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Article

A Study on the Effects of Chelated vs. Inorganic Trace Elements on Growth Performance, Survival and Carcass Yield in Broiler Chickens

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Abstract

High-quality, well-balanced feeding strategies are essential for optimizing poultry growth performance and for ensuring the safety of poultry products. Here, we evaluated the effects of chelated vs. inorganic trace minerals on the growth, survival and carcass characteristics of Cobb 500 broiler chickens. A large-scale feeding trial involved four dietary treatments at 21–35 days of age, with Group 1 receiving a control diet with mineral supplements of zinc (Zn), copper (Cu) and manganese (Mn) in sulfate form, based on a standard formulation. A further three experimental diets contained chelated forms of Zn (Group 2), Cu (Group 3) and a mineral premix MINTREX[®] that provides Zn, Cu and Mn (Group 4). Broilers were raised to 42 days of age under commercial production conditions. Feeding chelated trace minerals resulted in significantly higher body weights during the rearing period, including a 10% increase in pre-slaughter weight compared to the controls ($p < 0.01$). Moreover, survival rates improved from 87% in the controls to 95–96% in the treatment groups ($p < 0.001$), and carcass evaluation revealed a 15–17% increase in eviscerated carcass weight in birds fed chelated supplements ($p < 0.05$). Greater yields of muscle, liver and skin with subcutaneous fat were observed, as was improved production of total edible carcass components. Among the treatments, MINTREX[®] provided the greatest enhancement effects in performance and slaughter traits. These findings demonstrate that dietary chelated minerals, whether single or combined, may have positive effects on the broiler carcass yield and support their inclusion in poultry production systems.



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Keywords: poultry nutrition; broiler chickens; mineral supplementation; chelated microelements; zinc glycinate; copper glycinate; manganese chelate; growth performance; carcass yield; survival rate

1. Introduction

Ensuring the quality and environmental safety of agricultural products through organic farming technologies is one of the central objectives of modern food supply and security [1]. The integration of breeding programs, nutritional management and husbandry practices [2] aims to optimize the output of poultry meat and eggs, while improving economic efficiency [3,4]. Consequently, poultry production also offers superior feed conversion efficiency for protein and energy, relative to other livestock systems [5,6].

Demands for increasingly stringent quality and safety standards of poultry products, however, prompt the industry to adopt even more innovative production and nutritional technologies [7]. They also encourage the use of high-performance genetic lines, breeds and crosses with enhanced growth rates and feed conversion ratios (FCR) [8–10]. The realization of this genetic potential [11–13], however, depends on improved nutrition regimes. Unfortunately, the current feeding strategies often fail to supply adequate levels of essential minerals and bioactive compounds, and this both limits performance and compromises meat quality [14,15]. Traditional supplementation with inorganic mineral salts has demonstrated limited efficiency due to low bioavailability, increased nutrient wastage and higher production costs [16]. Poor absorption of inorganic microelements thus remains a key nutritional bottleneck in poultry meat production [17,18].

The rapid growth of the poultry industry has heightened the need for more bioavailable mineral sources to mitigate nutritional and environmental stressors [17–19]. Advances in nutritional biochemistry demonstrated that chelated microelement compounds can increase bioavailability and utilization efficiency substantially [20–22]. Amino acid–metal chelates act as stable, highly absorbable delivery systems for essential trace elements [23,24]. The most commonly applied chelated elements—copper (Cu), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), and manganese (Mn)—are typically supplied as sulfate- or glycine-bound complexes, each with specific absorption and metabolic profiles [25–29].

Chelated microelements are absorbed in the gastrointestinal tract as stable complexes of divalent metals with protein hydrolysates or amino acids, enhancing intestinal permeability and absorption efficiency [17,30]. Present in various forms, glycinate demonstrate several advantages: (1) high stability under acidic gut conditions [31]; (2) reduced antagonistic interactions with dietary phytates; (3) minimal competition among mineral ions; and (4) efficient transport across the intestinal epithelium [27,28]. Consequently, chelated microelements represent a promising alternative to conventional mineral sources, addressing nutritional limitations that hinder genetic potential, while supporting sustainable and environmentally responsible poultry production.

Several studies confirm the positive effects of chelated trace minerals on productivity and physiological traits. Khaghani et al. [32] reported that Fe, Zn, and Cu glycinate supplementation in laying hens improved eggshell thickness and strength while reducing blood cholesterol and increasing yolk quality indices. In the jejunum and ileum of broilers, organic Zn with a moderate chelation intensity increases the expression of associated transporters [33]. Yaqoob et al. [34] demonstrated that replacing inorganic trace minerals with organic glycinate enhanced the liver antioxidant status and egg quality in broiler breeders. De Marco et al. [35] found that glycine-complexed trace minerals improved broiler performance, slaughter yield and mineral retention. Similarly, Kwiecień et al. [36] observed that Cu glycinate supplementation enhanced femur strength characteristics compared to Cu sulfate. These findings indicate that organic glycinate may replace conventional sulfates without impairing growth or bone quality.

The superior performance of chelated minerals stems from their structural similarity to naturally occurring complexes, enabling efficient transport across biological membranes and immediate cellular utilization without prior metabolic transformation [37]. In addition

to their nutritional role, chelated metal complexes can exhibit biocatalytic and enzyme-mimetic properties [38], contributing to the development of new regulators of mineral metabolism and compounds with bactericidal, antiviral, or antiallergic activity [39,40]. This multifunctionality underscores the broad significance of chelation chemistry in nutrition, pharmacology and feed technology [41]. In pharmaceuticals, metal complexes are widely used as biologically active compounds—examples include insulin (Zn complex), vitamin B₁₂ (cobalt complex) and cisplatin (platinum complex) [42].

The growing intensification of poultry production necessitates the use of nutraceuticals (vitamins, probiotics, prebiotics and trace minerals [43–47]) and effective premix formulations to sustain optimal productivity under high-density conditions. These compounds also support growth and improve carcass yield and composition [39]. Previously, we conducted preliminary studies under the vivarium conditions and on a limited flock to test the efficacy of chelated trace elements in rearing broilers in terms of their growth, slaughter traits, meat safety and quality [23,48]. In the current study, we expanded on this research to examine in detail the impact of chelates on broiler feeding and productivity. The underlying hypothesis of the current investigation is therefore that chelated (organic) trace elements can be absorbed better by the body of broiler chickens compared to inorganic forms. We propose that this potentially enhances growth, survival, meat yield and quality, thereby increasing the poultry production efficiency. This study, conducted on a larger production flock, therefore aimed to further evaluate the performance, survival and slaughter yield of broiler chickens whose diet had been supplemented. Supplements containing chelated micronutrients alone were compared to those incorporated into a premix formulation.

2. Materials and Methods

2.1. Birds and Experimental Design

A large-scale experiment was conducted on 1200 Cobb 500 hybrid broiler chickens of both sexes at the poultry farm of OJSC “Putivsky Broiler”. All animal procedures strictly complied with the European Union (EU) Directive 2010/63/EU [49], as amended by the EU Regulation 2019/1010 [50], and other relevant requirements [51,52], ensuring compliance with ethical standards for animal experimentation. The trial lasted 42 days. The birds were reared in an intensive production system in the same feeding and microclimate conditions. In particular, broilers were fed diets that were balanced according to their requirements for energy, nutrients, and biologically active substances, with ad libitum access to feed and water, as described elsewhere [53–55]. The microclimate of the facility was automatically controlled.

The healthy birds were randomly divided into four groups (control and experimental) of 300 individuals each, according to the principle of analogs. The control Group 1 received a basal diet according to a standard recipe (Table 1) supplemented with inorganic (sulfated) trace elements in the form of ZnSO₄, CuSO₄ and MnSO₄ (Table 2). The content of the latter, added from the 21st day to the 35th day of broiler raising, was 92–100 µg per 1 kg feed for both Zn and Mn and 9–10 µg per 1 kg feed for Cu (Table 2). Three experimental groups were fed a diet enhanced with chelated forms (glycinates) of these mineral additives, instead of sulfates. Group 2 received the feed enriched with a chelated form of Zn (92–100 µg per 1 kg feed). Group 3 was given the feed enriched with a chelated form of Cu (9–10 µg per 1 kg feed). Group 4 was fed a diet supplemented with the premix MINTREX[®] (Novus International, Inc., Chesterfield, MO, USA), used as the source of chelated microelements (92–100 µg per 1 kg feed for both Zn and Mn and 9–10 µg per 1 kg feed for Cu; Table 2).

Table 1. Basal feed rations for broilers in the rearing period.

| Component, % | Diet | | |
|------------------------------------|---------|--------|----------|
| | Starter | Grower | Finisher |
| Wheat | 38.574 | 42.739 | 39.303 |
| Soybean meal | 35.957 | 32.439 | 27.361 |
| Corn | 20.000 | 20.000 | 25.000 |
| Soybean oil | 1.000 | 1.591 | 2.409 |
| Sunflower meal (crude protein 35%) | 0 | 0 | 2.000 |
| Limestone | 1.419 | 1.021 | 1.321 |
| Premix | 0.500 | 0.500 | 0.750 |
| Monocalcium phosphate | 0.891 | 0.482 | 0.421 |
| Salt | 0.390 | 0.386 | 0.385 |
| Lysine sulfate | 0.543 | 0.338 | 0.517 |
| DL-methionine (98.5%) | 0.330 | 0.246 | 0.230 |
| L-threonine (98%) | 0.200 | 0.093 | 0.138 |
| Betaine hydrochloride (72%) | 0.070 | 0.055 | 0.055 |
| SafMannan | 0.100 | 0.050 | 0.050 |
| Coccisan | 0.056 | 0.060 | 0.060 |

Table 2. Content of trace elements Zn, Cu and Mn (in µg per 1 kg feed) in broiler diets.

| Groups | Age, Days | Zn | Cu | Mn |
|--|-----------|-----|----|-----|
| 1 (control, mineral additives as sulfates) | 21–24 | 92 | 9 | 92 |
| | 25–36 | 100 | 10 | 100 |
| 2 (chelated Zn) | 21–24 | 92 | 0 | 0 |
| | 25–36 | 100 | 0 | 0 |
| 3 (chelated Cu) | 21–24 | 0 | 9 | 0 |
| | 25–36 | 0 | 10 | 0 |
| 4 (MINTREX [®] : chelated Zn + Mn + Cu) | 21–24 | 92 | 9 | 92 |
| | 25–36 | 100 | 10 | 100 |

The above methodology in the experimental design used can be briefly justified as follows. Doses of Zn, Cu or Mn in the diets of the three experimental groups were identical to those in the control group, with the only difference being in their chemical form, i.e., sulfates vs. chelates. This allowed for a correct assessment of bioavailability and efficacy of the microelement treatments, rather than their dose effect. In other words, the experimental design was based on equivalent doses, when chelated forms were administered in the same amounts of trace elements as in the control group (only their form differed, not the dose). This seems to be a standard and correct approach for such comparative treatment studies.

The molecular structure of chelated microelements includes chelates (glycinates) of Zn, Cu and Mn, bound to a hydroxy analog of methionine, where two ligands covalently bind a single metal atom (Figure 1).

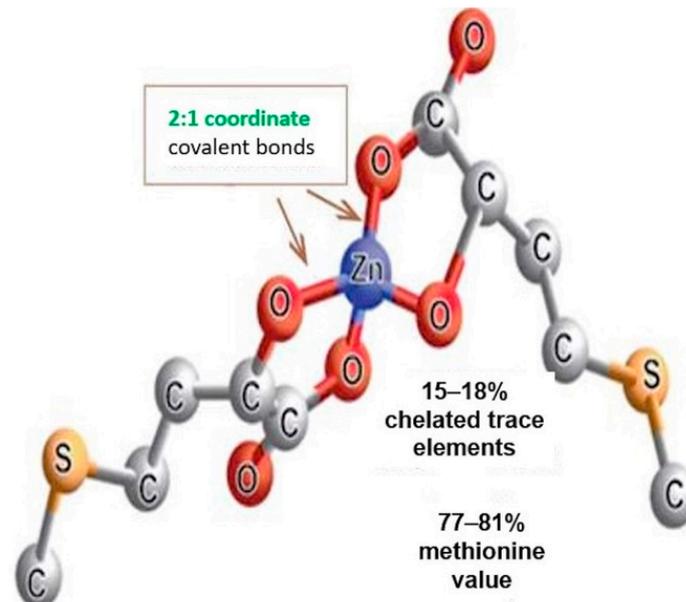


Figure 1. Chemical structure of the compound containing chelated zinc (Zn) (modified from [56]).

The composition and pharmaceutical compatibility of chelated microelement ingredients were analyzed using an MSBH-01 mass spectrometer (LLC SVP Akadempriyad, Sumy, Ukraine) with sample ionization by ^{252}Cf fission fragments [57,58].

2.2. Determination of Zootechnical Indicators

The performances of broiler chickens were assessed based on the major standard zootechnical parameters: body weight and survival as described elsewhere [59]. Body weight was measured individually using electronic scales (accurate to ± 1 g) at 7, 14, 21, 28, 35 and 42 days of age. Survival rate was recorded daily and over the whole rearing period, according to the total number of culled or dead birds. This rate was calculated as the percentage of birds remaining at the end of the experiment, relative to the initial number of chicks housed at the beginning of the trial in each group. The average daily feed intake was determined in g per head for each week period, i.e., 1–7, 8–14, 15–21, 22–28, 29–35, and 36–42 days of age). Similarly, FCR values in broiler chickens were computed based on feed consumption per 1 kg of body weight gain.

2.3. Pre-Slaughter Condition and Slaughter Procedure

The assessment of the pre-slaughter condition and subsequent meat quality and safety evaluation of broiler carcasses were conducted according to the Rules for Pre-slaughter Veterinary Inspection of Animals and Veterinary–Sanitary Expertise of Meat and Meat Products [60]. Bird behavior, feather condition, mucous membranes, eye and cloacal discharges, beak, comb and limb appearance, feces consistency, respiration and body temperature were all examined. Before slaughter, birds were fasted for 10 h with free access to water, which was restricted 3 h prior to slaughter. Body weight prior to slaughter was also measured.

Proper slaughter procedures were followed as described elsewhere [61,62]. Bleeding was performed by severing the neck vessels, after which carcasses were scalded at 51–57 °C for 2 min and manually defeathered. Unprocessed carcasses were weighed after bleeding. Uneviscerated carcass weight was measured for carcasses without blood and feathers, but with intact internal organs, head, and legs. Evisceration was carried out using standard methods [61–63]. Carcass yield and composition parameters (weights of uneviscerated, semi-eviscerated, and eviscerated carcasses, edible and inedible organs) were determined

according to the established procedures [52,64]. The semi-eviscerated carcass weight was determined without internal organs. The eviscerated carcass weight was produced without a head, up to the second cervical vertebra, legs up to the tarsal joint, neck skin at shoulder level, and all internal organs. Muscle weight included the breast, thighs, drumsticks, trunk, wings, and neck. Skin, including neck skin, was weighed with subcutaneous fat, liver without gallbladder, heart without pericardium, and gizzard without content and cuticle. Internal fat included mesenteric, gizzard and abdominal fat. The head was weighed up to the second cervical vertebra and legs up to the tarsal joint. Bones also included neck bones, and the intestine included contents.

2.4. Statistical Analyses

Data analysis was performed using Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA, USA) and STATISTICA 8 (Statsoft, Inc./TIBCO, Palo Alto, CA, USA) for repeated-measures analysis of variance (rANOVA). Results are presented as group means and standard errors of the mean ($M \pm SEM$), using Microsoft Excel. Statistical significance was tested using the non-parametric Mann–Whitney U-test and Student's *t*-test as implemented in the GraphPad online calculator [65], with differences considered significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$. Principal component analysis (PCA) and hierarchical clustering were performed using the Phantasm web platform (version 1.27.1) [66,67].

3. Results

3.1. Zootechnical Parameters

The body weights of broiler chickens during the 6 week rearing cycle is presented in Table 3. Body weight measurements demonstrated a significant increase in the chelated microelements groups at 14, 21, 28, 35 and 42 days of age compared to the controls ($p < 0.01$ or $p < 0.001$; Table 3). These results confirm a consistent positive effect of chelated trace elements on the broiler growth rate.

Table 3. Comparative body weight dynamics during 42 days of rearing and survival rate of Cobb-500 broiler chickens under the influence of chelated mineral supplements ($M \pm SEM$, $n = 300$).

| Parameter | Groups | | | |
|-------------------------------|---|----------------------------------|--------------------------------|-----------------------------------|
| | 1 Control (Mineral Additives as Sulfates) | Experimental (Chelated Minerals) | | |
| | | 2 (Zn) | 3 (Cu) | 4 (MINTREX®: Zn + Mn + Cu) |
| Body weight, g, at the age of | | | | |
| 1 day | 40.3 ± 0.5 | 40.4 ± 0.4 | 40.5 ± 0.3 | 40.9 ± 0.5 |
| 7 days | 118.2 ± 1.1 | 119.3 ± 1.4 | 119.4 ± 1.2 | 119.6 ± 1.3 |
| 14 days | 333.3 ± 3.2 | 355.4 ± 3.9 *** ¹ | 355.9 ± 3.9 *** ¹ | 356.1 ± 3.9 *** ¹ |
| 21 days | 791.2 ± 5.6 | 826.6 ± 8.3 *** ¹ | 826.8 ± 8.3 *** ¹ | 827.1 ± 8.3 *** ¹ |
| 28 days | 1265.0 ± 31.2 | 1359.5 ± 15.8 ** ¹ | 1359.7 ± 15.8 ** ¹ | 1360.5 ± 15.8 ** ¹ |
| 35 days | 1799.9 ± 22.7 | 1933.5 ± 31.7 *** ¹ | 1933.7 ± 31.7 *** ¹ | 1934.4 ± 31.7 *** ¹ |
| 42 days | 2435.4 ± 48.2 | 2654.3 ± 63.2 ** ¹ | 2653.6 ± 63.2 ** ¹ | 2658.4 ± 63.2 ** ¹ |
| No. of birds housed, head | 9871 | 9836 | 9821 | 9865 |
| No. of birds dead, head/% | 1321/13.38 | 536/5.45 | 521/5.31 | 412/4.17 |
| Survival rate, % | 86.62 ± 0.34 | 94.55 ± 0.23 *** ¹ | 94.69 ± 0.23 *** ¹ | 95.83 ± 0.20 *** ^{1,2,3} |

Note: M, mean; SEM, standard error of the mean; and *n*, number of birds per group. Significant increase at ** $p < 0.01$ and *** $p < 0.001$, relative to Groups 1 (control), 2 or 3 (shown as superscripts ^{1,2,3}).

Another important zootechnical performance parameter, i.e., survival rate obtained over the 42-day experimental period, is also shown in Table 3. Chick survival rates were 94.55% to 95.83% in the experimental groups, compared to 86.62% in the control group,

with statistically significant differences ($p < 0.001$). No gastrointestinal disorders were recorded in broiler chickens receiving chelated microelements throughout the study.

The average daily feed intake tended to be greater in the chelated mineral treatment groups compared to the controls (Table 4), with significant differences being observed at the ages of 15–21 ($p < 0.01$), 29–35 ($p < 0.05$) and 36–42 days ($p < 0.001$). On the other hand, while there was a tendency for lower FCR values in Groups 2–4, no significant differences between groups were observed in this feed efficiency indicator (Table 4).

Table 4. Average daily feed intake (in g per head; $M \pm SEM$, $n = 100$) and feed conversion ratio ($M \pm SEM$, $n = 50$) in broiler chickens.

| Age, Days | Groups | | | |
|---------------------------|--|----------------------------------|-----------------|----------------------------|
| | 1 Control (Mineral Additives as Sulfates) | Experimental (Chelated Minerals) | | |
| | | 2 (Zn) | 3 (Cu) | 4 (MINTREX®: Zn + Mn + Cu) |
| Average daily feed intake | | | | |
| 1–7 | 22.2 ± 1.5 | 23.5 ± 1.4 | 23.9 ± 1.3 | 24.1 ± 1.2 |
| 8–14 | 60.6 ± 1.1 | 61.2 ± 0.9 | 61.9 ± 1.4 | 62.1 ± 1.3 |
| 15–21 | 117.2 ± 1.2 | 122.4 ± 1.1 ** | 122.8 ± 1.3 ** | 123.2 ± 1.4 ** |
| 22–28 | 130.2 ± 0.9 | 131.4 ± 0.5 | 131.9 ± 0.6 | 132.4 ± 0.7 |
| 29–35 | 144.4 ± 0.8 | 146.2 ± 0.8 | 146.9 ± 0.9 * | 147.3 ± 0.6 ** |
| 36–42 | 150.5 ± 0.5 | 161.4 ± 0.6 *** | 161.8 ± 0.7 *** | 162.3 ± 0.6 *** |
| Feed conversion ratio | | | | |
| 1–7 | 2.01 ± 0.5 | 1.96 ± 0.5 | 1.96 ± 0.7 | 1.95 ± 0.5 |
| 8–14 | 2.10 ± 0.5 | 2.02 ± 0.5 | 2.02 ± 0.6 | 2.01 ± 0.5 |
| 15–21 | 2.46 ± 0.5 | 2.34 ± 0.5 | 2.34 ± 0.6 | 2.32 ± 0.5 |
| 22–28 | 2.10 ± 0.5 | 2.04 ± 0.5 | 2.04 ± 0.6 | 2.02 ± 0.5 |
| 29–35 | 1.78 ± 0.5 | 1.71 ± 0.5 | 1.71 ± 0.7 | 1.69 ± 0.4 |
| 36–42 | 1.83 ± 0.5 | 1.78 ± 0.5 | 1.78 ± 0.7 | 1.74 ± 0.4 |

Note: M, mean; SEM, standard error of the mean; n , number of birds per group. Significant increase in experimental groups at * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$, relative to Group 1 (control).

3.2. Pre- and Post-Slaughter External Veterinary Assessment

An ante-mortem veterinary inspection revealed no behavioral or physiological abnormalities in either group, nor significant differences between treatment groups. All birds exhibited normal behavioral responses to the external stimuli, maintained active locomotion with appropriate body positioning, and demonstrated unrestricted feed and water consumption. Physical examination parameters, including plumage condition (clean, dry, adherent), mucous membrane coloration (pale pink), ocular discharge (absent), beak condition (dry), comb coloration (pale pink), limb integrity (intact, without swelling), respiratory function (normal), and physiological body temperature (41–42 °C) were within the normal physiological ranges for both groups.

A post-mortem clinical examination confirmed proper bleeding in carcasses from both treatment groups. No hemorrhages, traumatic lesions, tissue induration, edema, or other pathological changes were observed in the cutaneous, subcutaneous, muscular, mucous, or serous tissues. The uropygial gland exhibited normal development, and keratinized scales maintained appropriate yellow coloration and adherence. Carcasses from the chelated microelement experimental group tended to exhibit a superior overall body condition and fat cover compared to the controls.

3.3. Slaughter Traits, Carcass Yield and Composition

After the growing period, the experimental birds were slaughtered and anatomically dissected. The results of these studies at 42 days of age, including pre-slaughter

body weights, carcass weights and carcass part characteristics, are summarized in Tables 5 and 6, respectively.

Table 5. Pre-slaughter body weights and carcass weights (in g) of Cobb-500 broiler chickens at 42 days of age (M ± SEM, n = 300).

| Parameter | Groups | | | |
|---------------------------------|---|----------------------------------|--------------------|-------------------------------|
| | 1 Control (Mineral Additives as Sulfates) | Experimental (Chelated Minerals) | | |
| | | 2 (Zn) | 3 (Cu) | 4 (MINTREX®: Zn + Mn + Cu) |
| Pre-slaughter body weight, g | 2321.30 ± 53.60 | 2414.60 ± 57.50 | 2412.60 ± 52.30 | 2553.80 ± 51.70 **1 |
| Unprocessed carcass weight | 2080.70 ± 74.60 | 2218.70 ± 62.40 | 2219.60 ± 62.90 | 2338.30 ± 72.30 *1 |
| Uneviscerated carcass weight | 2004.30 ± 66.10 | 2156.10 ± 55.80 | 2186.40 ± 55.80 *1 | 2289.30 ± 52.70 ***1 |
| Semi-eviscerated carcass weight | 1864.30 ± 59.80 | 1964.30 ± 59.80 | 1926.30 ± 14.08 | 2091.60 ± 57.80 **1,3 |
| Eviscerated carcass weight | 1547.20 ± 67.40 | 1685.00 ± 69.60 | 1783.00 ± 66.90 *1 | 1809.67 ± 55.50 **1 |

Note: M, mean; SEM, standard error of the mean; and n, number of birds per group. Significant increase at * p < 0.05, ** p < 0.01 and *** p < 0.001, relative to Groups 1 (control) or 3 (shown as superscripts ^{1,3}).

Table 6. Anatomical dissection results (in g) of Cobb-500 broiler chickens at 42 days of age (M ± SEM, n = 300).

| Parameter | Groups | | | |
|------------------------------|---|----------------------------------|---------------------|-------------------------------|
| | 1 Control (Mineral Additives as Sulfates) | Experimental (Chelated Minerals) | | |
| | | 2 (Zn) | 3 (Cu) | 4 (MINTREX®: Zn + Mn + Cu) |
| Muscles | 1023.5 ± 58.9 | 1152.6 ± 74.2 | 1173.4 ± 32.9 *1 | 1161.3 ± 48.1 |
| Skin | 142.3 ± 8.3 | 164.3 ± 10.1 | 195.3 ± 6.7 ***1,*2 | 203.7 ± 9.5 ***1,**2 |
| Liver | 50.2 ± 6.3 | 57.8 ± 7.3 | 57.8 ± 7.1 | 73.2 ± 7.2 *1 |
| Heart | 9.1 ± 0.3 | 9.3 ± 0.9 | 9.5 ± 0.6 | 10.9 ± 1.1 |
| Gizzard | 22.1 ± 1.9 | 24.6 ± 2.5 | 23.1 ± 2.7 | 23.8 ± 2.1 |
| Lungs | 12.6 ± 1.8 | 15.3 ± 1.4 | 15.1 ± 4.4 | 15.8 ± 2.3 |
| Kidneys | 11.3 ± 1.7 | 12.5 ± 1.7 | 12.4 ± 0.3 | 12.5 ± 1.8 |
| Internal fat | 30.3 ± 14.1 | 42.6 ± 10.8 | 44.4 ± 12.3 | 47.9 ± 10.9 |
| Total edible carcass parts | 1345.7 ± 27.4 | 1553.7 ± 22.3 ***1 | 1556.8 ± 38.1 ***1 | 1569.6 ± 21.4 ***1 |
| Head | 42.4 ± 1.8 | 43.3 ± 1.7 | 45.6 ± 1.7 | 50.3 ± 0.9 ***1,2,*3 |
| Bones | 358.3 ± 18.9 | 363.3 ± 23.5 | 374.5 ± 33.8 | 435.3 ± 54.9 |
| Esophagus and crop | 16.9 ± 3.8 | 17.2 ± 3.3 | 18.1 ± 3.9 | 24.4 ± 9.3 |
| Intestine | 99.4 ± 12.3 | 117.3 ± 12.6 | 120.0 ± 15.8 | 143.3 ± 7.4 **1 |
| Spleen | 3.4 ± 0.9 | 3.5 ± 1.1 | 3.5 ± 0.7 | 4.1 ± 0.6 |
| Trachea | 2.9 ± 1.2 | 3.1 ± 0.9 | 4.9 ± 1.3 | 3.7 ± 0.9 |
| Neck | 50.3 ± 5.8 | 51.5 ± 6.3 | 64.6 ± 7.2 | 52.4 ± 4.3 |
| Legs | 83.1 ± 5.6 | 92.1 ± 5.5 | 89.3 ± 10.4 | 88.4 ± 9.6 |
| Total inedible carcass parts | 837.3 ± 54.3 | 684.2 ± 27.3 | 729.5 ± 56.3 | 853.6 ± 39.5 |

Note: M, mean; SEM, standard error of the mean; and n, number of birds per group. Significant increase at * p < 0.05, ** p < 0.01 and *** p < 0.001, relative to Groups 1 (control), 2 or 3 (shown as superscripts ^{1,2,3}).

The pre-slaughter body weight measurements demonstrated certain improvements in the chelated microelement groups, although this was only significant in the experimental (treatment) Group 4, whose diet was supplemented with chelated forms of three microelements in the form of the MINTREX® premix. Broilers from this group showed a higher pre-slaughter body weight, with a statistically significant difference compared to the controls (p < 0.01; Table 5). Hereby, the pre-slaughter body weight advantage in the experimental Group 4 reached +232.5 g.

The unprocessed carcass weight was also significantly higher in the chelated microelement experimental Group 4 (2338.3 ± 72.3 g) compared to the controls (2080.7 ± 74.6 g), representing a 12.4% increase ($p < 0.05$; Table 5). Similarly, uneviscerated, semi-eviscerated and fully eviscerated carcass weights in Group 4 were significantly elevated by 14.2% ($p < 0.001$), 12.2% ($p < 0.01$) and 17.0% ($p < 0.01$), respectively (Table 5), meaning a 12–17% greater carcass weight across all evisceration stages ($p < 0.01$). The yield of uneviscerated and eviscerated carcasses was also significantly higher in the Cu-chelated experimental Group 3 (2186.4 ± 55.8 and 1783.0 ± 66.9 g, respectively) compared to the controls (2004.3 ± 66.1 and 1547.2 ± 67.4 g, respectively; $p < 0.05$; Table 5).

Analysis of edible tissue components revealed significant increases in the chelated treatment groups—muscles (14.6% in Group 3), skin (37.2% and 43.1% in Groups 3 and 4, respectively) and liver (45.8% in Group 4)—compared to the controls (Table 6). A probable increase in the skin on the subcutaneous fat index in experimental Groups 3 and 4 may indicate the influence of Cu on the formation of this index. Statistical significance was also achieved for the increased total edible carcass parts in Groups 2, 3 and 4, relative to the controls ($p < 0.001$), whereas there were no significant differences in the total inedible carcass parts between groups (Table 6). In particular, the indicator of edible carcass parts significantly increased in all experimental groups, namely in Group 2, where chelated Zn was used, by 15.5%; in Group 3, where Cu chelates were used, by 15.7%; and in Group 4, where Zn, Mn and Cu chelate elements were used together, by 16.6% compared to the control group (Table 6). Other edible and inedible components showed positive, though non-significant, yield trends. Statistical significance for yield percentages was achieved only for head and intestine yields in Group 4 ($p < 0.05$; Table 6).

As a result of the experiment conducted on broiler chickens, it was established that adding to the diet of feeds enriched with chelates of Zn, Mn and Cu, both together and separately, had a positive effect on indicators such as carcass weight after bleeding; uneviscerated, semi-eviscerated and eviscerated carcass weight (Table 5); muscle; skin; liver and edible carcass parts (Table 6), compared to poultry fed a standard diet during fattening. Thus, chelated trace element supplementations mostly enhanced slaughter traits and carcass yield quality.

3.4. Generalized Analysis of Productivity and Carcass Quantitative Characteristics

A generalized analysis of quantitative parameters—including live weight, carcass weight, proportions of carcass parts and survival rate—was conducted, using PCA and hierarchical clustering to assess the overall magnitude of differences in these indicators between broilers in the control and experimental groups (Figure 2).

Four feeding variants were compared: one control group receiving inorganic sulfates and three experimental groups supplemented with chelated additives. On the PCA plot (Figure 2a), the control group (Group 1) and the group receiving the MINTREX[®] complex (Group 4) were clearly separated from each other, indicating distinct differences, as well as from the two intermediate variants with single-element chelates of Zn (Group 2) and Cu (Group 3), which were positioned close together.

In the hierarchical clustering dendrogram (Figure 2b), the Zn and Cu single-chelate variants clustered together, while these two formed a higher-level cluster with the MINTREX[®] group at a considerable distance, suggesting pronounced differences in productive characteristics between birds that received single chelates and those that received the combined chelate supplement. The control group, who were fed a standard diet containing sulfated minerals, formed a separate and distinct cluster, indicating that its performance parameters were inferior to those of the chelate-supplemented groups.

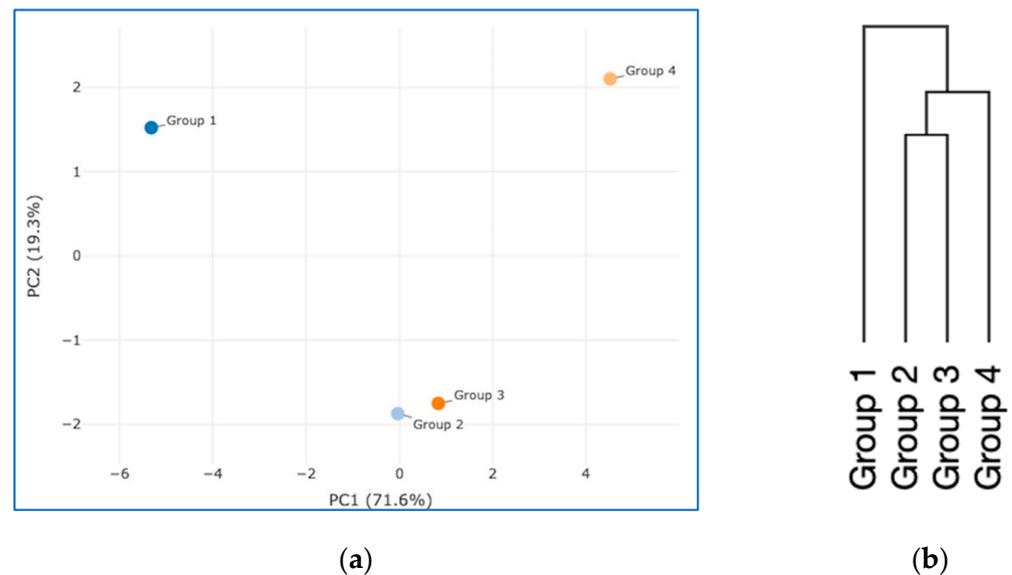


Figure 2. Principal component analysis (PCA) plot and hierarchical clustering dendrogram constructed based on the Euclidean distance metric (average linkage method), using all combined quantitative carcass characteristics of broilers in the control (1) and experimental (2–4) groups. (a) PCA plot showing principal component 1 (PC1) and principal component 2 (PC2), explaining 71.6% and 19.3% of the total variance, respectively. (b) Hierarchical clustering dendrogram illustrating the relationships among groups. Group designations: 1, control (no chelates); 2, Zn chelate; 3, Cu chelate; and 4, MINTREX[®] (Zn + Mn + Cu chelates).

Overall, chelated elements—and particularly their combined application—had a beneficial effect on several zootechnical parameters of broiler chickens and their carcasses. These findings support the potential use of chelated mineral complexes in poultry production for further validation and implementation under practical conditions.

4. Discussion

The administration of inorganic trace minerals (e.g., sulfates) and especially organic microelements (specifically, their chelates) is of particular interest in livestock feeding and production [68–72]. It is also widely used for optimizing productive and reproductive performance in poultry [73–75], including broilers [76–81]. Herein, we compared the performance effects following the supplementation of broiler diets with Zn, Cu and Mn as a combination of their sulfates, single chelates (Zn and Cu), and a premix complex of chelates (Zn + Mn + Cu).

4.1. Growth Performance, Feed Efficiency and Survival

The overall enhanced growth performance observed in broilers supplemented with chelated microelements, including a significantly increased final body weight (10% higher than in the controls; Tables 3 and 5), aligns with previous findings that established principles of mineral bioavailability and absorption efficiency [82–86]. This is facilitated by the key mechanism of action of chelates. That is, by binding to amino acids such as glycine, micronutrients are protected from interaction with other feed components, ensuring their improved intestinal absorption. This can potentially lead to better, healthier growth and development of broilers, efficient FCR, reduced mortality and improved meat performance.

The established increase in body weight differences over the experimental period suggests that there are cumulative benefits of improved microelement utilization. These findings corroborate previous studies demonstrating that partial replacement (25–50%) of inorganic microelements with chelated forms enhances the average daily gain. This

occurs while, simultaneously, the antioxidant enzyme activity (glutathione peroxidase and superoxide dismutase) in the blood serum increases [87,88]. They also promote increased bone mineral retention with reduced fecal mineral excretion [77,82]. This pattern of enhanced body weight suggests that enhanced metabolic efficiency, potentially attributed to the improved microelement bioavailability of organic mineral forms, facilitates enzymatic functions that are critical for nutrient metabolism compared to inorganic salts [89,90].

Similar improvements in feed efficiency and mineral retention with reduced excretion were also reported by Vieira et al. [91]. These studies documented superior FCR in broilers receiving organic minerals throughout a 48-day production cycle, with final body weights of 3.941 kg versus 3.881 kg ($p < 0.05$) compared to inorganic mineral supplementation. Silva et al. [75] demonstrated an improved feed intake in chickens that were fed diets with ZnSO₄, CuSO₄ and MnSO₄, and increased feed conversion efficiency in birds receiving the chelated source of these minerals. In the current study, we also observed a greater feed intake in Group 1, which were fed sulfates. However, the chelated microelements were supplemented in Groups 2–4 over a restricted period of broiler rearing (at 21–35 days); this might be why we did not establish significant effects on FCR.

The significantly enhanced survival rates (95–96% vs. 87%) and absence of gastrointestinal disorders in the chelated groups may suggest potential immunomodulatory benefits of enhanced microelement bioavailability [92,93]. This, however, requires further investigation through specific immune function assessments.

4.2. Carcass Quality

The significant improvements in carcass characteristics, including 12–17% increases in processed carcass weights (Table 5), demonstrate the commercial relevance of chelated microelement supplementation. These enhancements likely reflect enhanced protein synthesis efficiency and tissue development capacity associated with optimal microelement status [94–96].

We observed the greatest improvements in metabolically active tissues (e.g., muscles, skin, liver and total edible carcass parts; Table 6) in differential tissue response patterns, which suggests the targeted effects of enhanced microelement bioavailability on tissues with high metabolic demands [97,98]. This pattern is consistent with the known roles of Zn, Cu, and Mn in protein synthesis, cellular metabolism and antioxidant defense systems [99–101]. Chelated supplementation does not compromise the meat quality; it does, however, potentially enhance consumer acceptability [102,103]. Corresponding improvements may be attributed to the optimal collagen synthesis and muscle fiber development associated with adequate microelement status [94,104]. The progressive nature of performance enhancements throughout the experimental period suggests cumulative benefits of consistent microelement bioavailability, potentially affecting cellular metabolic processes, enzyme function and tissue development capacity [87,105,106]. These mechanisms warrant further investigation through detailed metabolic and molecular studies.

4.3. Commercial Implications

We herein demonstrate that chelated trace element supplementation can be beneficial for broiler growth performance, survival rate, carcass yield and edible carcass parts without adverse health effects. These results agree with Winiarska-Mieczan et al. [107] and Singh et al. [96], who observed improved mineral utilization and performance in broilers fed chelated forms of Fe, Cu, Mn, and Zn. Dong et al. [108] concluded that broiler production performance can be improved and the cecum microbiota optimized when an optimal amount of organic Zn is added to low-protein diets. Reducing the amount of crude protein

used in broiler production also turned out to be an economical strategy that reduced emissions of nitrogen pollutants into the atmosphere.

Dietary chelated microelements therefore represent an effective strategy for improving the overall meat productivity of broiler chickens, while maintaining their survival at higher rates. The comprehensive improvements in growth performance, survival rate and carcass characteristics demonstrate the commercial viability of chelated microelement supplementation in broiler production. The 10% improvement in pre-slaughter weight, combined with enhanced carcass yield and edible part parameters suggests favorable economic returns, despite potentially higher supplement costs. The improved survival rate provides additional commercial benefits, potentially increasing revenues from broiler meat production and reducing survival-related losses. These factors support the adoption of chelated microelement technology in commercial broiler production systems focused on optimizing both productivity and product quality. Moreover, chelated mineral supplements to broiler diets preserve the litter quality and welfare status while lowering the environmental emissions and broiler excretion of Zn, Mn, and Cu. This hence lessens the environmental effects of broiler production [77].

5. Conclusions

In this study, dietary supplementation with chelated trace microelements (Zn, Cu, and Mn) demonstrated advantages in terms of key broiler production performance and carcass characteristics compared to conventional sulfate forms. Birds receiving chelated minerals exhibited enhanced growth performance throughout the rearing period, achieving higher final body weights at 42 days of age, exceeding control group weights by 232.5 g ($p < 0.01$). Chelated microelement supplementation also positively affected carcass characteristics and yields. Eviscerated carcass weight increased by 17% ($p < 0.01$), indicating a substantial improvement in marketable yield. In addition, the total weight of edible carcass parts was significantly higher in experimental Groups 2, 3, and 4, relative to the control, confirming the beneficial effects of both individual and combined chelated trace mineral supplementation.

Overall, these findings suggest that chelated trace minerals enhance the growth performance and carcass yield of broiler chickens. They thus represent a promising nutritional strategy for modern poultry production. Their application may contribute to improved productivity, meat quality and resource efficiency, supporting sustainable poultry production systems. Further studies should focus on optimizing supplementation levels and evaluating the long-term economic impacts of chelated microelement supplementation in industrial settings.

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Abbreviations

The following abbreviations are used in this manuscript:

| | |
|-------------------|------------------------------|
| Ca | calcium |
| Cu | copper |
| CuSO ₄ | copper(II) sulfate |
| EU | European Union |
| Fe | iron |
| Mg | magnesium |
| Mn | manganese |
| MnSO ₄ | manganese(II) sulfate |
| PCA | principal component analysis |
| Zn | zinc |
| ZnSO ₄ | zinc sulfate |

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