremendous volume of literature on phosphorus nutrition and a large part of it pertains to the availability of phosphorus from various sources to animals. Much of this literature on availability deals with factors that influence the utilization of phosphorus in various ways. Another major portion relates to experimental techniques that have been developed to define more accurately the comparative or relative biological availability of phosphorus from various sources. Some of the factors that influence the utilization of phosphorus for the various species of animals are the type of ration fed, chemical form of the element, the calcium-phosphorus ratio, age of animal, sex, fat and energy levels, plane of nutrition, environment, hormones, disease and parasites, protein and trace element levels, interactions with other minerals and nutrients, chelating agents, the physical nature of phosphorus sources and other feedstuffs in the diet (especially particle size), feed processing and numerous others. Many of these factors have been investigated in detail and some of them have been found to influence the availability of phosphorus of one source to a greater degree than another, but in general the relative order of effectiveness of the various sources remains approximately the same under similar sets of circumstances.

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The information on phosphorus availability is presented separately for each of the major animal species of agricultural importance.

Sheep. For sheep, the value of phosphorus of plant origin has been questioned for many years. Shortly after radioactive phosphorus became available for nutritional studies, Lofgreen and Kleiber (1954), using an isotope technique, found that 94% of the phosphorus in an alfalfa hay was utilized by sheep, indicating quite high biological availability from this source. It is realized now that this finding should have been expected, inasmuch as the leaves from good quality alfalfa contain little, if any, phytate phosphorus (Pons, Stansbury and Hoffpauir, 1953). Phytate phosphorus, as it occurs in plants, generally is regarded as being substantially less biologically available than most inorganic phosphorus.

In investigations with inorganic phosphate sources, Ammerman and associates (1957) found differences in biological availability using a balance technique. From their experiments it was concluded that the relative rank of the phosphate sources for their biological availability was dicalcium phosphate, Curacao Island phosphate, soft phosphate, and a defluorinated phosphate. Endogenous phosphorus excretion, however, was not completely accounted for in this work. In later studies, Lofgreen (1960) utilized a radioisotope dilution technique in which endogenous phosphate interference was eliminated in order to determine the true digestibility of several inorganic phosphate supplements and calcium phytate. The availability data from these studies are presented in table 1. By assigning dicalcium phosphate the value of 100, the biological availabilities of other phosphate sources on a relative basis were bone meal, 92%; soft phosphate, 28% and calcium phytate, 66%. As will be seen from other experiments reviewed later in this report, the values determined on the inorganic phosphate using ruminant animals are in quite close agreement with values determined using monogastric animals.

TABLE 1. PHOSPHORUS ABSORPTION BY WETHERS [a]

Supplement	Phosphorus intake from supplement	Phosphorus absorbed from supplement	True digestibility	Biological value
	g/day	g/day	%	%
Dicalcium phosphate	3.43	1.71	50	100
Bone meal	3.86	1.76	46	92
Soft phosphate	3.76	0.52	14	28
Calcium phytate	3.91	1.29	33	66

[a] Lofgreen (1960).

TABLE 2. UTILIZATION OF INORGANIC PHOSPHATES BY SHEEP [a]

Phosphate salt	Relative availability: *In vivo* absorption	Relative availability: *In vitro* cellulose digestion
	%	%
Calcium Ortho— $Ca(H_2PO_4)_2 \cdot H_2O$	100	100
Calcium Meta— $Ca(PO_3)_2$	70	78
Calcium Pyro— $Ca_2P_2O_7$	54	0
Sodium Ortho— $NaH_2PO_4 \cdot H_2O$	—	107
Sodium Meta— $NaPO_3$	97	98
Sodium Pyro— $Na_2H_2P_2O_7$	82	100

[a] Chicco *et al.* (1965).

In a more recent study, Chicco *et al.* (1965) determined the relative biological availability of three different crystalline forms of calcium and sodium phosphates, utilizing both *in vivo* and *in vitro* techniques. The biological availability values from these studies are shown in table 2. On a relative basis, calcium metaphosphate was only 70% as available as the normal calcium orthophosphate salt, and the calcium pyrophosphate was very poorly available, having a 54% value in the *in vivo* trial.

The *in vitro* cellulose digestion data follow the same order of availability as found in the *in vivo* trial, but with values of somewhat different magnitude. The sodium forms of the salts were utilized well in both the *in vivo* and *in vitro* trials. The findings of these experiments are particularly significant in that they indicate the detrimental impact that improper manufacturing processes and higher termperatures can have on the biological availability of calcium phosphates.

Beef Cattle. As with other ruminants, the supplements commonly evaluated in phosphorus availability studies with beef cattle have been reagent and feed grade dicalcium phosphates, bone meal, phosphoric acid, defluorinated phosphates and soft phosphate. In most studies with this species, dicalcium phosphate has been found significantly more available than soft phosphate. Relative availabilities between other inorganic phosphates, however, are less definite and in some experiments, statistically significant differences between many of the commonly used feed

TABLE 3. BIOLOGICAL AVAILABILITY OF VARIOUS PHOSPHATE SOURCES FOR BEEF CATTLE

Source	Long[a]	Arrington[b]	Ammerman[c]	O'Donovan[d]
	%	%	%	%
Dicalcium phosphate	100	100	100	100
Defluorinated phosphate	...	71	95	93
Soft phosphate	17	68	88	...

[a] Growth response, Long *et al.* (1956).
[b] Net retention-isotope technique, Arrington *et al.* (1963).
[c] True absorption-depletion-repletion, Ammerman *et al.* (1965).
[d] True digestibility-balance trial, O'Donovan *et al.* (1965).

phosphates were not found. However, as shown in table 3, researchers from several stations, (O'Donovan *et al.,* 1965; Arrington *et al.,* 1963; Ammerman *et al.,* 1965; Long *et al.,* 1956) utilizing different assay techniques report the order of biological availability rank for mineral supplements fed to beef cattle to be dicalcium phosphate, followed by defluorinated phosphate and bone meal, with soft phosphate having the least availability. Phosphoric acid has been reported to be essentially equal in availability to bone meal (Richardson *et al.,* 1961) and to dicalcium phosphate (Tillman and Brethour, 1958). In a recent study, Johnson and McClure (1967) found ammonium polyphosphate solutions to be essentially equal to dicalcium phosphate in steer feeding trials.

Numerous studies have been conducted using microbiological techniques based on the concept that phosphate depleted rumen bacteria will rapidly digest cellulose only when supplied with adequate amounts of available phosphorus. There seems to be reasonable agreement between the microbiological *in vitro* results and *in vivo* animal experimentation results in studies to determine the biological availability of phosphate compounds, although there are exceptions, especially when evaluating relatively insoluble compounds (Anderson, Cheng and Burroughs, 1956; Ammerman *et al.,* 1965; Hall, Gaddy and Hobbs, 1959; Satchidanandam, 1961; Barth and Hansard, 1962; Hall *et al.,* 1961a, b; Raun, Cheng and Burroughs, 1956; Chicco *et al.,* 1964). Even though good information on phosphate availability is found from microbiological techniques, caution should be used in extrapolating artificial rumen results directly to the animal.

Dairy Cattle. A large volume of research has been reported on the need for and the utilization of phosphorus in dairy animals, but very little work has been reported on the comparative biological value of the various sources. Utilizing a ration in which approximately 53% of the phosphorus was from phytate, Mathur (1951), on the basis of phytate content of feces of mature cows, found the biological value of phosphorus from this source to be on the order of 50%.

Using dairy calves, Wise, Wentworth and Smith (1961) evaluated inorganic phosphate sources for their comparative value. Criteria studied in these experiments were body growth, bone growth, bone ash, blood serum phosphorus, and blood phosphatase levels. Of all the criteria evaluated in these studies, blood serum phosphorus was the most sensitive and most reliable biological availability measure. Although the data do not readily lend themselves to a relative biological availability calculation, the relative order of response in the two experiments was dicalcium phosphate, defluorinated phosphate, low fluorine rock phosphate and soft phosphate. These data are shown in table 4.

In later studies using improvement in plasma phosphorus levels as a measurement of biological availability, Arrington *et al.* (1962) essentially confirmed the findings of Wise and associates (1961).

Swine. About one-half or more of the phosphorus in cereal grains and proteins of vegetable source may occur as phytate salts or phytic acid, and on the basis of reports dating back to the work of Forbes in 1914, it has been established that the pig can utilize some, but variable amounts, of this phosphorus in metabolism. From several studies (Bayley and Thompson, 1969; Woodman and Evans, 1948; Besecker *et al.,* 1967; Noland, Funderburg and Johnson, 1968) summarized in table 5 involving several techniques, the availability of phosphorus from this source has been found

TABLE 4. EFFECT OF PHOSPHATE SOURCE ON TERMINAL SERUM PHOSPHORUS LEVELS[a]

Supplement	Terminal serum P	
	Exp. I	Exp. II
	mg %	mg %
Basal	2.83	4.69
Dicalcium phosphate	5.26	6.87
Defluorinated phosphate	4.13	6.44
Low F rock phosphate	4.12	6.18
Soft phosphate	3.07	5.87

[a] Wise *et al.* (1961).

TABLE 5. BIOLOGICAL VALUE OF PHYTATE PHOSPHORUS FOR SWINE

Researcher	Pig weight	Biological availability
	lb.	%
Bayley and Thompson (1969)	60	20 to 30
Woodman and Evans (1948)	50–90	30 to 40
Besecker *et al.* (1967)	50	18 to 24
Noland *et al.* (1968)	Growing	30 to 60
Average		25 to 40

to range from 20 to 60%, with an average value of 33% for pigs 50 to 90 lb. in weight. There is some indication that the ability of the pig to utilize phytate phosphorus improves with age.

A large number of studies has been conducted to determine the relative biological value of the various inorganic phosphate sources for pigs of different ages. The data from most of these experiments are difficult to compare since in most instances single levels of the phosphate supplements were tested in the experiments, thus preventing the development of response curves. Moreover, different criteria of response often were employed. The criteria studied have included growth rate, feed consumption, feed efficiency, bone ash, skeletal abnormalities, percent net retention of phosphorus, incidence of paralysis, litter size, blood phosphatase activity, rate of absorption, phosphorus balance, blood serum phosphorus levels, and others. In most cases, even when statistically significant differences were not found, the relative order of ranking of the phosphates according to biological response was indicated by the researchers in the reports. Several of these studies conducted over the past few years are presented in table 6.

Each researcher referred to in the table is identified by letter and the order of effectiveness of the phosphate sources in the various comparisons is indicated by number, with number one having the highest biological availability and number four the lowest availability. Based on the rankings shown in the table and tempered by qualifying statements from the various researchers, the supplements can be classified in the following order of rank for the pig. The soluble phosphates such as sodium phosphate, phosphoric acid and monocalcium phosphate about equal, having the highest biological availability, followed closely by dicalcium phosphate. These are followed by defluorinated phosphate and steamed bone meal, then low fluorine rock phosphate, and finally soft phosphate with the lowest availability.

Two reports (Dudley, 1960; Combs, 1962) included estimates of relative biological availability of several sources of phosphate for the pig. Their availability data are shown in table 7.

Differences in the magnitude of values between the two laboratories may have been due to criteria used for measurement. Bone ash was used by Combs (1962), whereas a balance technique was employed by Dudley (1960).

Laying Hens. As early as 1939, Common reported that the phosphorus in plants passed through the hen unhydrolyzed. Gillis, Norris and Heuser (1953) later found the phosphorus

TABLE 6. RELATIVE ORDER OF RESPONSE TO PHOSPHATE SUPPLEMENTS

	Researcher									
Supplement	A	B	C	D	E	F	G	H	I	J
Sodium acid phosphate	..	..	..	1	..	..	..	1	..	..
Phosphoric acid	1	..	..	2	..	..	..	..	..	..
Monocalcium phosphate	1	..	1	..	..	..	..	..	..	..
Dicalcium phosphate	1	1	2	3	1	1	1	1	1	1
Bone meal	2	..	3	3	..	..	2	..	1	..
Defluorinated phosphate	2	1	..	..	..	..	3	1	..	1
Low F rock	3	..	..	..	2	..	..	..	..	1
Soft phosphate	4	2	4	4	3	2	..	..	2	..

A—Plumlee *et al.* (1958).
B—Ammerman *et al.* (1963).
C—Combs (1962).
D—Dudley (1960).
E—Harmon *et al.* (1965).
F—Harmon *et al.* (1970).
G—Van Zante, Ross and Tribble (1967).
H—Futrell, Chaney and Scott (1969).
I—Chapman, Jr. (1955).
J—Chamberlain and Griffin (1963).

TABLE 7. RELATIVE BIOLOGICAL AVAILABILITY OF PHOSPHATES FOR SWINE

Supplement	Combs[a]	Dudley[b]
	%	%
Dicalcium phosphate	100	100
Monocalcium phosphate	120	...
Sodium acid phosphate	...	145
Phosphoric acid	...	124
Steamed bone meal	67	101
Soft phosphate	41	62

[a] Combs (1962).
[b] Dudley (1960).

from isolated calcium phytate to be less than 50% as biologically available as that from dicalcium phosphate or defluorinated phosphate as indicated by mortality, egg production and bone mineral changes. In other studies (Waldroup *et al.*, 1967; Singsen *et al.*, 1969a) phytate phosphorus was found to be 30% and 80% available. Nott, Morris and Taylor (1967) found that the value of phytate phosphorus was very largely dependent on the dietary calcium level and that when calcium intake was adequate for optimum egg shell quality, hens were unable to utilize any of their dietary phytate phosphorus. This finding is of considerable significance in view of the high levels of calcium incorporated into practical laying rations.

Singsen and others (1962) found phosphorus requirements to be directly related to the level of egg production and management conditions. These factors together with diet composition probably explain why some laboratories (Crowley *et al.*, 1961; Harms, Douglas and Waldroup, 1961; Salman, Ali and McGinnis, 1969) were unable to find differences in the biological availability of various sources of phosphates for the laying hen.

In a series of studies on the comparative availability of inorganic phosphates for the laying hen, Singsen *et al.* (1969a), on the basis of all performance characteristics, found the lowest availability for soft phosphate, with slightly higher availability for low fluorine rock phosphate and essentially equal availability for defluorinated and dicalcium phosphate. These data were only indicative, however, because the sources were included in the experimental rations at only one supplemental level.

In a follow-up study (Singsen *et al.*, 1969b), hens fed dicalcium phosphate had significantly higher egg production and a consistent and significantly lower mortality in all experiments when compared to Curacao (low fluorine rock) phosphate fed hens. The increased mortality differences due to phosphate sources ranged from 50 to 100% and were due almost entirely to cage layer osteoperosis (cage layer fatigue) (Riddell, Helmboldt and Singsen, 1967). Based on the accumulated data from this series of experiments, the low fluorine rock phosphate was assigned a biological availability of only 25% for the laying hen. These results point out the worth of calculating data on a hen-housed basis as contrasted to a hen-day basis in order that mortality effect can be expressed. A summary of biological availability values from several laboratories for the laying hen is shown in table 8.

Turkeys. Studies with turkey poults have shown phytate phosphorus to be essentially unavailable. Using radioisotope labeled phytate, Gillis, Keane and Collins (1957) found calcium phytate to be almost totally unavailable with less than 2% of the phosphorus being utilized.

In studies with inorganic sources, Wilcox and associates (1954, 1955), found wide differences in the ability of young turkeys to utilize various phosphates. Availability values ranged from very low to very high, based on growth rate and bone ash observations. The use of single levels of each phosphate supplement prevented the development of comparative response curves in these experiments.

In much of the early literature the inorganic phosphates evaluated were not completely described. As a result, some confusion exists due to the impact of differences in the physical state of hydration or crystalline modification of some of the phosphate sources on biological availabilty. In a series of experiments, Gillis, Edwards and Young (1962) and Scott, Butters and Ranit (1962) reported that for the turkey poult, the primary calcium phosphate salt is most biologically available, followed by the secondary salt, with the tertiary salt or tricalcium phosphate having the least biological availability of the three. In these studies it was pointed out that although the

TABLE 8. BIOLOGICAL VALUE OF PHOSPHORUS SOURCES FOR LAYING HENS

Researcher	Dicalcium phosphate	Defluorinated phosphate	Low F rock phosphate	Calcium phytate
	%	%	%	%
Gillis *et al.* (1953)	100	...	..	50
Gillis *et al.* (1953)	...	100	..	50
Nott *et al.* (1967)	...	...	..	0–?
Waldroup *et al.* (1967)	...	100	..	30
Singsen *et al.* (1969a)	100	...	..	80
Singsen *et al.* (1969b)	100	...	25	..

three salts rank in the same order for the two species, the chick is not nearly as sensitive to the differences in form of salt as the turkey poult.

Of considerable interest was the finding that hydrated dicalcium ($CaHPO_4 \cdot H_2O$) phosphate is an excellent source of phosphorus, whereas the anhydrous form of dicalcium phosphate ($CaHPO_4$) is very poorly utilized by the turkey (Gillis *et al.*, 1962; Scott *et al.*, 1962; Supplee, 1962; Rucker, Parker and Rogler, 1968). Several laboratories (Griffith and Young, 1963, 1967; Griffith, Young and Scott, 1966; Arnold *et al.*, 1967) have reported on their efforts to determine why this difference exists and what dietary modifications might influence it.

Sullivan (1966) has described a technique for determining the availability of phosphates for turkeys utilizing the combined responses of body weight, feed efficiency, and bone ash values. This method was devised in an attempt to put the assay on a more practical basis. There is need for effort in this direction, but as indicated in table 9 (adapted from his report) the method of combining the various criteria into one value greatly reduces the sensitivity of the assay.

Several samples of some of the sources were tested, but the maximum spread of average values found in this study was only 10 points of availability. In recalculating certain of these data and utilizing only the bone ash data portion, because of the sensitivity of this criterion, Edwards (1968) found availability values to be quite similar (table 10) in magnitude and relative rank to those values reported by other investigators for chicks and poults.

Chicks. The comparative utilization of phosphorus for starting chicks and broilers has been studied extensively by numerous investi-

TABLE 9. RELATIVE BIOLOGICAL AVAILABILITIES OF PHOSPHATE SOURCES FOR TURKEY POULTS [a]

Source	Range between samples	Average biological value
	%	%
Monocalcium phosphate	100	100
Dicalcium phosphate	95.7–101.0	98.2
Defluorinated phosphate	82.6– 98.2	93.0
Low F rock phosphate	...	91.2
Monocal-Dical phosphate	...	101.2
Sodium phosphate	...	100.4
Tricalicum phosphate	...	99.6

[a] Sullivan (1966).

TABLE 10. DIFFERENCES IN AVAILABILITY DUE TO METHOD OF CALCULATION

Sample	Source	Sullivan[a] values	Edwards[b] values
		%	%
	Monocalcium phosphate	100.0	100.0
1	Dicalcium phosphate	98.4	86.0
5	Defluorinated phosphate	82.6	30.0
10	Low F rock phosphate	91.2	53.0

[a] Sullivan (1966).
[b] Edwards (1968).

gators, but, as with other species, much of the data reported is more of a qualitative than of a quantitative nature. Gillis and associates (1954) were the first to quantitate the availability from various phosphatic compounds for the chick. The method was based on relating percentage of tibia ash from chicks fed a certain test supplement to that of chicks fed a reference standard, thus obtaining relative biological availability values. Values determined by the technique have a reproducibility of $\pm 5\%$ (Nelson and Walker, 1964). Although other investigators, in numerous reports, have suggested modifications and different techniques, little progress has been made toward improving the reproducibility of values as determined by the methods of Gillis *et al.* (1954) and Nelson and Walker (1964).

In most of the studies where comparative data are reported for the chick, the assay technique utilized has been similar to that described by Gillis and others (1954). In these studies where a common reference standard appears, comparisons can be made between assays and between laboratories. Relative biological availability data on various feed grade phosphate sources determined by several different laboratories (Gillis *et al.*, 1954; Nelson and Peeler, 1961; Nelson and Walker, 1964; Waldroup, Ammerman and Harms, 1965; Dilworth and Day, 1964) are compared in table 11. The biological value data of Waldroup and Dilworth were recalculated in order that comparisons could be made. It is apparent that relatively good agreement was obtained between various experiments and laboratories as to comparative biological availability of the phosphates.

Numerous studies have demonstrated that the level of calcium in the diet has a considerable influence on the response of chicks to certain phosphate sources. As a consequence, several assay techniques have been devised to treat phosphate sources individually within the same experiment rather than to maintain uniform condition throughout all treatment

TABLE 11. BIOLOGICAL AVAILABILITY OF PHOSPHATES FOR CHICKS

Source	Gillis A	Nelson B	Nelson C	Waldroup D	Dilworth E
	%	%	%	%	%
Beta-Tricalcium phosphate	100	100	100	..	100
Monocalcium phosphate	113	..	116	..	..
Dicalcium phosphate	98	97	97	97	..
Defluorinated phosphate	92	..	92	..	87
Bone meal	96	..	..	..	..
Low F rock	87	68	..	..	69
Soft phosphate	0	34	..	49	41

A—Gillis *et al.* (1954).
B—Nelson *et al.* (1961).
C—Nelson and Walker (1964).
D—Waldroup *et al.* (1965).
E—Dilworth and Day (1964).

groups. Applying this technique (Damron and Harms, 1970) appears to alter values of some phosphates in magnitude, but the comparative rank among the phosphates remains in essentially the same order as reported by others.

As with other animals, few investigators have studied the quantitative biological utilization of phytate phosphorus by chicks. In critical studies utilizing labeled phytate phosphorus, biological availability values of 10% (Gillis *et al.*, 1957) and 20% (Ashton, Evans and Williams, 1960) were reported.

Calcium

The value of a feedstuff as a source of calcium depends not only upon its calcium content, but also on the amount that the animal can extract and retain for its own use. Results of numerous experiments have been reported describing the many factors that have an influence on the absorption and retention of calcium. Some of the major factors reported are age, vitamin D level, hormone blood level and balance, amount of calcium fed, composition of diet, calcium status of animal, and the form of calcium fed.

In spite of the volume of research conducted on calcium nutrition over the years, relatively little information has been developed on the comparative biological availability of calcium from different feed sources for animals.

Turner, Hardin and Hartman (1927), Lindsey and Archibald (1925) and Hayden, Monroe and Crawford (1930) found dicalcium phosphate to be as good a source of calcium as that from natural sources for cattle. Using body weight gains in the same species, Lantow (1933) found little difference between rations containing monocalcium phosphate, bone meal, dicalcium phosphate or calcium from natural sources. Radioisotope procedures, however, allowed Hansard, Crowder and Lyke (1957) to more accurately measure endogenous calcium excretion in cattle and thereby calculate the true absorption. Using these techniques, 109 individual balance trials were conducted on young and mature cattle, pair fed a basal ration to which calcium was supplied from 15 different organic and inorganic sources. Their comparative biological availability results are presented in table 12. True digestibility of calcium was greater in young cattle than in mature steers. Calcium from inorganic sources appeared to be utilized more efficiently than that from alfalfa, lespedeza or orchard grass hays. Differences in calcium availability were not considered large, but the sources tended to classify themselves into three groups with bone meal, monocalcium and dicalcium phosphates having the highest availability for calcium, and the hay sources the lowest in availability. The availability of calcium in ground limestone, defluorinated phosphate and calcium carbonate was intermediate. In subsequent studies with feedlot cattle, Bushman *et al.* (1967) found no difference in calcium availability between ground limestone or dicalcium phosphate as measured by weight gain, feed consumption, bone ash, blood level or carcass data. However, the basal ration probably was completely adequate in calcium since no response was obtained from any calcium level fed.

Calcium levels of 0.40% and 0.88% of the

TABLE 12. BIOLOGICAL AVAILABILITY OF CALCIUM FROM VARIOUS SOURCES FOR YOUNG AND MATURE STEERS[a]

Calcium source	True digestibility		Biological availability	
	Mature	Young	Mature	Young
	%	%	%	%
Calcium carbonate, C.P.	40	51	100	100
Bone meal (Imported)	55	68	138	133
Calcium chloride, C.P.	53	[illegible]	132	120
Dicalcium phosphate, C.P.	50	64	125	126
Monocalcium phosphate, C.P.	56	61	140	120
Dicalcium phosphate (A)	49	58	122	114
Dicalcium phosphate (B)	38	56	95	110
Dicalcium phosphate (C)	56	60	140	120
Dicalcium phosphate (D)	51	60	127	120
Dicalcium phosphate (E)	55	58	138	114
Defluorinated phosphate	40	55	100	108
Ground limestone	37	45	93	88
Alfalfa hay	31	41	78	80
Lespedeza hay	36	50	90	98
Orchard grass hay	39	51	98	100

[a] Hansard *et al.* (1957).

ration furnished by limestone, oyster shell and gypsum were fed to weanling pigs (Combs and Wallace, 1962) in experiments designed to determine the influence of low and high levels on performance. The high levels of calcium significantly depressed growth rate and feed efficiency. However, the fact that all three calcium supplements influenced the results to approximately the same degree, would indicate that they probably were utilized essentially equally by the pig.

Considerably more research on the comparative value of calcium sources has been reported for poultry than for other animals. Investigations of several researchers failed to reveal any difference in biological availability between different calcium sources using bone ash and weight gain in chicks as criteria of response. The sources studied in these various comparisons included calcium carbonate, calcium sulfate, oyster shell, limestone, various calcium phosphates, gypsum, calcium gluconate, and fish meal. (Bethke, Kennard and Kick, 1929; Deobald *et al.*, 1936; Waldroup, Ammerman and Harms, 1964; Sanford and Mulla, 1965; Spandorf and Leong, 1965; Hurwitz and Rand, 1965).

In contrast to these reports, however, a number of researchers have reported differences in biological availability between various calcium carriers for young chicks. A summary of data from these biological availability trials is shown in table 13. Motzok *et al.* (1965) found the calcium in soft phosphate to be 70% as available as that in calcium carbonate and dicalcium phosphate. In these studies the effectiveness of calcium was found to be sensitive to the Ca:P ratio. Hurwitz and Rand (1965) found the calcium in gypsum to be 90% as available as limestone calcium when feed intake was equalized. In a study of the calcium availability of several feed grade calcium phosphates, using bone ash as the criterion of response, Dilworth *et al.* (1964) found the relative calcium availability in the sources to range from 68% to 95% as compared against calcium carbonate. The values reported are of the same order but somewhat higher than the phosphorus availability values reported for these phosphates (Nelson and Peeler, 1961; Dilworth and Day, 1964). In a similar study, Blair *et al.* (1965) found significant differences in the availability of calcium in calcium carbonate and various phosphate salts. Stillmak and Sunde (1971) reported the calcium in dolomitic limestone to be from 64 to 68% as available as that in pure calcium carbonate. The average availability was 66%. In other reports, differences in calcium availability were found when hydrated and anhydrous dicalcium phosphates were compared (Rucker *et al.*, 1968) and also when domestic and Mexican grown sesame meals were tested (Cuca and Sunde, 1967).

In studies with laying hens, Balloun and Marion (1962) found differences in relative efficacy of calcium lactate and calcium carbonate in the production of egg shells, and Buckner, Martin and Peter (1929) found calcium carbonate to be superior to a number of calcium salts for egg production as judged by egg shell weight. However, most laboratories have been unable to demonstrate significant differences in the biological availability of a number of calcium sources using egg production, egg shell quality and bone ash

TABLE 13. BIOLOGICAL AVAILABILITY OF CALCIUM FROM VARIOUS SOURCES FOR THE YOUNG CHICK

Calcium source	Relative availability				
	Motzok [a]	Hurwitz [b]	Dilworth [c]	Blair [d]	Stillmak [e]
	%	%	%	%	%
Calcium carbonate	100	100	100	100	100
Limestone	...	...	...	102	...
Dolomite	...	...	...	...	...
Gypsum	...	90	...	...	66
Bone meal	...	...	...	109	...
Low F rock	...	...	90	...	...
Soft phosphate	70	...	68	...	...
Defluorinated phosphate A	...	...	95	...	...
Defluorinated phosphate B	...	...	92	...	...
Tricalcium phosphate	...	...	...	115	...
Dicalcium phosphate	100	...	...	113	...

[a] Motzok, Arthur and Branion (1965).
[b] Hurwitz and Rand (1965).
[c] Dilworth, Day and Hill (1964).
[d] Blair, English and Michie (1965).
[e] Stillmak and Sunde (1971).

values as criteria (Buckner *et al.*, 1923; Hurwitz and Rand, 1965; Heywang and Lowe, 1962). Recently, oyster shell flakes were found to promote higher blood plasma levels, breaking strength and egg production when compared with pulverized limestone (Scott and Mullenhoff, 1970). This effect apparently is due principally to the physical form of the sources.

Magnesium

Magnesium has been recognized as an important dietary essential for many years, and under a number of feeding situations supplemental magnesium is required for optimum performance. Although needed by all species, the incidence of hypomagnesemia, or "grass tetany", especially in certain geographical regions, has stimuated special interest in the study of magnesium for ruminant animals.

As with other nutrients, an understanding of the efficiency of utilization of magnesium from various sources is important to sound nutrition. Several dietary factors have been reported (Rook and Storry, 1962; Care, 1964; Thomas, 1959) to influence magnesium availability in various ways. Some of these factors are: composition of diet; magnesium status of the animal; various dietary ions such as calcium, phosphorus, sodium, potassium, manganese and citrate; phytic acid and chelates in natural feedstuffs; abrupt changes in feeding systems; age and genetic differences in animals; dietary fat and vitamin D levels; nitrogen level and season of the year for forages; and numerous other factors. Many of the factors studied appear to have a negative effect on magnesium absorption, but others such as processing by cooking and grinding of grains and hays have been reported to increase magnesium absorption.

Although most of the factors mentioned above, and others, have been reported to influence absorption and utilization of magnesium to one degree or another, it is assumed that these factors exert their influence to approximately the same degree on magnesium from various sources, and therefore, will have little bearing on the relative or comparative availability of magnesium from the various sources.

A number of criteria have been used to measure magnesium availability. Much of the early information on availability used apparent absorption and blood plasma levels as criteria. Other researchers have employed percent urinary excretion of magnesium intake as an indication of availability. These techniques have been questioned for a number of reasons and it is probable that more recent studies involving complete balance trial data have more meaning.

Employing balance trials with mature wether sheep, Stillings and associates (1964) found average values for apparent availability of magnesium from low nitrogen-containing grass forages to range from 18 to 24%, while those from high nitrogen-containing forage ranged from 11 to 16%. Field (1967) found the mean true availability of magnesium in mixed forages to range from 16 to 26% in grazing sheep trials. Again, using balance trials, Lomba *et al.* (1968) reported the mean apparent digestibility of magnesium in rations consisting variously of hay, straw and concentrates to be 23.1% for dry cows and 27.8% for lactating dairy cows. Other experiments reviewed by Rook and Storry (1962) indicate the availability of magnesium in hay samples to vary from 23.3 to 26.3%.

Magnesium availability in concentrate feeds has generally been somewhat higher ranging up to 40% (Rook and Storry, 1962). Blaxter and McGill (1956) estimated the average availability of magnesium in a complete ruminant ration without mineral supplementation to be about 33%. The availability of magnesium reported in hays, forages, and concentrates for ruminant animals is summarized in table 14.

The availability of dietary magnesium for ruminants is generally considered to be somewhat lower than for simple stomached animals. Availability values of 61 to 95% have been reported for the rat (Kunkel and Pearson, 1948) and 65 to 86% for the guinea pig (Garner, 1950). Values of the same high order also have been reported for milk-fed calves the first few weeks of life (Smith, 1958). Subsequently, however, there usually is a marked decline in ability to absorb magnesium as age increases, so that older milk-fed calves will show values of only 30 to 50% of dietary intake (Blaxter and Rook, 1954). No good information on absorption of magnesium exists for poultry. The availability of magnesium reported for various monogastric animals is summarized in table 15.

Considerable variability has been observed in results from experiments conducted to determine the relative availability of magnesium from various salts. Huffman *et al.* (1941) without showing actual data, reported essen-

TABLE 14. AVAILABILITY OF MAGNESIUM IN HAYS, FORAGES AND CONCENTRATES FOR RUMINANTS

Researcher	Species	Feedstuff	Availability
			%
Stillings *et al.* (1964)	Sheep	Low N hay	18–24
		High N hay	11–16
Field (1967)	Sheep	Mixed pasture	16–26
Lomba *et al.* (1968)	Dry cows	Mixed hays	23.1
	Lact. cows	Mixed hays	27.8
Rook *et al.* (1962)	Cows	Hay	23.3–26.3
Rook *et al.* (1962)	Cows	Grain	37.5
Blaxter and McGill (1956)		Concentrates	33

tially equal availability from magnesium oxide, carbonate, chloride and phosphate salts. The efficiency of utilization of magnesium citrate, silicate, sulfate salts and of metallic magnesium, however, was markedly reduced for calves on whole milk rations. Blood plasma magnesium was used as the criterion of response in these studies. Storry and Rook (1963) compared the availability of a number of magnesium salts for dairy cows. In this case, the urinary loss of magnesium expressed as a percentage of magnesium in the supplement was given as the measure of availability. Their values ranged from 14.5% to 49.2%. Using magnesium oxide as the reference standard, the supplements had values of 54% for magnesium trisilicate on the low side up to 158% for magnesium citrate. In these studies blood magnesium levels were not found to be a suitable measure of availability. With beef steers on a magnesium low basal ration, Gerkin and Fontenot (1967) determined the availability of magnesium in dolomitic limestone to be 28% of that in magnesium oxide. Magnesium absorption based on excretion data was used as a measure of availability.

A recent report by Ammerman and associates (1972) compared the availability of several magnesium salts for sheep. Values were expressed as true net retention as determined in balance trials. Availability values ranged from 13.6% to 44.1% for the compounds tested. When reagent grade magnesium oxide was assigned a value of 100, the relative value of magnesium sulfate was 113% and that of reagent grade magnesium carbonate 86%. A sample of magnesite ore, a crude magnesium carbonate, was found to have too low an availability to calculate. In an extension of this work, feed consumption by magnesium deficient sheep was found to be useful as a measure of biological availability. Again, with reagent grade magnesium oxide employed as the standard, the relative availability for feed grade magnesium oxide was 85%, magnesium sulfate 65% and the carbonate 113%. In these studies the administration of the sulfate salt in a single daily dose may have been responsible for the progressive loss of appetite in the sulfate fed sheep. In the rat, using maintenance of serum magnesium as the criterion, values for sulfate and carbonate were found to be considerably higher than for the oxide and probably indicate a species difference (Kunkel and Pearson, 1948). Data from the various relative biological availability comparison trials are presented in table 16.

TABLE 15. AVAILABILITY OF MAGNESIUM IN MONOGASTRIC ANIMALS

Researcher	Species	Availability
		%
Kunkel and Pearson (1948)	Rat	61–95
Garner (1950)	Guinea Pig	65–86
Smith (1958)	Calf-first few weeks	70
Blaxter and Rook (1954)	Calf-older milk-fed	30–50

The literature can be summarized by indicating that the availability of magnesium in forages ranges from 10 to 25% with a mean of approximately 20%. Grains and concentrates range from 30 to 40%. The experimental data on relative availability of magnesium from the various mineral supplements vary considerably and more research is needed to define more accurately their relative efficiencies.

Sulfur

Sulfur metabolism in animals has been studied extensively, with an excellent accumulation of information and references reported in a recent Symposium: Sulfur in Nutrition (Muth and Oldfield, 1970).

TABLE 16. RELATIVE AVAILABILITIES OF MAGNESIUM IN VARIOUS SALTS

Researcher: Animal: Criterion:	Huffman[a] Calf Plasma Conc.	Storry[b] Cow Urine loss % of supp.	Ammerman[c] Sheep Balance trial	Ammerman[c] Sheep Feed cons.	Gerkin[d] Steer Absorp- tion	Kunkel[e] Rat Serum conc.
	%	%	%	%	%	%
Oxide-R.G.	100	100	100	100	100	100
Oxide-F.G.	...	...	...	85	...	...
Sulfate	<	58	113	65	...	164
Carbonate	100	...	86	113	...	154
Magnesite	...	...	X	...	...	...
Dolomite	...	...	...	...	28	...
Chloride	100	90	...	...	...	...
Citrate	<	148	...	...	...	...
Acetate	...	107	...	...	...	...
Nitrate	...	97	...	...	...	...
Lactate	...	98	...	...	...	...
Silicate	<	...	...	...	...	...
Trisilicate	...	66	...	...	...	...
Phosphate	100	...	...	...	...	...
Mg-Metal	<	...	...	...	...	...

[a] Huffman *et al.* (1941).
[b] Storry and Rook (1963).
[c] Ammerman *et al.* (1972).
[d] Gerkin and Fontenot (1967).
[e] Kunkel and Pearson (1948).

The ability of both ruminant and nonruminant animals to utilize sulfur-containing amino acids and inorganic sulfur compounds to various degrees has been recognized for many years. In the studies reported, methionine, elemental sulfur, and sodium sulfate have been the principal compounds used, although many other forms have been investigated. Very little information exists, however, on the comparative biological availability of the various forms of sulfur for animals.

Many of the studies have demonstrated that ruminants and nonruminant animals utilize sulfur from the various sources differently. Moreover, there is considerable evidence that sulfur from different sources may be utilized differently within the same species. For example, much of the sulfate fed to ruminants is rapidly converted to sulfide and absorbed through the rumen wall (Anderson, 1956; Bray, 1969a). Very little sulfate is absorbed in the rumen (Bray, 1969b) and also it apparently is poorly absorbed in the intestinal tract of ruminants (Bray, 1969a). In contrast, sulfate is very rapidly absorbed from the intestinal tract of monogastrics (Kulwich, Struglia and Pearson, 1958; Berry *et al.*, 1969; Machlin and Pearson, 1957). In nonruminants sulfur-containing amino acids are required in the diet. In ruminants the intervention of rumen microorganisms can convert inorganic sulfur compounds and sulfur-containing amino acids to microorganismal amino acids which can then be utilized by the host animal (Muth and Oldfield, 1970). Radioisotope studies (Pereira, Harper and Gould, 1966) indicate that labeled sulfur from supplemental methionine and sodium and barium sulfides appear principally in the protein fractions of milk but that sodium sulfate sulfur shows up mainly in the non-protein fraction. In tissue sulfur distribution studies with lambs, more radiosulfur from methionine appeared in the lung and pancreas than from elemental sulfur or sodium sulfate and more of the sulfur in nose cartilage came from sodium sulfate than from the other compounds investigated (Johnson, Goodrich and Meiske, 1971) indicating that sulfur from sodium sulfate may have entered a different body pool from that of methionine and elemental sulfur. These observations showing that animals can utilize sulfur from various sources differently complicate a discussion on the comparative biological availability of sulfur compounds.

In studies with sheep, Ewan (1957), evaluated calcium sulfate and found it to be an available source of sulfur for lambs. When high levels of sulfur were fed to lambs (Johnson, Meiske and Goodrich, 1968) it was observed that 0.5% sulfur from sodium sulfate did not reduce gains to as great an extent as an equal amount of sulfur from calcium sulfate, indicating differences in utilization between the sources. Feeding a semi-purified diet to lambs and using weight gain as the criterion of response, Sparks *et al.* (1954) found 0.4% elemental sulfur, 1.10% sodium sulfate and 0.47% methionine to permit the greatest gains for the three sulfur sources. On a sulfur basis, and assigning methionine a value of 100, the relative availabilities of the sulfur in sodium sulfate and elemental sulfur were 35.2% and 26.6%, respectively. In a similar biological availability trial based on weight gain in lambs, Albert *et al.* (1956) compared the effectiveness of sulfur from methionine, sodium sulfate and elemental sulfur. Five dietary levels of each compound were tested. Optimum daily gains were produced by 0.138% S from methionine, 0.29% S from sodium sulfate and 0.47% S from elemental sulfur. Assigning a value of 100 to methionine gives relative biological availabilities of 47.7% and 29.4% for sodium sulfate sulfur and elemental sulfur respectively. More recently, Johnson *et al.* (1971) utilizing a radioisotope technique estimated the true digestibility and retention of the sulfur from elemental sulfur, sodium sulfate and L-methionine and determined the percentage of sulfur from each source that was available for incorporation into wool, muscle tissue, and several other tissues and organs. Results showed a true retention of 70.0% S from L-methionine, 56.0% S from sodium sulfate and 26.8% S from elemental sulfur. On a relative basis, the availabilities were 100 for methionine, 80.0% for sodium sulfate and 38.3% for elemental sulfur. The results from the three lamb trials are summarized in table 17. On the basis of these experiments, the biological value of the sulfur in sodium sulfate is 54% and that of elemental sulfur 31% as compared with methionine arbitrarily set at 100.

In vitro digestion trials using purified cellulose and corn-fodder diets indicated sulfur from sodium sulfate to be approximately equal to the natural sulfur (presumably from S-amino acids) in corn-fodder in promoting cellulose digestion (Barton and Bull, 1971).

In studies with gilts using orally administered radioisotope ^{35}S, it has been reported (Berry *et al.*, 1969) that the sulfur from sodium sulfate is widely distributed in animal tissues. Evans and McGinnis (1946) using balance trials found some retention of dietary inorganic sulfur in the chick. Machlin and Pearson (1957) found 23% of the ingested ^{35}S from sodium sulfate to be retained by chicks, primarily as taurine and other sulfate containing compounds. This retention figure in chicks is in agreement with levels of ^{35}S from labeled sodium sulfate retained by the growing pig (Pfirter, Landis and Schurch, 1968).

Biological availability comparisons between various sulfur compounds have not been well defined using monogastric animals, but experiments with chicks indicate that soluble sulfate compounds such as sodium, potassium and magnesium sulfate promote weight gains and exert a sparing action on sulfur-containing amino acids, whereas calcium sulfate is not effective (Jukes, 1970; Ross and Harms, 1970). In contrast, Button *et al.* (1965) found calcium sulfate to be equal to sodium sulfate in promoting growth in rats. Gordon and Sizer (1955) reported that inorganic sulfate cannot replace dietary cystine or methionine for protein synthesis, although sulfate will apparently "spare" dietary sulfur amino acids for protein synthesis. In studies with rats, Michels and Smith (1965) presented evidence that there is a need for inorganic sulfur in order to prevent an increase in the sulfur amino acid requirement above that normally stated. In the research of Jukes (1970), the weight gain of chicks plotted against the log dose of sulfur additions from cystine and methionine or cystine and methionine plus sulfate showed that 0.21% amino acid sulfur was replaced by 0.5% sodium sulfate sulfur indicating that sodium sulfate was approxi-

TABLE 17. BIOLOGICAL AVAILABILITY OF SULFUR FROM VARIOUS SOURCES

Researcher	Criterion	Methionine	Sodium sulfate	Elem. S
		%	%	%
	Sheep			
Sparks *et al.* (1954)	Wt gain	100	35.2	26.6
Albert *et al.* (1956)	Wt gain	100	47.7	29.4
Johnson *et al.* (1971)	True retention ^{35}S	100	80.0	38.3
	Average	100	54	31
	Chicks			
Jukes (1970)	Wt gain	100	40	....

mately 40% efficient in its sparing action. This finding is summarized in table 17.

Further research is needed to determine more accurately the relative efficiency of the various organic and inorganic sources of sulfur for the various metabolic functions in monogastric animals.

Sodium

Very little information has been reported on the biological availability of sodium. Sodium salts are readily absorbed throughout the gastrointestinal tract, and generally the sodium from various sources has been considered fully available. However, recent research suggests that the chemical form in which sodium exists may influence its biological usefulness.

Results of some experiments (O'Dell and Savage, 1966) indicated that sodium supplements in the form of acetates, citrates and carbonates stimulated the growth of chicks whereas sodium chloride was ineffective. Since a proper cation balance is necessary for maximal growth of chicks (Nesheim *et al.*, 1964) and of guinea pigs (Grace and O'Dell, 1968), it is probable that these findings on sodium salts were a result of improper cation balance and level rather than of a true difference in biological availability.

Certain calcium phosphate feed supplements contain some sodium as a result of the manufacturing process. Nott and Combs (1969) compared the relative availability of the sodium in a defluorinated phosphate with that of sodium chloride. Using weight gain and feed consumption as the criteria of biological response, it was found that the sodium in the defluorinated phosphate sample investigated was 83% as available as the sodium from sodium chloride. The sodium in most defluorinated phosphates is present predominately as a calcium sodium phosphate complex (approximately $Ca_6Na_3(PO_4)_5$). Inasmuch as approximately 30 to 50% of the sodium in an animal's body (Scott, Nesheim and Young, 1969) is found firmly bound in bone, the findings of Nott and Combs (1969) suggest that sodium from the bone fraction of animal by-product feedstuffs may not be as biologically available as the sodium from soluble sodium salts and other natural sources.

Potassium

As with sodium, little work has been reported on the comparative biological availability of potassium from different sources. Large differences in availability probably should not be expected in view of the solubility and rapidity of absorption of the usual forms of potassium found in an animal's diet.

Roberts and St. Omer (1965) conducted a series of experiments involving yearling steers for the purpose of determining the potassium requirement for this species. Sources of potassium varied between experiments, and no direct comparisons were made, but the fact that essentially the same level of potassium from either KCl or K_2CO_3 was required for optimum weight gain and feed consumption may be an indication that these two sources are approximately equal in availability for yearling steers.

Shelton and Ellis (1965) fed 1, 2 and 3% $KHCO_3$ and equivalent amounts of potassium from KCl to growing lambs on an all concentrate ration based largely on sorghum grains. Both forms of potassium appeared to be equal in promoting growth, but only the KCl was found to be helpful in preventing urinary blockage from calculi.

In a study of the metabolism of macrominerals in several grass hays and legume hays by horses, (Fonnesbeck, 1967) little if any difference was observed in retention or excretion of potassium. It was concluded from these studies that the availability and metabolism of potassium from these various hays was essentially equal for the horse.

Grace and O'Dell (1968) investigated the potassium requirement of guinea pigs using a casein protein ration. A level of 0.46% potassium was required for maximum growth when the source was potassium acetate whereas 0.54% was required when KCl was fed. In view of the fact that the guinea pig is quite sensitive to acid diets, it is probable that the differences observed were due more to variations in the dietary cation:anion balance than to source of potassium (Nesheim *et al.*, 1964).

No direct determination of the biological availability of potassium from different sources has been reported using poultry. However, in a series of three separate experiments, Supplee and associates (1958, 1959, 1965) found essentially equivalent amounts of potassium from three different sources to be required for weight gain and prevention of mortality of young turkey poults. In each experiment, a level of between 0.56% and 0.60% potassium from KCl, K_2HPO_4 or $K_3C_6H_5O_2 \cdot H_2O$ was found equally effective giving at least an indication of similar availability from the three forms.

Solid evidence is lacking, but it would appear that KCl, K_2CO_3, $KHCO_3$, K_2HPO_4 and $K_3C_6H_5O_2 \cdot H_2O$ are approximately equal as sources of potassium for the various animal species studied and that the potassium from grass and legume hays also appears to be efficiently utilized.

Summary

The major metal ions required in animal nutrition are those of phosphorus, calcium, magnesium, sulfur, sodium and potassium. Some level of these elements occurs naturally in various forms in most feedstuffs. In addition, they also are added as supplements to feeds to balance dietary requirements. The supplements are chiefly chemical compounds of varying purity and composition, processed natural ores and by-products from various industrial processes. The forms in which these elements are present in feeds may vary widely in biological availability and thereby greatly influence their nutritional worth. The term *biological availability* is used as a measure of the ability of the element form under consideration to support some physiological process in relative numerical terms in comparison to a reference standard.

Phosphorus

Numerous factors influence the utilization of phosphorus, but in general the relative order of biological effectiveness of the various sources of phosphates, regardless of technique employed, remains approximately the same under similar sets of circumstances. Although certain species of animals respond differently to certain of the phosphate sources, a review of comparative utilization studies of sources for various species indicates the following general order of rank: The soluble phosphates such as sodium phosphate, phosphoric acid and monocalcium phosphate are approximately equal having the highest biological availability, followed closely by dicalcium phosphate. These are followed by defluorinated phosphate and steamed bone meal, then low fluorine rock phosphate and finally soft phosphate. Phytate phosphorus is intermediate in biological availability for ruminant animals and adult poultry, but is very low in biological availability for young poultry and swine. Relative biological availability values for the various phosphate sources by species are reported.

Calcium

Ruminant animals appear to be more sensitive to differences in calcium sources than poultry or swine. For the ruminant bone meal, monocalcium phosphate and dicalcium have the highest biological availability with hay sources of calcium the lowest. The availability of calcium in limestone, defluorinated phosphate and calcium carbonate is intermediate. In studies with chicks the calcium in dicalcium phosphate, calcium carbonate, limestone, bone meal and defluorinated phosphates are well utilized. Gypsum and low fluorine phosphate are moderately well utilized and dolomite and soft phosphate are the lowest in biological availability. Laying hens are less discriminating in that most calcium sources are relatively well utilized.

Magnesium

Most biological availability studies on magnesium have been conducted with ruminant animals. The availability of magnesium in forages ranges from 10% to 25% and that in grains and concentrates from 30% to 40%. Reagent grade and feed grade magnesium oxide, magnesium sulfate and magnesium carbonate appear to be well utilized by the ruminant animal whereas the magnesium in dolomite is poorly utilized. The availability of magnesium in its various salts is considerably greater for simple stomach animals than for ruminants. Comparative values are shown.

Sulfur

Methionine, sodium sulfate, potassium sulfate, calcium sulfate, and elemental sulfur are the usual sources of sulfur investigated for ruminant and nonruminant animals. For ruminants, on a relative basis, the biological availability of sulfur in sodium sulfate is 54% and for elemental sulfur is 31% as compared with 100% for methionine sulfur. Biological availabilities of sulfur from various sources have not been well defined for monogastric animals. Sodium, potassium and magnesium sulfates appear to be well utilized by the chick but calcium sulfate is poorly utilized.

Sodium

Most sodium salts are highly biologically available to animals. The sodium in defluor-

inated phosphates, however, appears to be only 83% as available as that in sodium chloride for the chick.

Potassium

Little work is reported on the comparative biological availability of potassium compounds. Potassium in the form of chloride, sulfate, phosphate, carbonate, acetate and that present in natural feedstuffs is well utilized.

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