JAST (Journal of Animal Science and Technology) TITLE PAGE

Upload this completed form to website with submission

ARTICLE INFORMATION	Fill in information in each box below
Article Type	Review article
Article Title (within 20 words without abbreviations)	Role and functions of Micro and Macro-minerals in swine nutrition: A short review
Running Title (within 10 words)	Micro and Macro-Minerals in swine nutrition
Author	Vetriselvi Sampath[a,1], Shanmugam Sureshkumar[a, 1], Woo Jeong Seok[1], In Ho Kim[1]
Affiliation	[1] Department of Animal Resource and Science, Dankook University, Cheonan, Choongnam - 31116, Korea. a Authors contributed equally
ORCID (for more information, please visit https://orcid.org)	Vetriselvi Sampath (https://orcid.org/0000-0002-6726-8568) Shanmugam Sureshkumar (https://orcid.org/0000-0002-3632-3114) Woo Jeong Seok (https://orcid.org/0000-0002-1758-7579) In Ho Kim (http://orcid.org/0000-0001-6652-2504)
Competing interests	No potential conflict of interest relevant to this article was reported.
Funding sources State funding sources (grants, funding sources, equipment, and supplies). Include name and number of grant if available.	Not applicable.
Acknowledgements	Not applicable.
Availability of data and material	Upon reasonable request, the datasets of this study can be available from the corresponding author.
Authors' contributions Please specify the authors' role using this form.	Conceptualization: Vetriselvi S, Sureshkumar S, Kim IH. Writing - original draft: Vetriselvi S, Sureshkumar S. Writing - review & editing: Woo JS, Kim IH.
Ethics approval and consent to participate	Not applicable.

CORRESPONDING AUTHOR CONTACT INFORMATION

For the corresponding author (responsible for correspondence, proofreading, and reprints)	Fill in information in each box below
First name, middle initial, last name	In Ho Kim
Email address – this is where your proofs will be sent	inhokim@dankook.ac.kr
Secondary Email address	
Address	Department of Animal Resource & Science, Dankook University No.29 Anseodong, Cheonan, Choongnam, 330-714, South Korea
Cell phone number	
Office phone number	+82-41-550-3652
Fax number	+82-41-565-2949

Abstract

Livestock production depends on the utilization of nutrients, and when this is accomplished, there is accelerated momentum toward growth with a low cost-to-feed ratio. Public concern over the consumption of pork with antibiotic residues in animals fed antibiotic growth promoters (AGP) has paved the way for using other natural additives to antibiotics, such as herbs and their products, probiotics, prebiotics, etc. Numerous feed additives are trending to achieve this goal, and a classic example is vitamins and minerals. Vitamins and minerals represent a relatively small percentage of the diet, but they are critical to animal health, well-being, and performance; both play a well-defined role in metabolism, and their requirements can vary depending on the physiological stage of the animals. At the same time, the absence of these vitamins and minerals in animal feed can impair the growth and development of muscles and bones. Most commercial feeds contain vitamins and trace minerals that meet nutrient requirements recommended by National Research Council and animal feeding standards. However, the potential variability and bioavailability of vitamins and trace elements in animal feeds remain controversial because daily feed intake varies, and vitamins are degraded by transportation, storage, and processing. Accordingly, the requirement for vitamins and minerals may need to be adjusted to reflect increased production levels, yet the information presented on this topic is still limited. Therefore, this review focuses on the role and function of different sources of minerals, the mode of action, the general need for micro and macro minerals in non-ruminant diets, and how they improve animal performance.

Keywords: minerals, swine, growth performance, nutrient value.

INTRODUCTION

In the last decade, there has been a significant increase in the efficiency of pork production, which has been reflected in improved offspring growth, better feed conversion, and higher reproductive performance of breeding herds. This type of pork production could change dramatically in the coming years as the need to ensure food safety, minimize environmental impacts, improve animal welfare, and optimize consumer health continues to improve the production efficiency of pork and nutritional quality. Given the magnitude of productivity changes between 2000 and 2010, most herds' basic genetics, management, and nutrition will also change. Besides, many scientists point out the need for macro minerals such as calcium (Ca), zinc oxide (ZnO), copper (Cu), and manganese (Mn) has remained the same; research conducted primarily in the 1950s and 1960s has much to do with modern swine. For example, the National Research Council [1] and the Agricultural Research Council [2] report that animal diet estimating zinc requirements is complex and needs more explanation on interacting factors. After several studies, they suggest that a dietary zinc level of 50 ppm (assuming that dietary calcium does not exceed 0.75%) may be the best option for preventing deficiency and avoiding hyperkeratosis or parakeratosis. In 1987, the Standing Committee on Agriculture [3] studied adequate dietary zinc intake and recommended that 45 mg/kg might be optimal for growing pigs and sows. Later, the National Research Council [4] reiterated that 50 ppm of dietary zinc might be optimal for pigs at any production cycle. Since 2010, we have been using the exact dosage of dietary zinc supplementation, based on studies conducted between 1960 – 1980 with the primary aim of preventing parakeratosis due to zinc deficiency. The same fact withstands for Ca, phosphorus (P), Mn, and Cu. The recommended daily intake of these minerals and the estimated feed intake of pigs of different classes remained the same during the 20 years from 1979 to 1998 [1,4].

In young pigs, the zinc (Zn) content of the premix is not considered and corresponds to the requirement due to the routine use of 3000 ppm of zinc oxide and the premix to control *E. coli* scours. Considering that Ca, P, Zn, Cu, and Mn also become essential minerals for structural development and physiological functions of growing and breeding pigs (Fig. 1). Since minerals play an essential role in growth and reproduction, their presence can affect the quality of the final product, which ultimately affects human health. In this review, therefore, we would like to discuss the importance of minerals, different sources of mineral supplements, their function and requirements, and how they help to improve pig performance for better productivity.

SOURCE AND FUNCTIONS OF MINERALS IN SWINE NUTRITION

Minerals are essential for the proper growth, productivity, and health of all farm animals (Fig.2). In particular, sodium chloride (NaCl), Ca, P, sulfur, potassium (K), Mn, Fe (iron), Cu, Co, iodine (I), ZnO, Mg (Magnesium), and Se (selenium) serve as essential minerals for sustainable animal development. However, Cu, Co, I, Zn, and Se are considered to be highly toxic when added to livestock diets in excess [5]. Minerals constitute only a tiny portion in pig feed, but significantly improve their growth performance, health status, and productivity. Typically, pigs require fifteen minerals in their diet; however, macro-minerals should be supplied significantly to improve their performance. Such macro-minerals are Ca, P, sodium (Na), chlorine (Cl), K, and Mg [6]. Approximately 5% of a pig's body weight is composed of minerals. Though these minerals are present in most feed grains, some contain inadequate levels to meet the requirements of pigs. Therefore, it is necessary to use additional minerals to balance the diet as they play an essential role in the digestion and structure of chromosomes, nerves, bones, hair, and milk, as well as in the metabolism of proteins, fats, and carbohydrates. It is also essential for most of the body's primary metabolic reactions, making it an important factor in growth, reproduction, and disease resistance. The efficiency of mineral intake always depends on the availability, source, and concentration of minerals used in the diet, as their interactions may vary depending on the health and needs of the individual animal. To date, most pigs are kept in confinement and rely mainly on daily feed, which provides more minerals to meet daily needs, and therefore it should be added to the diet arbitrarily.

Mg is considered one of the seven most essential macro-minerals in the diet of livestock because it plays a critical role as a cofactor for more than 300 enzymes [7]. This Mg is widely distributed in green leafy vegetables, nuts, seeds, dried beans, and whole grains [8]. It is also found in feed ingredients such as wheat bran, dried yeast, flaxseed, cottonseed, and green pastures. The average Mg content (g/kg DM) in cereals is estimated to be 1.1-1.3 g, while only 3.0-5.8 g in oil and fish meal containing 1.7-2.5 g [9]. Unlike Ca, Mg is readily available to ruminants (grazers) compared to non-ruminants. As for additives, oxides, carbonates, and sulfates are highly available sources of Mg for livestock [10]. Mainly, Mg oxide (MgO) is used as the highest mineral Mg source in feeds, and the MgO usually guarantees adequate uptake of Mg ions. Administration of Mg supplements is a best practice to improve the performance of livestock, especially fertility and yield. Previously, Gao et al. [11] study demonstrated that the inclusion of 150–300 mg/kg Mg supplementation increased the conception rate of sows by 11-15% and shortened the weaning to estrus interval in gilts by nine days.

Macro-minerals are a group of mineral elements that animals require in their diet to perform numerous physiological functions. Deficiencies of these elements in the animal's diet can lead to disease or dysfunction and must be addressed immediately. Ca and Mg are nutritionally essential minerals, especially Ca is a divalent extracellular cation, while Mg is an intracellular cation. Therefore, the cellular function of animals must be maintained by precise regulation to achieve better gastrointestinal absorption, renal reabsorption, and exchange with bone tissue in both cases. Most Ca supplements in swine diets are from inorganic sources because of inadequate Ca concentrations in the grain. In recent years, calcium carbonate (CaCO3) has been used extensively as a source of Ca in swine feed. It is usually obtained from pure limestone deposits (> 95% CaCO3) with Ca content between 36-38% and low impurities or trace traces of other minerals. These limestones have a granular appearance and are processed (extracted, selected, separated from impurities, coarsely crushed, and ground) and sorted by particle size to be used as a Ca source. Small fractions such as < 1.4 mm (~90%), < 1.0 mm (~8-9%), and < 0.5 mm (< 1%) are commonly used in swine feed. Ca readily interacts with various minerals in sediments such as P, sulfur, Zn, Cu, Mg, I, Mn, and Co. The ionic nature of these elements promotes the formation of insoluble complexes that precipitate and hinder their absorption and utilization in the gut. This Ca is considered a macro-mineral because it is present in the diet in amounts greater than 100 ppm. Cereals, oilseed meals, and many other plant components have very high and low Ca concentrations compared to animal proteins such as fish meal, meat and bone meal, and inorganic minerals such as limestone, CaCO3, and Ca3(PO4)2. Therefore, the demand for Ca has increased in modern sows with larger litters and higher milk production. Previously, Gao et al [11] reported that dietary Ca plays an essential role in the skeletal development of sows in late gestation. However, according to Miller et al [12], dietary calcium concentration in milk and other mineral elements is influenced by diet. In addition, Khoushabi et al [13] reported that higher mineral requirement (Ca) in late gestation affects colostrum synthesis by the mammary gland. in 1990, Mahan [14] said that high performance and prolonged farrowing time in sows are associated with a hypocalcemic response. Lower calcium availability reduces litter size, prolongs farrowing time, leads to more stillbirths, and causes skeletal problems in piglets.

Micro-mineral copper has a metabolic response that includes cellular respiration, tissue pigmentation, hemoglobin formation, and connective tissue development. CU is absorbed mainly in the upper gastrointestinal tract, especially the duodenum, but some Cu is absorbed in the stomach. Cu has been reported to have antimicrobial effects when administered at concentrations above pharmacological requirements (100-250 ppm) [15]. It is also an essential component of several metalloenzymes, including cytochrome C oxidase, lysyl oxidase, cytosolic Cu-Zn superoxide dismutase (SOD1), extracellular Cu-Zn superoxide dismutase 3 (SOD3), monoamine oxidase, and tyrosinase [16]. This Cu in pig feed comes from plant or animal ingredients or mineral supplements. The most commonly used cereal grains and their by-products in swine diets contain 4.4 to 38.4 mg/kg Cu on a per-feeding basis. However, the Cu content of individual plant feed ingredients varies depending on variety, soil type, maturity, and climatic conditions during growth [17]. Oilseed meals, including soybean, cottonseed, and flaxseed, generally have higher Cu concentrations than cereal grains [18]. Copper in dairy products such as skim milk, lactose, casein, and whey powder ranges from 0.10 to 6 mg/kg [19].

Minerals can perform various functions on farm animals. They can form the structural components of body organs and tissues, exemplified by Ca, P, and Mg; bones and teeth are exemplified by silicon, while muscle protein is exemplified by P and S. Moreover, Zn and P can provide structural stability to the molecules and membranes they also comprise an electrolyte in body fluids and tissues and are involved in maintaining osmotic pressure, acid-base balance, membrane permeability, and transmission of nerve impulses [20]. Sodium, potassium, chloride, calcium, and magnesium in the blood, cerebrospinal fluid, and gastric juice are the best examples of this physiological function. In addition, they can act as catalysts in enzymes and endocrine systems, as structural components and specific components of metalloenzymes and hormones, or as activators (coenzymes) in these systems. Since the late 1990s, the number and diversity of identified metalloenzymes and coenzymes have increased. The activities can be anabolic or catabolic, life-promoting (oxidants), or life-protective (antioxidants) [20]. It can also regulate cell replication and differentiation. Thereby, Ca affects signal transduction, and selenocysteine affects gene transcription.

MINERALS REQUIREMENT FOR PIG PERFORMANCE

Mineral requirements are challenging to determine, and most assessments are based on the minimum amounts needed to overcome deficiencies, not necessarily for productivity or immunity [21]. Several studies have been conducted over the past 40 years to determine the mineral requirements of genotypes and feeding systems that differ significantly from modern commercial swine operations. The EU government has primarily become the benchmark for limiting mineral intake to reduce pollution. As a result, the use of Cu and Zn in pig feeding has been severely restricted recently. However, the industry views these two minerals as cost-effective for promoting growth and reducing post-weaning diarrhea. In 1998, the NRC [4] recommended that 400 mg/kg Mg was optimal for swine. In livestock, diarrhea was the most apparent effect of high Mg intake. However, Van Heugten [22] reported that pigs fed high Mg supplements (i.e., seven times the minimum requirement) had dramatically reduced feed intake and weight gain.

Nutritional factors and age influence the Cu requirements in pigs. Newborn pigs typically require 5 to 10 mg Cu per kg of feed for normal metabolism [23]; as pigs age increase, Cu requirements may decrease. However, Kim et al. [24] demonstrate that 75 to 250 mg/kg of Cu supplement could increase growth performance and reduce diarrhea incidence in growing and weaning pigs, respectively. Similarly, Lorenzen and Smith. [25] reported that primiparous and multiparous sows require 10 mg Cu per kg feed supplement during gestation. According to NRC [19], feeding high levels of Cu, i.e., 60 mg Cu per kg, during pregnancy and lactation improves the reproductive performance of sows compared to sows fed diets containing 6 mg/kg Cu (Table 1). However, Cromwell et al [26] found that sows fed diets containing 250 mg/kg

Cu from $CuSO_4$ had lower shedding rates, farrowed larger litters of pigs, and had heavier pigs at birth and weaning compared to sows fed diets without added Cu.

FACTORS THAT AFFECT MINERAL REQUIREMENT IN PIGS

Understanding the principles of genetics, environment, herd health, management, and nutrition is more important for effective and profitable swine production because these sectors' output may touch the production volume and profitability [27]. In addition, numerous factors affect the mineral need of animals, including weather conditions, breeding, the chemical form of elements, and mineral intake. For instance, McDowell [28] addressed that livestock gains weight rapidly during the wet season because energy and protein supplies are adequate, and thus mineral requirements are high but in the dry season, animals with insufficient protein and energy lose weight, which reduces mineral requirements. For successful breeding, pigs require certain minerals. Chromium is required for insulin production, which affects progesterone production and follicle stimulation, and luteinizing hormone. Both hormones are needed to regulate ovulation, which greatly impacts fertility and litter size [29]. Manganese is required for progesterone production, and iron and chromium are required for hormone functions that affect fetal survival during pregnancy. Additionally, breeding sows can often lack mineral intake, especially when tissue reserves are worn-out [29]. Thus, uterine capacity, which determines the number of piglets born, requires an adequate dietary intake of selenium, iron, and chromium. Furthermore, Zn has become an essential nutrient for many physiological processes in the organism, supporting health and good growth and development. The major functions of Zn on a cellular level are to catch free radicals and to prevent lipid peroxidation as part of the antioxidant system. At the same time, zinc deficit in pigs may reduce the pork quality after slaughter and processing [30].

EFFICACY OF MINERALS SUPPLEMENT IN PIGS

Zinc oxide is inexpensive and may be the best alternative to antibiotics to control diarrhea after weaning. Therefore, dietary supplementation with ZnO is commonly used 2 to 3 weeks after weaning. However, excessive Zn concentrations in feces are of concern due to the environmental impact. Therefore, many studies have been conducted to evaluate the use of BioplexTM Zn as a possible substitute for ZnO due to its higher bioavailability. In 2003, Close [21] studied the immune response to pathogens and disease prevention by maintaining healthy epithelial tissue in pigs fed diets containing zinc. However, ZnO is known to alter the diversity of the microbiota in the gastrointestinal tract [31]. In light of efforts to limit or ban the use of antibiotics in swine diets, it is critical to learn more about how zinc affects the gut microbiota and its function; thus, it may contribute to the development of feeding Strategies to benefit animals in a cost-effective and eco-friendly environment. Bone is the principal deposit of calcium, containing more than 90% of the body, whereas the remaining 1% is essential for cell metabolism, blood clotting, enzyme activation, and neuromuscular action [32]. In most animals, calcium is absorbed in the duodenum and jejunum [33]. Vitamin D plays a vital role in the absorption and metabolism of calcium and phosphorus [34]. Moreover, calcium absorption is an active and passive process mediated by vitamin D [35]. In pigs, calcium absorption is increased by vitamin D, decreased by high dietary fat content, decreased by acidic dietary pH, and decreased by phyto-P. More recently, calcium carbonate has been widely used as a supplemental calcium source [36] because of its low cost and buffering capacity. Dietary calcium and phosphorus levels have been reported to affect reproduction and, thus longevity of sows [37]. Previous studies have reported that dietary calcium content can affect glucose and lipid metabolism [11].

Similarly, Zang et al [38] found that magnesium supplementation significantly shortened the interval between weaning and oestrus in gilts and sows ($P < 0.05$). It also increases the number of piglets born, born alive, and weaned in sows. Digestibility of crude fiber (secondary effect, $P < 0.05$) and crude protein ($P < 0.05$) in gilts and sows was significantly affected by magnesium during late gestation and lactation. Serum prolactin levels in sows and alkaline phosphate activity increased linearly with magnesium supplementation at farrowing and weaning ($P < 0.05$). Magnesium levels in sow colostrum and piglet serum increased after magnesium supplementation ($P < 0.05$). In addition, growth hormone levels in the serum of lactating sow piglets increased linearly ($P < 0.05$). Yang et al [39] reported that a diet supplemented with various calcium sources altered ADFI and partial gut microbial composition in weanling piglets, but had little effect on gut microbial function.

Adding 0.015% to 0.03% magnesium to sow diets could positively affect the reproductive parameters and serum mineral content [38]. Besides, sows that have passed three parities exhibit lower mineral content in their blood compared to nongravid gilts [40, 41]. As the sow's age increases, Ca and Mg stores in their body may decrease, making sows more dependent on dietary minerals, indicating an average effect and the need for dietary supplementation with high-quality soluble minerals [42]. Thus, adequate nutrition via the placenta is critical for normal fetal development because the maternal-fetal interface acts as a nutrient sensor that coordinates maternal nutrient supply and fetal metabolic needs [43,44]. Maternal mineral and vitamin status influence hormonal regulatory pathways linking maternal metabolism to the fetoplacental unit [45]. A calcium-rich diet has been shown to suppress calcitriol levels, thereby controlling lipogenesis and lipolysis. This affects lipid and energy metabolism in sows, fatty acids and triglycerides in the umbilical cord and placenta, and mRNA expression of the SLC2A2, FAS, FAB, CD36, and SCD genes, thereby affecting lipid and energy metabolism in development. Fetus and the downregulation of agouti signaling proteins [46, 47, 10].

Feeding 100 to 250 mg/kg Cu to weaning pigs improved ADG and ADFI [48,49]. Lower diarrhea incidence and higher feed conversion were also observed when a high concentration of Cu was included in diets for weaning and growing pigs [50]. Adding 60 to 250 mg Cu per kg to sows' diets during late gestation and lactation reduces pre-weaning mortality [51]. It increases the weaning weight of pigs (Wallace), presumably due to increased milk production. The higher ADFI in pigs fed Cu may be due to Cu's role in upregulating neuropeptide Y's mRNA expression [52], a neuropeptide considered to stimulate feed intake [53]. One of the suspected mechanisms of Cu to improve growth performance is that Cu can stimulate the activities of enzymes involved in nutrient digestion [54]. Adding high concentrations of Cu increased lipase and phospholipase A activities in the small intestine [55], which may lead to increased uptake of fatty acids and improved growth performance. In addition, Cu alters the 3-dimensional structure of bacterial proteins, which prevents bacteria from performing their normal functions [56]. In a previous study, Sterritt and Lester [57] reported that copper disrupted enzyme structures and functions of bacteria by binding to S- or carboxylate-containing groups and amino groups of proteins. A copper-rich diet did not improve the growth performance of germ-free pigs, but the copper-rich diet increased ADG and ADFI in conventionally raised pigs [58]. In addition, Wang et al [59] found that Cu-enriched diets for weanling pigs decreased the number of enterococci in the stomach and increased the lactobacillus population in the cecum of young pigs. The addition of 150 mg/kg Cu in the form of Cu hydroxychloride to diets for growing pigs also decreased microbial protein concentrations, probably due to the ability of Cu to inhibit the growth of microbes in the digestive tract of pigs [50]. This suggests that the observed improvement in growth performance in pigs fed Cu-supplemented diets is due to better digestibility and the presence of good bacteria (lactobacillus).

CONCLUSION

Dietary mineral concentrations are acceptable as long as the diet is palatable, does not restrict feed intake, and has the advantage of being simple and relatively constant. However, required dietary mineral concentrations are influenced by the efficiency of utilizing organic components in the diet. The total phosphorus requirement of the livestock might increase as production begins, but the proportion in the diet remains the same, while the calcium concentration required increases about 10-fold. In addition, Mg supplementation is essential to enhance farm animals' productive and reproductive performances. Regardless of whether the requirement is expressed in quantity or concentration, it may be significantly affected by factors limiting mineral uptake and utilization, remains debatable, and requires more detailed study.

REFERENCE

1. National Research Council. Nutrient Requirements of Swine – Eighth Revised Edition. National Academy of Sciences, Washington DC;1979.

2. Agricultural Research Council. The Nutrient Requirements of Pigs. Commonwealth Agricultural Bureaux, Slough; 1981.

3. Standing Committee on Agriculture. Feeding Standards for Australian Livestock – Pigs. CSIRO: East Melbourne; 1987.

4. National Research Council. Nutrient Requirements of Swine – Tenth Revised Edition. National Academy of Sciences, Washington DC; 1998.

5. Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. Heavy metal toxicity and the environment. Molecular, clinical, and environmental toxicology. 2012; 133-64. https://link.springer.com/chapter/10.1007/978-3-7643-8340-4_6.

6. Brian T. R. Macro Minerals for Swine Diets. 2010; Factsheets Number PIG 07-02-07; https://porkgateway.org/resource/macro-minerals-for-swine-diets.

7. Institute of Medicine (IOM). Food and Nutrition Board. Dietary Reference Intakes: Calcium, Phosphorus, Magnesium, Vitamin D and Fluoride. Washington, DC: National Academy Press, 1997.

8. Rude RK. Magnesium. In: Ross AC, Caballero B, Cousins RJ, Tucker KL, Ziegler TR, eds. Modern Nutrition in Health and Disease. 11th ed. Baltimore, Mass: Lippincott Williams & Wilkins; 2012; 159-75

9. Lipinski K, Stasiewicz M Purwin C, Z˙uk-Gołaszewska K. Effects of magnesium on pork quality. J Elem. 2011; 16, 325–337.

10. European Commission. Animal Feed. Available online: https://ec.europa.eu/food/safety/animal-feed_en (accessed on 16 September 2020)

11. Gao LM, Xie CY, Zhang TY, Wu X, Yin YL. Maternal supplementation with calcium varying with feeding time daily during late pregnancy affects lipid metabolism and transport of placenta in pigs. Biochem Biophys Res Commun. 2018; 505(2):624-30. https://doi.org/10.1016/j.bbrc.2018.09.143

12. Miller MB, Hartsock TG, Erez B, Douglass L, Alston-Mills B. Effect of dietary calcium concentrations during gestation and lactation in the sow on milk composition and litter growth. J Anim Sci. 1994; 1, 72(5):1315-9. https://doi.org/10.2527/1994.7251315x

13. Khoushabi F, Shadan MR, Miri A, Sharifi-Rad J. Determination of maternal serum zinc, iron, calcium and magnesium during pregnancy in pregnant women and umbilical cord blood and their association with outcome of pregnancy. Mater Socio Med. 2016; 28(2):104.

14. Mahan DC. Mineral nutrition of the sow: a review. J Anim Sci. 1990; 1, 68(2):573-82. https://doi.org/10.2527/1990.682573x

15. Shannon MC, Hill GM. Trace mineral supplementation for the intestinal health of young monogastric animals. Front Vet Sci. 2019; 13, 6:73. doi: 10.3389/fvets.2019.00073.

16. Manto M. Abnormal copper homeostasis: mechanisms and roles in neurodegeneration. Toxics. 2014; 18, 2(2):327-45. https://doi.org/10.3390/toxics2020327

17. Underwood EJ and Suttle NF.1999. The mineral nutrition of livestock 3rd edition.

18. O'Dell BL. Role of zinc in plasma membrane function. J Nutr. 2000; 1, 130(5):1432S-6S. https://doi.org/10.1093/jn/130.5.1432S

19. National Research Council. Nutrient requirements of swine. National Academy Press, Washington, DC. 2012.

20. Suttle NF. The mineral nutrition of livestock-4-th ed. Wallingford, Oxfordshire: CABI Publishing. 2010.

21. Close WH. Trace mineral nutrition of pigs revisited: meeting production and environmental objectives. Rec Adv Anim Nutr Australia. 2003; 14:133-42.

22. Van Heugten, E. 2009. Magnesium in pig nutrition. (Accessed 16th June 2021) https://www.pig333.com/articles/magnesium-in-pig-nutrition_580/

23. Hill GM, Miller ER, Whetter PA, Ullrey DE. Concentration of minerals in tissues of pigs from dams fed different levels of dietary zinc. J Anim Sci. 1983; 1, 57(1):130-8. https://doi.org/10.2527/jas1983.571130x

24. Kim M, Cho JH, Seong PN, Jung H, Jeong JY, Kim S, Kim H, Kim ES, Keum GB, Guevarra RB, Kim HB. Fecal microbiome shifts by different forms of copper supplementations in growing pigs. J Anim Sci Biotechnol. 2021;63(6):1386. https://doi.org/10.5187/jast.2021.e118.

25. Lorenzen EJ, Smith SE. Copper and manganese storage in the rat, rabbit, and guinea pig. J Nutr. 1947; 1, 33(2):143-54. https://doi.org/10.1093/jn/33.2.143

26. Cromwell GL, Monegue HJ, Stahly TS. Long-term effects of feeding a high copper diet to sows during gestation and lactation. J Anim Sci. 1993; 1, 71(11):2996-3002. https://doi.org/10.2527/1993.71112996x

27. General Nutrition Principles for Swine, p.2. 2007. Kansas Swine Nutrition Guide, KSU Ag Exp Station.

28. McDowell LR. Mineral deficiencies and toxicities and their effect on beef production in developing countries. In Symposium: Beef cattle production in developing countries University of Edinburgh, Scotland 1976 (pp. 216-241).

29. Jules Taylor-Pickard. Better sow performance with the right minerals. Pig progress. 2018.https://www.pigprogress.net/pigs/better-sow-performance-with-the-right-minerals/

30. Lebret, B. and M. Čandek-Potokar, 2022b: Review: Pork quality attributes from farm to Part Processed pork Animal 16: 100383.

31. Katouli M, Melin L, Jensen-Waern M, Wallgren P, Möllby R. The effect of zinc oxide supplementation on the stability of the intestinal flora with special reference to composition of coliforms in weaned pigs. J Appl Microbiol. 1999; 87(4):564-73. https://doi.org/10.1046/j.1365-2672.1999.00853.x

32. Ammerman CB, Baker DP, Lewis AJ, editors. Bioavailability of nutrients for animals: Amino acids, minerals, vitamins. Elsevier; 1995 Jul 19.

33. Bronner F. Mechanisms of intestinal calcium absorption. J Cell Biochem. 2003; 1, 88(2):387-93. https://doi.org/10.1002/jcb.10330

34. National Research Council. Mineral Tolerance of Animals National Academies Press, Washington, DC, USA. 2005.

35. Norman AW. Studies on the vitamin D endocrine system in the avian. J Nutr. 1987; 1,117(4):797-807. https://doi.org/10.1093/jn/117.4.797

36. Mun J, Lee C, Hosseindoust A, Ha S, Tajudeen H, Kim J. Calcium chloride is a better calcium source rather than calcium carbonate for weanling pigs. J Anim Sci Biotechnol. 2022;64(5):871-84. DOI: https://doi.org/10.5187/jast.2022.e53.

37. Arthur SR, Kornegay ET, Thomas HR, Veit HP, Notter DR, Webb Jr KE, Baker JL. Restricted energy intake and elevated calcium and phosphorus intake for gilts during growth. IV. Characterization of metacarpal, metatarsal, femur, humerus and turbinate bones of sows during three parities. J Anim Sci. 1983; 1, 57(5):1200-14. https://doi.org/10.2527/jas1983.5751200x

38. Zang J, Chen J, Tian J, Wang A, Liu H, Hu S, Che X, Ma Y, Wang J, Wang C, Du G. Effects of magnesium on the performance of sows and their piglets. J Anim Sci. Biotechnol. 2014; 5(1):1-8. https://doi.org/10.1186/2049-1891-5-39

39. Yang A, Wang K, Peng X, Lv F, Wang Y, Cui Y, Wang Y, Qu D, Zhou J, Si H. Effects of Different Sources of Calcium in the Diet on Growth Performance, Blood Metabolic Parameters, and Intestinal Bacterial Community and Function of Weaned Piglets. Front Nutr. 2022;9.

40. Mahan DC, Newton EA. Effect of initial breeding weight on macro-and micromineral composition over a three-parity period using a high-producing sow genotype. J Anim Sci. 1995; 1, 73(1):151-8. https://doi.org/10.2527/1995.731151x

41. Mahan D, Taylor-Pickard J. Meeting the mineral needs of highly prolific sows. Pig Progr. 2008, 24:21-3.

42. Pinotti L, Manoni M, Ferrari L, Tretola M, Cazzola R, Givens I. The contribution of dietary magnesium in farm animals and human nutrition. Nutrients. 2021; 4;13(2):509.

43. Vonnahme KA, Lemley CO, Caton JS, Meyer AM. Impacts of maternal nutrition on vascularity of nutrient transferring tissues during gestation and lactation. Nutrients. 2015; 13,7(5):3497-523. https://doi.org/10.3390/nu7053497

44. Thayer ZM, Rutherford J, Kuzawa CW. The maternal nutritional buffering model: An evolutionary framework for pregnancy nutritional intervention. Evol Med Public Health. 2020 (1):14-27. https://doi.org/10.1093/emph/eoz037

45. Christian P, Stewart CP. Maternal micronutrient deficiency, fetal development, and the risk of chronic disease. J Nutr. 2010; 1;140(3):437-45. https://doi.org/10.3945/jn.109.116327

46. Parikh SJ, Yanovski JA. Calcium intake and adiposity. Am J Clin Nutr. 2003; 1, 77(2):281-7. https://doi.org/10.1093/ajcn/77.2.281.

47. Zemel MB, Sun X. Dietary calcium and dairy products modulate oxidative and inflammatory stress in mice and humans. J Nutr. 2008; 1,138(6):1047-52. https://doi.org/10.1093/jn/138.6.1047

48. Pérez VG, Waguespack AM, Bidner TD, Southern LL, Fakler TM, Ward TL, Steidinger M, Pettigrew JE. Additivity of effects from dietary copper and zinc on growth performance and fecal microbiota of pigs after weaning. J Anim Sci. 2011; 1, 89(2):414-25. https://doi.org/10.2527/jas.2010-2839

49. Hill GM, Cromwell GL, Crenshaw TD, Dove CR, Ewan RC, Knabe DA, Lewis AJ, Libal GW, Mahan DC, Shurson GC, Southern LL. Growth promotion effects and plasma changes from feeding high dietary concentrations of zinc and copper to weanling pigs (regional study). J Anim Sci. 2000; 1, 78(4):1010-6. https://doi.org/10.2527/2000.7841010x

50. Espinosa CD, Fry RS, Usry JL, Stein HH. Effects of copper hydroxychloride and choice white grease on growth performance and blood characteristics of weanling pigs kept at normal ambient temperature or under heat stress. Anim Feed Sci. Technol. 2019;1, 256:114257. https://doi.org/10.1016/j.anifeedsci.2019.114257

51. Thacker PA. Effect of high levels of copper or dichlorvos during late gestation and lactation on sow productivity. Can J Anim Sci. 1991;1,71(1):227-32. https://doi.org/10.4141/cjas91-025

52. Li J, Yan L, Zheng X, Liu G, Zhang N, Wang Z. Effect of high dietary copper on weight gain and neuropeptide Y level in the hypothalamus of pigs. J Trace Elem Med Biol. 2008; 19, 22(1):33-8. https://doi.org/10.1016/j.jtemb.2007.10.003

53. Gehlert DR. Role of hypothalamic neuropeptide Y in feeding and obesity. Neuropeptides. 1999;1, 33(5):329-38. https://doi.org/10.1054/npep.1999.0057

54. Dove CR. The effect of copper level on nutrient utilization of weanling pigs. J Anim Sci. 1995; 1, 73(1):166-71. https://doi.org/10.2527/1995.731166x

55. Luo XG, Dove CR. Effect of dietary copper and fat on nutrient utilization, digestive enzyme activities, and tissue mineral levels in weanling pigs. J Anim Sci.1996;1, 74(8):1888-96. https://doi.org/10.2527/1996.7481888x

56. Thurman RB, Gerba CP, Bitton G. The molecular mechanisms of copper and silver ion disinfection of bacteria and viruses. Crit Rev Environ Sci Technol. 1989;1,18(4):295-315. https://doi.org/10.1080/10643388909388351

57. Sterritt RM, Lester JN. Interactions of heavy metals with bacteria. Sci Total Environ. 1980; 1,14(1):5-17. https://doi.org/10.1016/0048-9697(80)90122-9

58. Shurson GC, Ku PK, Waxler GL, Yokoyama MT, Miller ER. Physiological relationships between microbiological status and dietary copper levels in the pig. J Anim Sci. 1990;1, 68(4):1061-71. https://doi.org/10.2527/1990.6841061x

59. Wang MQ, Du YJ, Wang C, Tao WJ, He YD, Li H. Effects of copper-loaded chitosan nanoparticles on intestinal microflora and morphology in weaned piglets. Biol Trace Elem Res. 2012; 149(2):184-9. https://doi.org/10.1007/s12011-012-9410-0.

Table 1. Requirement level of minerals in swine nutrition

Minerals	Requirement level	Animals	Reference
Magnesium	400 mg/kg diet	Swine	NRC, 1998 [4]
Copper	5 to 10 mg/ kg diet	Weaning Pigs	Hill et al., 1983 [23]
Copper	5 to 6 mg/kg diet	growing pigs	ARC, 1981 [2]
Copper	10 mg /kg diet	Gestation sows	Lorenzen and Smith, 1947 [25]
Copper	6 mg/kg diet	Lactation sows	NRC, 2012 [18]

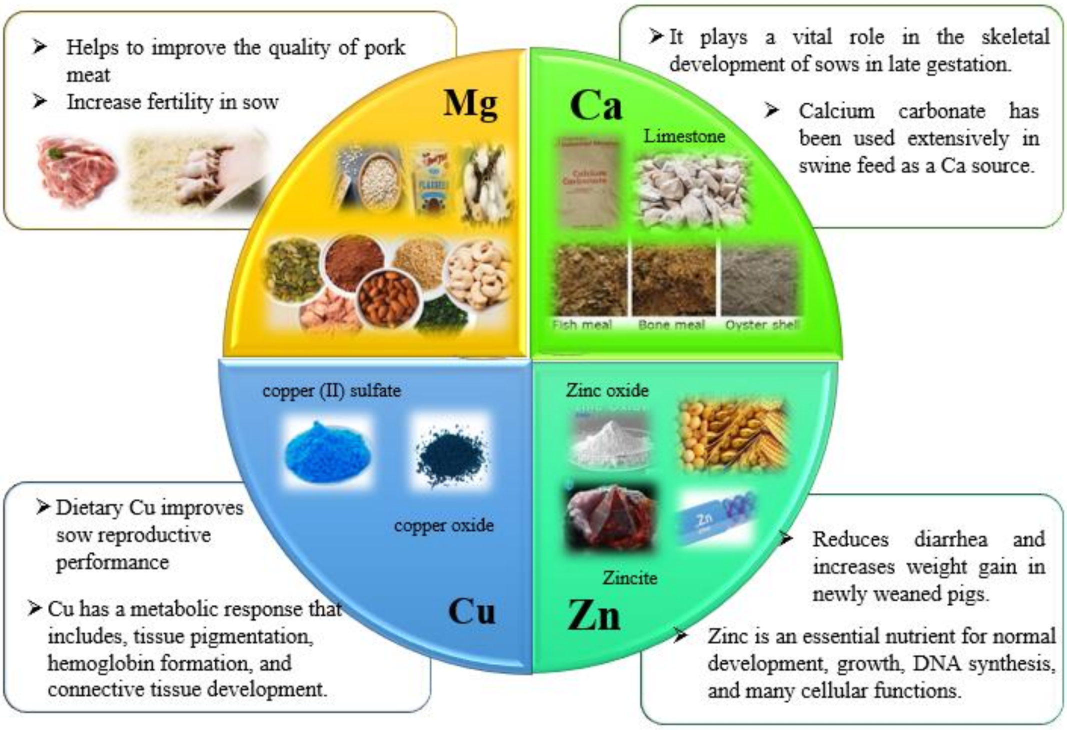

Fig. 1. Health benefits and beneficial application of Micro and Macro-Minerals in non-ruminant.

445

60.

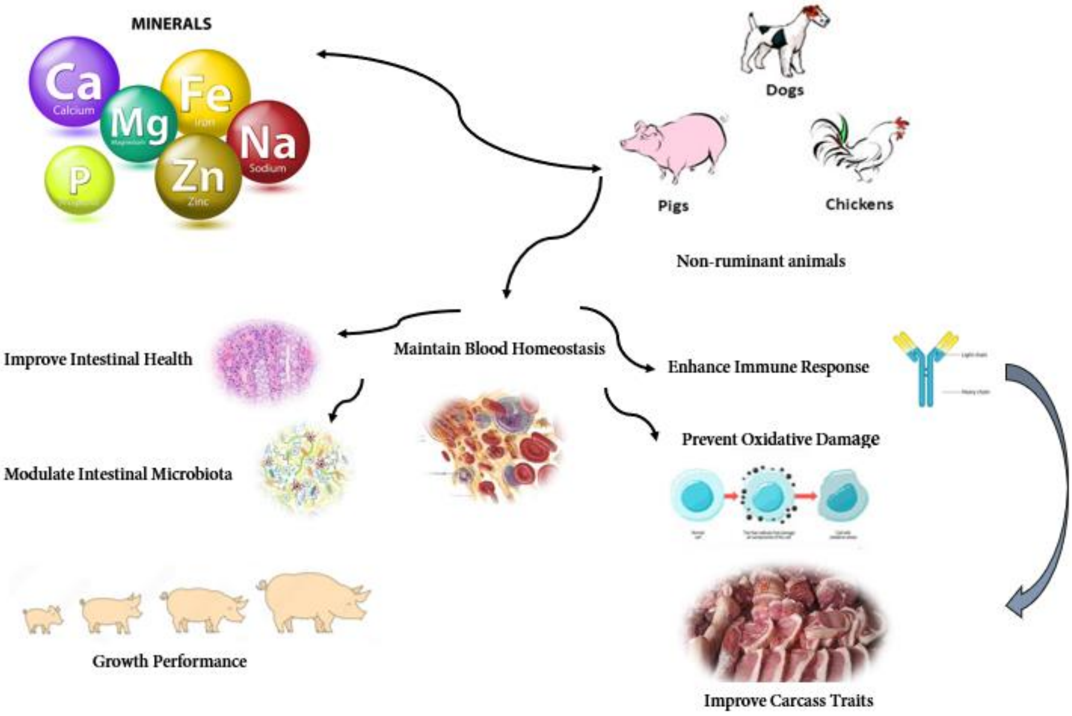

Fig. 2. Schematic view on the mode of action of the microminerals in non-ruminant diets.