Journal of Animal Science and Veterinary Medicine
Volume 11(4), pages 254-268, August 2026
Article Number: B54CDA094
ISSN: 2536-7099
https://doi.org/10.31248/JASVM2026.671
https://integrityresjournals.org/journal/JASVM

Full Length Research

Age-related allometric growth patterns of skull morphometry in Kuri cattle (*Bos taurus*) part (1): Dorsal and lateral aspect

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Received Date: 10 June 2026 | Accepted Date: 19 July 2026 | Published Date: 30 August 2026

ABSTRACT: The present study evaluated age-related changes in the skull morphology of Kuri cattle, an indigenous breed native to the Lake Chad Basin. A total of 30 skulls (15 males and 15 females) were collected from selected abattoirs in Nigeria and classified into three age groups: young (< 3 years), middle-aged (3–5 years), and aged (> 5 years). Following preparation by hot-water maceration and hydrogen peroxide bleaching, 27 cranial measurements comprising 13 dorsal and 14 lateral parameters were recorded using standard osteometric techniques. Data were expressed as mean ± standard deviation and analysed using one-way analysis of variance (ANOVA), Pearson's correlation analysis, regression scatter plots, principal component analysis (PCA), boxplots, and correlation heatmaps, with statistical significance set at $p < 0.05$. Significant age-related increases were observed in several dorsal cranial parameters, including incisive–nuchal length (44.51 ± 3.66 to 55.89 ± 3.49 cm), viscerocranial length (23.21 ± 1.83 to 28.54 ± 1.59 cm), nasal length, nasal width, and interfrontal suture length ($p < 0.05$), indicating progressive craniofacial growth and skeletal maturation. Likewise, lateral measurements such as infraorbital foramen to alveolar tooth distance (2.85 ± 0.37 to 3.66 ± 0.47 cm), facial tuberosity to infraorbital foramen distance (3.96 ± 0.32 to 5.25 ± 0.68 cm), orbital circumferences, and orbital diameters increased significantly with advancing age ($p < 0.05$). Pearson's correlation, regression analyses, PCA biplots, and correlation heatmaps demonstrated strong positive associations and clustering among craniofacial growth variables. In contrast, supraorbital and infraorbital foraminal measurements exhibited minimal age-related variation, indicating early developmental stabilisation of neurovascular landmarks. These findings establish baseline morphometric reference data for Kuri cattle and provide valuable information for comparative anatomy, breed characterisation, forensic identification, regional anaesthesia, craniofacial surgery, and future developmental studies.

Keywords: Cranial morphometry; Kuri cattle; skull anatomy; viscerocranium.

INTRODUCTION

The White Lake cattle, commonly referred to as Kuri, are classified under *Bos taurus longifrons* (Hamitic longhorn group) and are mostly found grazing along the shores of Lake Chad (Gambo *et al*., 2016). This breed is distinguished by its remarkable body size, which is seldom observed among African taurine cattle, as well as its robust skeletal development (Epstein, 1971; Gambo *et al*., 2019). One of its most distinctive anatomical features is the presence of markedly enlarged, bulbous horns (Gambo *et al*., 2015a), characterised by a spongy internal structure and a thin outer cortex (Epstein, 1971). This morphological adaptation is believed to facilitate survival within the semi-aquatic environment of the Lake Chad basin (Malbrant *et al*., 1947). In addition, these breeds of cattle are proficient swimmers and are known to dedicate a substantial portion of their time in water (Gambo *et al*., 2015b).

Lake Chad is widely regarded as the geographical origin of this breed (Malbrant *et al*., 1947) and is bordered by Chad, Cameroon, Niger, and Nigeria (Gambo *et al*., 2019). Unlike many other African cattle breeds, the Kuri lacks a hump, a feature that contributes to their relatively compact body conformation (Gambo *et al*., 2019). The breed's conspicuously large horns, in combination with the absence of a hump, constitute its most recognisable physical attributes (Gambo *et al*., 2015b). In terms of body mass, Kuri cattle typically attain an average weight of approximately 550 kg, although under feedlot management conditions, weights may increase to between 600 and 700 kg (Epstein, 1971; Queval *et al*., 1971). Despite its distinctive characteristics, the exact population size of the breed remains uncertain, with estimates ranging from 100,000 to 400,000 individuals (Tawah *et al*., 1997).

Cranial morphometry provides fundamental information for comparative anatomy, functional morphology, taxonomy, evolutionary biology and veterinary clinical practice. Precise morphometric characterisation of the skull is particularly important for identifying anatomical landmarks required for regional anaesthesia, dehorning, trephination, fracture repair, maxillofacial surgery and other craniofacial surgical procedures (König & Liebich, 2007; Monfared, 2013b). Moreover, craniometric analyses have been extensively used to differentiate breeds and species, evaluate ontogenetic development and sexual dimorphism, investigate evolutionary adaptations, and support zooarchaeological and forensic studies (Bartosiewicz, 1980; Karimi *et al*., 2011; Özkan *et al*., 2019; Çakar *et al*., 2024; Gündemir *et al*., 2025). Numerous studies have demonstrated that skull morphology changes throughout postnatal growth owing to differential skeletal development, masticatory function and allometric growth (Weston, 2003; Monfared, 2013a; Çakar *et al*., 2024).

Despite the biological, economic and conservation importance of Kuri cattle, anatomical investigations of the breed remain limited. Earlier studies were largely confined to dental abnormalities (Gambo *et al*., 2015a), the mandibular and maxillofacial regions for regional anaesthesia (Gambo *et al*., 2015b), and the morphology of selected craniofacial foramina (Gambo *et al*., 2016). More recently, research on Kuri cattle has expanded to include genetic characterisation of indigenous cattle populations (Ng'ang'a *et al*., 2026), morphometric prediction of body weight, production systems and reproductive management (Grema *et al*., 2017; Okoh *et al*., 2025). However, these investigations have focused primarily on genetic diversity, body conformation and husbandry practices, with little attention given to skeletal anatomy and osteometry. Consequently, comprehensive osteometric investigations of the Kuri skull remain scarce. To the best of our knowledge, no published study has evaluated age-related variation in the dorsal and lateral cranial morphometry of Kuri cattle. This represents a significant knowledge gap because cranial morphology undergoes continuous modification during postnatal development, influencing biomechanical function, breed characterisation, comparative anatomy and clinical application (Weston, 2003). The absence of baseline age-related craniometric data therefore highlights the novelty and scientific significance of the present study.

Establishing baseline age-related craniometric data for Kuri cattle is essential for improving anatomical knowledge of this rare indigenous breed, facilitating breed characterisation and comparative morphological studies, supporting accurate regional anaesthetic techniques and craniofacial surgical procedures, and providing reference information for conservation programmes, selective breeding strategies and future zooarchaeological investigations. Accordingly, the present study investigated age-related variations in the dorsal and lateral craniometric characteristics of the skull of Kuri cattle using standard osteometric measurements.

MATERIALS AND METHODS

Sample collection

The study was conducted on thirty (30) clinically healthy Kuri cattle (*Bos taurus*), comprising 15 males and 15 females. A purposive (criterion-based) sampling procedure was employed to select animals from four major abattoirs located within the geographical distribution range of the breed in Nigeria. These included Shomolu-Bariga Abattoir (Lagos State), Bodija Abattoir (Oyo State), Ijebu-Igbo Abattoir (Ogun State), and Main Abattoir (Borno State). Sampling specimens from multiple locations was intended to obtain a representative sample of the Kuri cattle population while minimising the influence of local management and environmental factors on skull morphology. Prior to sample collection, all animals underwent physical examination to ensure the absence of visible skeletal abnormalities, craniofacial deformities, or musculoskeletal disorders that could influence cranial morphometry. Age estimation was performed using dentition, based on the eruption and replacement patterns of the permanent incisors, following the method described by Pasquini *et al*. (1982). Sex was confirmed by visual examination of the external genitalia, including the perineal and inguinal regions. The selected animals were subsequently categorised into three age groups: young (<3 years; $n = 10$), middle-aged (3–5 years; $n = 10$), and aged (>5 years; $n = 10$). To minimise potential sex-related variation in the morphometric analysis, each age group comprised an equal number of males and females (5 males and 5 females). Following routine commercial slaughter, the heads of the selected Kuri cattle were collected immediately after exsanguination. Each specimen was individually labelled according to age group and sex before being transported under appropriate hygienic conditions to the Gross Anatomy Laboratory, University of Maiduguri, Borno State, Nigeria for specimen preparation and morphometric evaluation. During transportation and handling, particular care was taken to prevent damage to the cranial structures and anatomical landmarks required for subsequent osteometric measurements.

Specimen preparation

The skulls were prepared according to the hot water maceration technique as described by Olopade and Onwuka (2005) and Yahaya *et al*. (2012a). All soft tissues adhering to the skulls, including fascia, muscles, ligaments, and tendons, were carefully removed using scissors and a scalpel. The skulls were subsequently placed in three separate maceration pots filled with water to allow clear identification and differentiation. The samples were heated to boiling, after which the water was replaced. Polycarboxylate detergents were added to enhance the removal of fat, bone marrow, and any residual soft tissue. The macerated skulls were then immersed in 30% hydrogen peroxide for two days, thoroughly rinsed with water, and air-dried under sunlight. After preparation, the morphology and structural attributes of the cleaned skull bones were examined, and their metric dimensions were measured in centimetres (cm). Photographic documentation of the bones from different anatomical orientations was obtained using a Panasonic digital camera with a 16-megapixel Leica-installed lens, which was used in the production of figures in this study.

Osteometric parameters

A total of twenty-seven (27) osteometric parameters, comprising thirteen (13) dorsal and fourteen (14) lateral measurements, were obtained from each skull using standard osteometric techniques. Linear measurements were recorded using a graduated metric ruler (cm) for relatively long cranial dimensions, while a digital Vernier calliper (0.01 mm precision) was used to measure shorter linear distances, widths, diameters, and foraminal dimensions with high accuracy. A flexible measuring thread was employed to determine curved structures, such as the orbital circumference, after which the thread length was measured using the metric ruler. A pair of dividers was used to transfer distances between irregular anatomical landmarks onto the ruler when direct measurement was impractical, whereas a drawing compass facilitated the accurate identification and measurement of circular or curved cranial structures. Prior to measurement, each skull was positioned on a flat horizontal surface in a standardised anatomical orientation to ensure consistency. All measurements were taken according to established anatomical landmarks described by Olopade and Onwuka (2005) and Yahaya *et al*. (2012a). Each osteometric parameter was measured three consecutive times under identical conditions, and the mean of the three readings was used for statistical analysis. Care was also taken to identify anatomical landmarks consistently throughout the study, thereby minimising measurement error and enhancing the reliability, credibility, and reproducibility of the findings.

Landmarks for Osteometric measurements and indices

According to the method adopted by Olopade and Onwuka (2005) and Gambo *et al*. (2019), the following 27 landmarks of the dorsal and lateral surfaces of the skull (Figures 1 and 2) were considered.

1. Incisive – Nuchal length (**INL**): Maximum dimensions of the skull when laid on an even surface from the rostral tip of the incisive bone to the caudal level of the nuchal protuberance.
2. Supraorbital width (**SOBW**): Maximum distance between the dorsomedial edges of the orbit at the frontal bone.
3. Intermedial canthi length (**IMCL**): Distance between the two medial canthi.
4. Interlateral canthi length (**ILCL**): Distance between the two lateral canthi.
5. Interfrontal suture length (**IFSL**): Maximum length of the interfrontal suture.
6. Interfrontal Suture to right supraorbital foramen (**ISRSOF**): Distance between the right supraorbital foramen and the interfrontal suture directed medially.
7. Interfrontal Suture to left supraorbital foramen (**ISLSOF**): Distance between the left supraorbital foramen and the interfrontal suture directed medially.
8. Intercornual protuberance to line of intersection of right (**ICPLIR**): Distance between intercornual protuberance and the line of intersection of 5 above.
9. Intercornual protuberance to line of intersection of left (**ICPLIL**): Distance between intercornual protuberance and line of intersection of 6 above.
10. Nasal length at midline (**NLM**): Maximum length of nasal bone along the midline.
11. Nasal length at lateral prongs (**NLLP**): Maximum length of nasal bone at the level of the lateral nasal prongs.
12. Nasal width (**NW**): Maximum width of the two nasal bones.
13. Viscerocranial length (**VCrL**): Maximum distance from the nasofrontal suture to the infraorbital foramen to the root of the alveolar tooth.
14. Infraorbital foramen to root of alveolar tooth (**IFRAT**): The measurement is from the level of the mid-ventral margin of the infraorbital foramen to the root of the alveolar tooth directly ventral to it.
15. Infraorbital foramen height (**IOFH**): The distance between the dorsal and ventral margins of the infraorbital foramen at its widest point.

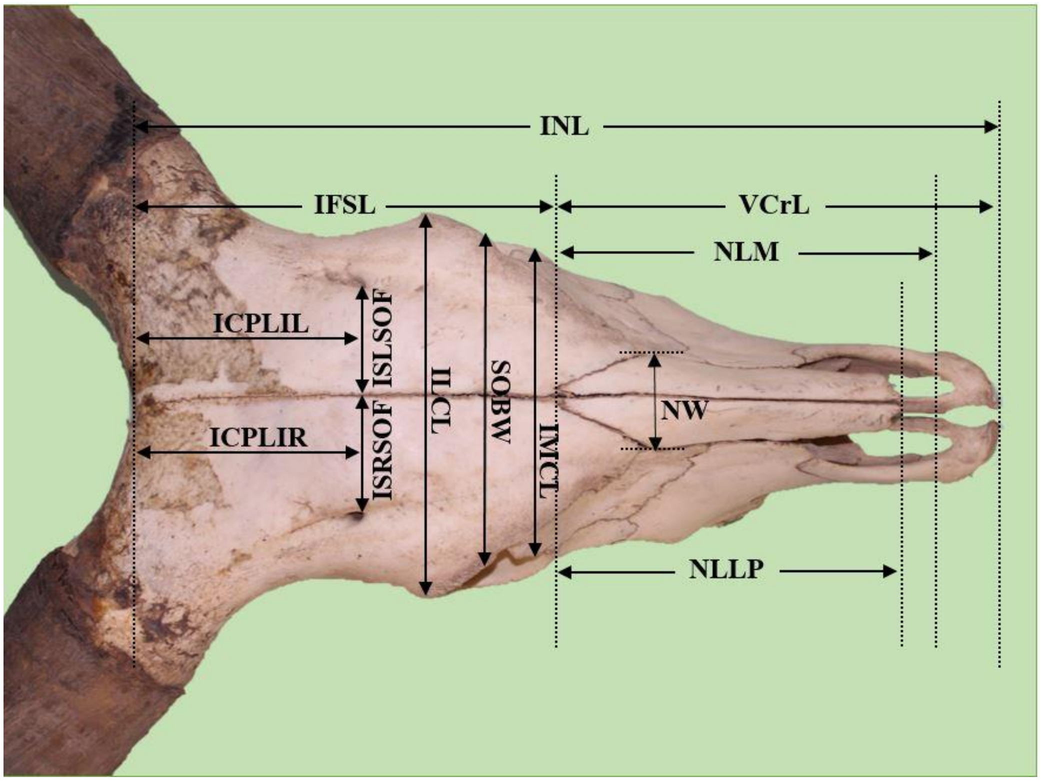

Figure 1. Dorsal surface of the Kuri skull showing morphometric landmarks and measurements. Incisive – Nuchal length (**INL**); Supraorbital width (**SOBW**); Intermedial canthi length (**IMCL**); Interlateral canthi length (**ILCL**); Interfrontal suture length (**IFSL**); Interfrontal Suture to right supraorbital foramen (**ISRSOF**); Interfrontal Suture to left supraorbital foramen (**ISLSOF**); Intercornual protuberance to line of intersection of Right (**ICPLIR**); Intercornual protuberance to line of intersection of left (**ICPLIL**); Nasal length at midline (**NLM**); Nasal length at lateral prongs (**NLLP**); Nasal width (**NW**); Viscerocranial length (**VCrL**).

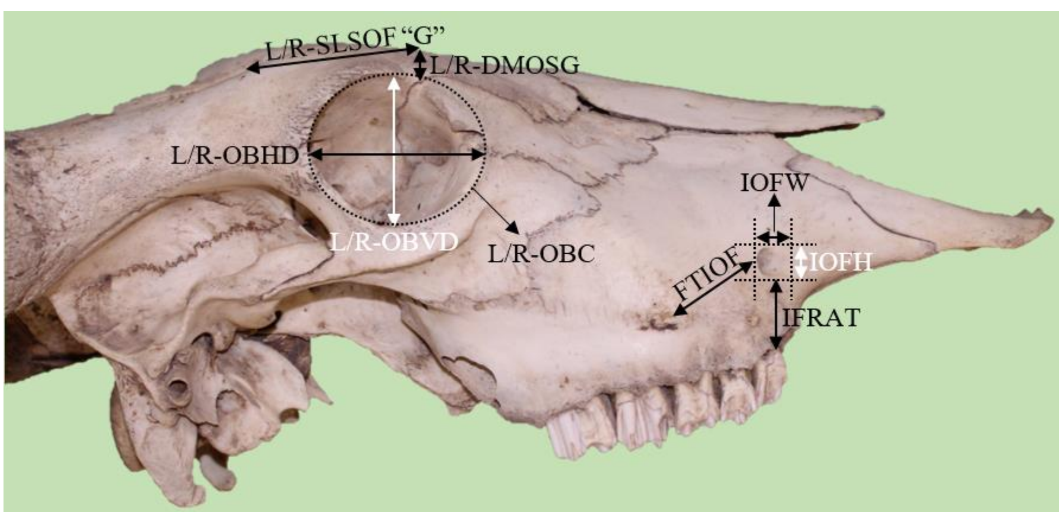

Figure 2. Lateral surface of the Kuri skull showing morphometric landmarks and measurements. Infraorbital foramen to root of alveolar tooth (**IFRAT**); Infraorbital foramen height (**IOFH**); Infraorbital foramen width (**IOFW**); Facial tuberosity to infraorbital foramen (**FTIOF**); Right dorsomedial margin of the orbit to supraorbital groove (**RDMOSG**); Left dorsomedial margin of the orbit to supraorbital groove (**LDMOSG**); Right Supraorbital line to supraorbital foramen (**RSLSOF**); Left Supraorbital line to supraorbital foramen (**LSLSOF**); Left orbital circumference (**LOBC**); Right orbital circumference (**ROBC**); Left orbital horizontal diameter (**LOBHD**); Right orbital horizontal diameter (**ROBHD**); Left orbital vertical diameter (**LOBVD**); Right orbital vertical diameter (**ROBVD**).

16. Infraorbital foramen width (**IOFW**): Distance between the rostral and caudal margins of the infraorbital foramen at the middle.
17. Facial tuberosity to infraorbital foramen (**FTIOF**): From the level of the most lateral bulging of the facial tuberosity to the mid-caudal margin of the infraorbital foramen.
18. Right dorsomedial margin of the orbit to supraorbital groove (**RDMOSG**): Measurement from the lateral aspect of the dorsorostral margin of the orbit to the supraorbital groove point “G”.
19. Left dorsomedial margin of the orbit to supraorbital groove (**LDMOSG**): Measurement from the lateral aspect of the dorsorostral margin of the orbit to the supraorbital groove point “G”.
20. Right Supraorbital line to supraorbital foramen (**RSLSOF**): Distance from the point “G” produced in right supraorbital groove caudally to the supraorbital foramen
21. Left Supraorbital line to supraorbital foramen (**LSLSOF**): Distance from the point “G” produced in the left supraorbital groove caudally to the supraorbital foramen.
22. Left orbital circumference (**LOBC**): Length of the circumference of the lateral margins of the left orbit.
23. Right orbital circumference (**ROBC**): Length of the circumference of the lateral margins of the right orbit.
24. Left orbital horizontal diameter (**LOBHD**): Horizontal distance between the rostral and caudal margins of the left orbit.
25. Right orbital horizontal diameter (**ROBHD**): Horizontal distance between the rostral and caudal margins of the right orbit.
26. Left orbital vertical diameter (**LOBVD**): Vertical distance between the dorsal and ventral margins of the left orbit.
27. Right orbital vertical diameter (**ROBVD**): Vertical distance between the dorsal and ventral margins of the right orbit.

Ethical approval

Ethical approval for this study was obtained from the Faculty of Veterinary Medicine Animal Use and Ethics Committee (AUEC), University of Maiduguri. The study utilised heads collected from cattle slaughtered as part of routine commercial meat processing, and no animals were slaughtered specifically for research purposes. Sample collection complied with institutional guidelines governing the use of abattoir-derived biological materials for research.

Statistical analysis

The morphometric measurements were assessed for normal distribution and presented as mean ± standard deviation. Variations among the different age categories (young, middle-aged, and aged) were determined using analysis of variance (ANOVA). Pearson’s correlation analysis was employed to examine relationships among the groups. In addition, graphical tools such as boxplots, regression scatter plots, principal component analysis (PCA) biplots, and correlation heatmaps were used to demonstrate the patterns of variation and associations among the morphometric parameters. All statistical analyses were conducted using IBM SPSS Statistics developed by IBM. Statistical significance was accepted at $p<0.05$.

RESULTS

Dorsal skull indices of young, middle-aged, and aged Kuri cattle

A total of thirteen (13) indices were recorded from the dorsal aspect of the Kuri cattle skull (Table 1). The dorsal skull morphometric parameters of Kuri cattle demonstrated clear age-associated variations across the three age groups evaluated (young, middle-aged, and aged). Most of the measured parameters increased progressively with age, indicating continued cranial growth and skeletal maturation in the breed. The mean INL and SOBW were 44.51 ± 3.66 cm, 49.97 ± 2.93 cm, and 55.89 ± 3.49 cm and 13.81 ± 1.15 cm, 15.64 ± 1.42 cm, and 16.55 ± 1.63 cm, respectively. The mean INL shows a highly significant increase ($p < 0.05$) among the three age groups from young to old. But the mean SOBW of the middle-aged and aged was significantly higher than that of the young. The mean IMCL, ILCL, and IFSL of the three age brackets of the Kuri cattle were 13.39 ± 1.18 cm, 15.45 ± 1.04 cm, and 15.92 ± 1.18 cm; 19.36 ± 1.49 cm, 21.36 ± 1.41 cm, and 23.23 ± 2.42 cm; and 20.82 ± 1.89 cm, 23.29 ± 1.67 cm, and 25.13 ± 2.55 cm, respectively. The mean values of IMCL and IFSL were significantly ($p < 0.05$) higher in the middle-aged and aged compared to the young, but there was no significant difference between the middle-aged and the aged. However, the ILCL value of the young is significantly lower than that of the aged, but the middle-aged did not differ significantly from the young and aged. The ISRSOF and ISLSOF of the young, middle-aged, and aged Kuri cattle were 5.99 ± 0.70 cm and 6.09 ± 0.79 cm; 6.41 ± 1.08 cm and 6.45 ± 1.09 cm; and 6.56 ± 0.79 cm, 6.45 ± 1.09 cm, and 6.66 ± 1.11 cm, respectively. The ISRSOF and ISLSOF values were not significant between all three age groups. The mean ICPLIR and ICPLIL of the young, middle-aged, and aged Kuri cattle were 11.25 ± 1.60 cm and 12.88 ± 1.65 cm; 13.79 ± 1.53 cm and 11.30 ± 1.72 cm; and 13.19 ± 1.28 cm and 13.76 ± 1.47 cm, respectively. The mean NLM, NLLP, and NW of the young, middle-aged, and aged Kuri cattle were 16.40 ± 1.68 cm, 18.70 ± 1.05 cm, and 21.06 ± 1.19 cm; 15.41 ± 1.83 cm, 18.32 ± 1.16 cm, and 20.76 ± 0.85 cm; and 5.39 ± 0.62 cm, 6.44 ± 0.75 cm, and 6.44 ± 0.50 cm, respectively. The

Table 1. Age-related comparison of dorsal skull morphometric parameters in Kuri cattle (mean ± SD).

Parameter (cm)	Young (n=10)	Middle-age (n=10)	Aged (n=10)	Total
INL	44.51±3.66^{a}	49.97±2.93^{b}	55.89±3.49^{c}	50.12±5.74
SOBW	13.81±1.15^{a}	15.64±1.42^{b}	16.55±1.63^{b}	15.33±1.79
IMCL	13.39±1.18^{a}	15.45±1.04^{b}	15.92±1.18^{b}	14.92±2.03
ILCL	19.36±1.49^{a}	21.36±1.41^{a,b}	23.23±2.42^{b}	21.32±2.39
IFSL	20.82±1.89^{a}	23.29±1.67^{b}	25.13±2.55^{b}	23.08±2.69
ISRSOF	5.99±0.70^{a}	6.41±1.08^{a}	6.56±0.99^{a}	6.32±0.94
ISLSOF	6.09±0.79^{a}	6.45±1.09^{a}	6.66±1.11^{a}	6.40±1.00
ICPLIR	11.25±1.60^{a}	12.88±1.65^{a,b}	13.79±1.53^{b}	12.64±1.87
ICPLIL	11.30±1.72^{a}	13.19±1.28^{b}	13.76±1.47^{b}	12.75±1.80
NLM	16.40±1.68^{a}	18.70±1.05^{b}	21.06±1.19^{c}	18.72±2.33
NLLP	16.41±1.83^{a}	18.32±1.16^{b}	20.76±0.85^{c}	18.50±2.23
NW	5.39±0.62^{a}	6.44±0.75^{b}	6.44±0.50^{b}	6.09±0.79
VCrL	23.21±1.83^{a}	25.89±1.39^{b}	28.54±1.59^{c}	25.88±2.70

^{a,b,c} Mean ± SD with same superscripts are not significantly different along the rows. Mean difference is significant at p< 0.05.

Table 2. Age-related comparison of lateral skull morphometric parameters in Kuri cattle (mean ± SD).

Parameter (cm)	Young (n=10)	Middle-age (n=10)	Aged (n=10)	Total
IFRAT	2.85±0.37^{a}	3.40±0.44^{b}	3.66±0.47^{b}	3.30±0.54
IOFH	1.10±0.13^{a,b}	1.01±0.15^{a}	1.22±0.17^{b}	1.11±0.17
IOFW	0.93±0.17^{a}	0.96±0.15^{a}	0.96±0.22^{a}	0.94±0.18
FTIOF	3.96±0.32^{a}	4.71±0.41^{b}	5.25±0.68^{b}	4.64±0.72
RDMOSG	2.98±0.52^{a}	3.53±0.55^{a}	3.02±0.44^{a}	3.18±0.55
LDMOSG	3.04±0.40^{a}	3.50±0.52^{a}	3.02±0.44^{a}	3.19±0.50
RSLSOF	7.00±0.77^{a}	7.12±1.36^{a}	8.87±1.03^{b}	7.66±1.36
LSLSOF	6.86±0.77^{a}	7.25±1.48^{a}	8.84±1.00^{b}	7.65±1.39
LOBC	20.31±1.24^{a}	21.71±0.62^{a,b}	22.89±1.96^{b}	21.64±1.72
ROBC	20.12±1.29^{a}	21.68±0.78^{a,b}	23.25±2.00^{b}	21.68±1.90
LOBHD	7.00±0.45^{a}	7.06±0.47^{a}	7.80±0.78^{b}	7.29±0.68
ROBHD	6.94±0.50^{a}	7.06±0.42^{a}	7.78±0.84^{b}	7.26±0.70
LOBVD	5.88±0.37^{a}	6.46±0.25^{b}	6.71±0.47^{b}	6.35±0.51
ROBVD	5.90±0.32^{a}	6.50±0.24^{b}	6.88±0.68^{b}	6.43±0.60

^{a,b,c} Mean ± SD with same superscripts are not significantly different along the rows. *Mean difference is significant at p<0.05.

mean values of NLM and NLLP are significantly different among the three age groups. The mean value of NW of the middle-aged and aged is significantly higher than that of the young, but the middle-aged and aged groups did not differ significantly. The mean VCrL was 23.21 ± 1.83 cm, 25.89 ± 1.39 cm, and 28.54 ± 1.59 cm. The mean values of VCrL significantly differ in all three age brackets. These parameters exhibited progressive and significant age-related increases, with aged cattle recording the highest values. These findings suggest continuous enlargement of the dorsal cranial region with advancing age.

Lateral skull indices of young, middle-aged, and aged Kuri cattle

A total of fourteen (14) indices were obtained from the lateral aspect of the skull of the young, middle-aged, and aged Kuri cattle (Table 2). The lateral skull measurements of Kuri cattle revealed notable age-dependent variations in several morphometric parameters, although some traits remained relatively constant across the different age categories. The mean IFRAT for young, middle-aged, and aged Kuri cattle was 2.85 ± 0.37 cm, 3.40 ± 0.44 cm, and 3.66 ± 0.47 cm, respectively. There was no significant difference between the middle-aged and the aged, but the young were significantly lower than the two older age groups. The mean IOFH and IOFW were 1.10 ± 0.13 cm, 1.01 ± 0.15 cm, and 1.22 ± 0.17 cm; and 0.93 ± 0.17 cm, 0.96 ± 0.15 cm, and 0.96 ± 0.22 cm, respectively. The mean FTIOF of young, middle-aged, and aged Kuri cattle was 3.96 ± 0.32 cm, 4.71 ± 0.41 cm, and 5.25 ± 0.68 cm, respectively. The mean FTIOF value of the young was significantly lower than the older age groups, but the two

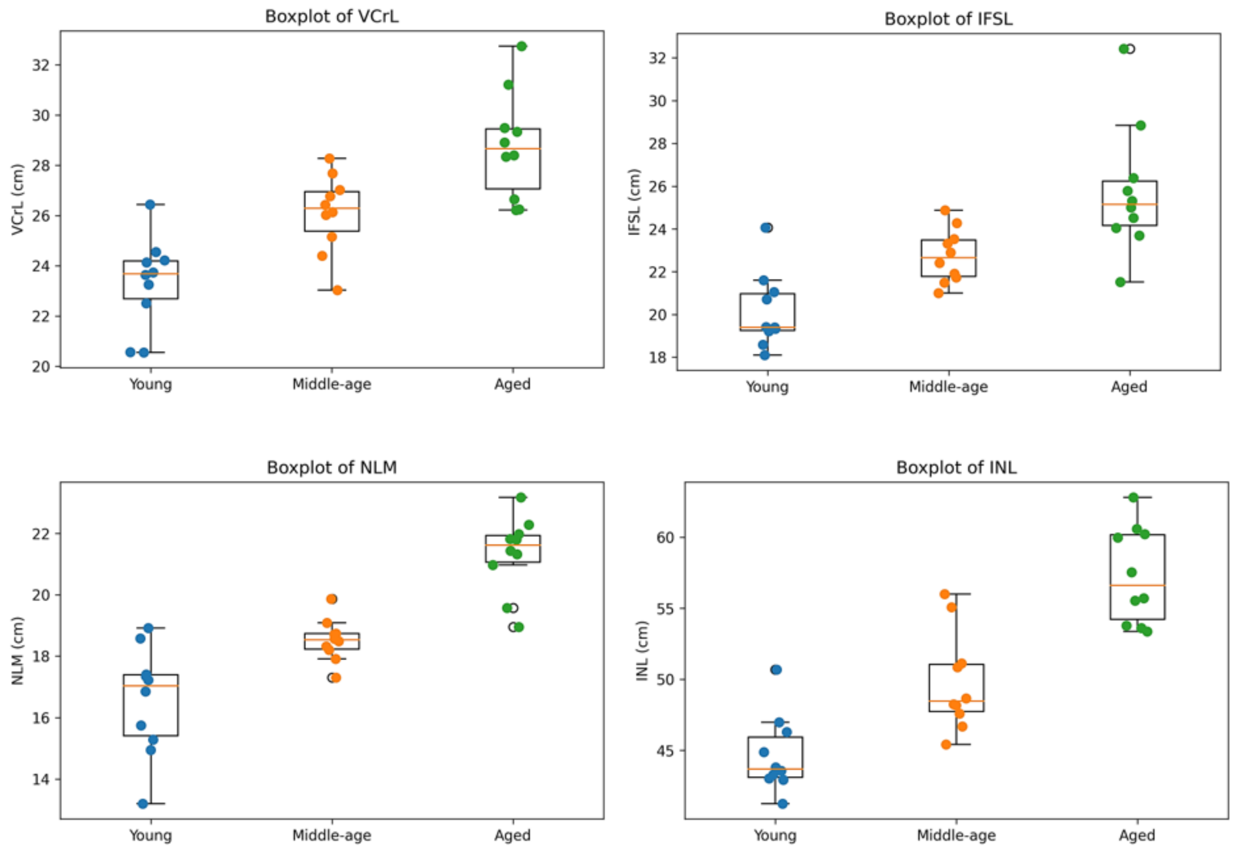

Figure 3. Boxplot showing age-related variations in dorsal skull morphometric parameters of Kuri cattle.

older ones were not significantly different. The mean RMDOSG and LMDOSG for young, middle-aged, and aged Kuri cattle were 2.98 ± 0.52 cm, 3.53 ± 0.55 cm, and 3.02 ± 0.44 cm; and 3.04 ± 0.40 cm, 3.50 ± 0.52 cm, and 3.02 ± 0.44 cm, respectively. The young, middle-aged, and aged Kuri cattle had mean RSLSOF and LSLSOF of 7.00 ± 0.77 cm, 7.12 ± 1.36 cm, and 8.87 ± 1.03 cm and 6.86 ± 0.77 cm, 7.25 ± 1.48 cm, and 8.84 ± 1.00 cm, respectively. The mean RSLSOF and LSLSOF values of the aged were significantly higher than those of the middle-aged and the young, but with no significant difference between the two younger groups. The mean LOBC and ROBC of these three age brackets were 20.31 ± 1.24 cm, 21.71 ± 0.62 cm, and 22.89 ± 1.96 cm and 20.12 ± 1.29 cm, 21.68 ± 0.78 cm, and 23.25 ± 2.00 cm, respectively. The mean LOBC and ROBC of the aged were significantly higher in the aged than in the young, but with no difference between the latter and the middle-aged. The mean LOBHD and ROBHD for these age groups in the Kuri cattle were 7.00 ± 0.45 cm, 7.06 ± 0.47 cm, and 7.80 ± 0.78 cm and 6.94 ± 0.50 cm, 7.06 ± 0.42 cm, and 7.78 ± 0.84 cm, respectively. The mean values of both LOBHD and ROBHD are significantly higher in the aged than the young and middle-aged, but the difference was not significant between the young and the middle-aged. The mean LOBVD and ROBVD of the young, middle-aged, and aged Kuri cattle were 5.88 ± 0.37 cm and 6.46 ± 0.25 cm and 6.71 ± 0.47 cm; and 5.90 ± 0.32 cm, 6.50 ± 0.24 cm, and 6.88 ± 0.68 cm, respectively. The mean values of both LOBVD and ROBVD are significantly higher ($p < 0.05$) in the middle-aged and aged over the young, but the difference is not significant between the middle-aged and the aged.

DISCUSSION

The present study provides a comprehensive quantitative evaluation of age-related changes in the dorsal and lateral skull morphology of Kuri cattle using conventional osteometry together with multivariate statistical approaches. These age-related changes were consistently demonstrated by Multivariate analysis (Figures 3-6), indicating that skull growth in Kuri cattle continues beyond early maturity through coordinated craniofacial remodelling. Similar patterns of prolonged postnatal skull growth have been reported in cattle (Rajathi, 2015; Çakar *et al*., 2024; Gündemir *et al*., 2025), buffaloes (Monfared, 2013a; Dalga and Aslan, 2025), sheep (Karimi *et al*., 2011), camels (Yahaya *et al*., 2012a), and European bison (Kobryńczuk *et al*., 2008).

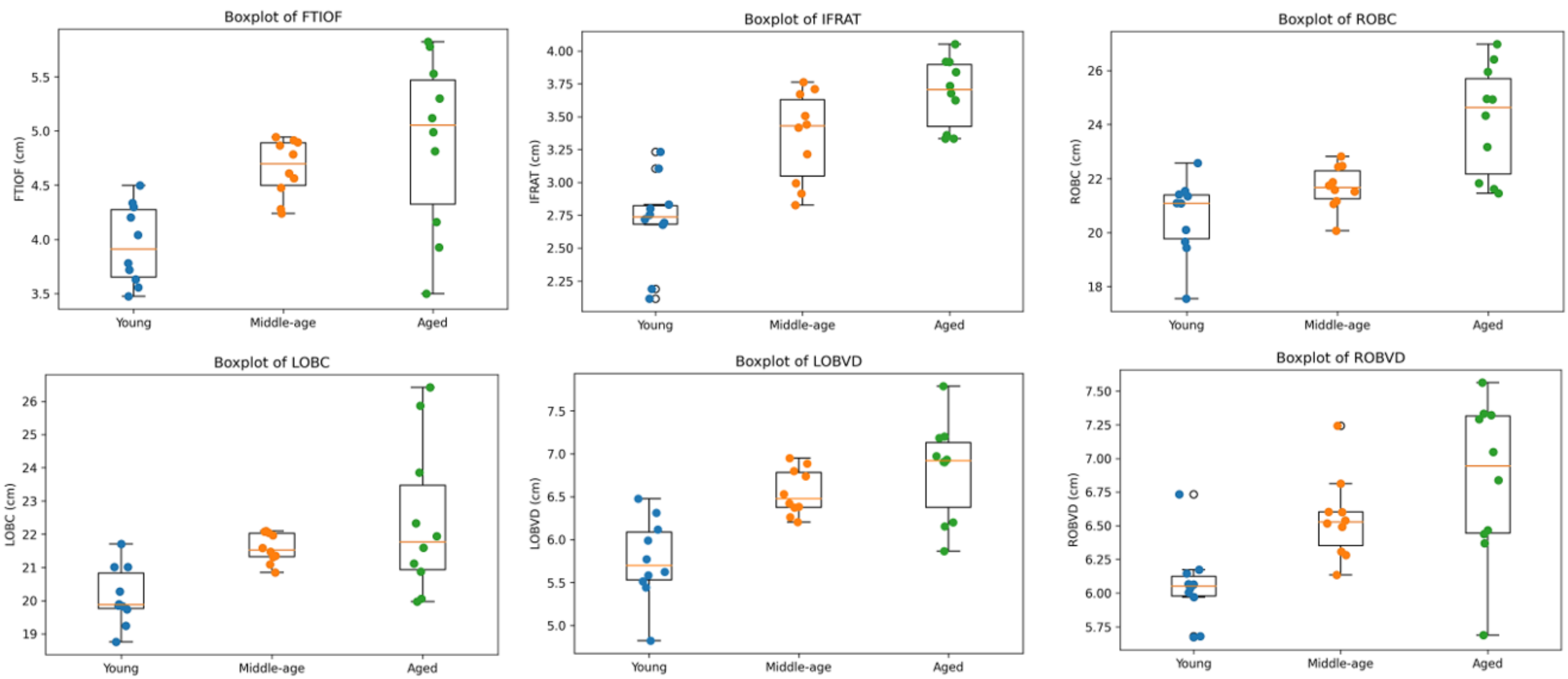

Figure 4. Boxplot showing age-related variations in lateral skull morphometric parameters of Kuri cattle.

The significant increase observed in inter-nasal length (INL) from 44.51 ± 3.66 cm in the young to 49.97 ± 2.93 cm in middle-aged, and 55.89 ± 3.49 cm in aged Kuri, represents an overall increase of approximately 25.6% with age. Likewise, nasal length median (NLM) increased from 16.40 ± 1.68 cm to 18.70 ± 1.05 cm, and 21.06 ± 1.19 cm, while nasal length lateral process (NLLP) increased from 16.41 ± 1.83 cm to 18.32 ± 1.16 cm and 20.76 ± 0.85 cm, respectively. Similarly, a significant increase in viscerocranial length (VCrL); from 23.21 ± 1.83 cm to 25.89 ± 1.39 cm, and 28.54 ± 1.59 cm suggests continuous elongation of the facial and neurocranial regions in Kuri cattle, as demonstrated by the dorsal scatter plot and PCA clustering patterns (Figures 5 and 7). Comparable craniofacial development has been reported in domestic cattle and water buffalo by Özkan *et al*. (2019), who recorded viscerocranial lengths of 29.80 ± 1.50 cm and 27.35 ± 3.74 cm, respectively. Recent findings reported by Gündemir *et al*. (2025) and Güzel *et al*. (2025) in indigenous cattle breeds of Türkiye demonstrated that cranial length parameters increase with maturation due to prolonged bone remodelling and pneumatization of cranial cavities. Similar craniofacial elongation patterns have also been described in buffaloes (Monfared, 2013; Dalga and Aslan, 2025), sheep (Karimi *et al*., 2011; Özüdoğru *et al*., 2023), and camels (Yahaya *et al*., 2012a, b).

The present study shows that supraorbital width (SOBW), intercornual medial crest length (IMCL), frontal sinus length (IFSL), and nasal width (NW) also increased significantly with age, indicating progressive dorsal expansion of the skull. Supraorbital width increased from 13.81 ± 1.15 cm

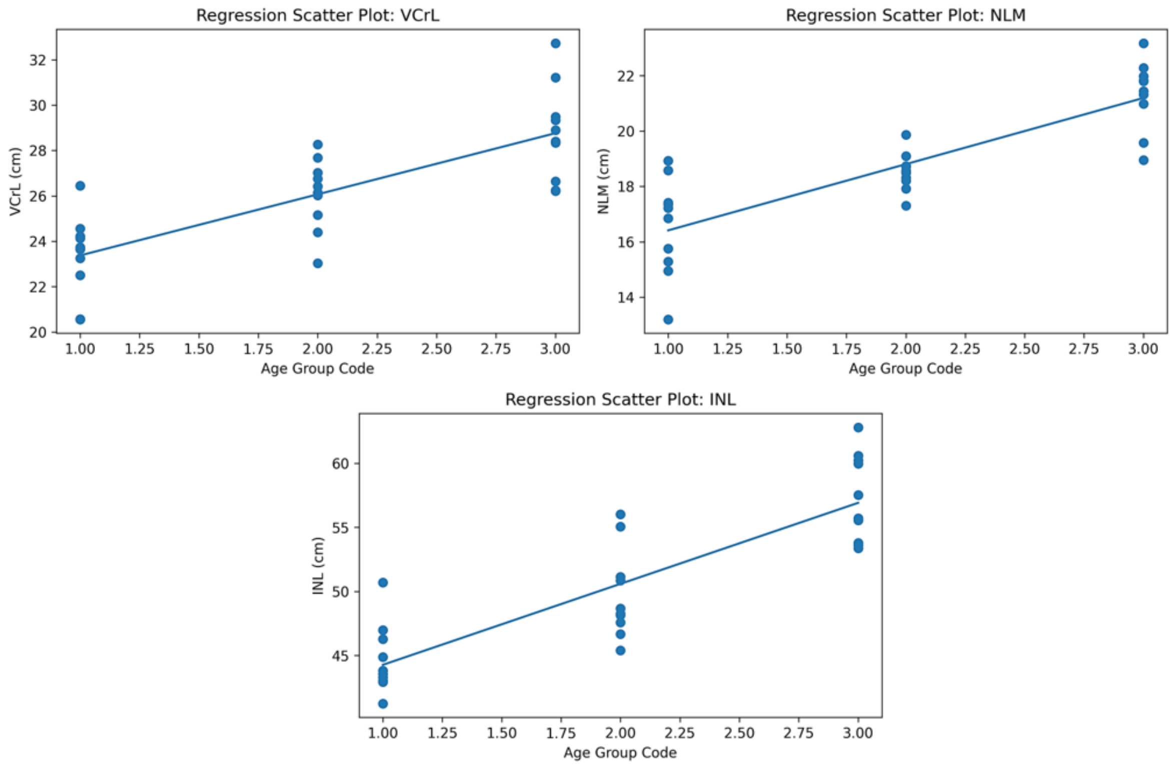

Figure 5. Regression scatter plot illustrating relationships among dorsal skull morphometric parameters in Kuri cattle across age groups.

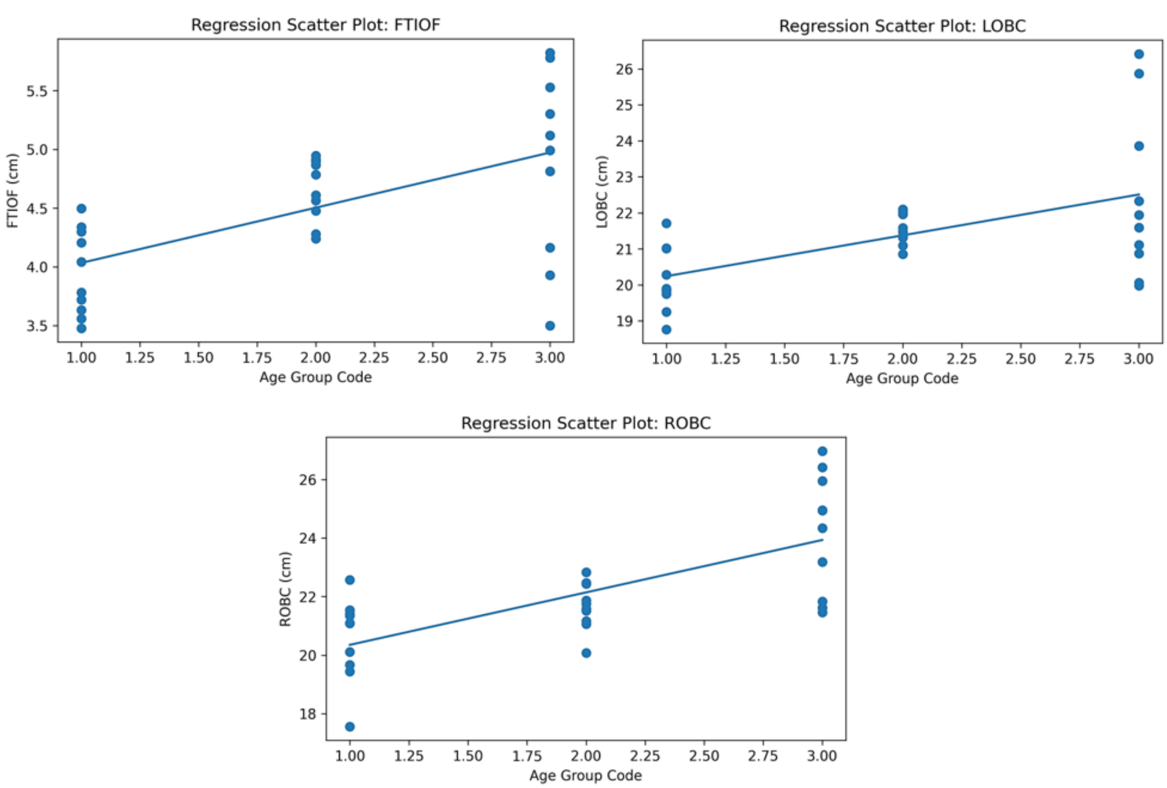

Figure 6. Regression scatter plot illustrating relationships among lateral skull morphometric parameters in Kuri cattle across age groups.

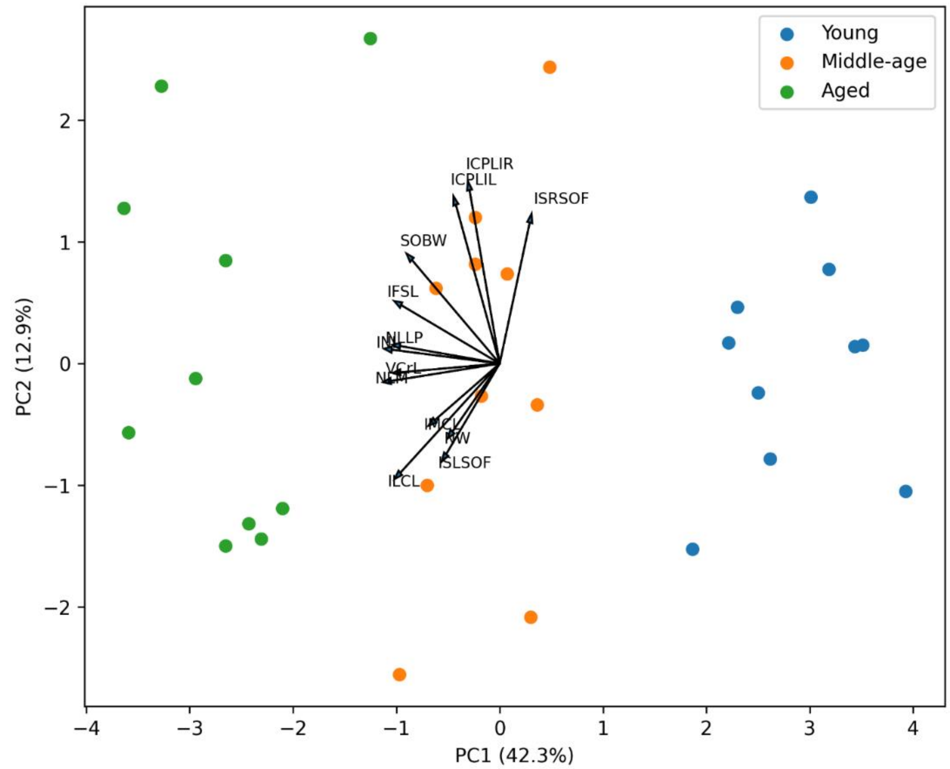

Figure 7. Principal component analysis (PCA) biplot of dorsal skull morphometric parameters in Kuri cattle.

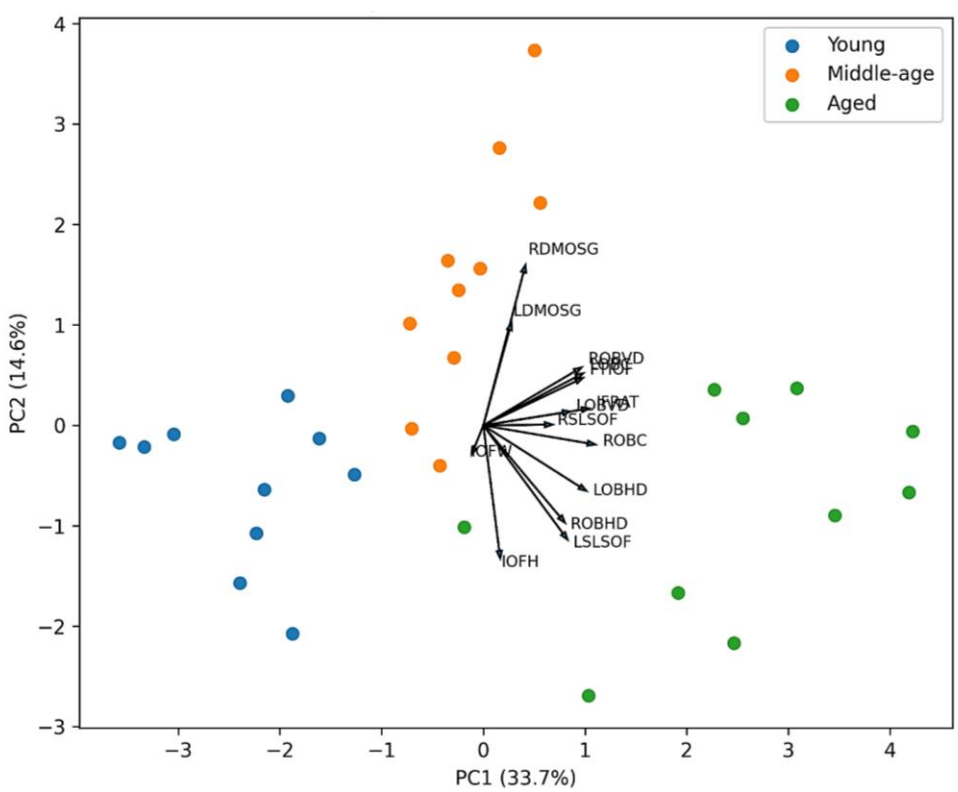

Figure 8. Principal component analysis (PCA) biplot of lateral skull morphometric parameters in Kuri cattle.

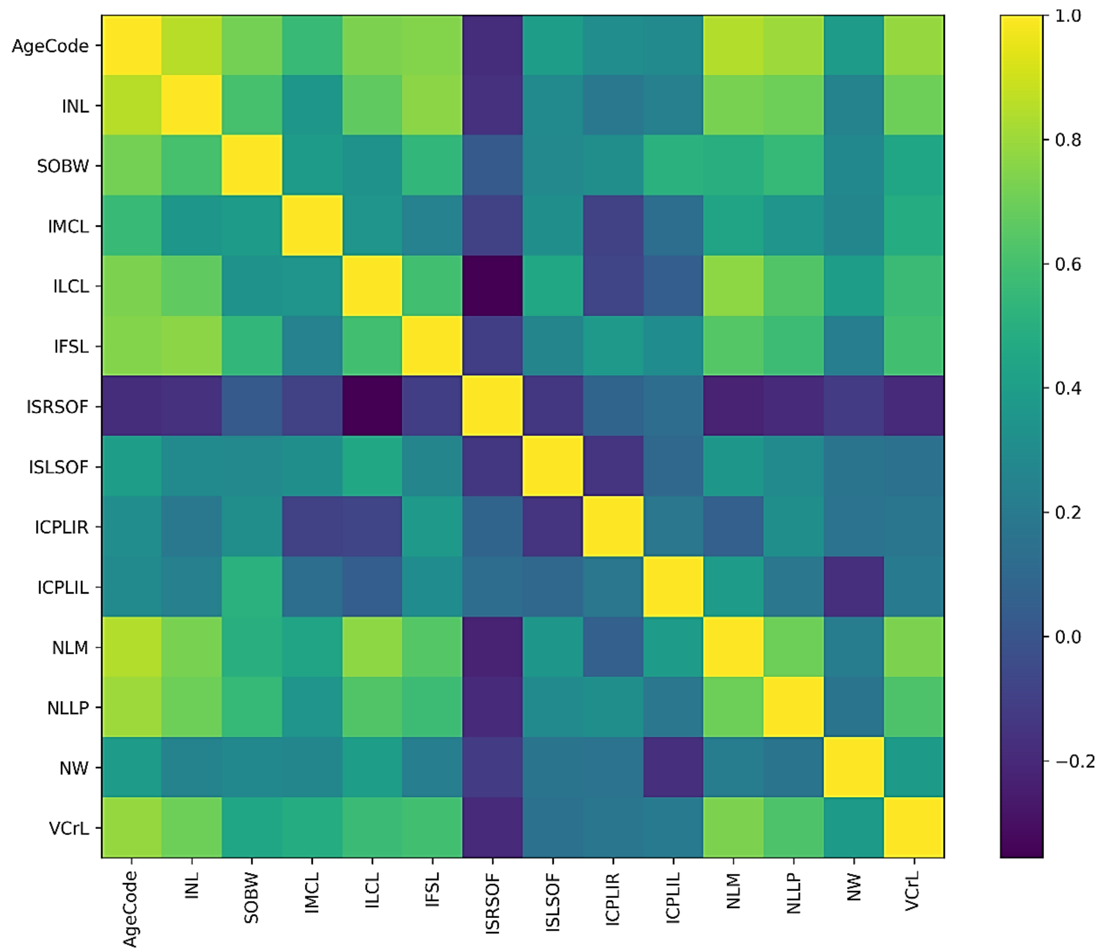

Figure 9. Correlation heatmap showing associations among dorsal skull morphometric parameters of Kuri cattle. Incisive – Nuchal length (**INL**); Supraorbital width (**SOBW**); Intermedial canthi length (**IMCL**); Interlateral canthi length (**ILCL**); Interfrontal suture length (**IFSL**); Interfrontal Suture to right supraorbital foramen (**ISRSOF**); Interfrontal Suture to left supraorbital foramen (**ISLSOF**); Intercornual protuberance to line of intersection of Right (**ICPLIR**); Intercornual protuberance to line of intersection of left (**ICPLIL**); Nasal length at midline (**NLM**); Nasal length at lateral prongs (**NLLP**); Nasal width (**NW**); Viscerocranial length (**VCrL**).

in young cattle to 15.64 ± 1.42 cm in middle-aged cattle and 16.55 ± 1.63 cm in aged cattle, whereas IMCL increased from 13.39 ± 1.18 cm to 15.45 ± 1.04 cm and 15.92 ± 1.18 cm, respectively. Strong positive associations among these parameters are evident in the dorsal correlation heatmap (Figure 9). Frontal sinus length increased from 20.82 ± 1.89 cm to 23.29 ± 1.67 cm and 25.13 ± 2.55 cm, while nasal width increased significantly from 5.39 ± 0.62 cm to 6.44 ± 0.75 cm, with no further increase in aged animals (6.44 ± 0.50 cm), suggesting that transverse cranial growth reaches maturity earlier than rostrocaudal expansion. Similar dorsal cranial development was reported by Özkan *et al*. (2019), who found skull base lengths of 48.62 ± 1.58 cm in domestic cattle and 45.01 ± 4.50 cm in water buffalo, together with skull lengths of 33.66 ± 1.15 cm and 29.52 ± 2.81 cm, respectively. Their frontal breadth measurements (17.40 ± 0.85 cm in cattle and 13.34 ± 1.78 cm in buffalo) further illustrate the substantial variation in dorsal cranial morphology among bovids. Likewise, Çakar *et al*. (2024) reported total skull lengths of 49.06 ± 2.81 cm in Holstein cattle and 48.60 ± 2.43 cm in Simmental cattle, confirming that cranial vault dimensions continue to increase with skeletal development before stabilising in aged animals. Frontal sinus enlargement has been associated with increasing skeletal robustness and adaptation to biomechanical stress in bovines (König and Liebich, 2007). Similar increases in frontal and orbital cranial dimensions were reported in European bison (Kobrynczuk *et al*., 2008; Gündemir and Szara, 2025). The attainment of near-mature dimensions in middle-aged cattle for some parameters suggests that portions of the cranial vault stabilise earlier than others, a phenomenon previously observed in buffaloes and sheep (Monfared, 2013;

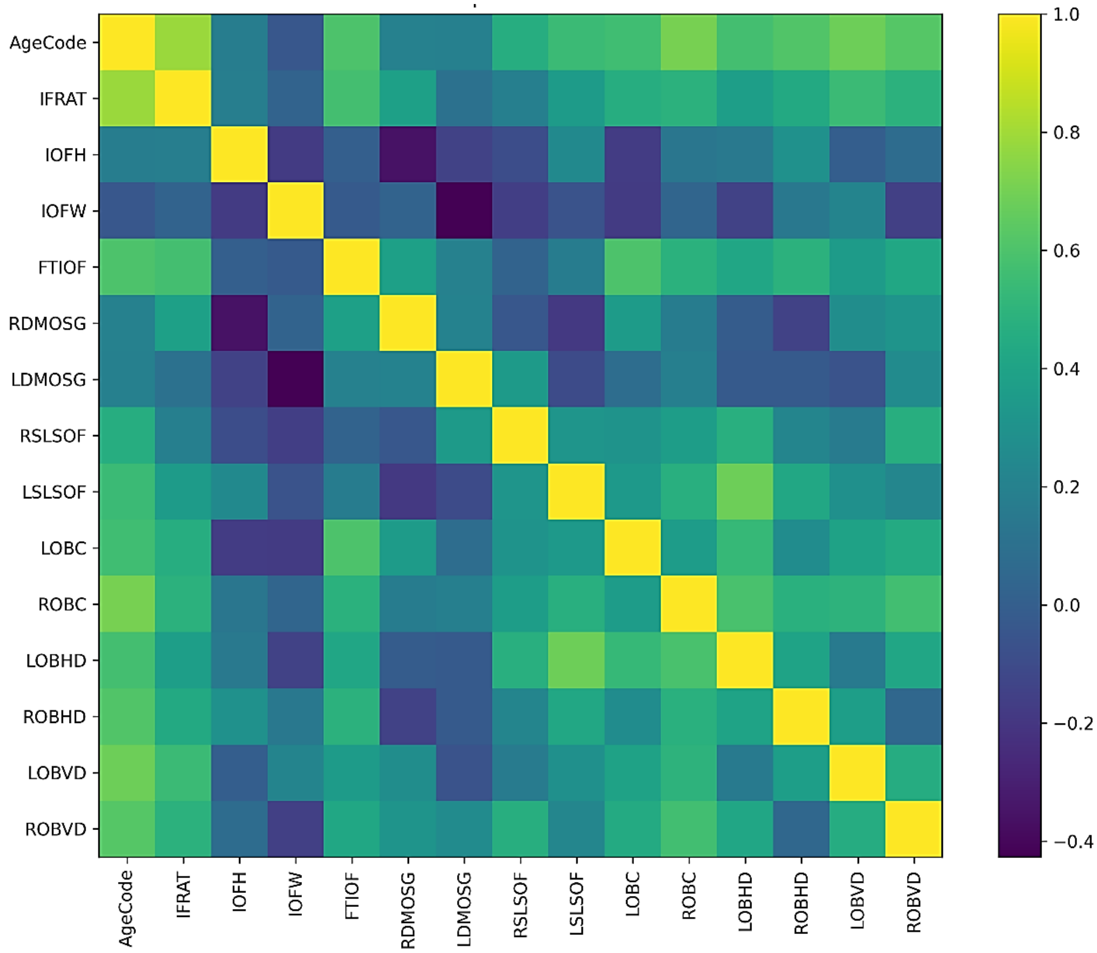

Figure 10. Correlation heatmap showing associations among lateral skull morphometric parameters of Kuri cattle. Infraorbital foramen to root of alveolar tooth (**IFRAT**); Infraorbital foramen height (**IOFH**); Infraorbital foramen width (**IOFW**); Facial tuberosity to infraorbital foramen (**FTIOF**); Right dorsomedial margin of the orbit to supraorbital groove (**RDMOSG**); Left dorsomedial margin of the orbit to supraorbital groove (**LDMOSG**); Right Supraorbital line to supraorbital foramen (**RSLSOF**); Left Supraorbital line to supraorbital foramen (**LSLSOF**); Left orbital circumference (**LOBC**); Right orbital circumference (**ROBC**); Left orbital horizontal diameter (**LOBHD**); Right orbital horizontal diameter (**ROBHD**); Left orbital vertical diameter (**LOBVD**); Right orbital vertical diameter (**ROBVD**).

Zehtabvar *et al*., 2024).

Although most dorsal cranial measurements increased significantly with age, the inter-right supraorbital foramina distance (ISRSOF) and inter-left supraorbital foramina distance (ISLSOF) remained statistically unchanged. ISRSOF increased only slightly from 5.99 ± 0.70 cm to 6.41 ± 1.08 cm and 6.56 ± 0.99 cm, while ISLSOF increased from 6.09 ± 0.79 cm to 6.45 ± 1.09 cm and 6.66 ± 1.11 cm. These relatively constant measurements suggest that the positions of major neurovascular foramina are established early during postnatal development and undergo minimal remodelling thereafter, which is also reflected by their weaker clustering pattern in the PCA biplot and moderate correlations in the heatmap (Figures 7 and 9). Similar findings were documented by Olopade and Onwuka (2005) and Kalita (2015), who noted that foramina-related measurements often remain relatively constant after early developmental stages because they primarily serve as neurovascular passage points. Stability of infraorbital and supraorbital foramina dimensions has also been reported in Iranian buffaloes (Monfared, 2013a) and Indian mithun (Choudhary *et al*., 2022).

The lateral skull measurements equally demonstrated progressive enlargement of the orbital and craniofacial regions with advancing age, clearly demonstrated in the lateral boxplots and regression plots (Figures 4 and 6). Infraorbital foramen to root of the alveolar tooth (IFRAT) increased significantly from 2.85 ± 0.37 cm to 3.40 ± 0.44 cm and 3.66 ± 0.47 cm, while frontotemporal to infraorbital foramen distance (FTIOF) increased from 3.96 ± 0.32 cm to 4.71 ± 0.41 cm and 5.25 ± 0.68 cm. Right and left supraorbital foramen–lacrimal suture lengths increased to

8.87 ± 1.03 cm and 8.84 ± 1.00 cm, respectively, in aged cattle. Comparable enlargement of the orbital region has been documented by Özkan *et al*. (2019), who reported orbital breadths of 13.68 ± 1.27 cm in domestic cattle and 10.14 ± 0.75 cm in water buffalo, together with frontal breadths of 16.99 ± 0.96 cm and 17.24 ± 0.95 cm, respectively. Holstein and Simmental cattle also exhibited orbital breadths of 13.74 ± 1.22 cm and 14.66 ± 1.63 cm, respectively (Çakar *et al*., 2024), indicating that orbital enlargement accompanies cranial maturation across bovine species. Similar observations were reported in studies on cattle and buffalo skulls by Nourinezhad *et al*. (2016), and Ince *et al*. (2015) in Khouzestan river buffalo, where orbital dimensions increased significantly with maturity. Enlargement of orbital circumference and orbital diameters has also been linked to increasing cranial robustness and ocular accommodation in mature animals (Dias *et al*., 2023; Silva *et al*., 2024).

Orbital dimensions also increased significantly with advancing age in Kuri cattle. Left orbital circumference increased from 20.31 ± 1.24 cm to 21.71 ± 0.62 cm and 22.89 ± 1.96 cm, while the corresponding right orbital circumference increased from 20.12 ± 1.29 cm to 21.68 ± 0.78 cm and 23.25 ± 2.00 cm. Left orbital horizontal diameter increased from 7.00 ± 0.45 cm to 7.80 ± 0.78 cm, whereas right orbital horizontal diameter increased from 6.94 ± 0.50 cm to 7.78 ± 0.84 cm. Likewise, left orbital vertical diameter increased from 5.88 ± 0.37 cm to 6.46 ± 0.25 cm and 6.71 ± 0.47 cm, while right orbital vertical diameter increased from 5.90 ± 0.32 cm to 6.50 ± 0.24 cm and 6.88 ± 0.68 cm. These relationships are further highlighted by the clustering of orbital variables in the PCA biplot and their strong positive correlations in the heatmap (Figures 8 and 10). Özkan *et al*. (2019) similarly reported orbital index values of 110.01 ± 7.24 in domestic cattle and 95.56 ± 8.48 in water buffalo, reflecting substantial orbital development associated with species-specific cranial morphology. Comparable findings were reported in blackbuck (Choudhary and Singh, 2015), red foxes (Sayed and Hamoda, 2021), and blue bull (Sathapathy *et al*., 2022), where orbital dimensions increased progressively with skeletal maturation. However, the similarity between middle-aged and aged groups for some orbital vertical diameters may indicate that vertical orbital growth plateaus earlier than horizontal expansion, as similarly observed by Zehtabvar *et al*. (2024) in Urial sheep.

Conversely, infraorbital foramen width (IOFW), right distance from the dorsal margin of the orbit to the supraorbital groove (RDMOSG), and left distance from the dorsal margin of the orbit to the supraorbital groove (LDMOSG) did not differ significantly among age groups. Infraorbital foramen width remained almost constant, ranging from 0.93 ± 0.17 cm to 0.96 ± 0.22 cm, whereas both RDMOSG and LDMOSG fluctuated around 3.0–3.5 cm. These findings indicate that clinically important neurovascular landmarks attain morphological stability relatively early in life and remain conserved throughout maturity. Similar observations have been reported in Iranian native cattle (Monfared, 2013), and domestic cattle and buffaloes (Özkan *et al*., 2019), highlighting the usefulness of these landmarks for regional anaesthesia, surgical orientation, and comparative osteological investigations (Olopade and Onwuka, 2005).

The present findings confirm that skull morphometry in Kuri cattle is strongly influenced by age, with most dorsal and lateral cranial dimensions increasing progressively from youth to aged, whereas foraminal landmarks remain relatively stable. When considered alongside morphometric studies in domestic cattle, water buffalo, Holstein, Simmental, sheep, camels, and other Bovidae species, these findings reinforce the concept that craniofacial growth and skeletal remodelling continue throughout maturity, while preserving the positional integrity of major neurovascular structures. This quantitative comparison further demonstrates that Kuri cattle exhibit cranial growth patterns comparable to those reported for other bovine species, while maintaining morphometric characteristics that reflect their unique genetic background and ecological adaptation.

Conclusion

The present study demonstrated that dorsal and lateral skull morphometric parameters of Kuri cattle are markedly influenced by age, with most cranial dimensions showing progressive increases from young to aged animals. The observed enlargement of cranial, orbital, and facial structures reflects continuous skeletal growth, craniofacial remodelling, and maturation characteristic of indigenous bovine breeds. While several parameters exhibited significant age-related variations, others such as selected foraminal measurements remained relatively stable, suggesting early establishment and maintenance of specific anatomical landmarks throughout growth. The study further provides valuable baseline morphometric reference values on the cranial anatomy for young, middle-aged, and aged Kuri cattle, a rare indigenous breed of the Lake Chad Basin, and establishes a reference for future anatomical, developmental, and functional studies involving indigenous African cattle breeds. These present findings have not been previously documented to the best of the available literature, thereby representing a novel contribution of the present study. Such information is also important for comparative anatomy, breed characterisation, taxonomy, forensic identification, and clinical applications, including regional anaesthesia and surgical interventions.

CONFLICT OF INTEREST

The authors affirm that no financial, personal, or professional conflicts of interest.

ACKNOWLEDGEMENTS

The authors appreciate the technical support received from Dogoli Mohammed and Mamman Bakoji of the Gross Anatomy Laboratory, Department of Veterinary Anatomy, University of Maiduguri, Nigeria. There was no funding received for the research.

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