Health Risk Assessment of Diabetes Mellitus II for Bioaccumulated Zinc in Some Ethno-Millets from Zawar Mines Udaipur (Rajasthan) India

Dr.Sunita Jain

sunitajain130799@gmail.com

Bhupal Nobles' University

Research Article

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Health Risk Assessment of Diabetes Mellitus II for Bioaccumulated Zinc in Some Ethno-Millets from Zawar Mines Udaipur (Rajasthan) India

Sunita Jain, Assistant Professor, Department of Botany, B N University, Udaipur (Raj.) India
sunitajain130799@gmail.com

Abstract

Rajasthan is one of India's most mineral-rich states, known for the abundance and variety of its minerals. The state possesses deposits of about 81 major and minor mineral types. Operative cum post-mining procedures and natural occurrence of high levels of minerals in soil make many health issues as they enter food chains and prolonged usage causes bio-magnification. Zinc en-routes through rhizosphere, roots, shoots and finally in grains. It is a co-factor for many enzymes and plays vital role in plant’s defense system by quenching free radicals, and thereby reducing ROS damage to cell components. Its concentration in staple foods specifically cereals and millets requires standard permissible limits. Hence, this study was conducted in order to assess the zinc levels in soil, its translocation in seven millet plants i.e. *Echinochloa colona*, *Echinochloa crusgalli*, *Eleusine coracana*, *Panicum miliaceum*, *Paspalum scrobiculatum*, *Setaria glauca* and *Setaria italica* and the impact of higher zinc accumulated grains on postprandial hyperglycemic biomarker enzymes, specifically α-amylase and α-glucosidase, total sugar content and total dietary fiber. Except for *Echinochloa colona* and *E. crusgalli* the zinc concentrations were higher in grains of the other five millets. The risk assessment for diabetes mellitus II reveals low levels of total sugar content in all five millets of test samples. Total dietary fiber didn't reveal significant variation among control and test samples. Anti α-amylase and anti α-glucosidase activity were comparatively higher in test samples of *Echinochloa colona* and *E. crusgalli* but only *E. colona* marked as safer for diabetic patients as grains of *E. crusgalli* had high levels of zinc. Dietary interventions play a preventive and supportive role by protecting against oxidative damage. Such research offers an evidence-based approach and policy suggestions for reducing human exposure to metals and metalloids consumed through diet. Continuous monitoring is recommended to mitigate ecological as well as human health risk.

Keywords- Zawar Mines, Zinc, Diabetes Mellitus II, Millets, Bio-concentration factor, Bioaccumulation factor, Translocation factor, Alpha-amylase, Alpha-glucosidase

Introduction

Wellbeing refers to the state of being healthy and happy and to the presence of high levels of positive functioning. It is a holistic state and is an outcome of various factors among which nutrition forms an essential vital line. In nutrition, various components form different pillars of health among which minerals are of utmost importance as they are the basic keys of various enzymatic functions. These minerals form a balanced metabolic entity between environment and human health but in minning zones and industrial areas, these entities have deviated from ideal levels leading to hazardous impacts (Naz et al., 2020; Repkina et al., 2023; Gao and Gnanachandrasamy, 2025; Yang et al., 2026). Metal is present in the soil in various forms—specially, exchangeable, oxidizable, reducible, and residual forms. Among these, only the exchangeable metal fraction contributes to metal mobility and is bioavailable to plants (Khoshgoftarmanesh et al., 2018; Zhang et al., 2018; Akhavan and Golchin, 2024; Dev et al., 2026). Rajasthan is rich in terms of mining zones and ores of various mineral deposits. The Zawar group of mines are rich in Lead –Zinc ore deposits and are situated in Rajasthan, India, approximately 40 km south of Udaipur. The zinc moiety in this region varies invariably and affects human health through both direct and indirect ways (Aery and Tiagi, 1985; D'Souza et al., 2023). Many plants growing in mining vicinity are bio-accumulators and indicate high levels of zinc in roots, shoots and grains when compared with control or non-mining sites. When such plants are ingested by the local populace for their ethno-botanical usage they affect many biological pathways. Cereals and millets impact more health conditions over other plant materials as being stapled food they are consumed in larger amounts and are used more frequently. In Rajasthan, out of the total population, 75.13% of the population lives in urban areas and 24.87% lives in rural areas. There are 17.83% scheduled castes and 13.48% scheduled tribes (Census, 2011). Tribal culture predominantly denies the practice of stored foods except for staple grains. Among grains, they prefer millets over cereals due to their economical and easy availability (Arora and Lohar, 2019; Shah et al., 2019; Lokur et al., 2023.).

Cereals and millets despite complex sugar entities carry a good amount of fiber which in turn affects satiety, a major cause of obesity and in turn affecting DMII by hindering obesity (Larsen et al., 2020). Therefore, in the present investigation the millets chiefly consumed by ethnic peoples were prioritized over other plant materials and six millets *Echinochloa colona*, *E. crusgalli*, *Eleusine coracana*, *Panicum miliaceum*, *Paspalum scrobiculatum*, *Setaria glauca* and *S. italica* were used as test samples.

Diabetes mellitus II (DMII) describes a category of metabolic disorders characterized by a high blood sugar level over a prolonged period of time. These persistent higher sugar levels specifically higher postprandial sugar levels are the basic cause of diabetic-associated multiple pathologies. Amylase and glycosidase are classified in the largest Glycosyl hydrolase family, GH13 (Samanta, 2022; An et al., 2023). They are the key carbohydrate degrading enzymes, help in breaking down of polysaccharides into smaller molecules and contribute to elevated blood glucose levels and postprandial hyperglycemia. Natural α-amylase inhibitors of plant origin have gained popularity as alternatives as they are safe and cost-effective and can manage diabetes mellitus II (Kashtoh and Baek, 2023; Khator and Monga, 2024). Transition metals are known to restrict α-amylase function by inducing changes to their native protein conformation. (Liao et al., 2019).

Depending on its concentration, Zn can serves as an essential micronutrient (Solanki, 2021; Mued et al., 2025), or can act as a hazardous heavy metal toxin (Kaur and Garg, 2021; Sheikh et al., 2025; Ulhassan et al., 2025). It is estimated that zinc is a vital co-factor for about 3,000 enzymes and plays vital role in plant's defense system by quenching free radicals, and thereby reducing ROS damage to cell components (Hübner and Haase, 2021; Shamsi et al, 2023). Zn often acts as a protein cofactor by binding directly with the oxygen, sulfur, and nitrogen atoms present in the side chains of specific amino acids: aspartate, cysteine, glutamate and histidine (Maret, 2024) and has significant impact on every aspect of a person's metabolic processes and overall health (Permyakov, 2021). The damaging consequences of heavy metals on human physical and mental well- being are largely associated to their capability to interfere with free radical scavenging mechanisms and metabolic pathways (Jomova et al., 2025). Essential nutrients, such as zinc, selenium, and other can reduce heavy metal bioavailability and toxicity (Sharma et al., 2020). Kumar and Dey, studied about nutritional approaches to reduce heavy metal impacts (Kumar and Dey, 2025). Zinc causes the chelation and immobilization of heavy metals which in turn prevents their absorption by plants from the soil (Hassan et al., 2022). At optimum concentration Zn mitigates heavy metals toxicity with hyper- accumulators capacity through the over expression of constitutive metal transporters and their efficient translocation capacity (Hassan et al., 2022; Bhat et al., 2025). It also induces the synthesis of metallothioneins, the cysteine-rich heavy metal binding proteins, which effectively immobilize zinc ions and prevent them from interfering with cellular functions (Roy et al., 2024). Fernandez-Cao and colleagues reported that a dietary zinc moderately above the DRI could reduce the development of DMII but not when intake is very high. Zinc plays important roles in the adequate insulin synthesis, secretion, and its translocation into the cells. In addition, zinc activates phosphoinositol-3-kinase and suppress pro-inflammatory cytokines (Fernández-Cao et al., 2019).

Excess Zn in the soil can interfere with the absorption and movement of other essential micronutrients and can directly harm cell membrane and organelles (Kaur and Garg, 2021). It can disturb nutrient homeostasis and other vital physiological activities, like biosynthesis of chlorophyll, photosynthetic efficiency, oxidative stress response, and membrane integrity (Shamsi et al., 2023; Pandey et al., 2024). Its presence above threshold limit triggers oxidative stress, cellular damage, and alteration in the structure and functions of enzymes and pigments (Sheikh et al., 2025). Jomova and coworkers also explain the role of redox-inactive zinc in oxidative stress and related disorders. It impairs the catalytic activity of various antioxidant enzymes, receptors and transporters, resulting in a high generation of free radicals (Jomova et al., 2025). Thus an adequate amount of zinc is essential for structural, catalytic and regulatory functions of various enzymes and their stability (Fariduddin et al., 2021; Costa et al., 2023; Razzaque et al., 2025).

Zn uptake in plants is determined by its availability in the soil and the plant's ability to absorb and manage its internal water and mineral levels (Adil et al., 2024). Naaz and coworker, explained the mechanism of Zn absorption from the soil, role of transporter proteins and factors governing zinc availability in the soil (Naaz et al., 2025). Numerous studies demonstrated that free radicals play a significant role in insulin resistance and diabetes mellitus. As pancreatic beta cells have low antioxidant enzymes and high number of metal transporters, making them highly susceptible to oxidative damage (Bjørklund et al., 2020). En-route of zinc in humans through contaminated soils via grains can impact sugar levels in diabetic patients (D'Souza et al., 2023). Exposure to hazardous metals from unregulated mining and industrialization, is known to contribute to oxidative stress and related diseases. There is currently no evidence linking heavy metals with type 2 diabetes, with the exception of arsenic (Chepkorir, 2022). Previous studies have examined the effect of varying zinc levels on tolerance, accumulation capacity, and stress responses in different millets species (Jatav et al., 2025; Naaz et al., 2025). Building on this line of research, the purpose of the current *in vitro* study was to assess the zinc levels in soils, its translocation within millet plants and the impact of higher zinc- accumulated millet grains on postprandial hyperglycemic biomarker enzymes i.e.α-amylase and α-glucosidase, total sugar content and total dietary fiber. Such studies on health risk assessment of dietary exposure to metallic trace elements like lead, cadmium and other toxic elements support continuous monitoring of toxic elements in staple foods, strengthen the management of food safety and support the creation of national policies. (Bazie et al., 2022; Huang et al., 2022; Choquenaira-Quispe, 2022; Kadala et al., 2026; Xie et al., 2026; Yeganeh et al., 2026).

2. Materials and Methods

2.1 Study Area

The Zawar Belt with zinc- lead deposits (Mochia, Balaria, Zawar Mala, Baroi and Bawa) situated within the Lower to Middle Proterozoic Aravalli Super groups, forming a 20 Km long mineralized zone that includes intercalated dolomite, quartzites and conglomerates, geographically spread around 24˚18' 48" and 24˚22' 48" N and 73˚40' and 73˚45'24" E in Rajasthan (Mukhopadhyay, 2023). A tropical continental monsoon is the prevailing climate type of the area. (Plate 1).

Plate 1: Zawar Belt with zinc lead deposits at Mochia, Balaria, Zawar Mala, Baroi and Bawa (24˚ 18' 48" and 24˚ 22' 48" N and 73˚ 40' and 73˚ 45'24" E)

2.2 Sample Collection

Rhizospheric soil samples were taken from the adjoining fields of Mochia, Balaria, Zawar Mala, Baroi and Bawa. The millet species i.e. *Echinochloa colona* (EC1), *E. crusgalli* (EC2), *Eleusine coracana* (EC3), *Panicum miliaceum* (PM), *Paspalum scrobiculatum* (PS), *Setaria glauca* (SG) and *S. italica* (SI) were gathered from 17 locations surrounding the mining and land fill area. Additionally, a control soil sample was also collected from a forested conserved land that was unaffected by mining activities. Metal contaminated free millet plant species were collected from mining deficit areas which were used as control. Soil samples and plant specimens were transported to the laboratory after being placed in pre-cleaned, sealable, airtight bags. Millets plant specimens (Herbarium Ac No- MC/MS 110-124/2023) were identified by Dr. S. S. Katewa, Department of Agrostology and Ethnobotany, Department of

Botany, MLSU, Udaipur (Raj.) and are kept in Department of Botany, B N University, Udaipur (Raj.) for future reference.

2.3 Sample Preparation and Analysis

Zinc was analyzed according to Ure (1990). The soil samples were oven-dried at 100˚C for 24 hours, ground to a fine powder and sieved through a sieve of 2.0 mm mash size to get rid of impurities from the samples. Vegetative millet plant materials were initially washed for the removal of dust and other adhered impurities. Later on, they were washed with deionized water and pressed over filter papers to remove moisture and subsequently seeds were ground and sieved to obtain fine powder for zinc analysis. 1.0 g of each sample were taken in 250 ml glass beakers and digested with concentrated nitric acid and perchloric acid by heating the mixture of samples on a hot plate in a fume cupboard at 200°C. The volume of sample solutions and control was made up to 10.0 ml with deionized water. Millets/Grains were analyzed for zinc by oven drying at 105˚C for two hours, subsequently cooled to room temperature and ground to a fine powder. 1 g of sample was turned to ash at 450˚C and digested to clear solution with 5 ml of HNO_3. The residue was made to 50 ml by adding deionized water. Metal content in an analyte was determined using atomic absorption spectrophotometer. Metallic bioaccumulation and translocation was assessed by three parameters viz. bio-concentration factor (BCF), bioaccumulation factor (BAF) and translocation factor (TF). They were determined according to Liu et al., 2008, Alloway, 2012, Chowdhury and Maiti, 2016.

i. $$\mathrm{BCF} = \frac{C_{root}}{C_{soil}}$$

ii. $$\mathrm{BAF} = \frac{C_{shoot}}{C_{soil}}$$

iii. $$\mathrm{TF} = \frac{C_{shoot}}{C_{root}}$$

C_{root}, C_{shoot} and C_{soil} are metal concentrations in the plant root, shoot and rhizosphere respectively. The concentrations are expressed as (mg /kg). TF >1 depicts that translocation of metals was functionally made to the shoot from the root. BAF is further represented as hyper-accumulator, accumulator and excluder to plant species which accumulates metals as >1, 1 and <1, respectively.

2.4 *In Vitro* Biochemical Evaluation for Anti-diabetic Potential

Ethno anti-hyperglycemic millets were screened for their anti-diabetic potential for four parameters viz.-Total Sugar Content (TSC), Total Dietary Fiber (TDF), Anti α-amylase Activity (AAA) and Anti α-glucosidase Activity (AGA). For *in vitro* studies, the aqueous extract was prepared by cold maceration of respective grains by soaking 100g in 500ml of distilled water for 24 hours and followed by filtration. Respective extracts were stored at 5-8 $^{\circ}$C in dark bottles.

Total Sugar Content

Carbohydrates were first hydrolyzed into simple sugars using dilute hydrochloric acid. The millet samples were weighed (100 mg) and into boiling tubes, HCl (2.5 N, % ml) was added and the tubes were kept in a boiling water bath for 3 hours for hydrolysis. The tubes were cooled to room temperature. Sodium carbonate was added to the samples until the effervescence ceased. This neutralized the samples. The volume was made up to 100 ml and centrifuged. The supernatant was collected and 0.1 ml aliquots were taken for analysis. The standards were prepared by taking 0, 0.2, 0.4, 0.5, 0.8, and 1 ml of the working standards. Zero (0) served as blank. The volume was made up to 1 ml in all the tubes including the sample tubes by adding distilled water. To all tubes 4 ml anthrone reagent was added. The tubes were heated for eight minutes in a boiling water bath. The contents of the tube were cooled rapidly and the dark green color was read at 630 nm. A standard graph was drawn by plotting the concentration of the standard on the X-axis versus absorbance on the Y-axis.

$$\textbf{Total sugar content} = \frac{\textbf{mg of glucose X 100}}{\textbf{Volume of the test sample}}$$

Total Dietary Fiber

Total dietary fiber was screened using a combination of enzymatic and gravimetric methods (AOAC International, 1997). Fat-free dried samples bran were gelatinized with heat stable α-amylase and then enzymatically digested with protease and amyloglucosidase enzymes to remove the protein and starch present in the sample and subsequently ethanol was added to precipitate the soluble dietary fiber. The residue was washed with ethanol and acetone and was dried and weighed. One portion of the sample was analyzed for protein while the other part was turned to ash using muffle furnaces. TDF was calculated as the weight of the residue minus the weight of the protein and ash reported as a percentage of the original sample weight.

$$\textbf{TDF\%} = \frac{[(\textbf{R Sample} - \textbf{P Sample} - \textbf{A Sample}) - \textbf{B}] * \textbf{100}}{\textbf{S}}$$

Where, Residue weight (mg) (R) = W2-W1; Ash weight (mg) (A) = W3-W1; B = R (blank) – P (blank) - A (blank); P = Protein weight (mg) and S = Sample weight (mg).

Anti α-amylase Activity

The assay mixture containing 200 µl of 0.02M sodium phosphate buffer, 20 µl of enzyme and the aqueous millet extract in the concentration range 20-100 μgml^{-1} were incubated for 10 minutes at room temperature followed by the addition of 200 µl of starch in all test tubes. The reaction was terminated with the addition of 400 µl DNS (3,5-Dinitrosalicylic acid) reagent and placed in a boiling water bath for 5 minutes, cooled and diluted with 15 ml of distilled water and absorbance was measured at 540 nm. The control samples were prepared without any millet extract. The % inhibition was calculated according to the formula (Jung et al., 2006).

$$\textbf{Inhibition}\ (\%) = \frac{\textbf{Abs}_{\textbf{540}}\ (\textbf{control}) - \textbf{Abs}_{\textbf{540}}\ (\textbf{extract}) * \textbf{100}}{\textbf{Abs}_{\textbf{540}}(\textbf{control})}$$

Anti α-glucosidase activity

The yeast alpha glucosidase was dissolved in 100 mM phosphate buffer pH 6.8 and was used as the enzyme extract. P-Nitrophenyl-α-D-glucopyranoside was used as the substrate. Aqueous millet extracts were used in the concentration ranging from 20-100 μgml^{-1}. Different concentrations of millet extracts were mixed with 320 µl of 100 mM phosphate buffer pH 6.8 at 30°C for 5 minutes. 3 ml of 50 mM sodium hydroxide was added to the mixture and the absorbance was read at 410 nm. The control samples were prepared without any extracts. The % inhibition was calculated according to the formula (Jung et al., 2006).

$$\textbf{Inhibition}\ (\%) = \frac{\textbf{Abs}_{\textbf{410}}\ (\textbf{control}) - \textbf{Abs}_{\textbf{410}}\ (\textbf{extract}) * \textbf{100}}{\textbf{Abs}_{\textbf{410}}(\textbf{control})}$$

The IC 50 values for both α-amylase and α-glucosidase were determined from plots of percent inhibition versus log inhibitor concentration and were calculated by nonlinear regression analysis from the mean inhibitory values. Acarbose was used as the reference α-amylase and α-glucosidase inhibitor.

2.5 Statistical Analysis

The data obtained in triplicate were subjected to ANOVA at a significance level of $P<0.001$, 0.01 and 0.05.

3. Result and Discussion

Food in any society is essentially an indispensable means of survival. The human need for food has done much to shape society in a particular way through all the activities concerned with food production, distribution and utilization. Food, therefore, is not only a source of satisfying innate biological instinct or a bio-chemical process but is also a social and cultural factor. The identity of each ethnic group can be known or established through its food habits, food ways and food ideology.

The quality of food is also a sign and symbol of wealth or status in society. In the current era, the soil is continuously contaminated through various anthropogenic activities such as mining activity, industrial emissions, vehicular emissions and atmospheric deposition (Karki and Verma, 2020). In mining sites, bio-magnification of metals in crops and plants of adjoining areas is a common observation and their channelization through food chain causes alarming clinical pathologies among which endocrine maladies are of utmost prominent (Iya et al., 2025).

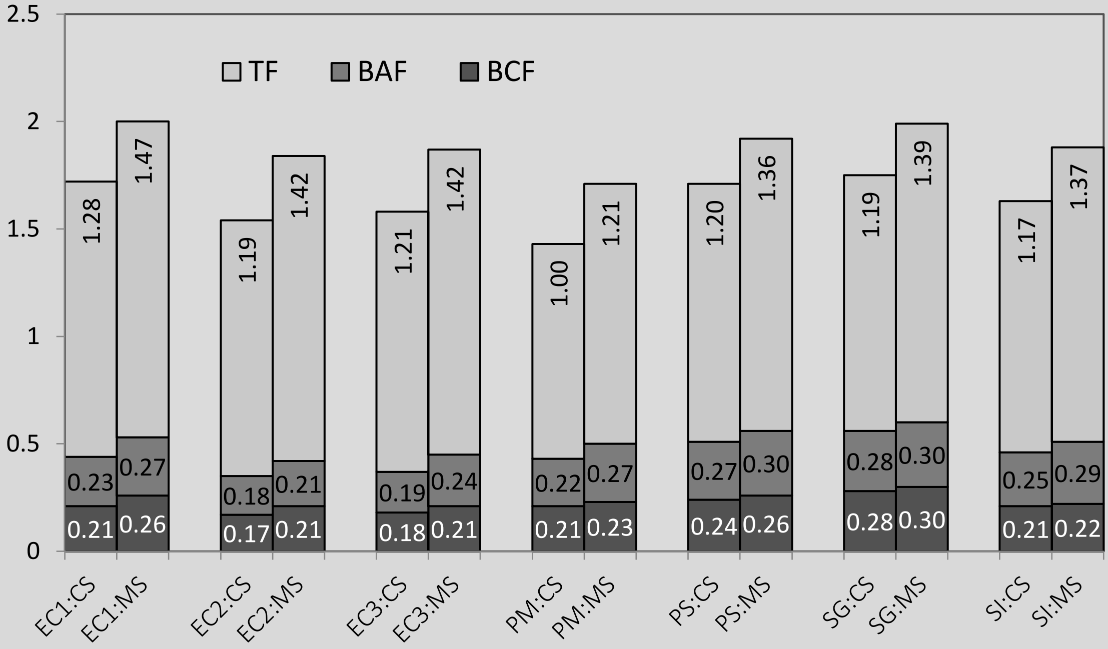
Rajasthan state inhabits a large number of nomadic, seminomadic, tribal and rural population which resides in remote areas and depends on ethno-foods for their survival among which millets are more popular. The soil samples and millet crops are grown in mining adjoining areas of up to five kilometers of Mochia, Balaria, Zawar Mala, Baroi and Bawa differ in zinc concentrations as compared to control non-mining sites.

3.1 Bio-concentration factor (BCF), Bioaccumulation factor (BAF) and Translocation factor (TF):

Zinc concentration in soil samples and rhizosphere was between 27 to 30 $mgkg^{-1}$ in control sites while 35.5 to 36.87 $mgkg^{-1}$ in mining sites. Highest bio-concentration factor of zinc in control sites was obtained in *Setaria glauca* (0.28) followed by *Paspalum scrobiculatum* (0.24) whereas in mining sites, similar to the control site both the species had similar higher concentration but in addition, *Echinochloa colona* had comparatively higher accumulation in mining site as compared to control site revealing significant bioaccumulation in root tissue. Comparison of bio-concentration factor (BCF) in between control sites and mining sites reveals a higher preference of 23.81% accumulation in *Echinochloa colona* followed by 23.53% in *E. crusgalli* and 16.67% in *Eleusine coracana.* BCF was comparatively lower in *Panicum miliaceum, Paspalum scrobiculatum*, *Setaria glauca* and *S. italica* and were in the range of 4 to 9 %. The zinc content in roots and shoots was nearly similar in *Setaria glauca* whereas it was 12.50 % more in *Paspalum scrobiculatum* in the mining site as compared to the control site. Bioaccumulation factor (BAF) was significantly high in mining sites i.e.7.14 to 26.32% over control site as being higher in *Eleusine coracana* (26.32%) followed by *Panicum miliaceum* (22.73%) and *Echinochloa colona* (17.39%) while lowest in *Setaria glauca* (7.14%). Translocation factor (TF) was found to be higher in all the studied millet species in the mining site by 13.33 to 21%. TF was found to be 21% higher mining site as compared to control in *Panicum miliaceum* followed by 19.33% in *Echinochloa crusgalli*. Change in TF over both the sites was nearly similar in *Echinochloa colona*, *Eleusine coracana*, *Setaria glauca* and *Setaria italic* (Figure 1).

BAF values of all the millets were less than one indicating their excluder nature but the values were still higher up to 24% in crops growing in mining adjoining fields as compared to control sites. In addition higher TF values specifically of *Panicum miliaceum* and *Echinochloa crusgalli* indicates accumulation of zinc in significant quantities in aerial parts. Higher bioaccumulation of zinc in staple food/ millets and their daily consumption over long periods can cause chronic diseases (Asdeo, 2014; Naaz et al., 2020).

Figure 1: Comparison of Bioconcentration factor (BCF), Bioaccumulation factor (BAF) and Translocation factor (TF) of studied millets in control site (CS) and mining site (MS)



Echinochloa colona (EC1), *Echinochloa crusgalli* (EC2), *Eleusine coracana* (EC3), *Panicum miliaceum* (PM), *Paspalum scrobiculatum* (PS), *Setaria glauca* (SG) and *Setaria italica* (SI)

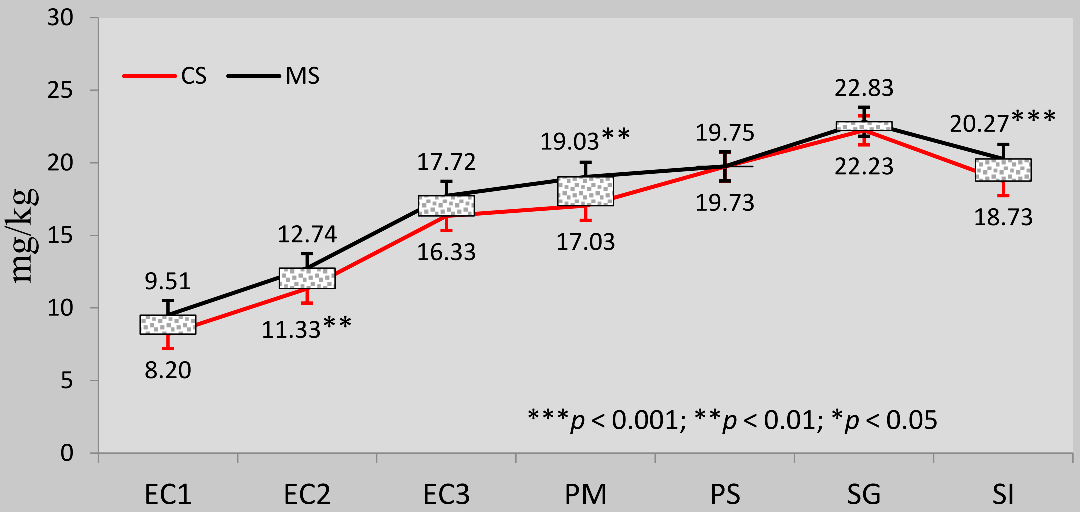
3.2 Zinc concentration in grains:

Zinc concentration differed in grains of all the studied millets except in *Paspalum scrobiculatum* in which the concentration was nearly similar i.e. 19.73 and 19.75 mgkg^{-1} in both control and mining site. Zinc concentration was higher up to 16.02% in grains collected from mining sites in *Echinochloa colona* followed by 12.41% and 11.74% in *Echinochloa crusgalli* and *Panicum miliaceum* respectively (Figure 2).

Higher accumulation of zinc in grains in mining site may lead to chronic maladies and impairment of organs passively leading to endocrine dysfunctions as the Recommended Dietary Allowance of zinc for adults is 11 mg per day for men and 8 mg/ day for women while the tolerable upper intake level for adults is 40 mg per day, a value based on reduction in erythrocyte copper-zinc superoxide dismutase activity (Cousins, 1989; El Dib et al., 2015; Jomova et al., 2025). Nearly 100 specific enzymes (e.g., EC 1.1.1.1 alcohol dehydrogenase) depend on zinc for their catalytic action. Zinc deficiency impairs various activities including major biochemical pathways regulated through metalloenzymes (Vallee and Galdes, 1984;

Thompson, 2022; Kashtoh and Baek, 2023). Higher intakes of 150–450 mg of zinc per day have been associated with chronic effects as low copper status, altered iron function, reduced immune function, and reduced levels of high-density lipoproteins (Varaprasad et al., 2021). Reductions in a copper-containing enzyme, a marker of copper status, have been reported with even moderately high zinc intakes of approximately 60 mg/day for up to 10 weeks (Cheng and Chen, 2021; Jomova et al., 2025).

Figure 2: Comparison of Zinc concentration in grains of studied millets at mining site (MS) and control site (CS)

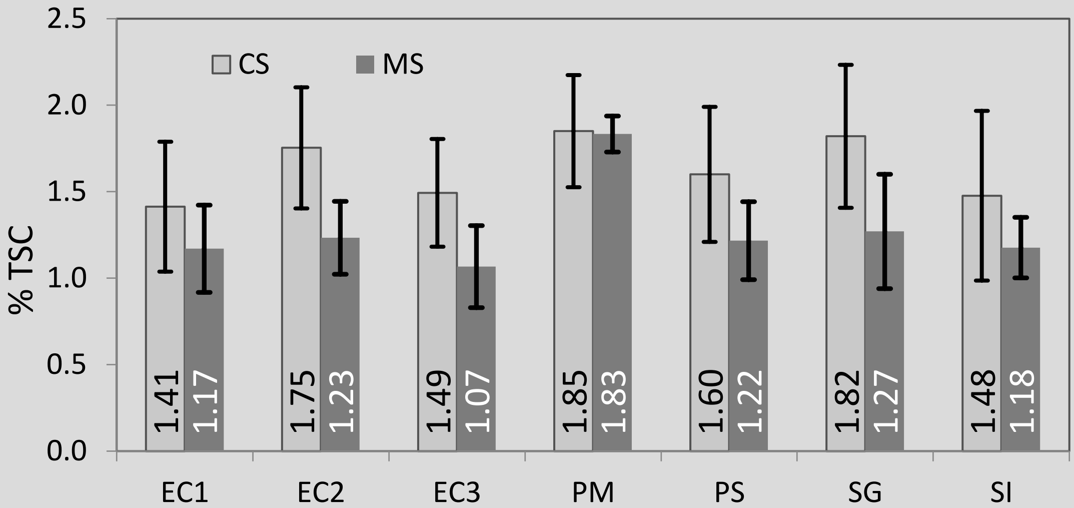


Echinochloa colona (EC1), *Echinochloa crusgalli* (EC2), *Eleusine coracana* (EC3), *Panicum miliaceum* (PM), *Paspalum scrobiculatum* (PS), *Setaria glauca* (SG) and *Setaria italica*

3.3 Total Sugar Content (TSC) and Total Dietary Fiber (TDF)

Total sugar content (TSC) was found to be lower in all millets growing in zinc contaminated soils except in *Panicum miliaceum* in which the TSC in grains differed only by 0.90% in control and test samples. TSC decreased by 30.22% in *Setaria glauca,* 29.66% in *Echinochloa crusgalli* and 28.57% in *Eleusine coracana* (Figure 3).

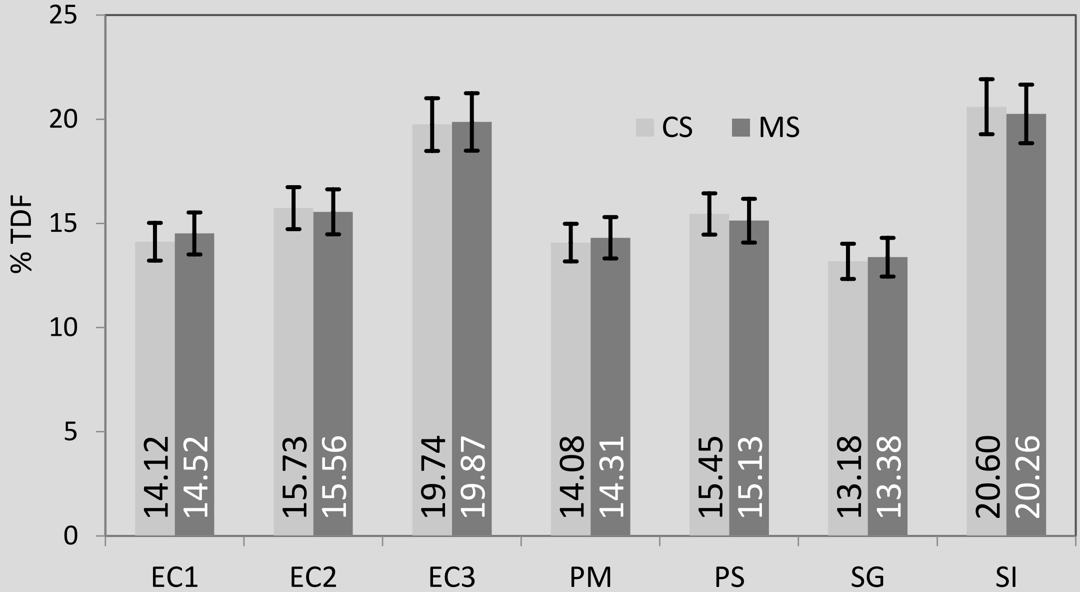
Figure 3: Comparative % total sugar content (TSC) in grains of studied millets in mining site (MS) and control site (CS)



Echinochloa colona (EC1), *Echinochloa crusgalli* (EC2), *Eleusine coracana* (EC3), *Panicum miliaceum* (PM), *Paspalum scrobiculatum* (PS), *Setaria glauca* (SG) and *Setaria italica* (SI); ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

Total Dietary Fiber (TDF) did not differ largely in all test samples as compared to control samples revealing no effect of zinc concentrations in soil and was not affected by translocation factor. TDF was found to be slightly higher in *Echinochloa colona* (2.82%), *Panicum miliaceum* (1.65%) and *Setaria glauca* (1.51%) at zinc contaminated mining sites while decreased slightly in *Paspalum scrobiculatum* (2.09%) followed by and *Setaria italica* (1.68%) and *Echinochloa crusgalli* (1.13%) (Figure 4).

Figure 4: Comparative % total dietary fibre (TDF) in grains of studied millets in mining site (MS) and control site (CS)



Echinochloa colona (EC1), *Echinochloa crusgalli* (EC2), *Eleusine coracana* (EC3), *Panicum miliaceum* (PM), *Paspalum scrobiculatum* (PS), *Setaria glauca* (SG) and *Setaria italica* (SI); ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

Prevailing beliefs over the past regarding sugars and diabetes admonished that added sugar primarily sucrose should be avoided and that naturally occurring sugars should be restricted in the diabetic diet. Support for these beliefs was based largely on results from animal and human studies suggesting that simple sugars would confer a higher postprandial glycemia than starch. Consequently, diets for diabetic patients have been sugar restricted for fear of stimulating hyperglycemia, exaggerating insulin response to carbohydrates and causing possible cardiomyocyte dysfunction and/or accelerated loss of β-cells (Paul et al., 2021).

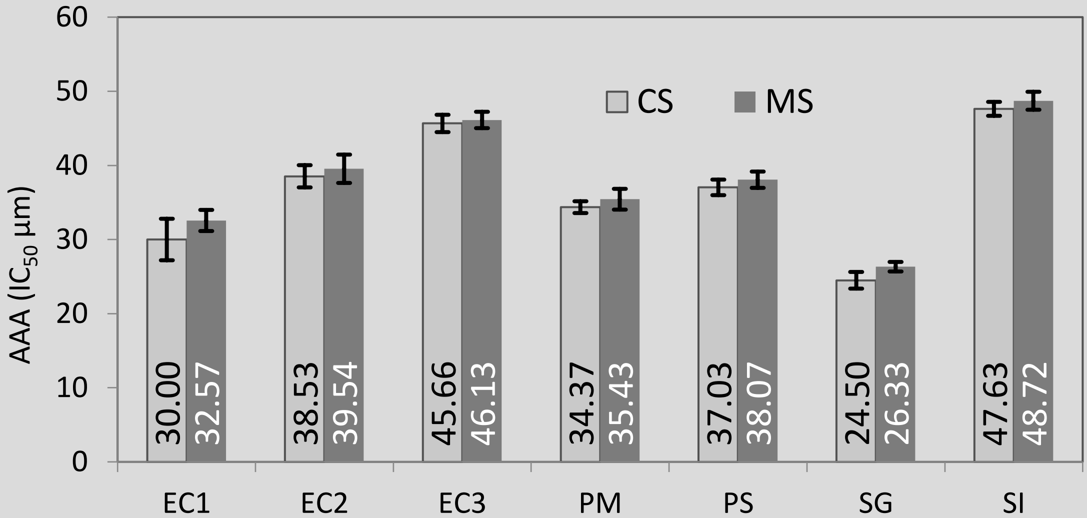
Several metabolic studies have reported that the inclusion of a moderate amount of dietary sucrose within a balanced diabetic diet did not elicit subsequent deleterious effects on glycemic control. Different types of sugars may have variable metabolic effects on glycemia or lipemia (Volek et al., 2021). Additionally, it is recommended that an increase of dietary fiber, particularly the soluble type, should be taken by T2D patients. It is reasoned that soluble fiber reduces enzyme access to its substrates through the viscosity effect.

Studies concluded that fibers intake and obesity are inversely correlated, indicating fibers role in starch and cholesterol control (Alahmari et al., 2024; Razouki et al., 2025). Reduction in total sugar content and persistence of dietary fibers in zinc contaminated sites may help in regulating and managing glycemic levels in DMII patients (Chasapis et al., 2012; Dubey et al., 2020; Bjørklund et al., 2020).

3.4 Antiα-amylase Activity (AAA) and Anti α-glucosidase Activity (AGA)

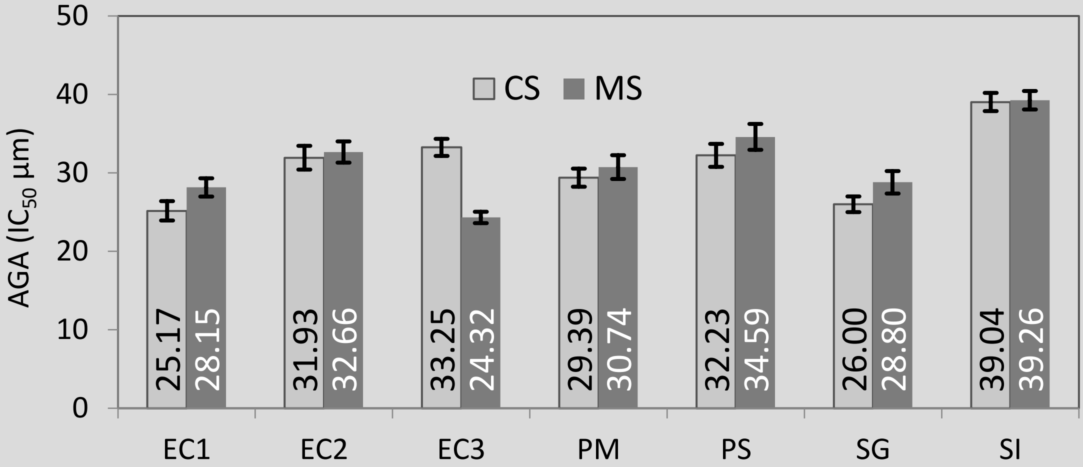
Highest AAA was obtained in *Setaria italica* as 47.63% in CS and 48.72% in MS followed by *Eleusine coracana* as 45.66% in CS and 46.13% inhibition in MS but comparison of inhibitory activity on both CS and MS didn't varied significantly revealing neutral impact of zinc concentrations in plant parts and rhizosphere while comparison of activities in CS and MS reveals increased AAA by 8.57% in *Echinochloa colona* and 7.48% in *Setaria glauca* (Figure 5). As akin to the activity of AAA, AGA was also found to be increased by 11.84% and10.77% in both *Echinochloa colona* and *Setaria glauca* while was nearly equal on both CS and MS in *Setaria italica* while contrary to all other millets responses AGA of *Eleusine* decreased sharply in zinc contaminated site by 26.86% (Figure 6).

Figure 5: Comparative Anti α-amylase activity(AAA) in grains of studied millets in mining site (MS) and control site (CS)



Echinochloa colona (EC1), *Echinochloa crusgalli* (EC2), *Eleusine coracana* (EC3), *Panicum miliaceum* (PM), *Paspalum scrobiculatum* (PS), *Setaria glauca* (SG) and *Setaria italica* (SI); ****p* < 0.001; ***p* < 0.01; **p* < 0.05

Figure 6: Comparative Anti α-glucosidase activity (AGA) in grains of studied millets in mining site (MS) and control site (CS)



Echinochloa colona (EC1), *Echinochloa crusgalli* (EC2), *Eleusine coracana* (EC3), *Panicum miliaceum* (PM), *Paspalum scrobiculatum* (PS), *Setaria glauca* (SG) and *Setaria italica* (SI); ***p < 0.001; **p < 0.01; *p < 0.05

4. Conclusion

The highest bioconcentration factor and bioaccumulation was found in *Setaria glauca* but the translocation efficacy was not at par with that of BCF and BAF but still, the grains were having maximum zinc concentration among all studied millets. Total sugar content was lower in test samples as compared to control samples and total dietary fiber did not change significantly revealing a positive characteristic of zinc concentrations. The level or activity of key enzymes i.e. α-amylase and α-glucosidase determine the status of postprandial hyperglycemia. The inhibitors of these enzymes play a primordial role in DMII management. The grains of *Echinochloa colona* and *Setaria glauca* obtained from the mining site revealed the highest anti α-amylase and anti α-glucosidase activity revealing their preferred usage over other millets in diabetic patients but the zinc concentration in *Setaria glauca* is more than ingestible permissible limits and hence cannot be subjected for usage as higher levels lead to acute and chronic zinc toxicity causing a disturbance in copper metabolism, reduced iron function and high density lipoproteins, neutropenia, atherogenic cardiac function etc. The zinc concentration though improves AAA and AGA but also impairs other pancreatic alpha cell and therefore usage of *Echinochloa crusgalli*, *Eleusine coracana*, *Panicum miliaceum*, *Paspalum scrobiculatum*, *Setaria glauca* and *S. italic* have higher zinc concentrations in their grains and therefore should be avoided. Higher zinc concentrations also indicate pollution load which may cause bio-magnification if used for prolonged periods. *Echinochloa colona*is safer as it has permissible limits of zinc in grains and is rich in anti α-amylase and anti α-glucosidase activity and therefore can help in better management of glycemic levels in diabetic patients.

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