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SEASONAL DYNAMICS OF LEAD TRANSFER FROM SOIL TO FORAGE AND ITS ASSOCIATION WITH BLOOD LEAD (PB) AND GLUCOSE LEVELS IN BUFFALOES

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Abstract

Heavy metal contamination in the environment endangers the health and productivity of cattle. This study looked at the seasonal variations in lead (Pb) concentrations in buffalo soil, feed, and blood plasma, as well as Pb bio-concentration variables and changes in blood glucose levels. Soil, forage, and blood plasma samples were obtained from lactating, dry, and young buffaloes over the summer, autumn, winter, and spring seasons. Mean Pb concentrations in soil ranged from 15.37 to 16.94 mg/kg, remaining below the FAO/WHO permitted limit of 100 mg/kg, while forage Pb levels ranged from 5.98 to 6.24 mg/kg, above the recommended limit of 0.3 mg/kg for plants. Blood plasma Pb concentrations were from 0.389 to 0.592 mg/L in breastfeeding buffaloes, 0.505 to 0.566 mg/L in dry buffaloes, and 0.595 to 0.851 mg/L in young buffaloes, all exceeding the hazardous threshold of 0.3 mg/L. Seasonal influences had a substantial impact on Pb concentrations in soil and blood plasma of breastfeeding and young buffaloes ($p<0.05$). Bio-concentration factors demonstrated that Pb was efficiently transferred from soil to pasture (0.460-0.604) and from forage to blood plasma, especially in young buffaloes (0.271-0.360). Blood glucose concentrations varied seasonally, with mean values of 29.77-32.71 mg/dl in breastfeeding, 23.90-34.10 mg/dl in dry, and 31.10-33.80 mg/dl in young buffaloes, all below established physiological ranges. Results showed significant Pb buildup throughout the soil-forage-animal continuum and suggest potential metabolic stress in buffaloes, emphasizing the importance of continuous monitoring and management of grazing systems.

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Introduction

Agricultural ecosystems are at great risk of environmental and animal health hazards because of the persistence, bioavailability, and transfer of trophic status along the soil-plant-animal continuum due to heavy metal contamination, especially lead (Pb) (Kumar et al., 2020). Lead is an inessential, most dangerous element, which comes to soils by both natural and man-made sources, including industrial emissions, traffic exhaust, disposal of waste, and irrigation with polluted water (Ali et al., 2024). When Lead (Pb) is found in field soils, it may be accumulated in the root zone of the plant, moved to the portions of the food source that are eaten, and ultimately ingested by grazing cattle, so it may enter the greater food web (Bouida et al., 2022).

Plants that thrive on contaminated soils were reported to accumulate Pb in the above-ground tissues, and bioaccumulation and transfer factors indicated the levels of plants exposure and differences in plant species (Asare et al., 2023). The importance of this uptake mechanism is in the fact that non-essential heavy metals such as Pb may disrupt haematopoietic systems, enzymes, cause oxidative stress, and impair nutrient metabolism in grazing ruminants (Afzal and Mahreen, 2024). It is already known that elevated blood Pb levels in livestock are biomarkers of systemic exposure and potential toxicosis, and their levels have been reported to exceed acceptable levels in the animals grazing on contaminated pastures (Pareja-Carrera et al., 2024).

Kinetic Pb accumulation in the environment in matrices is influenced by seasonal change. Pb levels in the soil, forage and animal tissues can be affected by seasonal changes in soil moisture, growth cycle of plants, and feeding habits of animals. The seasonal trends are of particular significance in the agro-ecology of subtropics as the temperature, precipitation, and fodder availability can differ significantly and affect both plant intake and animal exposure (Desai et al., 2023). Other than direct Pb damage, exposure to heavy metal can disrupt other metabolic systems such as glucose regulation. The impacts of nutritional stress and endocrine changes following prolonged contact with metal might be the cause of poor energy metabolism in ruminants (Nogara et al., 2024; Palani et al., 2025). The level of blood glucose on buffaloes is a significant indicator of energy status and metabolic condition. The concentrations that are not in the norm (e.g. below 36-52mg/dl) may signify stress, illnesses, or environmental issues (Saqib et al., 2022).

Kovacik et al. (2017) performed a study to evaluate the biochemical, hematological and heavy metals profile in blood samples collected from the sheep. Assesment indicated that concentration of Hg, Cu and Pb were higher and Cd and Zn were lower in spring. Research also indicated that seasonal variations have significant effect on the biochemical and hematological profile which directly affects the health of ruminants. Significant relation was found between alkaline phospatase and lead (r=0.53) in winter and lead and calcium (r=0.73) in spring season. A positive correlation was calculated between cadmium and red cell distribution width (r=0.77) and red cell distribution width(RDW) and copper (Cu) (r=0.75).

Gjengedal et al. (2015) estimated the 43 elements in plants species native to alpine and boreal areas of sogndal and pristine site in western Norway. Concentration of metals in plants species of Norway were compared with finland and Russia. Levels of Pb and Cd in southern norway had higher concentrations. It was speculated that this might be due to air pollution which caused acidification of soil.

Despite significant research on heavy metal contamination in soils and plants, studies that combine seasonal Pb variation with transfer factors and physiological implications such as blood glucose status in buffaloes are scarce, particularly in South Asian contexts. The current study assessed Pb in soils, fodder, and buffalo blood plasma throughout four seasons and investigated associated bio-concentration variables and blood glucose trends. These findings shed light on the magnitude of environmental Pb exposure and its biological

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implications for animal health under seasonal conditions.

Materials and methods

Study Site

The research was conducted at "Livestock Experiment Station Chak No. 61/Mb, Khushab", Punjab, Pakistan. It is a highly populous city with one million twenty-seven thousand ninty three individuals. It is situated between 32.2883° N, 72.2831° E. It is located approximately one sixty kilometers from the capital. This area of Punjab has faced the problem of Heavy Water due to atomic activities. Natural Uranium Research Reactor is situated here. Pakistan's Special Weapons Program is carried here.

It is situated near the bank of river Jhelum in East. Weather condition is extreme summer and winter. Land is hilly and sandy consists of flat terrain, plains. Floods are common in low areas due to over flow of river Jhelum. The land is mainly hilly and sandy that's why it is not suitable for irrigation. Mostly people have adopted the profession of livestock farming.



Plate-I: Geographical Location of Research Site

Samples Collection and Preparation

Reagents

Distill water obtained from biological Laboratory (University of Sargodha) was used throughout the work. Hydrochloric acid (10%), Sulphuric acid (40%), hydrogen peroxide (35%) were analytical reagents. All glass wares used during research work were of Pyrex brands. All glass wares and plastic materials used treated for a 24 hour in 10% HCl and rinsed within distilled water and then with double distilled water.

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Soil

Ten feeding sites were selected from where the fodder samples under study were collected. The soil samples were collected twelve to fifteen centimetres below the surface level using a common measuring steel scale (Sanchez, 1976). 10 samples were collected in each season. After collecting samples, they were allowed to dry and sealed in paper bags and labelled.

After the duration of 15 days the soil samples were taken out from the oven and subjected to "wet digestion method" for determining the soil composition. In this process four mili liter of sulphuric acid and eight mili litter of hydrogen peroxide was mixed in soil and placed in a digestion chamber. After the process of digestion, the residue takes out from digestion chamber and mixed with double distilled H_2O making its volume upto 50 mL. Then the digestion solution was filtered through commonly laboratory used Whatman filter paper. The samples were dried and prepared according to the method (Anonymous, 1990).

Forage

The samples of forage were taken from the selected sites with the help of sterilized apparatus. The forages that have been selected for sampling were commonly used to offer Buffaloes. Composite fodder samples were collected that were being served to the buffaloes at the time of blood collection. Traditionally mixed fodders (at least two fodder species) are served to the buffaloes. The schedule of forage samples during different seasons were below (Table 1).

Table 1: The collected forage samples during different seasons

Samplings	Season	Common Name	Scientific name
1st	Summer	Maize,Jowar	*Zea mays, Sorghum bicolor*
2nd	Autumn	Bajra,Guar	*Pennisetum glaucum,Cyamopsis tetragonoloba*
3rd	Winter	Barseeem,Lucerne	*Trifolium alexandrinum, Medicago sativa*
4th	Spring	Sarsoon,Barseem	*Brassica campestris,Trifolium alexandrinum*

Digestion

In a flask 1 g of dried sample were mixed with 2 mL of sulphuric acid and 4 mL of hydrogen per oxide. Digestion solution was made and it was put in a digestion chamber. At the end of the digestion process, a residue of the digested food was combined with double distilled water. The Whatmann filter paper was used to filter the diluted solution. The digested solution was stored in plastic bottles and labeled.

Blood Plasma

The animals used in the Nili-Ravi buffaloes that were kept under the field conditions were those that were used in the study. In recent studies thirty buffaloes (Nili-Ravi) have been picked and categorized into three teams lactating, non lactating and young. The sampling was performed in various seasons (summer, autumn, winter and spring) and 10 blood plasma samples were taken at each category of Nili-Ravi buffaloes in each of the sampling periods. Sterilized needle was used to draw the blood out of jugular vein. Blood was kept in heparin Na-Citrate voiles within a short period of time in order to prevent coagulation. The serum was separated using centrifugation to draw the form blood. Centrifugation serum was stored in small viols at -20 °C.

Sample preparation

In measuring flask 1 mL of serum was mixed with sulphuric acid and hydrogen per oxide in 1:2 proportion and put in the digestion chamber. It was then digested and rinsed with double distilled water and filtrated the remaining of the digestion. The evacuated material was removed out of the digested

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chamber and was further diluted with fifty mL of the double distilled water. Plastic bottles were used to store filtrate.

Quality control

To guarantee accuracy of the heavy metal analysis of virtually all the heavy metals, the protocol of the National Institute of Standard and Technology, Standard Reference Material (SRM 1570) were adopted. This was obtained in ±2 percent of the certified values. Measurement of adulteration and consistency of facts was introduced under quality controls indicators. The apparatus was standardized using bank and drift standards, after five readings were taken. The variance coefficients were used to analyze the replicates. 10 percent variance was said to be accurate.

Standard Preparation

Precised calibrations of before using atomic absorption spectrophotometer and flame photometer required standard preparation to numerate the exact readings. To clean glass ware (flask, funnel) against contamination it was washed using de-ionized water. Weighing was done using analytic balance. The weight of the samples was determined by dissolving them in a little bit of aqua or solvent. It consisted in making certain that the sample was totally dissolved and then working on it. Dilution was done using hot plate. Measurement of the amount of sample using volumetric flask:Measure all the glass ware with de-ionized water into the flask that remained drop of the sample had been transferred. Many times wash the beaker with de-ionized water.

Using pipit, mixed the water below the meniscus with double distilled water until the mark has been reached. Clamped the stopper and mixed the flask using the stirring many times to obtain a complete homogenous solution. The last beaker of solution should be 100 mL.

Principle of Atomic Absorption Spectrometer

The concentration of metals and ions in a certain sample was determined with the help of Atomic Absorption Spectrometer. In this method the sample was changed into vapours and stops it in to atomic structure on flame, which indicate light at wavelengths. The element to be studied was used as a cathode of the lamp. One of the rays of light was passed in the flame. The atoms were excited by rays consumed. The concentration of element is shown by the intensity of light. The quantity of light consumed on the screen through reflecting light on the screen quantifies the concentration of metal or ion being studied.

Graphite furnace is used to convert the sample in to the atoms of lower molecular weight in the process of atomic absorption spectrometry. This element state was transformed by cathode lamp. Lamp used the same cathode to examine the specific element in observed solution. As an illustration, copper ions were observed using copper cathode. The energy was needed to move the ions of cathode to the sample solution. There is a wide range of AAS setups of lamps to identify the specific element by rotating cathode. Atoms needed energy in the form of cathode lamp in order to jump to high energy levels and they decayed releasing a number of light. This was a light that was emitted to radiate directly to ground atoms on analysed solutions. These unmoved mass of electrons sheds light. It possesses always a specified number of wavelengths. Since the number required to energize the electron in the atom is constant, by the light radiation, the spectrometers have the capability of capturing the readings of the light that is absorbed. Similarly, the element can also be measured, and this is directly proportional to the amount of elements calculated. The calculated unit used is part per million (ppm). The concentration of lead (Pb) was detected by atomic absorption spectrum by intensity of light emitted by sample solution.

Biochemical Profile

Glucose Determination

Concentration of glucose in blood plasma was determined by spectrophotometrically. 10 mL of blood sample was taken and than subjected to centrifuge to separated the serum. In serum

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concentration of glucose was determined by using a kit (Randox, UK) according to methods.

Haematological Test

The UniCelDxH 800 analyser was used to analyse the blood samples. The UniCelDxH 800 Analyzer provides the following: CBC, Leukocyte 5-Part Differential (Diff), Reticulocyte (Retic), and Nucleated Red Blood Cell (NRBC) on whole blood.

Statistical Analysis

Calculate the means of each replicate with SD for all measuring parameters and the data thus obtained was subjected to statistical Software SPSS (Statistical Package for Social Sciences) software and One-way ANOVA was applied with descriptive analysis, transfer factor and correlation to find the level of probability (Levels of statistical significance: 0.05, 0.01 and 0.001) among different parameters (Steel *et al.* 2006).

Results and Discussion

Lead (Pb)

Soil Analysis

Table 2 and Table 3 present the results of ANOVA, as well as average Pb concentration of soil samples in samples of different seasons. The sampling seasons showed ($P<0.05$) considerable impact on the mean Pb contents of the soil samples. The average Pb at different times of sampling varied between 15.37 and 16.94 mg/kg. The increased Pb concentrations in the soil samples were observed in summer sampling season and decreased Pb concentrations were observed in autumn sampling season. The average content of Pb in the different seasons of sampling were 15.94 mg/kg (summer), 15.37 mg/kg (autumn), 16.94mg/kg (winter) and 16.88mg/kg (spring). The rank of the observed mean Pb contents in each of the soil samples was ranked with summer, winter, spring and autumn. The Pb contents on average in the soil samples were not patterned (Figure 1) in terms of upward and downward trends across the various sampling seasons. The top limit of Pb in the soil is 100 mg/kg recommended by FAO/WHO (2001). The current study is below this allowable limit (Nazir et al., 2015).

Forage Analysis

Table 2 and Table 3 include the results of ANOVA and the mean of Pb concentration in forage samples at different seasons of sampling. There was no significant ($P<0.05$) influence of the sampling seasons on the mean Pb content of the forage samples. The average levels of Pb at different seasons of sampling were ranging between 5.98 and 6.24 mg/kg. The observed higher mean Pb concentrations in forage samples were in the summer season of sampling and lower Pb concentrations in the forage samples were observed in the autumn season of sampling. The averages of Pb in the different seasons of the sampling were 6.24 mg/kg (summer), 5.98 mg/kg (autumn), 6.09 mg/kg (winter), 6.13mg /kg (spring). Rank of the mean Pb contents in the entire samples of forage was established as summer>spring>winter>autumn. The average Pb concentrations of the forage samples were irregularly increasing and decreasing with various seasons of sampling (Figure 1).

The FAO/WHO (2001) recommended the highest permissible amount of Pb in plants as 0.3 mg/kg. The Pb value that is obtained in this study is far greater than this limit. The review study conducted by Rehman et al. (2017) showed that the concentrations of the Pb found in the different plant species growing in different localities in Pakistan varied between 0.03 and 44 mg/kg. Most of these researches concentrated on the plant cultivated in the soils which were contaminated by anthropogenic processes such as mining, industrial wastes and water usage of waste water. The causes of metal toxicity may be nature and texture of soil, content of humus in soil, and chemical interaction in various constituents of soil (Grigoryan et al., 1990).

The level of toxicity of the forage of the area under study was not found to be suitable in grazing of animals. Conversely, the present values were lower than those that were reported by Oluokun et al. (2007). The samples of the

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plants were observed to contain more Pb than the samples of the soils, hence it can be said that the plants readily accumulate this metal, and thus the choice of forage to the animals is a significant factor to prevent the occurrence of metal toxicity (Farr, 2004).

Blood Plasma Analysis

Table 2 and Table 3 demonstrate the results of ANOVA and average Pb concentration in the blood plasma samples during different seasons in lactating and young buffaloes as well as non-significantly ($p>0.05$) affected by the sampling seasons in dry buffaloes. The averages of Pb in blood plasma of lactating buffaloes were 0.457 mg/L (summer), 0.389 mg/L (autumn), 0.592 mg/L (winter), 0.584mg/L (spring).

On average, the concentration of Pb in blood plasma of dry buffaloes was 0.524 mg/L (summer), 0.566 mg/L (autumn), 0.505 mg/L(winter) and 0.522mg/L (spring). An average of Pb in blood plasma of youthful buffaloes was; 0.851mg/L (summer), 0.838mg/L (autumn), 0.595mg/L (winter) and 0.699mg/L (spring). It was found that the higher mean Pb concentrations were found in young buffaloes in summer season and lower mean Pb contents were found in lactating buffaloes in autumn sampling season (Figure 1). The detected sequence of Pb contents was winter> spring >summer> autumn in lactating buffaloes, autumn>summer> spring >winter in dry buffaloes and summer>autumn>spring>winter in young buffaloes.

The ones established in this experiment were greater than the toxic figure of 0.3 mg/L that was described by Osweiler et al. (1985). This situation did not work with ruminants. Going this way, one can say there is the necessity of conditioned soil and forage to desired Pb level in the ruminant blood plasma. Pb upper level affects the entire body of animals throughout the globe (Radostits et al., 1994).

Table 2: Analysis of variance for Pb concentrations in soil, forage and blood plasma influenced by different seasons

Source of Variation (SOV)	Degrees of Freedom (df)	Mean Squares				
		Soil	Forage	Blood plasma		
				Lactating Buffaloes	Dry Buffaloes	Young Buffaloes
Sampling Season	3	17.278*	0.350^{ns}	0.298*	0.020^{ns}	0.444***
Error	36	1.513	0.596	0.015	0.013	0.016

P <0.001= ***, P <0.05 = *, P >0.05=ns

Table 3: Descriptive analysis for Pb concentrations in soil, forage and blood plasma influenced by different seasons

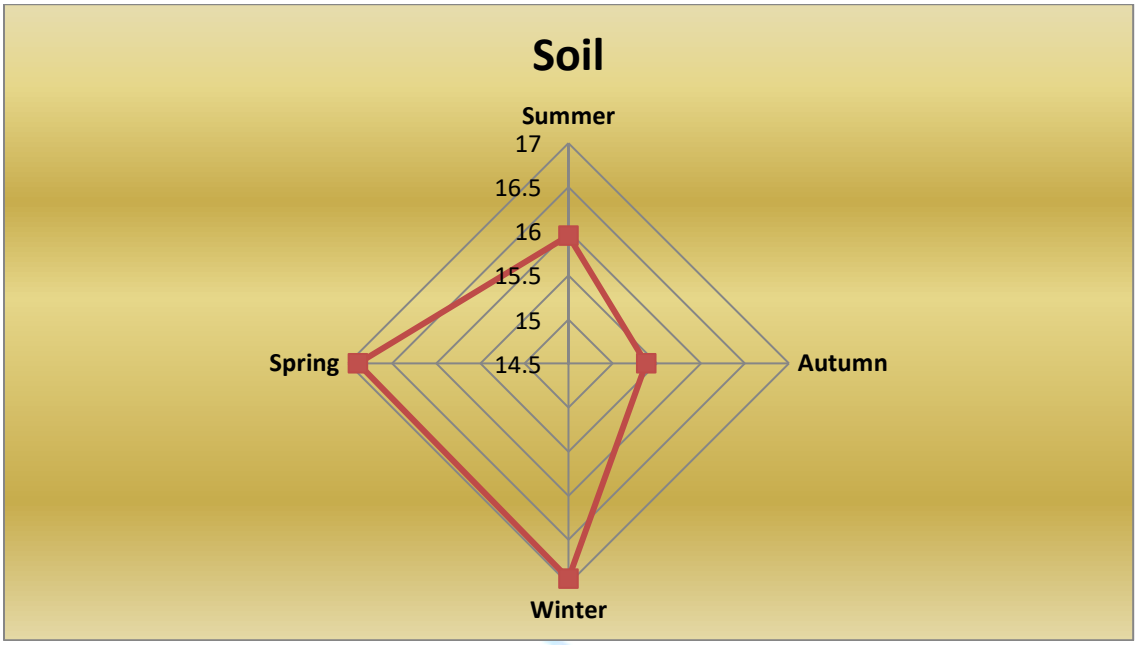
Parameters	Soil	Forage	Blood plasma		
			Lactating Buffaloes	Dry Buffaloes	Young Buffaloes
Mean	16.290	6.119	0.506	0.530	0.747
Std. Error±	0.215	0.096	0.015	0.015	0.017
Median	15.932	6.001	0.476	0.501	0.768

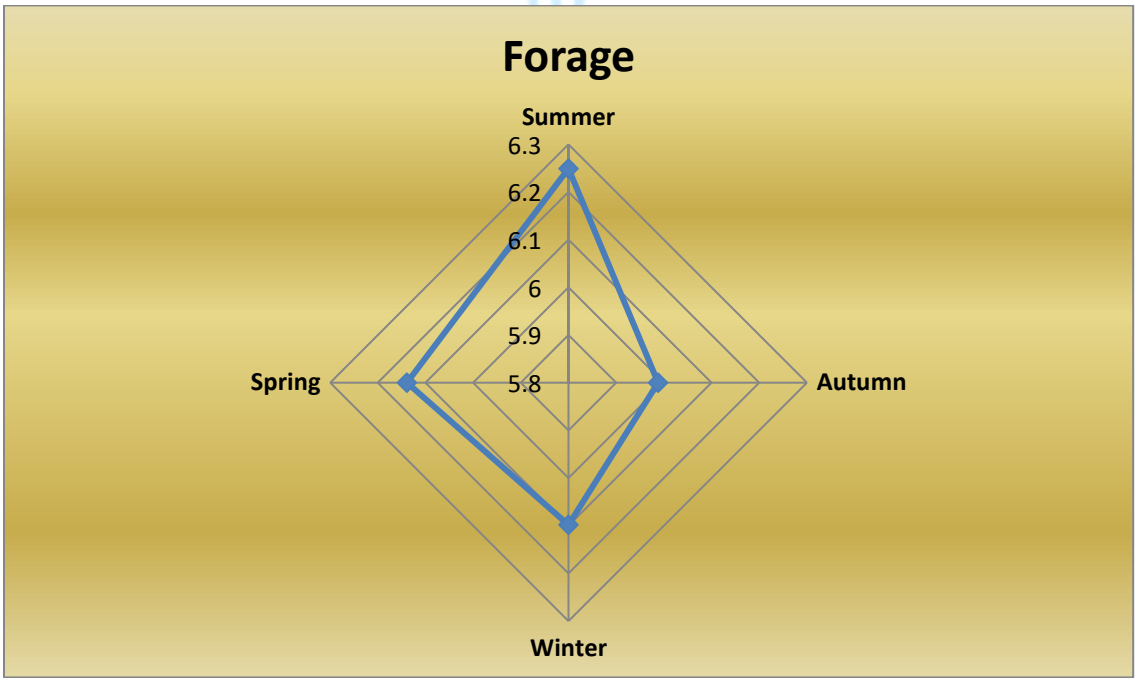
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Mode	13.765[a]	6.001	0.427[a]	0.427[a]	0.525[a]
Std. Deviation	2.347	1.047	0.168	0.162	0.185
Minimum	11.398	2.693	0.253	0.301	0.332
Maximum	21.439	8.988	0.986	0.975	0.991

a. Multiple modes exist. The smallest value is shown





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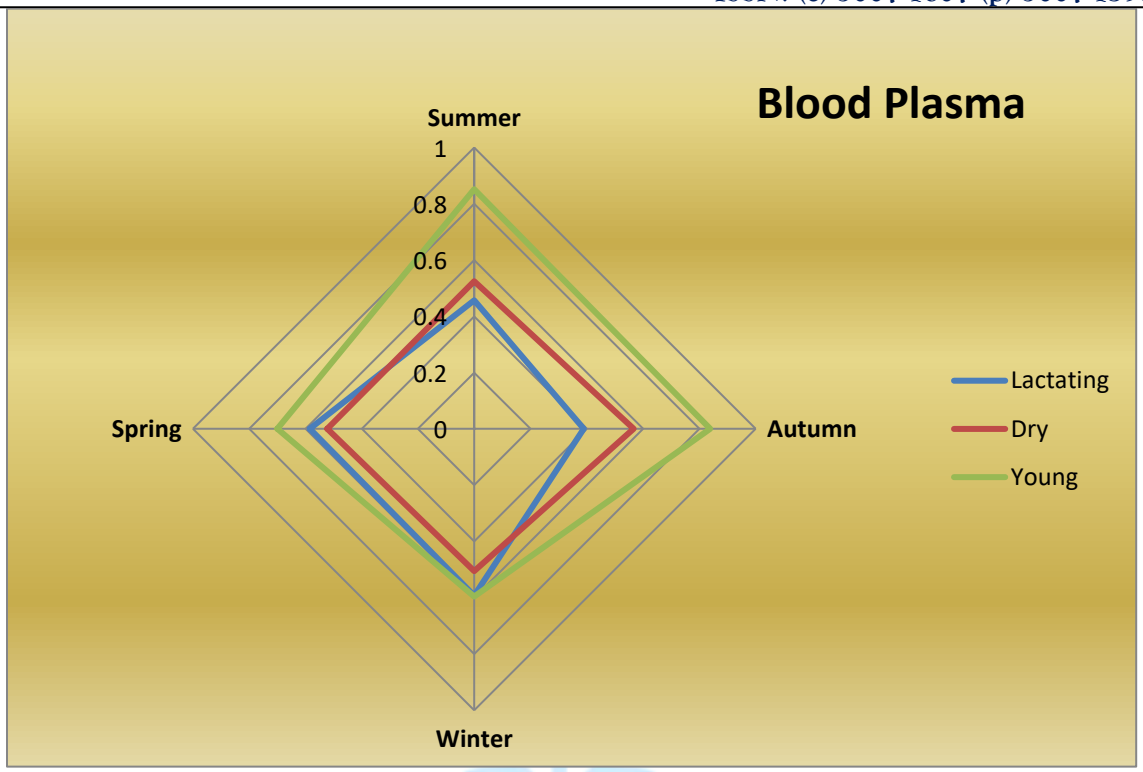


Figure 1: Fluctuations in Pb values in soil, forage and blood plasma during different seasons

Bio-concentration factor of Lead (Pb)

The bio-concentrations factor values of Pb from soil-forage-blood plasma are showed in Table 4. The detected transfer factors for Pb concentration from soil to forage during different sampling season were 0.460 (summer), 0.464 (autumn), 0.604 (winter) and 0.519 (spring).The observed transfer factors for Pb concentration from forage to blood plasma in lactating buffaloes were 0.187 (summer), 0.167 (autumn), 0.270 (winter) and 0.262 (spring). In dry buffaloes, the detected transfer factor for Pb were 0.214 (summer), 0.243 (autumn), 0.230 (winter) and 0.234 (spring). The transfer factors of Pb concentration from forage to young buffaloes during various periods were 0.348 (summer), 0.360 (autumn), 0.271 (winter) and 0.314 (spring). The lowest transfer factor for Pb concentration was found in forage-young buffalo at autumn sampling season and the highest was in soil-forage during winter sampling season (Figure 2).

Table 4: Bio-concentrations factor of Pb from soil-forage-blood plasma

Sampling Season	Bio-concentrations factor			
	Soil to Forage	Forage to Blood Plasma		
		Lactating Buffalo	Dry Buffalo	Young Buffalo
Summer	0.460	0.187	0.214	0.348
Autumn	0.464	0.167	0.243	0.360
Winter	0.604	0.270	0.230	0.271
Spring	0.519	0.262	0.234	0.314

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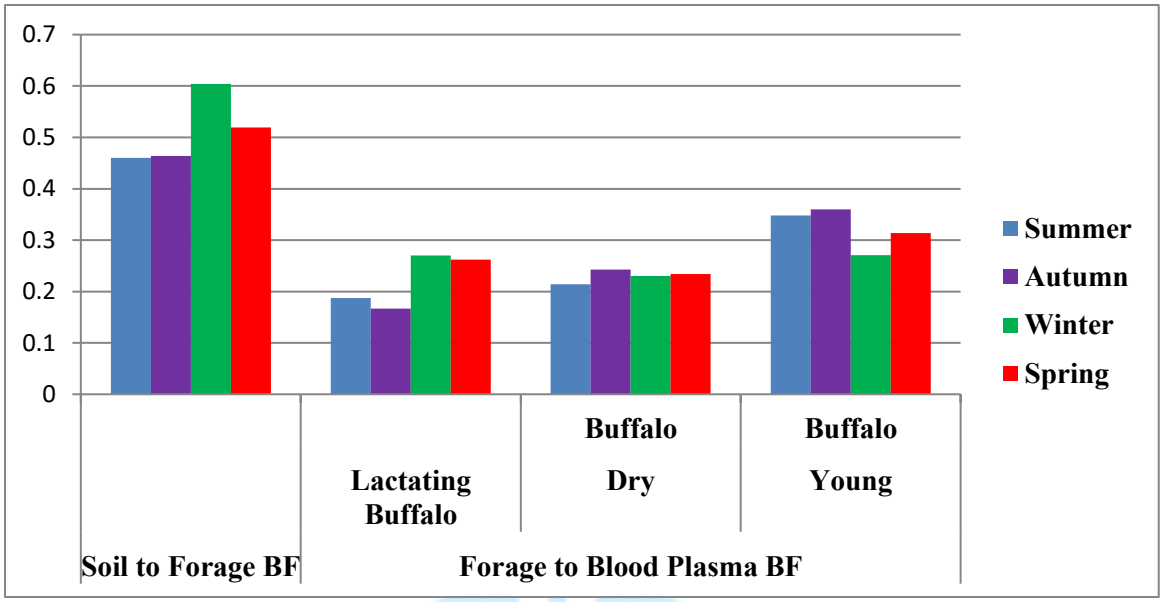


Figure 2: Bio-concentration factor of Lead (Pb) in soil to forage and forage to blood in different seasons

Blood Glucose Concentration

The glucose level in the blood plasma samples were significantly ($p<0.001$) influenced by the seasons of the year during which the samples were taken in lactating and young buffaloes and non-significantly ($p>0.05$) in dry buffaloes (Table 5 & 6). The average glucose content of blood plasma in lactating buffaloes was 29.77 mg/dl (summer), 32.10mg/dl (autumn), 32.71mg/dl (winter), 31.97 mg/dl (spring). Dry buffaloes had the following mean glucose concentrations in blood plasma: 34.10mg/dl (summer), 32.63mg/dl (autumn), 24.74mg/dl (winter) 23.90mg/dl (spring). youthful buffaloes had an average glucose level of 31.28 mg/dl (summer), 31.10mg/dl (autumn), 3203mg/dl (winter) and 33.80mg/dl (spring) in the blood plasma. The bigger mean glucose concentrations were found in dry buffaloes in summer season and the smaller mean glucose contents were found in dry buffaloes in winter sampling season (Figure 3). The identified sequence of glucose contents were winter>autumn>spring>summer in lactating buffaloes, summer>autumn>spring>winter in dry buffaloes and spring>winter>summer> autumn in young buffaloes.

The level of glucose in blood portrays the amount of energy needed in the body (Goff et al., 1991; Kupczynski and Chudoba-Drozdowska, 2002). Milk production requires that lactose, which is a by- product of glucose metabolism, is present (Darul and Kruczynska, 2005).

Current values of blood glucose level are below the appropriate level of glucose (36-52 mg/dl) reported by Jain and Lasmanis (1978).Conversely, Winnicka (2008) gave the range of recommended serum glucose level level as 39.6-81.08mg/dl. The present glucose values are also less than this range that was reported by Winnicka (2008). The values may be disrupted due to illnesses (Bombik et al., 2002).

There were higher values of glucose per Abd Ellah et al. (2014) and Qureshi et al. (2002) than the glucose values in this research. Glucose values were lower than the current ones described by Mandali et al. (2002) and Prajapati et al. (2005). The current results were less than the given range 72.00 to 75.60 mg/dl by Borghese (2005). The glucose level is checked

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randomly in blood of the animal, which is the measure of the food quality of the animal (Campanile et al., 1997; Montemurro et al., 1997). Various hormones control the target level of glucose insulin, cortisol, glucagon and human growth hormone.

Table 5: Analysis of variance for glucose concentrations in blood plasma of buffaloes influenced by different seasons

Source of Variation (SOV)	Degrees of Freedom (df)	Mean Squares		
		Lactating Buffaloes	Dry Buffaloes	Young Buffaloes
Sampling Season	3	16.596 ^{ns}	277.609***	15.255 ^{ns}
Error	36	10.798	10.290	11.923

P <0.001= ***, P >0.05=ns

Table 6: Descriptive analysis for glucose concentrations in blood plasma of buffaloes influenced by different seasons

Parameters	Blood plasma		
	Lactating Buffaloes	Dry Buffaloes	Young Buffaloes
Mean	31.637	28.842	32.050
Std. Error±	0.375	0.564	0.428
Median	32.00	30.00	32.000
Mode	32.000[a]	32.000[a]	30.000[a]
Std. Deviation	4.112	6.181	4.685
Minimum	20.000	14.000	18.000
Maximum	41.000	42.000	45.000

a. Multiple modes exist. The smallest value is shown

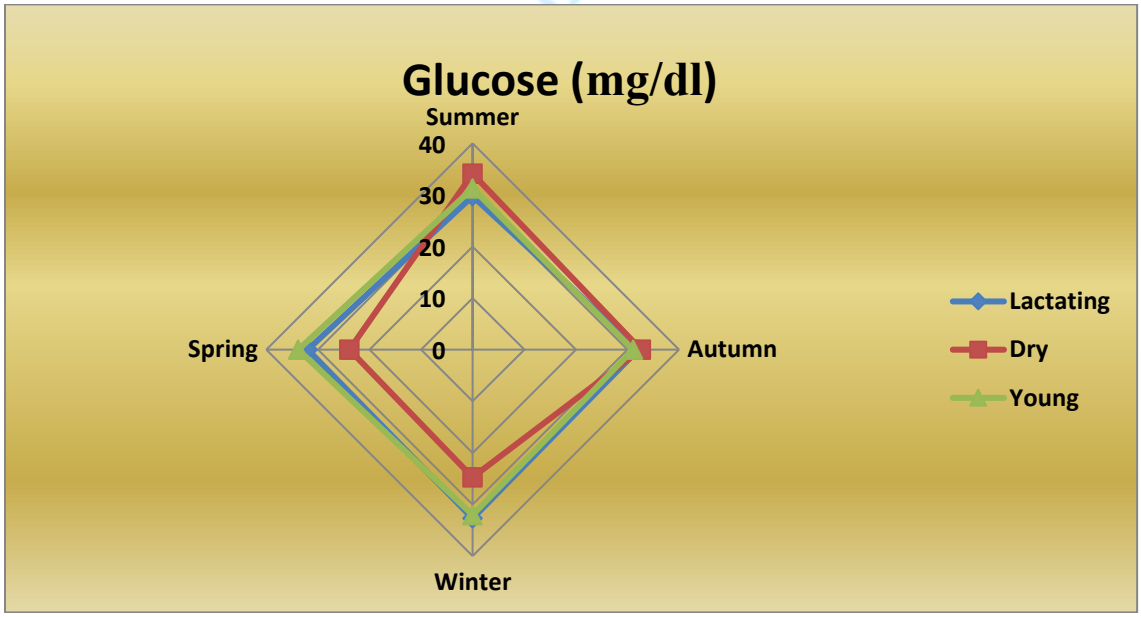


Figure 3: Fluctuations in glucose values in blood plasma of buffaloes during different seasons

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Conclusion

The current study shows strong seasonal fluctuation in lead (Pb) distribution across soil, forage, and buffalo blood plasma, demonstrating the efficacy of the soil-forage-animal pathway in transmitting Pb within grazing habitats. Although soil Pb concentrations were below the FAO/WHO permitted range, hay tests regularly showed Pb levels significantly beyond recommended plant thresholds, showing a high accumulating potential of forage species. This disproportionate transfer was aided by increasing bio-concentration factors, notably during the winter, showing increased Pb mobility from soil to forage under seasonal conditions. Elevated Pb concentrations in buffalo blood plasma, particularly in young animals, exceeded defined hazardous limits, indicating prolonged dietary exposure through contaminated fodder. Seasonal changes in blood Pb levels among lactating and young buffaloes highlight the importance of environmental factors and physiological status in metal deposition. These data indicate that young buffaloes are more susceptible to Pb poisoning, most likely due to increased absorption efficiency and lower detoxifying capacity. In addition to metal exposure, blood glucose concentrations exhibited seasonal variation and remained below recommended physiological ranges across all buffalo categories. Reduced glucose levels may indicate metabolic stress associated with nutritional imbalances, environmental challenges, or chronic heavy metal exposure, with potential implications for growth, health, and productivity. The observed relationship between elevated Pb burden and suboptimal glucose status underscores the broader physiological impact of environmental contamination beyond direct toxic effects.

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