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THE ROLE OF SILICA NANOPARTICLES IN MODULATING GROWTH PERFORMANCE, ENZYME ACTIVITY, AND HEAVY METAL ACCUMULATION IN MUSCLE TISSUE OF COMMON CARP (*Cyprinus carpio. L*)

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ABSTRACT

This study investigated the effects of dietary supplementation with silicon nanoparticles (Si-NPs) on the growth performance, trace element concentrations, and serum enzyme activity of Cyprinus carpio (*C. carpio*) over a 90-day feeding trial. Four experimental diets with varying levels of Si-NPs were prepared: the first group (GRP1) was given 0 mg/kg, the second group (GRP2) received 1 mg/kg, the third group (GRP3) was supplemented with 2 mg/kg, and the fourth group (GRP4) had 3 mg/kg of Si-NPs. Results revealed that moderate levels of Si-NPs (1-2 mg/kg) significantly improved growth performance ($p < 0.05$), with GRP3 exhibiting the highest final weight (35 ± 0.44 g), weight gain (22.4 ± 0.5 g), and feed conversion ratio (1.269 ± 0.023). In contrast, GRP4 (3 mg/kg) showed reduced growth. Trace element analysis demonstrated that Si-NPs at 1-2 mg/kg enhanced the bioavailability of essential elements such as Sodium (Na), Iron (Fe), Magnesium (Mg), and Zinc (Zn), while higher doses disrupted trace element homeostasis. Serum enzyme activities, including Alanine Aminotransferase (ALT), Aspartate Aminotransferase (AST), Acid Phosphatase (ACP), Alkaline Phosphatase (ALP), and Lactate Dehydrogenase (LDH), were significantly reduced in GRP2 and GRP3, suggesting a protective effect against oxidative stress and tissue damage. However, enzyme activities of GRP4 returned to control values, implying a threshold effect. The research indicates the beneficial effect of Si-NPs as a food supplement for growth enhancement, nutrient assimilation, and protecting the fish against oxidative stress if dosing is carefully adjusted to avoid toxicity.

KEYWORDS: Aquaculture, *Cyprinus Carpio*, Growth Enhancement, Trace Element, Si-NPs.

1. INTRODUCTION:

Aquaculture is one of the fastest-growing sectors in global animal protein production (Hoseini and Al Sulivany, 2024). In the aquaculture sector, silicon nanoparticles (Si-NPs) have gained considerable interest due to their potential to boost disease resistance, improve growth rates, and alleviate environmental challenges, including the effects of heavy metal toxicity (Khalefa *et al.,* 2024). Si-NPs play a potential role in regulating immune functions by boosting the efficiency of antioxidant enzymes, lowering oxidative stress, and enhancing general fish health (Mahboub *et al.,* 2024; Rahman *et al.,* 2025). Additionally, these nanoparticles have been shown to reduce the harmful effects of heavy metals and combat pathogenic diseases, thereby supporting the sustainability and resilience of aquaculture systems (Khalefa *et al.,* 2024; Ali *et al.,* 2024). Their potential to enhance nutrient absorption and promote beneficial gut microbiota further solidifies their role as an effective and promising feed supplement in fish nutrition (Hussain *et al.,* 2024; Ghafarifarsani *et al.,* 2024; Hamed & Badran, 2024; El-Naby *et al.,* 2025).

In developing countries across Asia and Africa, the expansion of the aquaculture sector plays a vital role in ensuring economic stability and strengthening food security (Chan *et al.,* 2019). The effectiveness of aquaculture practices largely depends on the quality of feed, which directly impacts production efficiency and economic sustainability (Singha *et al.,* 2021). The use of Si-NPs in aquafeeds has been linked to enhanced feed efficiency and better growth outcomes in multiple fish species.

Heavy metal pollution in aquatic environments poses a serious risk to fish health, leading to oxidative stress, weakened immune systems, and impaired organ function (Banday *et al.,* 2019). Harmful metals like lead, cadmium, and mercury accumulate in fish tissues, disrupting cellular balance and metabolic processes, which

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ultimately hampers growth and weakens immune function (Balali-Mood *et al.,* 2021; Reda *et al.,* 2025). Moreover, incorporating Si-NPs into fish diets has been shown to revive antioxidant defense systems by lowering oxidative stress markers and boosting the activity of antioxidant enzymes in fish affected by trace element toxicity (Ro *et al.,* 2025).

Furthermore, the immunomodulatory properties of Si-NPs have garnered significant attention in aquaculture. Research suggests that including Si-NPs in fish diets notably strengthen immune responses by increasing immunoglobulin levels, boosting cytokine production, and upregulating immune-related gene expression, ultimately enhancing disease resistance in fish (Ghafarifarsani *et al.,* 2024; Hussain *et al.,* 2024). In common carp (*C. carpio*), the addition of Si-NPs has also demonstrated beneficial impacts on gut health, nutrient absorption, and overall growth performance, including improvements in body composition (Hamed and Badran, 2024). The incorporation of Si-NPs into aquafeeds has proven effective in promoting fish growth, optimizing enzyme activity, boosting immune system performance, and counteracting the harmful effects of heavy metal toxicity. However, these promising results, further research is necessary to determine the ideal dosage, assess long-term physiological impacts, and explore potential interactions with other functional feed additives. This study aims to investigate the effects of dietary Si-NPs on growth performance, enzyme activity, and metal accumulation in *C. carpio* (common carp), providing valuable insights into the application of nanotechnology for sustainable aquaculture practices.

2. MATERIALS AND METHODS:

Fish and Rearing Condition

One hundred twenty healthy *C. carpio* juveniles of the same age group, weighing 12.00±1.50 g and a total length of 8.50±1.20 cm, were obtained from Tawakal Fish Hatchery, Punjab, Pakistan. The fish was transported to the aquaculture laboratory of the Saline Water Aquaculture Research Center, Fisheries Department. Before the experiment began, the fish was acclimated to laboratory conditions for 15 days to allow physiological adaptation. To eliminate potential external pathogens, the fish were disinfected with sodium chloride (NaCl) solution (Sigma-Aldrich) for 1–2 minutes, as per the disinfection protocol provided by Zhang *et al.* (2024). During the acclimatization period, fish were given a standardized basal diet twice daily at fixed intervals to provide the best nutrition and health conditions (Laz-Figueroa *et al.,* 2024). After acclimatization, fish were allocated randomly into twelve glass aquaria, each measuring 120×40×50 cm^3 with a capacity of 100 liters.

Preparation of Experimental Diets:

Purely activated, 100% natural silica nanoparticles (SiO_2; Si-NPs) of case number item 7631-86-9, which were purchased from Sigma Aldrich, Pakistan. The Si-NPs were recovered by the use of ethanol and thus gave a size distribution between 300 nm to 400 nm with an average active density of 2.08±0.21 g/cm^3 is equivalent to approximately 3×10^{16} nanoparticles per gram. Post-purchasing, the Si-NPs were prepared at the Fish Aquaculture Laboratory, Saline Water Aquaculture Research Center, Fisheries Department, to enhance their bioavailability and functional characteristics so that they could be applied for fish nutrition study.

In Table 1, all the ingredients were ground into powders using a blender. Then, the required quantities of fish meal corn, soybean barely, ascorbic acid, premix, and Si-NPs were weighed with an electronic digital weighing balance. The ingredients were then blended in a feed mixer for 10 min. After that, slowly, 15ml of distilled water was poured and mixed to create a dough. This dough was then passed through a 2.0 mm diameter hand-driven pelleting machine. Extrusion-produced pellets were overnight stored at 45°C and then preserved at -18°C to be used later (Ceccotti *et al.,* 2019).

Table 1: Diet composition of fish-fed diets with different concentrations of Si-NPs during 90-day intervals

Ingredient	**GRP 0 (Si-NPs)**	**GRP1 (Si-NPs)**	**GRP2 (Si-NPs)**	**GRP3 (Si-NPs)**
Si-NPs	0 mg/kg	1 mg/kg	2 mg/kg	3 mg/kg
Fish Meal	16	16	16	16
Corn	14	13	12	11
Soybean	30	28	26	24
Barley	17	17	17	17
Wheat	20	20	20	20
Premix	2	2	2	2
Ascorbic acid	1	1	1	1

Experimental design:

The design of the experiment included four dietary treatments, each with three replicates with 10 fish stockings per tank, to minimize stress levels. The experimental diets were categorized and labelled as GRP-1; 0 mg/kg (control) Si-NP, GRP-2; 1 mg/kg Si-NP, GRP-3; 2 mg/kg Si-NP, and GRP-4; 3 mg/kg Si-NP inclusion levels respectively. The trial was fed for 90 days. For aeration to provide water quality, high-efficiency aquarium air pumps (SunSun CT-402, power: 6 W, airflow: 4.0 L/min) and industrial-grade air compressors (Hailea V-20, power: 50 W, airflow: 75 L/min; Hailea V-30, power: 60 W, airflow: 85 L/min; Resun LP-100, power: 180 W, airflow: 0.140 m^3/min) was utilized. The water quality parameters were traced daily in detail and adjusted as and when required to maintain proper conditions for fish growth and development. The pH, dissolved oxygen, and temperature values measured were 7.2 ± 0.20, 6.8 ± 0.5 mg/L, and 18 ± 0.4°C, respectively, to create a stable and controlled aquatic ecosystem for the experiment.

Growth Measurement

After rearing was completed, fish were fasted for 24 hours to allow complete gut clearance. Then, the individual fish were weighed on a high-accuracy digital balance (A&D HT-120) to record their final body weight. Growth performance parameters like initial weight (IW), final weight (FW), Weight gain (WG), feed intake (FI), and feed conversion ratio (FCR) were determined as below (Al Sulivany *et al.,* 2024; Owais *et al.,* 2024a. b; Abdulrahman and Al Sulivany, 2025).

WG (g) =FW -IW.

FI (g) = Total feed given (g)/ Number of fish - duration of feeding.

FCR = Feed intake (g) / WG (g).

Determination of Enzyme Activity Parameters

After weighing, the fish were anesthetized using an MS-222 (tricaine methane sulfonate, 0.1 g. l^{-1}, Sigma-Aldrich, USA) to minimize stress during the procedure. Blood samples were collected from the caudal vein using 5 ml syringes. The blood was then inserted into the gel tube without anticoagulants and centrifuged at 1500 rpm for 5 minutes to separate the serum for enzymatic activity parameters.

Preparation of Muscle and Heavy Metal Determination.

After blood sampling, five fish from each pond were euthanatized with a quick cranial percussion to avoid causing any undue stress. Under sterile conditions using sterile surgical scalpels, a muscle tissue piece of about 2g (1×1 cm) was removed from the mid-dorsal position of each fish. The tissue samples so collected were oven-dried at 80–85 °C for 24 hours to remove the moisture content. Following thorough drying, the samples were cooled to room temperature and finely powdered using a clean ceramic mortar and pestle to render them uniform (Ahmed & Hasan, 2019).

For heavy metal analysis, 0.5 g of the homogenized muscle sample was precisely weighed and transferred into Teflon digestion vessels, followed by the addition of 10 mL of concentrated nitric acid (HNO_3, 69%). The digestion process was performed in a Milestone ETHOS UP microwave digestion system under controlled conditions: ramping to 180 °C for 5 minutes, maintaining digestion at 180 °C for 10 minutes, and allowing a cooling phase of 6 minutes. The completely digested samples were then transferred to acid-cleaned volumetric flasks and diluted to a final volume of 10 mL using ultrapure deionized water. The prepared solutions were stored at 4 °C until further analysis (Al-Imarah *et al*., 2024). To quantify heavy metals, including Pb and Cd, Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) (PerkinElmer Avio 500) was utilized. The system was equipped with a radial torch and an argon saturation assembly to enhance signal stability. High-purity (99.999%) argon gas was used for plasma, auxiliary, and nebulizer functions, with optimized gas flow rates of 15.0 L/min for plasma, 1.3 L/min for auxiliary, and 0.58 L/min for nebulizer. The plasma generator's radio frequency (RF) power was set at 1.45 kW, and the plasma vertical height was adjusted to 8 mm for optimal detection sensitivity. The analytical parameters included a sample uptake time of 20 sec, a delay time of 5 sec, a rinse time of 10 sec, an initial stabilization time of 12 sec, and 5 sec between replicate analyses. The emission wavelengths were selected for their high sensitivity in detecting trace metals: Na^+ (589.592 nm), Co^{2+} (238.892 nm), Ni^{2+} (213.857 nm), Fe^{2+} (267.716 nm), Mg^{2+} (259.940 nm), Al^{3+} (285.213 nm), Zn^{2+} (220.353 nm), Pb^{2+} (327.395 nm), Cu^+ (231.604 nm), Cr^{3+} (396.152 nm), and Cd^{2+} (260.568 nm). Before sample analysis, the instrument was calibrated using certified multi-element standards to ensure precision and accuracy.

Ethical approval and consent:

All authors gave verbal informed consent for their participation. The study's design and procedures were reviewed and approved by the Animal Ethics Committee of the Institutional Research Committee under the Government Department of Fisheries, Punjab, Pakistan, in compliance with ethical standards (Code APF-129; 2023).

Statistical Analysis

Statistical analysis was performed using GraphPad Prism 9. A one-way analysis of variance (ANOVA) was conducted, followed by Dunnett's post hoc test to compare each experimental group with the control. Results are presented as means ± standard error (SE).

3. RESULTS:

The result of the study evaluated the growth performance of common carp feds diets supplemented with varying levels of Si-NPs, indicating clear differences among the groups (Table 2 and Figure 1; A, B, C, D, and E). The FW was highest in the GRP3 at 35±0.44 g, followed by GRP2 at 30.2±0.37 g, the GRP1 group at 25.8±0.37 g, and the GRP4 group at 22.8±0.33 g. Similarly, WG was greatest in GRP3 (22.4 g), significantly higher than in GRP2, GRP1, and GRP4. Feed intake (FI) was also highest in GRP3, while GRP4 had the lowest intake (18.34 g). The FCR was most reduced in GRP3 (1.269), whereas GRP4 showed the least efficiency

(1.646). Statistical analysis confirmed significant differences ($P < 0.05$) in FW, WG, FI, and FCR among the groups.

Table 2. The effects of Si-NPs on morphometric parameters and feed conversion ratio of *C. carpio* after 90 days of feeding trial.

Growth Parameters	GRP1 (0mg. kg^{-1})	GRP2 (1mg. kg^{-1})	GRP3 (2mg. kg^{-1})	GRP4 (3mg. kg^{-1})
IW (g)	12.4±0.24	12.2±0.37	12.6±0.24	11.6±0.4
FW (g)	25.8a±0.37	30.2b±0.37	35c±0.44	22.8d±0.33
WG (g)	13.4a±0.6	18b±0.44	22.4c±0.5	11.2d±0.66
FI (g)	20a±0.54	24.8b±0.2	28.4c±0.5	18.34a±0.9
FCR	1.498ac±0.034	1.381ab±0.036	1.269b±0.023	1.646c±0.06

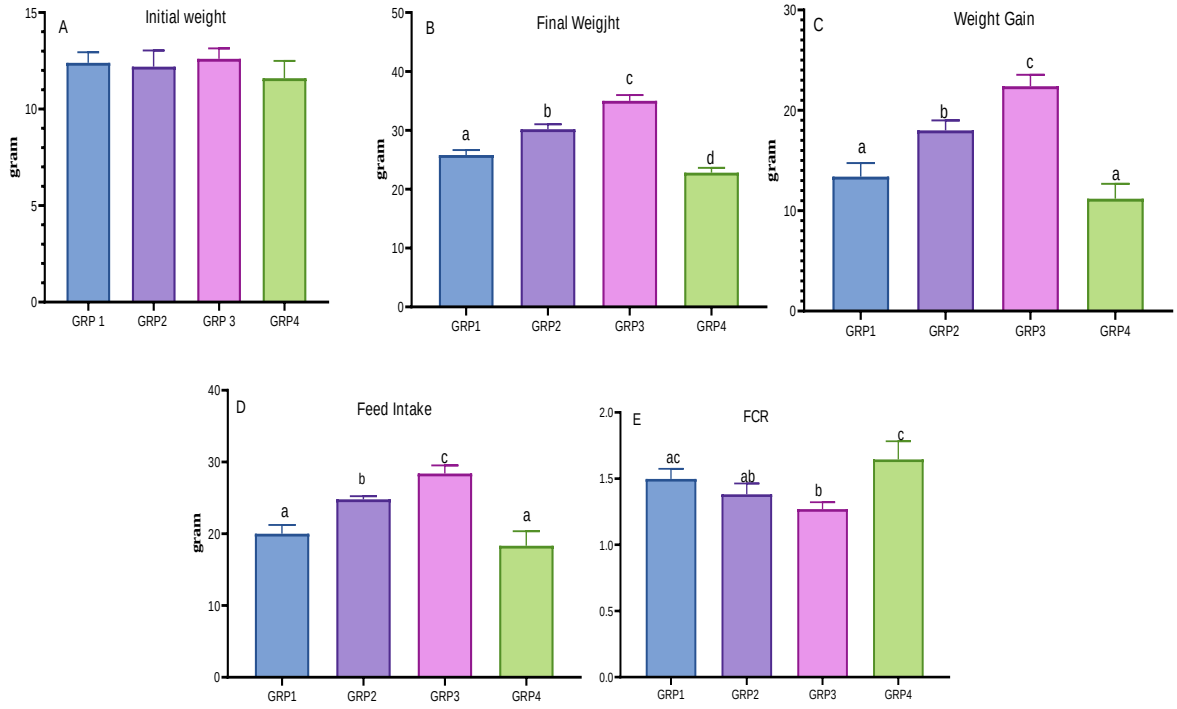

Figure 1. The effects of Si-NPs on morphometric parameters and feed conversion ratio of *C. carpio* after 90 days of feeding trial. A; Initial weight. B; Final Weight. C: Weight gain. D: Feed intake. E; for feed conversion ratio (FCR).

On the other hand, Table 3 and Figure 2; A, B, C, D, E, F, G, H, and I reveal that the effects of Si-NPs on trace element concentrations in the muscle tissue of fish revealed significant changes across the groups, GRP0, the Na levels were (54±0.32 mg/l), increasing to (59.6±0.92 mg/l) in GRP1, (63.6±0.5 mg/l) in GRP2, then reduced to (51.2±0.36 mg/l) in GRP3 ($P < 0.05$). Iron (Fe) showed a similar patent, beginning at (8.44±0.06 mg/l) in GRP0, elevating to (8.92±0.08 and 9.8±0.05) in GRP1 and GRP2 respectively, and then reducing in GRP3 ($P < 0.05$). Similarly, Mg also increased significantly ($P < 0.05$) in GRP0, GRP1, and GRP2 and then reduced in GRP3. Other elements, such as Co, Ni, Al, Zn, Cr, and Cd, also showed varying trends across the groups, with GRP2 often exhibiting the highest concentrations. Furthermore, some elements remained relatively stable. The level of Pb was consistent across all groups at 0.2 mg/l, showing no significant variation ($P > 0.05$). Also, Cu showed minimal changes, ranging from (0.85±0.002 mg/l) in GRP0 to (0.87±0.001 mg/l) in GRP2, with no significant differences among the groups ($P > 0.05$).

Table 3: The effects of SiNPs on the diet on trace elements in the muscle of *C. carpio* after 90 days of feeding trial.

Trace Element	GRP1 (0mg. kg^{-1})	GRP2 (1mg. kg^{-1})	GRP3 (2mg. kg^{-1})	GRP4 (3mg. kg^{-1})
Na (mg. l^{-1})	54^{a}±0.32	59.6^{b}±0.92	63.6^{c}±0.5	51.2^{a}±0.36
Co (mg. l^{-1})	0.003^{a}±0.0005	0.005^{ac}±0.0004	0.008^{bc}±0.0004	0.01^{b}±0.002
Ni (mg. l^{-1})	0.55^{a}±0.0009	0.66^{b}±0.0007	0.79^{c}±0.02	0.44^{d}±0.0005
Fe (mg. l^{-1})	8.44^{a}±0.06	8.92^{b}±0.08	9.8^{c}±0.05	8.06^{d}±0.04
Mg (mg. l^{-1})	31.2^{a}±0.58	35.6^{b}±0.5	40.4^{c}±0.8	28^{d}±0.4
Al (mg. l^{-1})	1.12^{a}±0.04	1.4^{b}±0.046	1.6^{c}±0.02	0.76^{d}±0.07
Zn (mg. l^{-1})	6.9^{a}±0.04	7.3^{b}±0.06	7.6^{c}±0.05	6.4^{d}±0.07
Pb (mg. l^{-1})	0.2^{a}±0.0003	0.2^{b}±0.0009	0.2^{c}±0.0009	0.2^{d}±0.0006
Cu (mg. l^{-1})	0.85±0.002	0.86±0.001	0.87±0.0006	0.84±0.0007
Cr (mg. l^{-1})	0.41^{a}±0.002	0.42^{a}±0.002	0.44^{b}±0.0012	0.37^{c}±0.001
Cd (mg. l^{-1})	0.01^{a}±0.0006	0.015^{b}±0.0007	0.02^{ab}±0.0003	0.02^{a}±0.0003

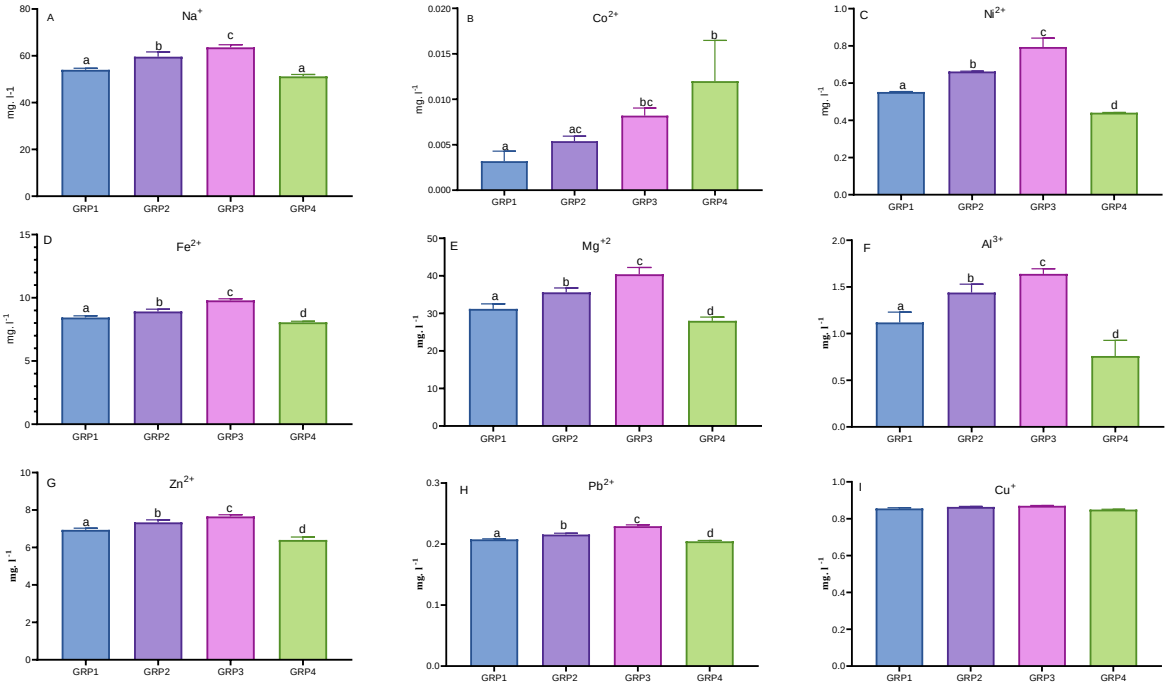

Figure 2. The effects of Si-NPs on trace elements in the muscle of *C. carpio* after 90 days of feeding trial.

The effect of different concentrations of Si-NPs on serum enzyme activity is presented in (Table 4. and Figure 3). In the GRP1, ALT activity was 14.4 ± 0.25 U/L, while AST levels were 81.8 ± 0.54 U/L. These values decreased significantly in GRP3, with ALT reducing to 11.2 ± 0.35 U/L and AST decreasing to 72.4 ± 1.2 U/L ($P < 0.05$). Similarly, ACP activity in GRP1 was 4.76 ± 0.05 U/L, but in GRP3, it diminished to 3.78 ± 0.12 U/L. LDH activity also showed a clear reduction from 230.4 ± 0.82 U/L in GRP1 to 210.4 ± 0.81 U/L in GRP3 ($P < 0.05$). On the other hand, in GRP4, serum enzyme activity levels returned to values similar to those in the control group, with ALT at 12.8 ± 0.2 U/L and AST at 82.2 ± 0.5 U/L, respectively.

Table 4: The effects of Si-NPs in the diet on Serum Enzyme activity of *C. carpio* during 90 days of feeding trial

Enzyme Activity	GRP1 (0mg. kg^{-1})	GRP2 (1mg. kg^{-1})	GRP3 (2mg. kg^{-1})	GRP4 (3mg. kg^{-1})
ALT (U/L)	14.4b±0.25	12.8a±0.37	11.2c±0.35	12.8a±0.2
AST (U/L)	81.8a±0.54	76.2bc±1.6	72.4c±1.2	82.2a±0.5
ACP (U/L)	4.76a±0.05	4.32ac±0.03	3.78b±0.12	4.54a±0.04
ALP (U/L)	174a±1.2	168.6a±2.2	157b±2.8	173.2a±0.96
LDH (U/L)	230.4a±0.82	220.6b±0.67	210.4cd±0.81	220.2d±2.08

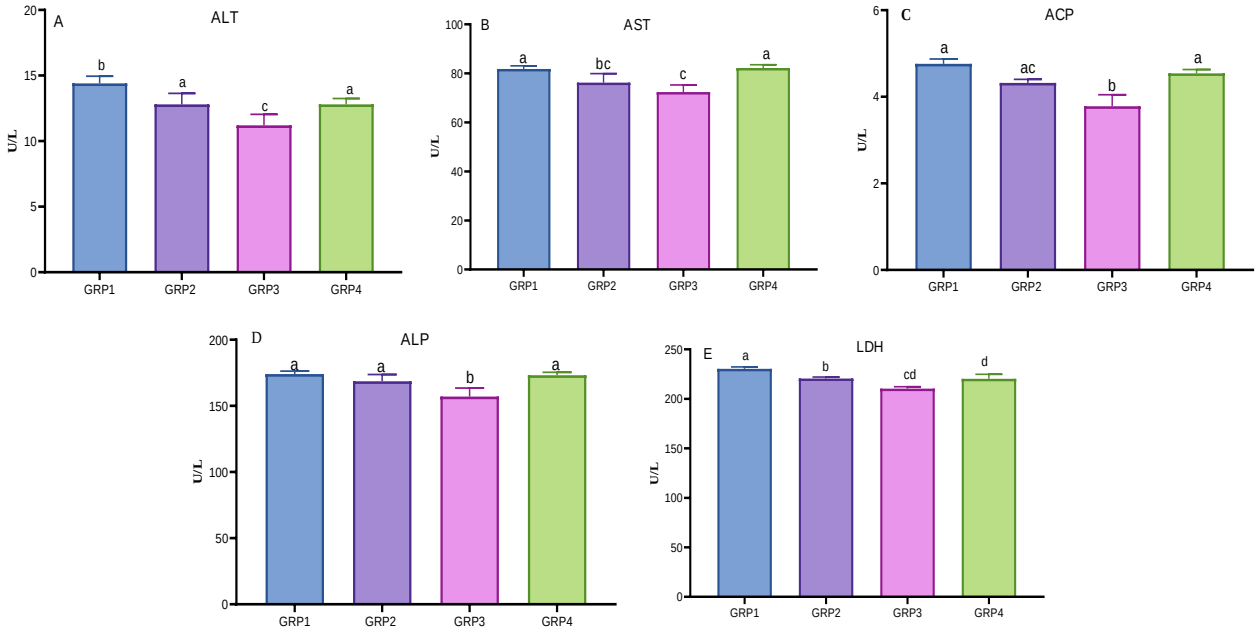

Figure 3. The effects of Si-NPs in the diet on Serum Enzyme activity of *C. carpio* during 90 days of feeding trial

4. DISCUSSION:

The experiment was conducted to evaluate the effects of Si-NPs on growth, heavy metals, and serum enzyme activity of *C. carpio* throughout the 90-day feeding trial. The current study confirmed that Si-NPs supplementation at 1 mg/kg (GRP2) and 2 mg/kg (GRP3) enhanced the growth performance of *C. carpio* significantly compared to the control group (GRP1). The growth parameters exhibited significant differences among the different treatment groups. Gao and Wang (2021) suggest that when silicon nanoparticles (Si-NPs) are used in moderate amounts, they can significantly enhance the absorption of nutrients and promote fish growth due to their ability to increase feed utilization and nutrient utilization. Similarly, Liu *et al.* (2020) experimented to check the effect of Si-NPs on fish. They confirmed that a medium concentration of Si-NPs increases feed utilization, nutrient utilization, and growth performance of fish.

The study also revealed that higher doses of Si-NPs, such as 3 mg/kg, negatively impacted the growth performance of GRP4, leading to poorer results. Similarly, Li *et al.* (2019) and Chen *et al.* (2020) Using high amounts of these nanoparticles has been shown to affect fish growth negatively, because these nanoparticles can interfere with metabolic processes, slowing them down, and their toxic nature at higher levels further damages the fish's health. Gao *et al.* (2021) explored the effects of sub-lethal levels of Si-NPs on growth-enhancing mechanisms. they found that Si-NPs positively

influenced gut health and enhanced nutrient absorption. This was evident through the increased bioavailability of essential amino acids and minerals, which are crucial for growth and development. Liu *et al.* (2020) also explained that Si-NPs promote growth, oxidative stress, and reduction of overall fish health, and they also act as antioxidants. Zhao *et al.* (2022) observed that nanoparticles play a role in boosting digestion and optimizing nutrient absorption. They achieve this by maintaining a healthy balance of gut bacteria and supporting the proliferation of beneficial microbial populations. In this study, a significant reduction in FCR in GRP2 and GRP3 was recorded, indicating the increased feed efficiency of Si-NPs. Furthermore, the improved FCR indicated that Si-NPs enhance protein synthesis and significantly increase the consumption of metabolic energy. On the other hand, metabolic imbalances were recorded in GRP4 due to increased FCR, indicating that the overload of nanoparticles makes it less efficient in converting feed to body weight. Hou *et al.* (2021) and Zhang *et al.* (2022) findings indicated that high concentrations of Si-NPs nanoparticles caused disruption of cell structure, swelling and can lead to oxidative stress that lessen the growth and survival and similarly Tacon *et al*. (2020) also described that changing feed to body weight more proficiently that indicated the best FCR which is an important factor in aquaculture profitability.

The current study also described the effect of Si-NPs on the heavy metals, including both essential and non-essential trace elements viz; Na, Co, Ni, Fe, Mg, Al, Zn, Pb, Cu, Cr, and Cd in C. *carpio*. The findings of the present study are important in checking the role of Si-NPs in maintaining homeostasis by regulating trace elements, seeing the ecological toxicology and aquaculture perspectives. Furthermore, most of the trace elements like Na, Co, Ni, Fe, Mg, Al, Zn, Pb, Cr, and Cd significantly improved the serum contents in GRP2 (1 mg/kg) and GRP3 (2 mg/kg) that indicated the moderate levels of Si-NPs increased absorption and bioavailability of such compounds. Hussain *et al.* (2024) described that a medium level of Si-NP nanoparticles improved nutrient absorption in the fish; similarly, Zhao *et al.* (2022) also studied the effect of nanoparticles on heavy metals and indicated increased permeability and absorption of elements. On theother hand, GRP4 (3 mg/kg) decreases the heavy metals viz; Na, Ni, Fe, Mg, Al, Zn, Pb, and Cr because due to increased Si-NPs. Torrealba *et al*. (2019) and Wang *et al.* (2024) studied the effect of Si-NPs on fish. They explained that high concentrations of Si-NPs disturb the homeostasis of trace elements due to nanoparticle-induced oxidative stress by disruptive metabolic pathways leading to deficiencies and imbalance. Jan *et al.* (2015) and Das et al. (2025) also studied the effect of Si-NPs on heavy metals in fish. They explained that at high concentrations of Si-NPs, some elements, particularly Fe and Zn, are significant in antioxidant defence systems and enzymatic functions.

The result also indicated that the effect of Si-NPs on serum enzyme activities such as (ALT, AST, ACP, ALP, and LDH) revealed significant alterations among the treatment groups and the results specify that moderate doses of Si-NPs reduced tissue damage and inhibited oxidative stress. In the present study, ALT and AST levels reduced GRP2 and GRP3, indicating that Si-NPs are able to save liver cells against oxidative damage, thus improving overall liver function. Similarly, the level of serum LDH activities was also reduced in GRP2 and GRP3, which may be due to the fact that this enzyme improved cellular integrity. Farooq and his colleagues also described that the moderate dose level of Si-NPs on serum enzymes might be effective in antioxidant and metabolic activities (Farooq *et al*., 2022). On the other hand, the high concentration of Si-NPs in GRP4 on serum enzymes recorded poor results that induced harmfulness at higher concentrations. Mehta (2025) observed the drops in the activities of serum enzymes due to the fact that this nanoparticle has strong antioxidant activity, scavenging the free radicals and reducing oxidative stress.

Researchers observed that the high concentrations of Si-NPs in the fish diet cause enzymes such as ALT and AST to become the main source of liver damage and are naturally upregulated as a reaction to oxidative stress (Min *et al.*, 2023). Mahboub *et al.* (2024) also studied that Excessive use of nanoparticles can lead to oxidative stress, inflammation, and damage to cell structures, ultimately inhibiting the health of tissues.

CONCLUSION:

In the present study, we concluded that Si-NP dietary supplementation of moderate levels (1–2 mg/kg) significantly enhanced *C. carpio* growth performance, feed conversion rate, and activity of enzymes. Si-NPs also influenced the levels of trace elements, with enhanced nutrient delivery at optimal dose levels, though causing adverse impacts at elevated dose levels (3 mg/kg). The findings reveal that Si-NPs can be a valuable aquaculture feed supplement, but the optimum dosage must be exercised to prevent potential toxicity. Further investigation is needed to ascertain long-term safety and impacts on the environment.

Statements And Declarations

Ethical Approval: Department of Fisheries Saline Water Aquaculture Research Center (APF-024).

Conflict of interest: The authors declared no potential conflict of interest.

Consent to Participate: All authors have consented to submit the article to this journal.

Consent to Publish: All authors have agreed to publish the article in this journal.

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