Elemental composition and ruminal digestion with nanosized forms of SiO$_2$, FeCo

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Abstract. Optimization of mineral nutrition is a necessary measure aimed to maintain high productivity and health of animals, including beef cattle, which forages may lack minerals. The paper studies the action of nanosized forms SiO$_2$, FeCo on health, ruminal digestion and elemental composition of ruminal fluid of animals. It is found that within the vitro studies the feed dry matter digestibility is maximum with the introduction of nanosized particles (NP) of SiO$_2$ in the concentration of 2 mg/ml. The results of morph-biochemical blood test (in vivo studies) show the activation of protein metabolism, lack of negative impact on animal health. The introduction of SiO$_2$ NP (II group) promotes the accumulation of silicon in ruminal fluid progressing in time: the difference with control group makes 3.8% and 31% in three and six hours respectively. The introduction of FeCo NP (III group) decreases the concentration of iron by 46% and 52% and cobalt by 40% and 50% in three and six hours respectively. SiO$_2$ NP stimulates dry matter digestibility thus affecting the fermentation activity of rumen microflora. The received results indicate the advisability of applying the suggested approach and require further study.

1. Introduction

Agents of metal nanoparticles (NP) are becoming more widespread in livestock production [1]. This is caused by their extraordinary biological properties – ability to get into tissues and organs, high surface area [2, 3].

One of the perspective directions of NP use both during post-embryonic [4] and embryonic periods of animals [5] is their use as sources of microelements. This is defined by relatively smaller toxicity [6, 7], higher bioavailability of elements from nanoparticles [8], which reduces the environmental impact [9] and allows making products enriched with mineral substances [10].

At present the application of nanosized minerals is approved on many animal species: broiler chicken [11-12], fish [4], minks [13], horses [14], pigs [15], sheep [16].

In this regard, the purpose of the study is to analyze the digestibility of forages and mineral exchange when using ultrasized forms of metals – microelements: FeCo, SiO$_2$ in feeding of baby-beef.

The study was carried out in two stages. The first stage – *in vitro* defined dry matter digestibility of feed at their mixing with SiO$_2$ (0.1; 0.25; 2.0 mg/ml) and FeCo (0.25; 0.35; 0.75 mg/ml) via “artificial rumen KPL 01”. According to the technique the samples of ground feed (500 mg) were mixed with NP in the corresponding concentration and placed in nylon bags. The bags were sewn up and fixed with a

[1] References and footnotes would be added in the final version of the paper.
clamp on a roller. Then the bags on the roller were kept for 48 hours in the “artificial rumen” device and the thermostat at t=39°C. Then the samples were washed under the flowing water and placed in pepsin solution in the “artificial rumen” and for 24 hours in the thermostat. Upon the completion of this procedure the samples were washed out in the flowing water and dried up to the constant weight. The choice of the concentration is caused by early studies [17].

2. Materials and methods
The studies were conducted at the center of collective use and the Center of Nanotechnologies in Agriculture of the Federal Research Centre of Biological Systems and Agro-technologies of the Russian Academy of Sciences. SiO₂ NP and NP of Fe and Co alloy by LLC Advanced Powder Technologies (Tomsk) were used as sources of microelements. Physical and chemical characteristics are shown in Table 1. The NP agents were prepared within 30 min in isotonic solution on sonicator UZDN-2T (NPP Akadempribor, Russia) (35 kHz, 300/450 W, 10 mk).

Table 1. Physical and chemical characteristics of nanoparticles

| NP            | Size, nm | Chemical and phase composition | Method    | Specific surface area (S_{SP} m²/g) |
|---------------|----------|---------------------------------|-----------|-------------------------------------|
| SiO₂          | 40±5     | SiO₂: 99.8%; Cl₂: <0.2%         | gas-phase | 55.4                                |
| FeCo (alloy)  | 62±8     | 70% Fe and 30% Co              | gas-phase | 45.2                                |

The dry matter digestibility of feed in vitro was defined by the mass difference of a feed sample with a bag and after two-stage incubation and drying until the constant weight at 60 °C according to the following formula:

$$K=(A-B)/C×100,$$

where

- \(K\) – coefficient of feed dry matter digestibility (%);
- \(A\) – initial weight of a feed sample with a bag (g);
- \(B\) – weight of a feed sample with a bag after digestion (g);
- \(C\) – initial weight of a feed sample without a bag (g).

The second stage in vivo assessed the features of ruminal digestion and microelemental composition of ruminal fluid at the introduction SiO₂ and FeCo NP. The studies were conducted on Red Steppe Breed bull-calfes with the average body weight of 300-310 kg at the age of 13 months. During the preparatory period (10 days) the bull-calfes were transferred to tie-up housing, individual feeding, according to detailed norms [18]. During the registration period the animals were randomly split into three groups (n=5): one control and two experimental groups. During the registration period (five days) the animals of experimental groups were given ultrafine with feed in the morning: I – control (without introduction), II – SiO₂ NP in a dose of 13 mg/kg of body weight, III – FeCo NP in a dose of 5 mg/kg of body weight. The fistula was placed to receive ruminal digesta. The samples of ruminal digesta (300 ml) were received before feeding, in 3 and 6 hours after feeding.

Morpho-biochemical blood tests were conducted at the end of the registration period to assess health and metabolic rate. Blood samples were taken from a tail vein in the morning, in 2-3 hours prior to feeding, for hematologic study – in vacuum test tubes with EDTA-K₃, for biochemical study – in vacuum test tubes with clot activator. Morphological indicators of blood were studied using automatic hematology analyzer URIT-2900 VetPlus analyzer (URIT Medical Electronic Co., Ltd., China). Biochemical composition of blood serum – on the biochemical analyzer CS-T240 (Dirui Industrial Co., Ltd., China) with the use of commercial biochemical kits for veterinary science (DIAKON-DS, Russia; Randox Laboratories Ltd., Great Britain).

Content of chemical elements (Ca, Cu, Fe, Li, Mg, Mn, Ni, As, Cr, K, Na, P, Zn, I, V, Co, Se, Ti, Al, Be, Cd, Pb, Hg, Sn, Sr) in ruminal fluid was determined on a mass spectrometer Elan 9000 and
atomic emission spectrometer Optima 2000V (Perkin Elmer, USA). The microwave decomposition system Multiwave 3000 (Anton Paar, Austria) was used for digestion.

The data are expressed as mean values ± standard error of the mean. The statistical analysis was performed using Statistica 10.0 (StatSoft Inc., USA) and Microsoft Excel (Microsoft, USA). The significant difference was estimated using the Student’s t-test at $p \leq 0.05$.

All experimental methods and techniques were approved by the Ethics Committee of the Federal Research Centre of Biological Systems and Agro-technologies.

3. Results

3.1 In vitro results

The analysis of the obtained data showed that the digestibility of a control sample within in vitro studies was below the one of experimental groups. The introduction of SiO$_2$ NP in a dose of 0.1 mg/ml increases dry matter digestibility by 16.5% ($P \leq 0.001$) in comparison with the control group. The increase of SiO$_2$ NP concentration up to 0.25 mg/ml increased digestibility in the control group by 17.4% ($P \leq 0.001$). The maximum concentration (2 mg/ml) of SiO$_2$ NP showed the reliable increase in digestibility in comparison with the control group by 18.7% ($P \leq 0.001$). Thus, we may observe the direct dependence of the gained effect and a dose of the introduced substance (Table 2).

| Group       | NP concentration, mg/ml | Digestibility, % |
|-------------|-------------------------|------------------|
| I (control) | -                       | 69.00±0,383      |
| II (SiO$_2$ NP) | 2.0             | 81.9±0,007***    |
|            | 0.25                     | 81.0±0,039***    |
|            | 0.1                      | 80.44±0,030***   |
| III (FeCo NP) | 0.25               | 69.10±0,058      |
|            | 0.35                     | 70.00±0,058      |
|            | 0.75                     | 71.22±0,017      |

Significant difference in relation to control *** $p \leq 0.001$.

When FeCo NP in the concentration of 0.25 mg/ml was introduced the digestibility difference in comparison with the control group was minimum. The increase of a dose of the substance led to the increase of digestibility: by 1.5% at FeCo NP concentration of 0.35 mg/ml; by 3.2% at the concentration of 0.75 mg/ml in comparison with the control group.

3.2 In vivo results

Morpho-biochemical blood values. The studies show that all analyzed values in all groups were within the admissible physiological norms. However, the study of morpho-biochemical blood values cannot be limited to physiological norms only, and it is important to estimate the emerging trends and insignificant shifts within this norm (Table 3).

The introduction of SiO$_2$ NP (II group) increases the content of monocytes by 2%, granulocytes by 3.7% and decreases thrombocytes by 15% ($P \leq 0.05$) in relation to the control group. The introduction of FeCo NP (III group) decreased the concentration of monocytes by 49.1% ($P \leq 0.01$) and increased haemoglobin by 6.0%. Reliable decrease by 17.8% is observed for thrombocytes in relation to the control group with the increase of granulocytes by 7%, lymphocytes by 23.6%, etc.
Table 3. Influence of SiO₂ and FeCo NP on morphological blood values of experimental animals

| Value                  | Group                              |
|------------------------|------------------------------------|
|                        | I (without introduction)           |
|                        | II (SiO₂ NP)                       |
|                        | III (FeCo NP)                      |
| leucocytes, 10⁹/l      | 12.0±0.95                          |
| lymphocytes, %         | 35.63±1.26                         |
| monocytes, %           | 27.73±1.78                         |
| granulocytes, %        | 36.63±1.78                         |
| erythrocytes, 10¹²/l   | 6.22±0.17                          |
| haemoglobin, g/l       | 84.00±1.52                         |
| hematocrit, %          | 24.83±0.33                         |
| thrombocytes, 10⁹/l    | 226.00±6.05                        |

Significant difference in relation to control; * p ≤ 0.05, ** p ≤ 0.01

Table 4. Biochemical indicators of blood serum of bull-calves (n=5) at NP introduction

| Indicator              | Group                              |
|------------------------|------------------------------------|
|                        | I (without introduction)           |
|                        | II (SiO₂ NP)                       |
|                        | III (FeCo NP)                      |
| ALAT, u/l              | 31.10±0.261                        |
| ASAT, u/l              | 100.37±8.211                       |
| ALKP, u/l              | 125.67±7.721                       |
| GGT, u/l               | 7.67±0.333                         |
| Uric acid, mcmol/l     | 28.00±1.431                        |
| Creatinin, mcmol/l     | 134.50±3.672                       |
| BUN, mmol/l            | 5.20±0.060                         |
| Magnesium, mmol/l L    | 0.42±0.024                         |
| Calcium, mmol/l        | 1.37±0.009                         |
| Glucose, mmol/l        | 2.56±0.085                         |
| Total protein, g/l     | 80.71±1.179                        |
| Albumen, g/l           | 32.00±2000                         |
| Cholesterol, mmol/l    | 2.81±0.036                         |
| Triglycerides, mmol/l  | 0.19±0.020                         |
| Iron, mcmol/l          | 23.77±1.373                        |
| Phosphorus, mmol/l     | 0.96±0.067                         |

Significant difference in relation to control; * p ≤ 0.05

The analysis of data shows that the introduction of SiO₂ NP (II group) increases enzyme activity of blood serum: ALAT by 6.6%, ASAT by 6.4%, GGT by 9.6%. The introduction of FeCo NP (III group) increases the activity of alkaline phosphatase by 20.6% (P≤0.05), ALAT by 16.1% in relation to the control group. Besides, there is a reliable increase in the total protein by 4.6% and direct bilirubin for 6.3% (Table 4).
From nitrogen compounds there is a reliable decrease of creatinine by 11.7% ($P \leq 0.05$) against the background of the introduction of SiO$_2$ NP (II group) in comparison with the control group. The introduction of FeCo NP (III group) is characterized by the increase of uric acid by 13.1% and iron by 21.5% in comparison with the control group. The BUN indicators tend to increase in the groups that received NP.

Elemental composition of ruminal fluid. The analysis of microelemental concentration of ruminal fluid revealed the differences in the action of NP agents on the exchange of chemical substances. Thus, in three hours after the introduction of SiO$_2$ NP (II group) iron is decreases by 5.5% ($P \leq 0.01$) with the increase of copper by 42.4%, calcium by 31.8%, manganese by 29.6%, etc. (Fig. 1A). The introduction of FeCo NP (III group) reduces the content of cobalt by 40%, iron by 46% ($P \leq 0.01$), and decreases chromium by 47% ($P \leq 0.05$) in relation to the control group (Fig. 1B).

The analysis of toxic chemical elements in ruminal fluid in 3 hours after SiO$_2$ NP feeding showed the decrease of aluminum by 60% ($P \leq 0.05$) in relation to the control group.

In 6 hours after the introduction of SiO$_2$ NP (II group) we observed the increase in the concentration of silicon by 31%, arsenic by 40%, nickel by 25.8%, barium by 12.6% in comparison with the control group.
group (Fig. 2 A). The opposite effect was achieved through the introduction of FeCo NP in a rumen thus decreasing the concentration of arsenic by 60%, nickel by 45.1% and vanadium by 60% (P≥0.01) in comparison with the control group (Fig. 2 B).

![Figure 2. Difference of chemical concentration in ruminal fluid of experimental animal groups in comparison with the control group in 6 hours after introduction: A – SiO$_2$ NP (II group); B – FeCo NP (III group), %](image)

The introduction of SiO$_2$ NP and FeCo NP in 6 hours after feeding reduced the concentration of aluminum in ruminal fluid by 17.2% and 62.6% respectively.

Thus, the obtained data show that the elemental structure of experimental groups differs from the control group. However, the three-hour exposure does not lead to significant changes between experimental groups whereas the six-hour exposure leads to the accumulation of chemical elements more against the background of SiO$_2$ NP introduction.

4. Discussion
The use of SiO$_2$ NP is caused by their inert profile of toxicity [19]. The introduction of silicon into a diet of cows increases dry matter digestibility [20]. SiO$_2$ particles stimulate synthesis by TNF-α [21-22] and
increase immunity at vaccination, especially antitubercular vaccination [23], which is especially for frequent cases of cattle tuberculosis [24]. Besides, silicon stabilizes cellular cytoskeleton and cytoplasmatic membranes thus promoting growth and differentiation of cells [25], which is especially important in case of symbiotic digestion of ruminants. It may seem perspective to use of SiO₂ NP for the improvement of vaccine protection [26].

High specialization of ruminants towards symbiotic digestion makes this process impossible without successful work of microorganisms. The introduction of microelement additive stimulates the growth of microorganisms in a rumen [27] and activates their enzymatic systems thus increasing the digestibility of feed components [28]. Rumen bacteria and infusoria become additional microorgans functioning as hydrolysis, transformation and synthesis [29]. SiO₂ nanoparticles increase microbial activity thus stimulating their enzyme systems [30], which, on the one hand, indicates the lack of cytotoxic effect of the studied nanoparticles, and on the other hand, the creation of optimum conditions for microflora. According to different estimates, the microbial populations connected with feed particles are responsible for 88-91% of endoglucanase, xylanase activity, 70% – amylase activity and 75% – protease activity in a rumen of ruminants and a large intestine of nonruminants [31].

It is proved that the introduction of minerals into a diet positively influences the growth indicators, digestibility and nutrient availability. The introduction of cobalt into a diet of animals improves physiological and biochemical indicators and increases the productivity of cattle and rabbits [32]. Iron in combination with cobalt stimulates the growth of animals, increases digestibility of feed components [4]. The digestibility of dry matter, organic matter, and crude protein is increased with the addition of selenium [33]. Various forms of zinc improve the growth indicators due to the increase of nitrogen deduction and fat availability of growing minks [34]. The digestibility of cellulose increases only after the application of microelements [28].

Morpho-biochemical blood indicators exert a positive impact on health and metabolism of animals. Thus, the experiment does not illustrate leukocytosis, which demonstrates lack of inflammatory reaction to NP introduction. Haemoglobin and hematocrit values increase as a result of NP introduction. The ability to increase the haemoglobin concentration is also described for other NP [35, 36]. The tendency of thrombocytes reduction against the background of SiO₂ NP introduction decreases blood viscosity and reduces perfusion through microcirculatory vessels. Similar results are described for titanium nanoparticles [37, 38].

Silicon is able to activate functional activity of granulocytes and to intensify metabolic processes [39]. Besides, the study shows the ability of silicon to activate monocytes and develop peritoneal macrophages, which leads to the release of interleukin-1 [40].

In the experiment the activity of alkaline phosphatase was the highest in the group receiving FeCo NP. We know the influence of cobalt on osteoblasts against the background of the active use of calcium and phosphorus with the increase alkaline phosphatase activity [41], which explains low content of phosphorus and calcium. High activity of metabolism is confirmed by the dynamics of urea and creatinine concentration. Creatinine, being the dehydrated form of creatine participating in energy exchange in muscles [42], decreases against the background of NP introduction in comparison with the control group, which is quite natural due to active transition of creatinine into creatine phosphate and its arrival into muscles in the form of energy at the activation of biochemical processes [43].

Getting to a rumen, the microelements are absorbed by symbiotic microorganisms, which number increases with the introduction of mineral additives and consequently their enzymatic activity is growing. The combination of different mechanisms of action of bacterial and fungal cellulose increases the efficiency of cellulose digestion in a rumen [44]. Joining the process of ruminal digestion, the microorganisms closely interact with plant matter [45]. In turn, microorganisms of a rumen can influence metabolism of other nutrients, such as nitrogen and sulfur [46].

It is known that metal ions act as cofactors of some enzymes, including microorganisms and animalcula [47], the probability of their influence on enzyme system of rumen microbiota is respectively high. In this regard, the mechanism of action of ultrafine particles on microbiont canes can be described as a result of transformation of ultrafine particles with the formation of ions, which, according to some
authors, are mainly responsible for their toxicity for living organisms [48, 49]. We believe that this can be the reason of accumulation of chemical elements by rumen microorganisms.

The experiment showed the decrease of the concentration of iron and cobalt in ruminal fluid against the background of introduction of FeCo NP (III group). One of the reasons for such reduction may be homeostasis decreasing negative effects of iron surplus in an organism accompanied with the formation of free radicals, suppression of immunity, etc., which are retained by a well working system of stabilization [50]. Such decrease of iron concentration was noted in muscles of rats with the introduction of iron nanoparticles and their agglomerates [51].

When comparing two experimental groups we revealed that the introduction of SiO$_2$ NP increases the content of silicon, zinc, phosphorus, calcium and other elements in ruminal fluid, whereas the introduction of FeCo NP led to the decrease of iron and cobalt concentration in ruminal fluid, and such decrease was accruing over time. This might be caused by the ability of many species of rumen bacteria to accumulate microelements. The stimulating effect of small doses of NP on ruminal metabolism and toxic action of high NP concentrations is still insufficiently studied. At the same time a wall of a rumen is penetrable for microelements in both directions. It is important to know that bacteria mainly serve as the “food” for protozoa and the reduction macro- and essential elements in three and six hours after feeding may be caused by absorption or standard digestion.

5. Conclusion

Thus, it is found that within the vitro studies the feed dry matter digestibility is maximum with the introduction of nanosized particles (NP) of SiO2 in the concentration of 2 mg/ml. The results of morpho-biochemical blood test (in vivo studies) show the activation of protein metabolism, lack of negative impact on health of animals. The introduction SiO$_2$ NP (II group) promotes the accumulation of silicon in ruminal fluid progressing in time: the difference with the control group makes 3.8% and 31% in three and six hours respectively. The introduction of FeCo NP (III group) decreases the concentration of iron by 46% and 52% and cobalt by 40% and 50% in three and six hours respectively. SiO$_2$ NP stimulates dry matter digestibility thus affecting enzymatic activity of rumen microflora.

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