

Review Article

The Use of Nanominerals in Animal Nutrition as a Way to Improve the Composition and Quality of Animal Products

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The demand for protein of animal origin and consumer awareness has been systematically increasing over recent years. This fact obliges breeders to provide animals with the best possible breeding conditions, which will condition the productivity of animals and the quality of products obtained from them. Nowadays, this is especially important because consumers are looking for food that is characterized by prohealth properties, a longer shelf life, and high sensory quality. Good results in improving the composition and quality of products of animal origin bring the use of nanominerals in animal nutrition. The purpose of this work was to collect and systematize knowledge related to the possibility of improving the composition and quality of animal products using minerals in the form of nanoparticles in animal nutrition.

1. Introduction

The term nanotechnology was first used by the now-deceased Norio Taniguchi in 1974, while its concepts were developed by Richard Feynman in 1959 [1–3]. It is defined as a study of phenomena and manipulations in atomic, molecular, and macromolecular scales, where properties differ from those on a larger scale [4]. The FDA in 2006, on the contrary, defined nanomaterials as particles smaller than micrometric scales, which exhibit specific properties [5]. In the agriculture and food industry, nanotechnology was discussed for the first time in the US Department of Agriculture (USDA) action plan published in September 2003 [6]. Currently, it is used to provide greater control over the nature of food, such as taste, texture, processing speed, heat tolerance, durability, safety, bioavailability of nutrients and its packaging [7–9].

Nanotechnology is also used in feeding farm animals [10]. The most important applications in this area are

nanominerals. They are characterized by a particle size of 1 to 100 nm. Some of these are stable at high temperature and pressure [11], and in addition, they can be easily assimilated in the digestive system [12]. This results in a better interaction with other biologically active substances due to the larger surface area *in vivo* [13]. Nanoparticles of gold can penetrate the small intestinal epithelium and further spread to the blood, brain, lungs, heart, kidneys, spleen, liver, and stomach [14]. The properties of nanominerals are determined primarily by their size, shape, and crystal structure [15].

Some surface-functionalized nanominerals and nano-components can bind and remove toxins and pathogens. Silver nanoparticles, for example, exhibit a strong antimicrobial effect [16–18]. The use of nanominerals, such as nano-selenium, nano-chromium, or nano-zinc, however, may improve the animal production parameters, their healthiness, and the quality of products obtained from them, especially that the conducted research proves that

they can be used better than the inorganic salts of these elements and chelates used on a large scale in the feed industry [19].

2. The Use of Nanominerals to Improve the Composition and Quality of Eggs

Eggs are very much appreciated by consumers due to their relatively low price, taste, and high nutritional value. Due to the popularity of this product, consumers often pay attention to its size, freshness, appearance, cholesterol content, fatty acid profile, as well as the content of minerals. In addition, food production, which will be characterized by a higher content of biologically active ingredients, and better quality becomes more and more important due to the growing consumer awareness and common shortages [20]. A good solution to the problem may be enriching food already at the level of animal husbandry, using feed additives in which biologically active ingredients, such as micro- and macroelements, will be characterized by better bioavailability [21]. Such a solution may be nanominerals used in animal nutrition. Attempts to improve the composition and quality of eggs using nanominerals have already been carried out several times.

Radwan et al. [22] used nano-selenium and sodium selenite in laying hens' nutrition. Analysis of the results showed that the use of nano-selenium had no effect on egg weight, feed intake, and most egg quality parameters. However, it turned out that egg production and feed conversion ratio were better in the nano-selenium groups. In addition, the groups receiving nano-selenium were also characterized by the highest concentration of this element in eggs. In egg yolk stored at room temperature for 15 days from hens receiving nano-selenium, higher activity of glutathione peroxidase and lower malondialdehyde content were also found. The addition of nano-selenium also improved the fatty acid profile in eggs by reducing the ratio of saturated to unsaturated acids. The addition of this nanomineral significantly decreased the level of total lipids and total cholesterol, as well as increased the level of its HDL fraction in egg yolk and plasma of laying hens. It should be noted, however, that all experimental groups were characterized by fatty liver with focal inflammatory cells aggregation. Salah-Eldin et al. [23] used selenium-methionine nanocomposite in feeding laying hens. They divided birds into 7 groups. The control group received sodium selenite in the amount of 0.3 mg/kg of feed. The experimental groups, on the contrary, received yeast enriched with selenium or a selenium-methionine nanocomposite in the amount of 0.1, 0.2, or 0.3 mg/kg of feed. The analysis of the results did not show any significant effect of the used preparations on birds' laying. It turned out, however, that the mass of eggs increased significantly ($P < 0.05$) along with the increase in the selenium level. The highest concentration of selenium ($P < 0.05$) was characterized by groups receiving selenium yeast, then those receiving the selenium-methionine nanocomposite. The lowest concentration of selenium was observed in the eggs of groups receiving sodium selenite.

Tsai et al. [24] performed an experiment that aimed at investigating how dietary supplementation with zinc oxide nanoparticles influences the retention of this element, egg production, shell quality, immune response, and serum aging parameters. In sample 1, the hens were divided into 4 groups: control, receiving zinc oxide, zinc-methionine, and nano-zinc. The control group received 40 mg Zn/kg of feed while the experimental groups 60 mg. In this test, the retention of nutrients and the bioavailability of zinc were evaluated. In sample 2, 68-week-old laying hens were also assigned to 4 groups, as in sample 1. This test evaluated egg production and shell quality, immune response, and serum parameters. Analysis of the results in sample 1 showed that the applied additives did not affect the retention of nutrients; however, the retention of zinc was significantly ($P < 0.05$) higher in the groups receiving nano-zinc and zinc-methionine. Analysis of the results in sample 2 showed that the thickness of the eggshell was significantly ($P < 0.05$) higher in the groups receiving nano-zinc and zinc-methionine compared with the control group. However, there was no difference in the immune response. The concentration of growth hormone in the blood serum and carbonic anhydrase were also significantly ($P < 0.05$) higher in the groups receiving nano-zinc and zinc-methionine in comparison with the control group. Serum albumin was significantly ($P < 0.05$) lower in the zinc-methionine group compared with the control group. Olgun and Yildiz [25] conducted a study to assess the effectiveness of dietary forms of zinc and its doses in terms of egg production efficiency, egg quality, and bone characteristics in laying hens. Zinc was given in four forms: zinc sulphate and zinc oxide in inorganic form, zinc-glycine in organic form, and powder of nano-zinc oxide in various doses (50, 75, and 100 mg/kg of feed). The addition of zinc-glycine significantly reduced egg mass and feed conversion ratio compared with the zinc sulphate group. Supplementation of nano-zinc oxide in the amount of 100 mg/kg of feed significantly reduced the thickness of the eggshell; however, these eggs were also characterized by the highest mass. These studies also showed that the addition of nano-zinc adversely affects bone mechanical properties. Abedini et al. [26] examined the effect of zinc oxide (ZnO-NP) nanoparticles on yield, egg quality, zinc content in tissues, bone parameters, superoxide dismutase activity, and malondialdehyde content in laying hens. The birds were assigned to 4 groups. In the control group, the zinc was not supplemented, while the hens from the experimental groups received 40, 80, and 120 mg Zn/kg with ZnO-NP. The hens receiving feed with the addition of 40 and 80 mg ZnO-NP were characterized by higher feed intake and higher egg mass compared with birds from other groups. The same groups were characterized by a thicker eggshell and its strength. All groups receiving zinc oxide nanoparticles were characterized by a better Haugh index than birds from the control group. All groups receiving zinc oxide nanoparticles also showed a higher content of zinc in the plasma, tibia, liver, pancreas, and egg compared with the control group. Supplementation of zinc oxide also increased the activity of superoxide dismutase in the liver, pancreas, and plasma of the studied birds. In addition, eggs from

chickens receiving the addition of zinc oxide were characterized by a significantly lower content of malondialdehyde.

Sirirat et al. [27] investigated the effect of chromium picolinate nanoparticles on yield, egg quality, mineral retention, and deposition in laying tissues. The analysis of the results showed no significant effect of the additives used, and their doses on birds body mass, feed intake, and egg production. It has been shown, however, that the use of nanoparticles of chromium picolinate can significantly ($P < 0.05$) improve egg quality. It has also been shown that the use of this preparation increases the accumulation of chromium, calcium, and phosphorus in the liver; chromium in the yolk; and calcium in the eggshell. Amiri, Andi, and Shahamat [28] conducted experiments on Japanese quail. They added different levels of nano-chromium to feed. The control group did not receive nano-chromium, while the experimental groups received 200 ppb, 400 ppb, 600 ppb, and 800 ppb of this mineral, respectively. Analysis of the results showed that the use of nano-chromium in the feed of Japanese quail increases egg weight, yolk mass, dense protein height, protein mass, mass and shell thickness, and the Haugh index ($P < 0.05$). However, it did not increase the chromium content in the egg and blood of the birds studied. Sathyabama and Jagadeeswaran [29] used various sources of chromium (inorganic, organic, and nano) in laying hens' nutrition to determine their effect on production parameters, mineral retention, and mineral accumulation in the tissues of the studied birds. They showed that none of the forms used had an impact on body weight, feed intake, production, and egg weight. However, chromium in the organic form and nano-chromium significantly increase ($P < 0.05$) the retention of chromium, zinc, iron, calcium, and phosphorus. In addition, organic chromium and nano-chromium in the amount of 400 $\mu\text{g}/\text{kg}$ of feed increased the concentration of chromium and zinc in the plasma, liver, and eggshell; calcium in the liver and eggshell; and zinc in egg yolk. Sathyabama et al. [30] also investigated the effect of various chromium forms and levels on egg quality. They showed that eggs from chickens receiving the addition of nano-chromium and organic chromium in the amount of 400 $\mu\text{g}/\text{kg}$ of feed and nano-chromium in the amount of 200 $\mu\text{g}/\text{kg}$ of feed are characterized significantly ($P < 0.05$) with higher shell strength than eggs of hens from the group control and receiving chromium in an inorganic form. However, the applied additives did not affect other egg quality parameters.

Ganjigohari et al. [31] conducted experiments on laying hens. They wanted to check if it was possible to replace calcium carbonate with nano-calcium carbonate. The birds were divided into 6 groups. The feed in the control group contained 8.06% calcium carbonate, the feed in the negative control contained 6.045% calcium carbonate, and in the feed of experimental groups, 4.03% calcium carbonate was replaced with 2.015%, 1.01%, 0.252%, and 0.126% of nano-calcium carbonate, respectively. The additives used did not affect the mass of eggs. However, it was noted that egg production was significantly ($P < 0.05$) lower in the group receiving 0.126% nano-calcium carbonate than in other groups. The hens from the control group were characterized

by the best feed conversion ratio ($P < 0.05$). The best quality of the eggshell was also noted in the control group ($P < 0.05$). Other experiments of these authors were carried out in the same layout [32]. This time, the authors also found that the group receiving the lowest level of nano-calcium carbonate was characterized by the lowest production of eggs; in addition, these eggs were characterized by the lowest shape index ($P < 0.05$). The additives used did not affect the weight of eggs, the feed conversion rate, and the Haugh index. Hen eggs from the group receiving 0.126% nano-calcium carbonate were characterized by the best yolk colour ($P < 0.05$).

3. The Use of Nanominerals to Improve the Composition and Quality of Meat

There are some differences between definitions of what "meat" is in life sciences, but overall, we can assume that meat is a tissue mostly composed from a muscle flesh. Muscle flesh consists roughly from 75% of water, about 20% of proteins, 1–10% of fat, and 1% of glycogen [33]. Meat plays many important roles in human life, like cultural, religious, and most important as a nourishment—source of proteins, various minerals, fatty acids, or vitamins [34].

With rapid development of modern animal farming and ever-growing awareness of consumers [35], meat quality must be on constant rise, both in terms of its nutritious and organoleptic properties [36]. Because of that fact, animal farming industry is searching for new ways to improve the overall quality of the meat and resources resulting from its processing, and one of the recently developed ways, bio-fortification with utilization of nanotechnology, shows great potential in doing so. Current research in the field is mainly focusing on feed enrichment with nano-sized particles and its effects on properties of meat.

Ahmadi et al. [37] conducted an experiment in which nano-selenium was added to the feed provided *ad libitum* to 180 Ross and 308 chicks that were divided into 6 groups with 10 birds each and 3 replicates of group. Supplementation has significantly ($P < 0.05$) improved weight gain and feed conversion rate during the entire experiment. Breast and drumsticks percentages were significantly higher ($P < 0.05$) in chicks with nano-selenium supplementation than in the control group. Additionally, abdominal fat percentage was significantly ($P < 0.05$) lower in the nano-selenium-supplemented group than in the control. Bakhshalinejad et al. [38] performed an experiment where they were investigating effects of sodium selenite, selenium-enriched yeast, DL-selenomethionine, and nano-selenium addition to the feed at levels from 0.1 to 0.4 mg/kg Se. Nano-selenium feed supplementation has affected EPEF (European Production Efficiency Factor) value which was significantly ($P < 0.05$) higher than that in the groups fed with sodium selenite. Survival rates were not affected by different sources of selenium or selenium levels. In case of breast muscles, significant differences in total superoxide dismutase activity, total antioxidant capacity, and malondialdehyde levels were observed after comparing nano-selenium with sodium selenite. Different sources and levels of selenium had no impact on major thigh muscle composition. Selenium content of

thigh muscle was affected by sources of supplemental selenium and levels ($P < 0.001$). There were significant ($P < 0.05$) contrast differences among comparison of organic vs. inorganic sources of selenium and nano-selenium vs. sodium selenite. Cai et al. [39] have investigated the effect of nano-selenium on performance, meat quality, immune function, oxidation resistance, and tissue selenium content in broilers. The experiment was conducted on 540 Arbor Acres broilers randomly allocated into 1 group out of the 5 with 6 replicates each. Groups consisted from 18 chickens. Following levels of nano-selenium supplementation were utilized during the experiment: 0.0, 0.3, 0.5, 1, and 2 mg/kg of nano-selenium. No significant differences were observed in performance, meat colour, and immune oxygen index. After 42 days, a significant quadratic effect of supplementation has been observed on peroxidase activity in serum, liver, and muscles; free radical inhibition in serum and liver; contents of IgM, glutathione, and malondialdehyde in serum. Considering all the analysed parameters, Cai et al. have suggested that the optimal level of supplementation lies between 0.3 and 0.5 mg/kg of nano-selenium, and that supplementation should not exceed 1 mg/kg nano-selenium with worst parameters received at 2 mg/kg of selenium supplementation. El-Deep et al. [40] have used nano-selenium supplementation in feeding thirty-six 15-day-old broiler chicks. Chickens were kept at temperatures either $22 \pm 1^\circ\text{C}$ or $35 \pm 1^\circ\text{C}$. Chickens were supplemented for 15 days with 0.3 mg/kg of nano-selenium. El-Deep et al. report that high ambient temperature significantly depressed body weight gain, feed intake, feed conversion ratio, breast muscle weight, and abdominal fat weight, while feeding nano-selenium significantly ($P < 0.05$) reduced these negative effects of high ambient temperature; in comparison with the control group, they also report that the usage of sodium selenite does not yield similar results. Li et al. [41] conducted an experiment where three hundred and sixty 50-day-old Chinese Subei male chickens were randomly allocated into four groups. Chickens in each group were fed with feed containing 0.3 mg Se/kg of following enrichments: sodium selenite, selenium-enriched yeast, selenomethionine, and nano-selenium for 40 days. Dietary selenium-enriched yeast, selenomethionine, and nano-selenium supplementation increased the activity of glutathione peroxidase in serum and breast muscles and decreased the concentration of malondialdehyde in serum and carbonyl in breast muscles compared with the sodium selenite group ($P < 0.05$). Additionally, selenomethionine and nano-selenium supplementation increased pH (45 min), total protein solubility, and myofibrillar protein solubility, as well as significantly ($P < 0.05$) decreased the shear force value compared with the group enriched with sodium selenite. Chickens in the selenium-enriched yeast and selenomethionine groups were exhibiting significantly ($P < 0.05$) lower cooking loss compared with the sodium selenite group. In conclusion, nano-selenium has significantly improved the quality of chicken meat. Liu et al. [42] examined the effects of corn-soybean diet supplementation with sodium selenite, nano-elemental selenium, and enriched yeast A and B on 2250 chicks that were divided into 5 groups with 6 replicates each. Obtained

results have shown that there were no significant ($P > 0.52$) differences between each treatment in terms of growth performance. Selenium-enriched yeast B significantly ($P < 0.05$) increased selenium concentration in the liver and breast muscles in comparison with other diets. No significant ($P > 0.66$) differences were observed in the liver and breast muscle Se concentrations between other utilized enrichments. Selim et al. [43] have used 400 one-day-old Arbor Acres chickens that were allocated in 10 experimental treatments, with 5 sources of Se, namely, sodium selenite, selenomethionine, zinc-L-selenomethionine, powder form of nano-selenium, and liquid form of nano-selenium; additionally, two levels of supplementation were used, 0.15 and 0.3 ppm. Feeding has been conducted in three phases: 1–10, 11–24, and 24–50 days. Results of the experiment have shown that selenomethionine, zinc-L-selenomethionine, nano-selenium powder, and liquid form of nano-selenium at level 0.30 ppm have resulted in significant ($P < 0.05$) improvement in growth performance, oxidation levels, carcass abdominal fat %, giblets %, and Se concentrations in both muscles and the liver. Selim et al. state that further research on the topic of Se-based feed enrichment is still needed. Zhou and Wang [44] have conducted an experiment in order to investigate the effect of feed supplementation with nano-elemental Se (nano-selenium) on growth performance, tissue Se distribution, meat quality, and glutathione peroxidase (GSHPx) activity in 360 Guangxi Yellow chickens. During the experiment, following treatments with 30 chickens in each were used: T-1, T-2, and T-3 treatment groups with 3 replicates. Diets for the control, T-1, T-2, and T-3 groups consisted of unmodified feed without addition (0.00) and enriched feeds (0.10, 0.30, and 0.50 mg/kg) of nano-selenium. Improved final body weight, daily body weight gain, feed conversion ratio, and survival rate ($P < 0.05$) were observed in the groups supplemented with nano-selenium as compared with the control groups after conclusion of the experiment. Groups receiving nano-selenium supplementation showed higher ($P < 0.05$) hepatic and muscle Se contents, drip loss percentage, inosine 5'-monophosphate content, and GSHPx activities in the serum and liver in comparison with the control group. For the T-2 and T-3 groups, in final body weight, daily weight gain, muscle Se content, breast drip loss, and GSHPx activities in the serum and liver were significantly improved ($P < 0.05$) compared with the T-1 group. No significant differences were observed in final body weight, daily weight gain, and GSHPx activities in the serum and liver between the T-2 and T-3 groups. It could be concluded from this study that supplementation of diet with 0.30 mg/kg of nano-Se was the most effective in increasing the growth performance and feed conversion ratios of chickens, the Se content of tissues, and the quality of the meat.

Liu et al. [45] performed an 8-week feeding trial to investigate effects of feed enrichment with sodium selenite, selenium nanoparticle (nano-Se), selenium yeast (Se-yeast). Sodium selenite and selenium nanoparticles were supplemented at 0.2 mg/kg Se, and selenium yeast (Se-yeast) was supplemented at 0.1, 0.2, 0.4, and 0.8 mg/kg in basal diet; no Se was added to control. Following parameters were

analysed: growth, selenium status, antioxidant activities, muscle composition, and meat quality of blunt snout bream. The results have shown that groups of 0.2 and 0.4 mg/kg Se-yeast had significantly ($P < 0.05$) higher weight gain and nano-Se 0.2 and 0.4 mg/kg Se-yeast had significantly lower feed conversion ratio when compared with the control group. The Se concentrations of the whole body, muscle, and liver linearly increased with increasing dietary Se-yeast levels. The group of 0.4 mg/kg Se Se-yeast significantly increased activities of catalase and glutathione peroxidase. Muscle colour of nano-Se, 0.2 and 0.4 mg/kg Se Se-yeast groups and the water holding capacity of 0.4 and 0.8 mg/kg Se Se-yeast groups were significantly better ($P < 0.05$) compared with the control group. Liu et al. concluded that Se-yeast and nano-Se had a better growth performance than sodium selenite at 0.2 mg/kg Se, and supplementing appropriate Se-yeast in diet can improve meat quality of blunt snout bream.

4. The Use of Nanominerals to Improve the Composition and Quality of Milk

For some time, there has been a systematic increase in demand for dairy products in developing countries. This is related to the fact that milk is a good source of nutrients, and its consumption affects the health and well-being of people. On average, about 88.5% of water, 11.5% of dry matter, 4.7% of lactose, 3.7% of fat, and 3.7% of protein can be found in cow's milk [46]. In addition, milk contains many biologically active compounds, such as immunoglobulins, hormones, cytokines, polyamides, nucleotides, peptides, fatty acids, fat-soluble vitamins (A, E, and K), carotenoids, and phospholipids. It also contains minerals and organic acid salts, which share milk from 0.65 to 0.7%. It should be remembered that the content of minerals (especially micronutrients) in milk depends on their content in feed [47, 48], which is why it is so important to use preparations with high bioavailability, which may be nanominerals.

So far, several studies have been carried out regarding the use of nanominerals in ruminant nutrition. However, they were designed to check how nanominerals affect animal health, digestibility of feed ingredients, and reduction of odors [49, 50]. Work on the possibility of improving the composition and quality of milk with the use of nanominerals was hardly ever produced. However, Rajendran et al. [51] used nano-zinc in feeding dairy cows. Their research has shown that the use of this nanomineral reduces the number of somatic cells in cow's milk with subclinical *mastitis*. In the course of these studies, it was also found that the use of nano-zinc in feeding dairy cows improves milk production compared with conventional sources of zinc. Considering the many positive effects that nanominerals have had on the composition and quality of other animal products, such as eggs and meat, research into the possibility of improving the quality of milk using these materials should also be carried out.

5. Summary

In recent years, there has been an increasing number of studies devoted to the possibility of improving the composition and quality of animal products using nanominerals in animal nutrition. Scientists manage to produce eggs, meat, or milk characterized by a higher content of minerals, better taste, smell, appearance, and suitability for longer storage. To date, many methods have been developed to improving food composition and quality; however, one of the cheapest and most effective is the use of feed additives. During many studies, it was shown that micro- and macroelements in the form of nanoparticles can be better absorbed by animals, which improves the quality of products obtained from them. This is particularly important in the case of supplementing the deficiencies of minerals commonly found in the human population. However, it should be remembered that sometimes the boundary between deficiency and excess of individual components can be very small (e.g., in the case of selenium), and excess mineral components can be as dangerous as their deficiency. Therefore, it should be considered whether the enrichment of animal products with the aid of feed supplementation with various levels and forms of minerals will consequently be safe for human health and life, especially since no concrete proposal of the optimal level of nanominerals used in animal nutrition has emerged. It should be also remembered that their use does not always bring the intended effect. Sometimes, it turns out that inorganic and organic forms of minerals are better absorbed, and the use of nanoforms not only does not improve but sometimes it negatively affects the production parameters of farm animals. Therefore, despite many promising results, the study on the use of nanominerals should be continued.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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