

Age-related allometric growth patterns of skull morphometry in Kuri cattle (*Bos taurus*) part (2): Caudal (Occipital) and ventral aspect

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ABSTRACT: Skull morphometry is essential for understanding postnatal skeletal development and breed variation in domestic ruminants. This study investigated age-related morphometric changes in the caudal and ventral skull regions of Kuri cattle and established baseline cranial reference values for this indigenous African taurine breed. Thirty clinically healthy cattle comprising 15 males and 15 females were purposively sampled from four Nigerian abattoirs and classified into young (<3 years), middle-aged (3–5 years), and aged (>5 years) groups, respectively. Following hot-water maceration, thirty-three cranial measurements were recorded using standardised osteometric methods. Data were analysed using one-way ANOVA, Pearson correlation, regression analysis, principal component analysis, boxplots, correlation heatmaps, and allometric scaling relative to condylobasal length (CBL). One-way ANOVA revealed significant age-related variation in numerous cranial parameters. Among caudal measurements, MICW, IJPW, PCPL, IPCW, WSH1, WSH2, and SH differed significantly among age groups ($p < 0.05$), with values increasing from 24.50 ± 1.62 cm in young to 29.40 ± 2.02 cm in aged cattle. In contrast, the IPFM, FMH, FMW, FMC, FMI, IPEOP, and neurocranial volume showed no significant age-related differences. Ventral skull measurements revealed significant increases in IPSL, IISL, ChW, MZW, IOL, and CBL with age ($p < 0.001$). Hard palate length increased significantly from 24.59 ± 1.59 cm in young cattle to 27.80 ± 1.25 cm in middle-aged and 29.72 ± 1.66 cm in aged cattle. Allometric analysis revealed variable scaling relationships relative to CBL. Positive allometry predominated in facial and palatal structures, particularly IPSL1 ($b = 1.910$), ChL ($b = 1.763$), RIFW ($b = 1.631$), PWM3 ($b = 1.589$), and IPSL2 ($b = 1.549$), whereas FMH ($b = 0.625$) and FMC ($b = 0.636$) exhibited negative allometry. Neurocranial structures and NCV showed largely isometric growth. These findings indicate that age-related changes were more pronounced in measurements associated with the facial skeleton and cranial base, whereas several neurocranial measurements remained relatively stable. The morphometric reference values generated provide valuable baseline data for comparative anatomy, breed characterisation, diagnostic imaging, surgical planning, veterinary education, and future developmental studies.

Keywords: African taurine, allometric growth, postnatal development, skull morphometry.

INTRODUCTION

The mammalian skull is among the most structurally complex regions of the skeleton, providing mechanical protection for the brain, supporting the sensory organs,

and serving as the primary attachment site for muscles (König and Liebich, 2007; Fostowicz-Frelik and Tseng, 2023). In domestic ruminants, the skull serves as the

principal anatomical framework for the upper respiratory and digestive systems, supports the dentition and masticatory apparatus, and articulates with the vertebral column through the atlanto-occipital joint, thereby facilitating head support and movement (Monfared, 2013a, 2013b; Mansour *et al.*, 2023). Beyond its biological functions, cranial morphology provides valuable information for breed characterisation, species identification, comparative anatomy, forensic investigations, and veterinary clinical practice (Karimi *et al.*, 2011; Özkan *et al.*, 2019). Accurate knowledge of cranial anatomy is fundamental for regional anaesthesia, diagnostic imaging, surgical planning, and the interpretation of normal and pathological cranial structures in veterinary medicine (Çakar *et al.*, 2024; Turgut, 2025).

Morphometric studies have consistently demonstrated that cranial dimensions vary among species, breeds, sexes, age groups, and geographical populations (Çakar *et al.*, 2024; Gündemir *et al.*, 2025). These variations are influenced by genetic background, ontogenetic development, allometric growth, environmental adaptation, nutrition, and selective breeding (Chipping, 2024; Gündemir and Szara, 2025). Sexual dimorphism has likewise been recognised as an important determinant of cranial morphology in both domestic and wild mammals, with significant differences observed in skull size and proportions between males and females (Kobryńczuk *et al.*, 2008; Dalga and Aslan, 2025). Consequently, cranial morphometry has become an indispensable tool for evaluating phenotypic diversity, breed discrimination, taxonomic classification, evolutionary relationships, and functional adaptations among domestic and wild ruminants (Güzel *et al.*, 2025; Zehtabvar *et al.*, 2024).

Recent advances in morphometric techniques have substantially improved the precision of cranial investigations. Computed tomography has enabled detailed evaluation of cranial structures in cattle and other ruminants (Turgut, 2025; Zehtabvar *et al.*, 2024). Three-dimensional reconstruction has further enhanced visualisation and quantitative assessment of skull morphology (Güzel *et al.*, 2025). Likewise, principal component analysis and discriminant function analysis have become valuable statistical tools for distinguishing closely related breeds and species (Dalga and Aslan, 2025). These modern approaches have significantly expanded comparative anatomical studies of the ruminant skull.

Numerous studies have described the gross morphology and morphometric characteristics of the skull in domestic cattle. Morphometric analyses have been reported in indigenous Iranian cattle (Monfared, 2013b), Indian crossbred cattle (Rajathi, 2015), Simmental and Holstein cattle (Çakar *et al.*, 2024), Turkish indigenous and exotic cattle breeds (Gündemir *et al.*, 2025), and Holstein cattle using computed tomography (Turgut, 2025). Comparative investigations between cattle and buffalo have also demonstrated significant interspecific differences in cranial

dimensions (Özkan *et al.*, 2019).

Similarly, extensive craniometric investigations have been conducted in other bovids and wild ruminants. Detailed skull morphometry has been described in domestic buffaloes (Monfared, 2013a; Nourinezhad *et al.*, 2016; Dalga and Aslan, 2025), mithun (*Bos frontalis*) (Choudhary *et al.*, 2022), European bison (*Bison bonasus*) (Kobryńczuk *et al.*, 2008; Gündemir and Szara, 2025), sheep (Karimi *et al.*, 2011; Özüdoğru *et al.*, 2023), goats (Sarma, 2006), blue bull (*Boselaphus tragocamelus*) (Sathapathy *et al.*, 2022), urial sheep (*Ovis vignei*) (Zehtabvar *et al.*, 2024), blackbuck (*Antilope cervicapra*) (Choudhary and Singh, 2015), and South American deer (da Silva *et al.*, 2024). Collectively, these investigations demonstrate the increasing importance of cranial morphometry in veterinary anatomy, taxonomy, and comparative biology.

More recently, anatomical investigations have increasingly focused on specific cranial regions rather than considering the skull as a single anatomical unit. The caudal (occipital) aspect contains the foramen magnum, occipital condyles, nuchal crest, and paracondylar processes, all of which are essential for articulation with the atlas and attachment of cervical musculature (König and Liebich, 2007). The ventral aspect of the skull includes the basioccipital, basisphenoid, presphenoid, pterygoid, palatine, and temporal regions, together with the tympanic bullae and numerous neurovascular foramina (Pasquini, 1982). These structures are of considerable clinical importance because they serve as landmarks for regional anaesthesia, surgical approaches, diagnostic imaging, and osteological identification (Olopade and Onwuka, 2005; Monfared, 2013a; Dias *et al.*, 2023).

Several recent studies have specifically examined the caudal and ventral regions of the skull in domestic and wild ruminants. Nourinezhad *et al.* (2016) described the morphometric features of the occipital region in river buffalo and emphasised their value in anatomical identification. Choudhary *et al.* (2022) documented the ventral cranial morphology of Indian mithun, providing baseline anatomical data for the species. Turgut (2025) used computed tomography to characterise the skull base of Holstein cattle, while Zehtabvar *et al.* (2024) combined computed tomography with morphometric and volumetric analyses to describe the skull of urial sheep. Three-dimensional modelling has also been successfully applied to characterise cranial morphology in indigenous Turkish cattle breeds (Güzel *et al.*, 2025). Similar region-specific morphometric investigations have been reported in sheep (Karimi *et al.*, 2011), goats (Sarma, 2006), European bison (Gündemir and Szara, 2025), and cervids (da Silva *et al.*, 2024). Despite these advances, comprehensive quantitative descriptions of the caudal and ventral aspects of indigenous African cattle remain remarkably scarce.

This lack of detailed anatomical information represents an important gap in the comparative anatomy of indigenous

African cattle. Comprehensive morphometric characterisation of the occipital and ventral aspects of the Kuri skull would provide baseline reference values for comparative anatomy, facilitate breed differentiation, improve regional anaesthetic and surgical procedures involving the craniovertebral junction, and strengthen osteological identification in zooarchaeological and conservation studies. Such information would also contribute to understanding functional adaptations of this unique indigenous breed.

Therefore, the present study was undertaken to investigate age-related variation in the caudal (occipital) and ventral skull morphology of Kuri cattle. Specifically, the objectives were to: describe the gross anatomical features of the caudal and ventral aspects of the skull; quantify selected osteometric parameters across young, middle-aged, and aged cattle; determine which cranial measurements exhibit significant age-related variation; and evaluate relationships and scaling patterns among cranial variables using correlation, regression, and allometric analyses. The study quantifies important osteometric parameters, documents the morphology of major cranial landmarks, and compares the findings with published reports on cattle, buffaloes, sheep, goats, bison, and other wild ruminants. To the best of our knowledge, this is the first investigation to comprehensively characterise both the caudal and ventral aspects of the Kuri cattle skull. The findings will provide novel baseline anatomical data for comparative veterinary anatomy, clinical practice, morphofunctional investigations, conservation biology, and future studies on indigenous African cattle.

MATERIALS AND METHODS

Sample collection

This study was carried out using thirty (30) apparently healthy Kuri cattle (*Bos taurus*), comprising fifteen (15) males and fifteen (15) females. The animals were stratified into three age groups: young (<3 years; $n = 10$), middle-aged (3–5 years; $n = 10$), and aged (>5 years; $n = 10$). To reduce the influence of sexual dimorphism on cranial measurements, each age category contained an equal number of male and female animals (5 males and 5 females). Prior to inclusion in the study, all animals were subjected to routine physical examination to confirm the absence of craniofacial abnormalities, skeletal deformities, or musculoskeletal conditions that could affect skull morphology. Age determination was based on dentition, specifically the eruption and replacement pattern of permanent incisors, according to the criteria described by Pasquini (1982). Sex identification was established through examination of the external reproductive organs and associated anatomical features. The heads were

obtained immediately after slaughter from four major abattoirs located within the recognised distribution range of Kuri cattle in Nigeria. The abattoirs included Shomolu–Bariga Abattoir (Lagos State), Bodija Abattoir (Oyo State), Ijebu-Igbo Abattoir (Ogun State), and the Maiduguri Central Abattoir (Borno State). Sampling from different geographical locations was undertaken to ensure broad representation of the breed and to minimise potential variations associated with regional management practices. Following collection, each specimen was appropriately coded according to age category and sex before being transported to the Gross Anatomy Laboratory for preparation and morphometric analysis. During handling and transportation, particular attention was given to preserving the integrity of cranial structures and anatomical landmarks to ensure the accuracy and reliability of subsequent measurements.

Ethical approval

The study involved collection of skulls from animals slaughtered for routine commercial purposes, and no animals were slaughtered specifically for this research. Therefore, ethical clearance was obtained from the Institutional Animal Use and Ethics Committee (AUEC), Faculty of Veterinary Medicine, University of Maiduguri. Permission for specimen (Kuri skull) collection was also obtained from the relevant abattoir authorities, and the study was conducted in accordance with institutional guidelines.

Specimen preparation

Preparation of the skull specimens was carried out using the hot-water maceration method described by Çakar *et al.* (2024) and Ari *et al.* (2026). Initially, all remaining soft tissues attached to the heads, including muscles, fasciae, ligaments, tendons, and connective tissues, were carefully dissected and removed using scalpels and scissors. The skulls were subsequently transferred into individual containers, each filled with approximately 60 L of water, and boiled at approximately 100°C for 6–8 hours to promote the detachment and removal of any remaining soft tissues. After boiling, the maceration water was replaced as required until all residual soft tissues were removed. Approximately 450 g of polycarboxylate detergent was then added to facilitate the breakdown and removal of residual adipose tissue, bone marrow fragments, and other soft tissue remnants adhering to the skulls. After complete maceration, the skulls were immersed in a 30% hydrogen peroxide solution for 48 hours to achieve bleaching and further cleaning of the osseous structures. The specimens were subsequently rinsed thoroughly with clean water and allowed to air-dry at room temperature of about 25–28°C for 7 days in a well-

ventilated laboratory environment. The cleaned skulls were examined for gross morphological features and used for morphometric analyses. All measurements were recorded in centimetres (cm). Photographs of the skulls from different anatomical views were obtained using a Panasonic digital camera equipped with a 16-megapixel Leica lens. The images were subsequently used for illustration and figure preparation.

Osteometric parameters

A total of thirty-three (33) osteometric parameter measurements were evaluated to investigate age-related allometric changes in the Kuri cattle skull. These consisted of fourteen (14) parameters obtained from the caudal (occipital) aspect and nineteen (19) parameters obtained from the ventral aspect of the skull. Measurements were taken using standard osteometric instruments, including metric rulers, vernier callipers, dividers, compasses, and measuring threads, depending on the anatomical structure being assessed. The selection of morphometric variables and anatomical reference points was based primarily on established craniometric protocols reported by Olopade and Onwuka (2005) and Özkan *et al.* (2019). Where necessary, additional anatomical landmarks were identified and adapted to accommodate the distinctive cranial morphology of the Kuri cattle breed.

Landmark and osteometric measurements

According to the method adopted by Olopade and Onwuka (2005) and Özkan *et al.* (2019), the following thirty-three (33) osteometric parameters of the caudal (occipital) and ventral surfaces of the skull were measured using predefined anatomical landmarks on each skull (Figures 1 and 2). These measurements were obtained following established craniometric procedures and were used for subsequent morphometric and allometric analyses.

1. Intercornual Protuberance to Foramen Magnum (IPFM): Distance between the intercornual protuberance and the dorsal brim of the foramen magnum at the midline.
2. Foramen magnum height (FMH): Mid-vertical height of the foramen magnum.
3. Foramen magnum width (FMW): Width of the foramen magnum at the median protuberance of the two condyles into the foramen magnum.
4. Foramen magnum circumference (FMC): Length of the foramen magnum circumference.
5. Foramen magnum index (FMI): $\frac{FMH \times 100}{FMW}$
6. Maximum intercondylar width (MICW): Maximum distance between the two occipital condyles at the caudal surface.
7. Interjugular process width (IJPW): Maximum distance between the tips of the two jugular processes.
8. Paracondylar process length (PCPL): Distance between the tips of the paracondylar (jugular) process directly to its junction with the squamous occipital bone.
9. Interparacondylar width (PCW): The widest breadth between the most lateral ends of the paracondylar process.
10. Whole skull height 1 (WSH1): Distance between the most ventral part of the skull (without mandible) and the highest point of the skull when laid on an even surface.
11. Whole skull height 2 (WSH2): Distance between the most ventral part of the skull (without the mandible) and the intercornual protuberance.
12. Skull height (SH): Vertical distance from the highest point of the skull at the intercornual protuberance to the lowest ventral point of the skull without the mandible.
13. Intercornual protuberance to external occipital protuberance (IPEOP): Contour length of the distance between the intercornual protuberance and the external occipital protuberance.
14. Neurocranial volume (NCV): The volume of the neurocranium in millilitres. To be measured by using fresh plasticine to block all the foramina leading to the neurocranium except the foramen magnum. The neurocranium was filled with fine-quality millet grains, which were then emptied into a measuring cylinder to determine the volume.
15. Interpalatine suture length 1 (IPSL1): Maximum length of the horizontal parts of the palatine at the suture.
16. Interpalatine suture length 2 (IPSL2): Maximum length of the horizontal parts of the palatine process of the maxilla at the suture.
17. Interpalatine suture length (IPSLM): Maximum length of the horizontal parts of the palatine and palatine process of the maxilla at the suture. (i.e., 42 + 43).
18. Interincisive suture length (IISL): Maximum distance from mid-rostral tip of the incisive bone to the incisive-maxillary junction at the palatal surface.
19. Left incisive fissure length (LIFL): Maximum rostro-caudal distance of the incisive fissure.
20. Right incisive fissure length (RIFL): Maximum rostro-caudal distance of the incisive fissure.
21. Left incisive fissure width (LIFW): Maximum width of the incisive fissure.
22. Right incisive fissure width (RIFW): Maximum width of the incisive fissure.
23. Hard palate length (HPL): Maximum distance at the midline of the caudal end of the hard palate to the most rostral margin of the incisive bone. (i.e., 44 + 45).
24. Palatine width at premolar 1 (PWP1): width between the median aspects of alveoli at premolar one.
25. Palatine width at molar 1 (PWM1): width between the

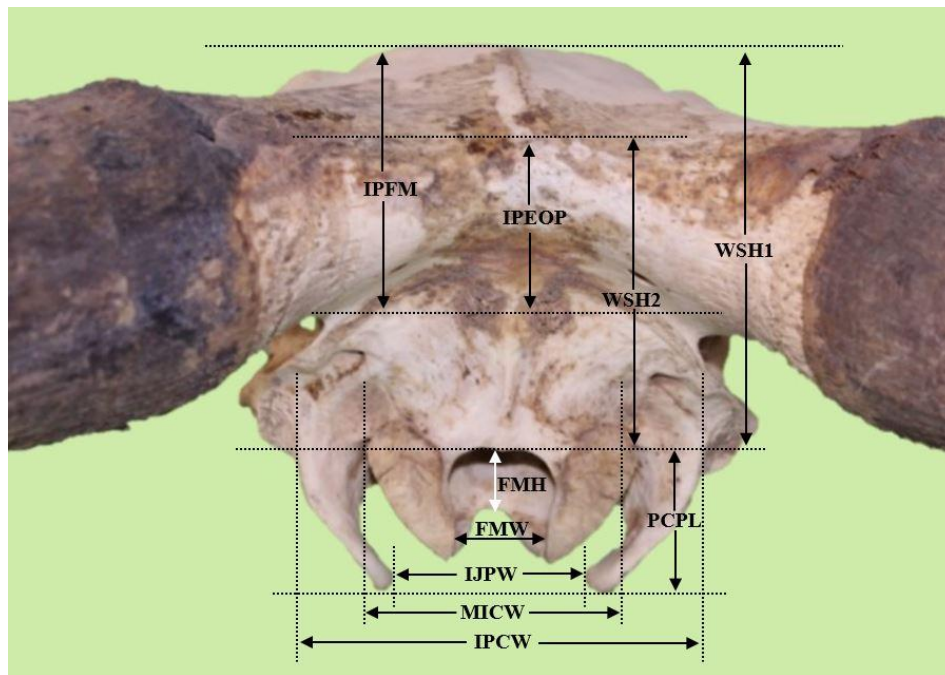


Figure 1. Measurements of the Kuri cattle skull without mandible (Caudal or occipital view) showing Intercornual protuberance to external occipital protuberance (IPEOP), Intercornual Protuberance to Foramen magnum (IPFM), Foramen magnum height (FMH), Foramen magnum width (FMW), Maximum intercondylar width (MICW), Interjugular process width (IJPW), Paracondylar process length (PCPL), Interparacondylar width (IPCW), Whole skull height 1 (WSH1), and Whole skull height 2 (WSH2).

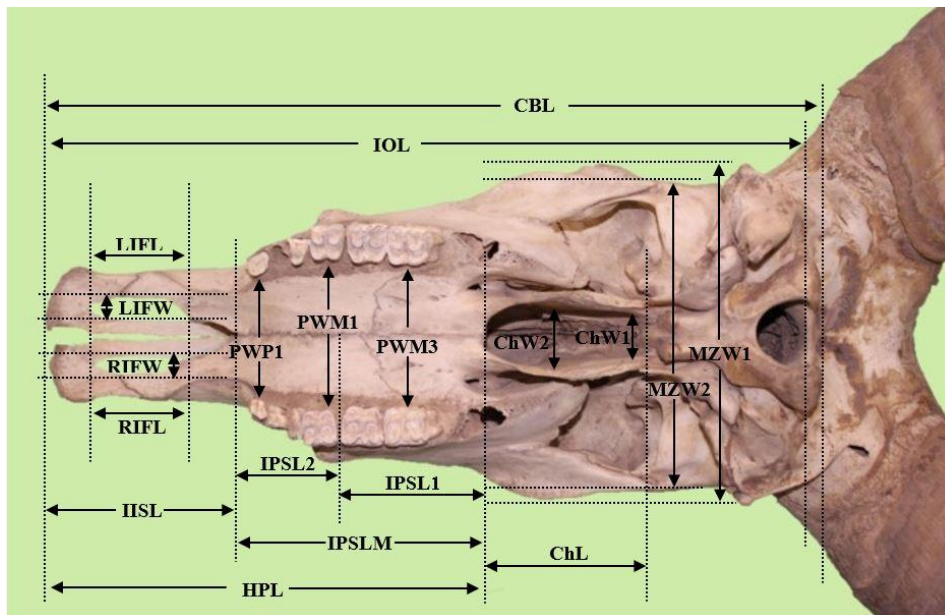


Figure 2. Measurements of the Kuri cattle skull without mandible (ventral view) showing Left Incisive fissure length (LIFL), Right Incisive fissure length (RIFL), Left Incisive fissure width (LIFW), Right Incisive fissure width (RIFW), Palatine width at premolar 1 (PWP1), Palatine width at molar 1 (PWM1), Palatine width at molar 3 (PWM3), Choana width 1 (ChW1), Choana width 2 (ChW2), Hard palate length (HPL), Choana length (ChL), Maximum zygomatic width 1 (MZW1), Maximum zygomatic width 2 (MZW2), Interincisive suture length (IISL), Interpalatine suture length 1 (IPSL1), Interpalatine suture length 2 (IPSL2), Interpalatine suture length (IPSLM), Incisivo-occipital length (IOL), and Condylolbasal length (CBL).

- median aspects of alveoli at molar one.
26. Palatine width at molar 3 (PWM3): width between the median aspects of alveoli at molar three.
 27. Choana length (ChL): Distance between the basisphenoid and the most caudal margin of the hard palate.
 28. Choana width 1 (ChW1): Distance between the medial margins of the two pterygoid crests.
 29. Choana width 2 (ChW2): Distance between the medial margins of the pterygoid hamulus.
 30. Maximum zygomatic width 1 (MZW1): Maximum distance between the zygomatic arches at the level of the orbit.
 31. Maximum zygomatic width 2 (MZW2): Maximum distance between the zygomatic arches at the junction of the zygomatic process of the temporal bone and the temporal process of the zygomatic bone.
 32. Incisivo-occipital length (IOL): Maximum distance between the most rostral end of the incisive and the caudal limits of the external occipital protuberance.
 33. Condylbasal length (CBL): Length of the skull measured from the caudal surface of the occipital condyles to the rostral tip of the incisive bones.

Statistical analysis

Data were analyzed using IBM SPSS Statistics version 31.0. Descriptive statistics were expressed as mean $\pm$ standard deviation. Normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. Age-related differences were evaluated using one-way ANOVA, followed by Tukey's HSD post hoc test. Pearson's correlation and linear regression analyses were used to assess relationships among morphometric variables. Principal Component Analysis (PCA), boxplots, and correlation heatmaps were used to visualise patterns of variation and associations. To minimize the risk of Type I error associated with multiple comparisons, Tukey's HSD adjustment was applied to post hoc analyses, while results from exploratory correlation analyses were interpreted with caution. Statistical significance was accepted at $p < 0.05$, and exact p -values were reported where appropriate.

RESULTS

Caudal (occipital) skull morphometry of young, middle-aged, and aged Kuri cattle

A total of fourteen (14) morphometric parameters were measured on the caudal aspect of the skull in young, middle-aged, and aged Kuri cattle (Table 1). The mean intercornual protuberance-to-foramen magnum distance (IPFM) increased slightly with age, ranging from $9.98 \pm$

0.68 cm in young animals to 10.71 ± 1.16 cm in aged animals; however, no significant age-related differences were observed. The foramen magnum measurements, including foramen magnum height (FMH), width (FMW), circumference (FMC), and index (FMI), showed no significant differences among the three age groups. Mean FMH ranged from 3.84 ± 0.33 cm to 4.05 ± 0.35 cm, whereas FMW varied between 3.69 ± 0.44 cm and 3.78 ± 0.32 cm. Significant age-related increases were observed in several occipital dimensions. Maximum intercondylar width (MICW) increased from 9.70 ± 0.89 cm in young cattle to 10.73 ± 0.44 cm in middle-aged and 10.86 ± 0.99 cm in aged cattle, with middle-aged and aged animals differing significantly from young animals. The interparacondylar width (IPCW) exhibited a significant age-related increase ($p < 0.05$), with mean values rising from 13.57 ± 0.89 cm in young cattle to 15.13 ± 0.39 cm in middle-aged animals and 16.65 ± 1.26 cm in aged cattle. Paracondylar process length (PCPL) showed significant elongation from 5.46 ± 0.44 cm in young animals to 6.48 ± 0.37 cm and 6.33 ± 0.53 cm in middle-aged and aged cattle, respectively. Whole skull height measured from the occipital region (WSH1) increased significantly with age, measuring 16.30 ± 1.18 cm in young cattle, 18.20 ± 1.00 cm in middle-aged cattle, and 19.34 ± 1.97 cm in aged cattle. In contrast, WSH2 did not differ significantly among age categories. Skull height (SH) exhibited a consistent and significant increase across all age groups, with mean values ranging from 24.50 ± 1.62 cm in young cattle to 29.40 ± 2.02 cm in aged cattle. The intercornual protuberance to external occipital protuberance distance (IPEOP) and neurocranial volume (NCV) showed no significant age-related differences. Neurocranial volume varied from 463.00 ± 35.49 ml in young animals to 502.20 ± 77.64 ml in aged cattle.

Ventral skull morphometry of young, middle-aged, and aged Kuri cattle

A total of nineteen (19) morphometric parameters were recorded from the ventral aspect of the skull (Table 2). Significant age-related increases were observed in the lengths of the interpalatine suture. The interpalatine suture length measured at different levels (IPSL1, IPSL2, and IPSLM) increased significantly with advancing age ($p < 0.05$). IPSL1 increased progressively from 5.92 ± 0.72 cm in young cattle to 6.79 ± 0.54 cm in middle-aged animals and 7.68 ± 0.93 cm in aged cattle. Similarly, IPSL2 and IPSLM showed marked increases, indicating elongation of the palatine region during maturation. The incisive suture length (IISL) also increased significantly, with aged cattle exhibiting significantly greater values (11.45 ± 1.15 cm) than young cattle (9.80 ± 0.75 cm), while middle-aged animals showed intermediate measurements. Conversely, the left incisive foramen length (LIFL) did not differ

Table 1. Age-related comparison of caudal (occipital) skull morphometric parameters in Kuri cattle (mean $\pm$ SD).

Parameter	Young(n=10)	Middle-age(n=10)	Aged(n=10)	Total
IPFM (cm)	9.98 $\pm$ 0.68 ^a	10.15 $\pm$ 0.98 ^a	10.71 $\pm$ 1.16 ^a	10.28 $\pm$ 0.98
FMH (cm)	3.98 $\pm$ 0.24 ^a	3.84 $\pm$ 0.33 ^a	4.05 $\pm$ 0.35 ^a	3.96 $\pm$ 0.31
FMW (cm)	3.78 $\pm$ 0.32 ^a	3.76 $\pm$ 0.37 ^a	3.69 $\pm$ 0.44 ^a	3.74 $\pm$ 0.37
FMC (cm)	13.55 $\pm$ 0.78 ^a	13.31 $\pm$ 0.58 ^a	14.08 $\pm$ 1.30 ^a	13.65 $\pm$ 0.96
FMI	105.72 $\pm$ 8.49 ^a	102.74 $\pm$ 10.32 ^a	110.94 $\pm$ 13.85 ^a	106.47 $\pm$ 11.26
MICW (cm)	9.70 $\pm$ 0.89 ^a	10.73 $\pm$ 0.44 ^b	10.86 $\pm$ 0.99 ^b	10.43 $\pm$ 0.94
IJPW (cm)	7.95 $\pm$ 1.48 ^a	7.83 $\pm$ 0.68 ^a	8.87 $\pm$ 1.09 ^a	8.22 $\pm$ 1.19
PCPL (cm)	5.46 $\pm$ 0.44 ^a	6.48 $\pm$ 0.37 ^b	6.33 $\pm$ 0.53 ^b	6.09 $\pm$ 0.63
IPCW (cm)	13.57 $\pm$ 0.89 ^a	15.13 $\pm$ 0.39 ^b	16.65 $\pm$ 1.26 ^c	15.12 $\pm$ 1.56
WSH1 (cm)	16.30 $\pm$ 1.18 ^a	18.20 $\pm$ 1.00 ^b	19.34 $\pm$ 1.97 ^b	17.95 $\pm$ 1.89
WSH2 (cm)	14.91 $\pm$ 1.36 ^a	15.91 $\pm$ 1.30 ^a	16.44 $\pm$ 1.39 ^a	15.75 $\pm$ 1.45
SH (cm)	24.50 $\pm$ 1.62 ^a	26.71 $\pm$ 1.52 ^b	29.40 $\pm$ 2.02 ^c	26.87 $\pm$ 2.64
IPEOP (cm)	8.46 $\pm$ 1.10 ^a	8.84 $\pm$ 0.92 ^a	9.15 $\pm$ 1.32 ^a	8.82 $\pm$ 1.12
NCV (mL)	463.00 $\pm$ 35.49 ^a	468.90 $\pm$ 39.27 ^a	502.20 $\pm$ 77.64 ^a	478.03 $\pm$ 55.21

^{a,b,c} Mean $\pm$ SD with same superscripts are not significantly different along the rows. Mean difference is significant at $p < 0.05$. ^{oo} Parameter without unit. ^{ml} Unit in milliliter.

Table 2. Age-related comparison of ventral skull morphometric parameters in Kuri cattle (mean $\pm$ SD).

Parameter	Young (n=10)	Middle-age (n=10)	Aged (n=10)	Total
IPSL1 (cm)	5.92 $\pm$ 0.72 ^a	6.79 $\pm$ 0.54 ^b	7.68 $\pm$ 0.93 ^c	6.80 $\pm$ 1.03
IPSL2 (cm)	8.87 $\pm$ 1.06 ^a	10.15 $\pm$ 0.93 ^b	10.59 $\pm$ 1.09 ^b	9.87 $\pm$ 1.24
IPSLM (cm)	14.79 $\pm$ 1.46 ^a	16.94 $\pm$ 1.09 ^b	18.27 $\pm$ 1.23 ^b	16.67 $\pm$ 1.90
IISL (cm)	9.80 $\pm$ 0.75 ^a	10.86 $\pm$ 0.99 ^{a,b}	11.45 $\pm$ 1.15 ^b	10.70 $\pm$ 1.17
LIFL (cm)	6.14 $\pm$ 0.42 ^a	6.74 $\pm$ 0.78 ^a	6.72 $\pm$ 0.57 ^a	6.53 $\pm$ 0.65
RIFL (cm)	6.09 $\pm$ 0.35 ^a	6.77 $\pm$ 0.75 ^b	6.75 $\pm$ 0.60 ^b	6.54 $\pm$ 0.65
LIFW (cm)	1.50 $\pm$ 0.13 ^a	1.62 $\pm$ 0.20 ^a	1.67 $\pm$ 0.15 ^a	1.60 $\pm$ 0.18
RIFW (cm)	1.51 $\pm$ 0.13 ^a	1.61 $\pm$ 0.26 ^a	1.66 $\pm$ 0.18 ^a	1.59 $\pm$ 0.20
HPL (cm)	24.59 $\pm$ 1.59 ^a	27.80 $\pm$ 1.25 ^b	29.72 $\pm$ 1.66 ^c	27.37 $\pm$ 2.60
PWP1 (cm)	5.92 $\pm$ 0.29 ^a	6.88 $\pm$ 0.57 ^b	7.78 $\pm$ 0.56 ^c	6.86 $\pm$ 0.91
PWM1 (cm)	6.94 $\pm$ 0.27 ^a	7.91 $\pm$ 0.27 ^b	8.89 $\pm$ 0.57 ^c	7.91 $\pm$ 0.91
PWM3 (cm)	6.96 $\pm$ 0.34 ^a	7.49 $\pm$ 0.38 ^a	8.43 $\pm$ 0.65 ^b	7.63 $\pm$ 0.77
ChL (cm)	9.54 $\pm$ 0.95 ^a	10.09 $\pm$ 0.83 ^a	11.30 $\pm$ 1.12 ^b	10.31 $\pm$ 1.20
ChW1 (cm)	3.03 $\pm$ 0.27 ^a	3.44 $\pm$ 0.44 ^b	3.75 $\pm$ 0.27 ^b	3.41 $\pm$ 0.44
ChW2 (cm)	2.75 $\pm$ 0.24 ^a	3.04 $\pm$ 0.50 ^{a,b}	3.33 $\pm$ 0.52 ^b	3.04 $\pm$ 0.49
MZW1 (cm)	17.75 $\pm$ 0.84 ^a	19.11 $\pm$ 0.74 ^a	21.24 $\pm$ 1.94 ^b	19.37 $\pm$ 1.92
MZW2 (cm)	17.40 $\pm$ 0.85 ^a	18.80 $\pm$ 0.68 ^b	20.04 $\pm$ 1.49 ^c	18.75 $\pm$ 1.50
IOL (cm)	43.55 $\pm$ 2.58 ^a	47.34 $\pm$ 1.98 ^b	51.15 $\pm$ 2.74 ^c	47.35 $\pm$ 3.94
CBL (cm)	43.31 $\pm$ 2.38 ^a	46.91 $\pm$ 1.85 ^b	50.32 $\pm$ 2.68 ^c	46.85 $\pm$ 3.68

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

significantly among age groups, whereas the right incisive foramen length (RIFL) increased significantly from young to middle-aged and aged animals. Both the left and right incisive foramen widths (LIFW and RIFW) remained statistically unchanged across age groups. The hard palate length (HPL) increased progressively from 24.59 $\pm$ 1.59 cm in young cattle to 27.80 $\pm$ 1.25 cm in middle-aged

cattle and 29.72 $\pm$ 1.66 cm in aged cattle. Likewise, the palatine width measurements (PWP1, PWM1, and PWM3) all showed significant increases with age. Measurements associated with the choanae also increased during growth. The choanal length (ChL) was significantly greater in aged cattle than in young and middle-aged animals, while both choanal widths (ChW1 and ChW2) exhibited significant

Table 3. One-way ANOVA summary of age-related effects on skull morphometric parameters in Kuri cattle.

Parameter	F-value	p-value	Significance
IPFM (cm)	1.82	0.181	NS
FMH (cm)	1.74	0.195	NS
FMW (cm)	0.28	0.756	NS
FMC (cm)	2.56	0.095	NS
FMI	1.67	0.207	NS
MICW (cm)	8.43	0.001	**
IJPW (cm)	4.95	0.015	*
PCPL (cm)	22.31	<0.001	***
IPCW (cm)	36.84	<0.001	***
WSH1 (cm)	12.73	<0.001	***
WSH2 (cm)	3.41	0.048	*
SH (cm)	28.92	<0.001	***
IPEOP (cm)	1.14	0.335	NS
NCV (mL)	2.27	0.123	NS
IPSL1 (cm)	31.45	<0.001	***
IPSL2 (cm)	14.26	<0.001	***
IPSLM (cm)	25.67	<0.001	***
IISL (cm)	7.91	0.002	**
LIFL (cm)	2.74	0.083	NS
RIFL (cm)	5.12	0.013	*
LIFW (cm)	1.96	0.16	NS
RIFW (cm)	1.87	0.173	NS
HPL (cm)	42.11	<0.001	***
PWP1 (cm)	56.82	<0.001	***
PWM1 (cm)	71.34	<0.001	***
PWM3 (cm)	18.25	<0.001	***
ChL (cm)	9.77	<0.001	***
ChW1 (cm)	11.84	<0.001	***
ChW2 (cm)	6.62	0.004	**
MZW1 (cm)	17.53	<0.001	***
MZW2 (cm)	31.47	<0.001	***
IOL (cm)	58.61	<0.001	***
CBL (cm)	73.88	<0.001	***

NS: not significant ($p > 0.05$); * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

age-related enlargement, although ChW2 showed an intermediate value in middle-aged cattle. The maxillary zygomatic widths (MZW1 and MZW2) increased significantly with age. MZW1 was significantly greater in aged cattle than in young and middle-aged animals, whereas MZW2 demonstrated a progressive increase across all three age groups. Similarly, both the overall skull length (IOL) and the condylobasal length (CBL) exhibited highly significant age-related increases, rising from 43.55 ± 2.58 cm and 43.31 ± 2.38 cm, respectively, in young cattle to 51.15 ± 2.74 cm and 50.32 ± 2.68 cm in aged cattle.

ANOVA Analysis of age-related effects on skull morphometric parameters in Kuri cattle

One-way ANOVA revealed significant age-related variation

in numerous skull morphometric parameters of Kuri cattle (Table 3). Among the caudal skull measurements, MICW, IJPW, PCPL, IPCW, WSH1, WSH2, and SH differed significantly among age groups ($p < 0.05$). In contrast, IPFM, FMH, FMW, FMC, FMI, IPEOP, and NCV showed no significant differences ($p > 0.05$). The most significant caudal parameters were IPCW ($F = 36.84$, $p < 0.001$), SH ($F = 28.92$, $p < 0.001$), and PCPL ($F = 22.31$, $p < 0.001$).

Among the ventral skull measurements, IPSL1, IPSL2, IPSLM, HPL, PWP1, PWM1, PWM3, ChL, ChW1, MZW1, MZW2, IOL, and CBL exhibited highly significant age-related differences ($p < 0.001$). Significant differences were also detected for IISL, RIFL, and ChW2 ($p < 0.05$). In contrast, LIFL, LIFW, and RIFW did not differ significantly among age groups. Condylobasal length (CBL) recorded the highest F-value ($F = 73.88$, $p < 0.001$), followed by PWM1 ($F = 71.34$, $p < 0.001$), IOL ($F = 58.61$, $p < 0.001$), and PWP1 ($F = 56.82$, $p < 0.001$), respectively.

Table 4. Allometric coefficients and scaling relationships of skull morphometric parameters relative to condylobasal length (CBL) in Kuri cattle.

Parameter	a	b	95% CI of b	R ²	Classification
IPFM (cm)	0.286	0.949	0.73–1.17	0.625	Isometry
FMH (cm)	0.389	0.625	0.41–0.84	0.386	Negative allometry
FMW (cm)	0.433	0.639	0.36–0.92	0.255	Isometry
FMC (cm)	1.318	0.636	0.49–0.78	0.523	Negative allometry
FMI	4.812	0.932	0.71–1.15	0.486	Isometry
MICW (cm)	0.807	1.061	0.93–1.19	0.823	Isometry
IJPW (cm)	0.293	1.510	1.25–1.77	0.652	Positive allometry
PCPL (cm)	0.321	1.196	0.98–1.41	0.789	Isometry
IPCW (cm)	0.236	1.288	1.18–1.39	0.977	Positive allometry
WSH1 (cm)	0.286	1.292	1.17–1.41	0.949	Positive allometry
WSH2 (cm)	0.415	1.055	0.91–1.20	0.797	Isometry
SH (cm)	0.653	1.239	1.15–1.33	0.994	Positive allometry
IPEOP (cm)	0.271	1.280	0.97–1.59	0.619	Isometry
NCV (mL)	7.184	1.097	0.83–1.36	0.586	Isometry
IPSL1 (cm)	0.005	1.910	1.80–2.02	0.985	Positive allometry
IPSL2 (cm)	0.030	1.549	1.39–1.71	0.898	Positive allometry
IPSLM (cm)	0.038	1.48	1.36–1.60	0.979	Positive allometry
IISL (cm)	0.182	1.309	1.15–1.47	0.899	Positive allometry
LIFL (cm)	0.419	1.029	0.84–1.22	0.671	Isometry
RIFL (cm)	0.396	1.048	0.85–1.25	0.701	Isometry
HPL (cm)	0.290	1.216	1.12–1.31	0.984	Positive allometry
PWP1 (cm)	0.010	1.631	1.49–1.77	0.952	Positive allometry
PWM1 (cm)	0.021	1.376	1.24–1.51	0.932	Positive allometry
PWM3 (cm)	0.054	1.231	1.12–1.34	0.965	Positive allometry
ChL (cm)	0.042	1.406	1.25–1.56	0.914	Positive allometry
ChW1 (cm)	0.006	1.589	1.39–1.79	0.911	Positive allometry
ChW2 (cm)	0.004	1.763	1.47–2.05	0.780	Positive allometry
MZW1 (cm)	0.319	1.187	1.08–1.29	0.949	Positive allometry
MZW2 (cm)	0.507	0.990	0.90–1.08	0.972	Isometry
IOL (cm)	0.872	1.063	1.01–1.12	0.999	Positive allometry

NS: not significant ($p > 0.05$); * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Allometric analysis

Allometric analysis revealed marked variation in the scaling patterns of skull morphometric parameters relative to condylobasal length (CBL) (Table 4). Among the caudal skull measurements, FMH ($b = 0.625$) and FMC ($b = 0.636$) exhibited significant negative allometry. Conversely, IJPW ($b = 1.510$), IPCW ($b = 1.288$), WSH1 ($b = 1.292$), and SH ($b = 1.239$) showed positive allometry. Several caudal measurements, including IPFM, FMI, MICW, PCPL, WSH2, IPEOP, and NCV, exhibited isometric scaling.

Most ventral skull parameters displayed positive allometry. The strongest positive allometric relationships were observed for IPSL1 ($b = 1.910$), ChL ($b = 1.763$), RIFW ($b = 1.631$), PWM3 ($b = 1.589$), IPSL2 ($b = 1.549$), and IPSLM ($b = 1.480$). Additional positive allometric

growth was recorded for IISL, LIFW, HPL, PWP1, PWM1, ChW1, and MZW1. In contrast, LIFL, RIFL, and ChW2 exhibited isometric growth, maintaining proportional relationships with overall skull length.

The coefficients of determination (R^2) ranged from 0.255 to 0.999, indicating variable but generally strong associations between skull measurements and CBL. The highest R^2 values were observed for MZW1 (0.999), SH (0.994), IPSL1 (0.985), LIFW (0.984), IPCW (0.977), and IPSLM (0.979), respectively.

DISCUSSION

Morphometric evaluation of the skull provides valuable insight into craniofacial growth, functional adaptation, phylogenetic relationships, and breed differentiation in

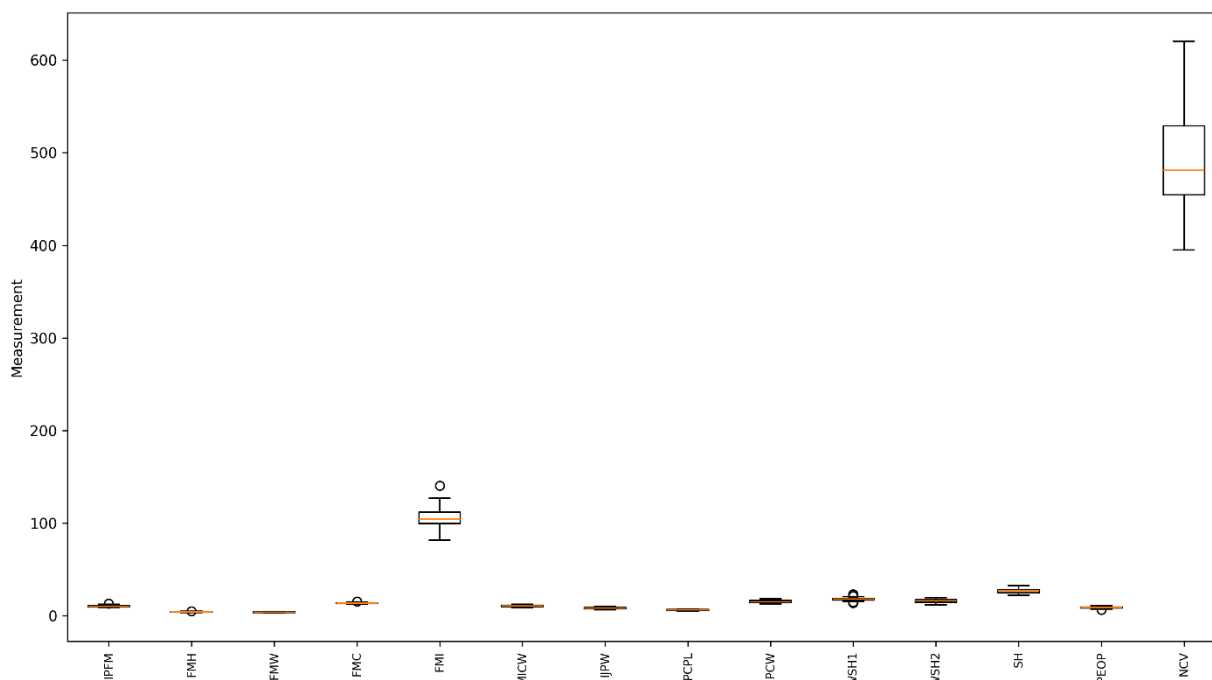


Figure 3. Boxplot showing age-related variations in caudal (occipital) skull morphometric parameters of Kuri cattle.

domestic and wild ruminants (Çakar *et al.*, 2024; Gündemir *et al.*, 2025). Unlike previous investigations that primarily described the overall skull morphology of cattle and buffaloes (Özkan *et al.*, 2019; Turgut, 2025), the present study specifically examined age-related morphological changes in the caudal (occipital) and ventral aspects of the skull of Kuri cattle. To the best of our knowledge, this represents the first comprehensive morphometric investigation of these anatomical regions in this unique indigenous African taurine breed.

The present study demonstrated that several occipital measurements increased significantly with advancing age, particularly maximum intercondylar width, paracondylar process length, interparacondylar width, and skull height, indicating continuous postnatal expansion of the caudal skull, as illustrated by the progressive upward trend in the boxplots (Figure 3). These findings support the concept that the occipital region continues to remodel after birth to accommodate increasing muscular attachment and mechanical loading associated with progressive body growth. Similar age-dependent enlargement of cranial dimensions has been reported in Holstein cattle using computed tomography (Turgut, 2025), Turkish indigenous cattle breeds (Gündemir *et al.*, 2025), domestic buffalo (Monfared, 2013a; Dalga and Aslan, 2025), Mehraban sheep (Karimi *et al.*, 2011), and mithun (*Bos frontalis*) (Choudhary *et al.*, 2022). Likewise, Güzel *et al.* (2025) reported that East and South Anatolian Red cattle possessed mean greatest breadths of the occipital condyles of 10.72 ± 1.04 cm and 10.55 ± 0.83 cm,

respectively, greatest breadths between the paracondylar process bases of 14.92 ± 1.45 cm and 14.61 ± 1.36 cm, and foramen magnum dimensions of 3.88 ± 0.41 cm in width and 3.79 ± 0.38 cm in height in East Anatolian Red cattle, with no significant breed differences ($p > 0.05$). These findings indicate that although absolute occipital dimensions differ among indigenous cattle breeds, the proportional organisation of the caudal skull remains highly conserved. Similarly, Çakar *et al.* (2024) demonstrated that although the overall skull index did not differ significantly between Holstein (43.64 ± 2.45) and Simmental (44.87 ± 2.43) cattle ($p = 0.071$), significant breed differences existed in the basal index (48.09 ± 2.78 vs. 50.13 ± 3.01 ; $P = 0.013$) and orbital index (98.27 ± 6.80 vs. 92.86 ± 5.46 ; $p = 0.002$). These findings indicate that proportional differences in the cranial base and orbital region may occur even among closely related cattle breeds, reflecting breed-specific cranial adaptation while maintaining relatively conserved overall skull proportions.

The extensive development of the occipital region observed in the present study agrees with comparative morphometric data reported for domestic cattle by Özkan *et al.* (2019), who recorded a greatest occipital breadth (GBOC) of 11.33 ± 0.57 cm and a greatest breadth between the jugular processes (GBPP) of 17.26 ± 0.81 cm. These measurements were considerably greater than those of water buffaloes (9.84 ± 0.57 cm and 15.13 ± 1.46 cm, respectively), demonstrating species-specific differences in occipital morphology. Such differences probably reflect variation in craniovertebral biomechanics,

muscular development, and breed-specific adaptation to different production environments. Although the present study measured different occipital variables, the observed age-related enlargement follows the same developmental trend described in domestic cattle and supports the progressive reinforcement of the caudal skull during skeletal maturation.

Interestingly, IPFM and IPEOP did not differ significantly among age groups, indicating that the relative positions of major occipital landmarks remain remarkably conserved throughout postnatal development. This anatomical stability is advantageous because these landmarks serve as reliable reference points for morphometric investigations, radiographic interpretation, and surgical orientation. Similar preservation of cranial landmarks has been reported in domestic cattle (Çakar *et al.*, 2024), buffaloes (Monfared, 2013a), and European bison (Gündemir and Szara, 2025), suggesting that positional relationships within the occipital complex are established early during skeletal development as shown in the boxplots (Figure 3).

Measurements of the foramen magnum (FMH, FMW, FMC, and FMI) likewise showed no significant age-related differences, indicating that the dimensions of this structure approach adult size relatively early in life. The boxplots in Figure 3 similarly demonstrate minimal variation in these measurements across the different age groups. Comparable findings have been reported in the river buffalo, where the occipital region continued to enlarge while the dimensions of the foramen magnum remained relatively constant (Nourinezhad *et al.*, 2016). Özkan *et al.* (2019) similarly reported that adult domestic cattle possess a mean foramen magnum height of 3.89 ± 0.22 cm, only moderately greater than the 3.45 ± 0.37 cm observed in water buffaloes despite much larger differences in surrounding occipital dimensions. Likewise, Güzel *et al.* (2025) reported foramen magnum widths of 3.88 ± 0.41 cm and 3.77 ± 0.44 cm and heights of 3.79 ± 0.38 cm and 3.87 ± 0.23 cm in East and South Anatolian Red cattle, respectively, with corresponding foramen magnum indices of 98.33 ± 11.78 and 104.00 ± 14.24 , none of which differed significantly between the two breeds ($p > 0.05$). Furthermore, Çakar *et al.* (2024) found that the foramen magnum index did not differ significantly between Holstein (99.32 ± 13.58) and Simmental (98.21 ± 16.83) cattle ($P = 0.794$), indicating that the proportional dimensions of the foramen magnum remain highly conserved among cattle breeds. Together, these observations support the concept that structures protecting the caudal brainstem and spinal cord mature earlier than the surrounding skeletal framework, thereby maintaining neurological integrity while permitting continued postnatal expansion of adjacent bones.

The absence of significant differences in neurocranial volume among age groups further supports this interpretation. Developmental studies have consistently

demonstrated that the neurocranium exhibits negative allometric growth relative to the viscerocranium because brain growth is largely completed before full somatic maturation (Fostowicz-Frelik and Tseng, 2023). Consequently, postnatal cranial enlargement occurs predominantly through remodelling of the facial skeleton and supporting structures rather than expansion of the cranial cavity. Similar developmental patterns have been described in cattle (Turgut, 2025), buffaloes (Dalga and Aslan, 2025), and other mammals (Chipping, 2024). However, the present findings differ from those reported in one-humped camels, where neurocranial dimensions continued to increase significantly with age (Yahaya *et al.*, 2012a), suggesting that species-specific developmental trajectories exist among large herbivores. The graphical presentation in Figure 3 similarly demonstrates substantial overlap among age groups, corroborating the statistical finding of non-significant differences in neurocranial volume.

The ventral aspect of the skull exhibited the most pronounced age-related changes. Significant increases in IPSL1, IPSL2, IPSLM, IISL, IOL, and CBL indicate progressive elongation of the basicranium and facial skeleton during postnatal development, a pattern clearly demonstrated by the age-related shifts in the ventral skull boxplots (Figure 4). Similar elongation of the cranial base has been documented in domestic cattle (Turgut, 2025), Turkish cattle breeds (Gündemir *et al.*, 2025), buffaloes (Özkan *et al.*, 2019), and mithun (Choudhary *et al.*, 2022). Özkan *et al.* (2019) reported a condylobasal length of 519.56 ± 15.85 mm in cattle compared with 48.23 ± 4.59 cm in water buffaloes, while basal length averaged 48.62 ± 1.58 cm and 45.01 ± 4.49 cm, respectively. Likewise, Güzel *et al.* (2025) recorded condylobasal lengths of 44.72 ± 2.79 cm and 44.69 ± 4.28 cm, basal lengths of 42.10 ± 3.32 cm and 42.04 ± 4.97 cm, viscerocranial lengths of 24.34 ± 2.32 cm and 24.64 ± 2.75 cm, and lateral facial lengths of 32.15 ± 2.12 cm and 32.00 ± 3.15 cm in East and South Anatolian Red cattle, respectively, with no statistically significant breed differences. Similarly, Çakar *et al.* (2024) observed no significant differences between Holstein and Simmental cattle in the facial index (60.09 ± 3.67 vs. 58.62 ± 4.85), frontal index (96.03 ± 5.93 vs. 96.40 ± 6.43), length-length index (83.56 ± 6.06 vs. 86.38 ± 7.69), and palatal index (52.37 ± 2.07 vs. 52.06 ± 2.74), indicating that proportional relationships among the facial and palatal components remain relatively conserved despite breed differences in absolute skull dimensions. These observations collectively indicate that elongation of the ventral skull is a characteristic feature of postnatal growth in bovids and contributes substantially to overall cranial development.

The progressive increase in hard palate length (HPL) across respective ages demonstrates continuous elongation of the palate. Likewise, the palatine width (PWP1, PWM1, and PWM3) shows significant increases

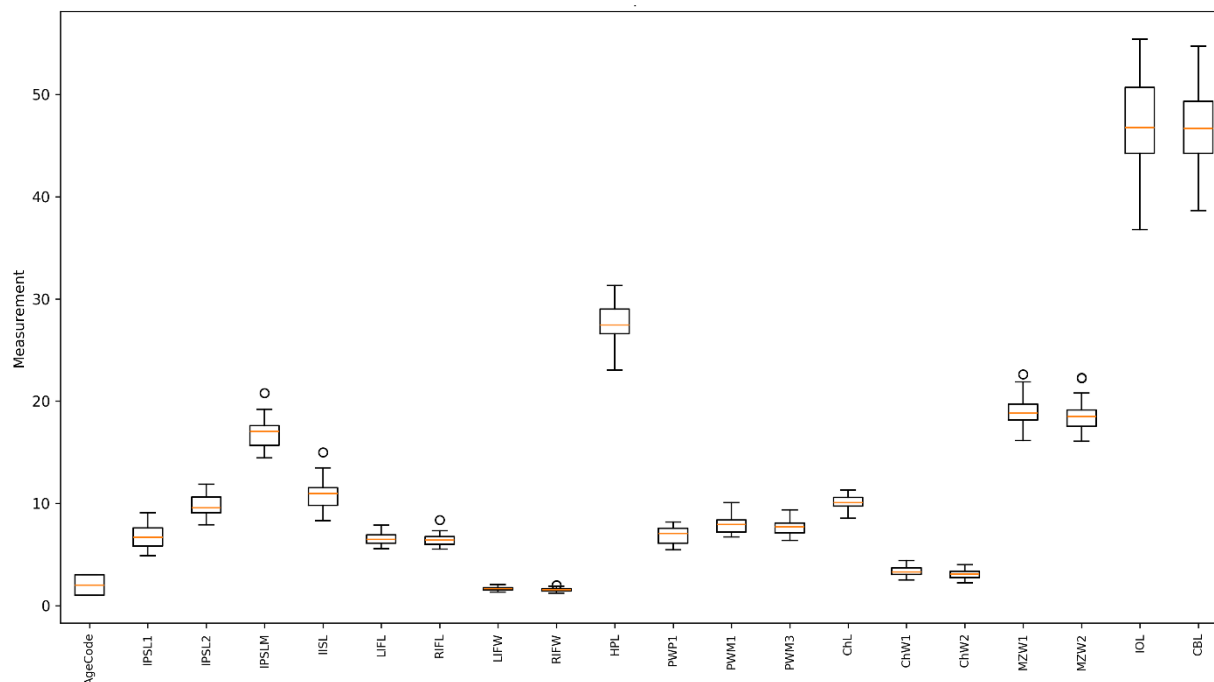


Figure 4. Boxplot showing age-related variations in ventral skull morphometric parameters of Kuri cattle.

with age, indicating progressive widening of the palatal region, respectively. Whereas, the progressive increase of MZW2 across all three age groups indicates continued lateral expansion of the facial skeleton. This enlargement of the palatine and zygomatic regions probably reflects increasing functional demands associated with mastication. Expansion of these structures provides a larger surface area for attachment of the masseter, pterygoid, and temporalis muscles, thereby enhancing bite force and feeding efficiency in mature animals. Comparable functional relationships between facial elongation, skull width, and masticatory performance have been described in British cattle (Chipping, 2024), Simmental and Holstein cattle (Çakar *et al.*, 2024), East and South Anatolian Red cattle (Güzel *et al.*, 2025), and European bison (Gündemir and Szara, 2025).

The pronounced age-related increases observed in condylobasal length (CBL), PWM1, and PWP1 suggest that cranial growth in Kuri cattle is not uniform across the different regions of the skull. The relatively limited changes observed in structures surrounding the foramen magnum and neurocranial region may indicate that these components attain their mature dimensions earlier than other cranial regions. This pattern suggests a differential timing of growth and developmental stabilisation across the Kuri cattle skull. Likewise, enlargement of the choanal region observed in the present study may represent an adaptive response to increasing respiratory demands accompanying greater body size and metabolic activity. The consistent increase in these measurements across

age groups is also evident, where older animals generally exhibited higher median values and broader morphometric dimensions than young cattle (Figure 4).

An important finding of the present investigation is that age-related changes were predominantly observed in structures associated with the viscerocranium and occipital musculature, whereas dimensions directly related to the neurocranium remained relatively constant. This developmental pattern agrees with the principles of cranial allometry described for mammals, whereby facial structures continue growing for a longer period than neurocranial structures (Fostowicz-Frelik and Tseng, 2023). Such differential growth enables enlargement of the feeding apparatus and cervical musculature without compromising protection of the central nervous system. Collectively, the age-dependent distribution patterns visually reinforce this differential growth between the viscerocranium and neurocranium as indicated in Figures 3 and 4, respectively.

The regression scatter plots in Figure 5 further demonstrate positive age-associated relationships among the principal occipital morphometric variables, indicating coordinated enlargement of the caudal skull during maturation. Likewise, the ventral skull regression plots in Figure 6 reveal similar positive trends among the palatine, zygomatic, and longitudinal skull measurements, supporting the continuous growth of the facial skeleton with advancing age. Multivariate analysis further supported these observations. The PCA biplots in Figures 7 and 8 demonstrated that the morphometric variables clustered

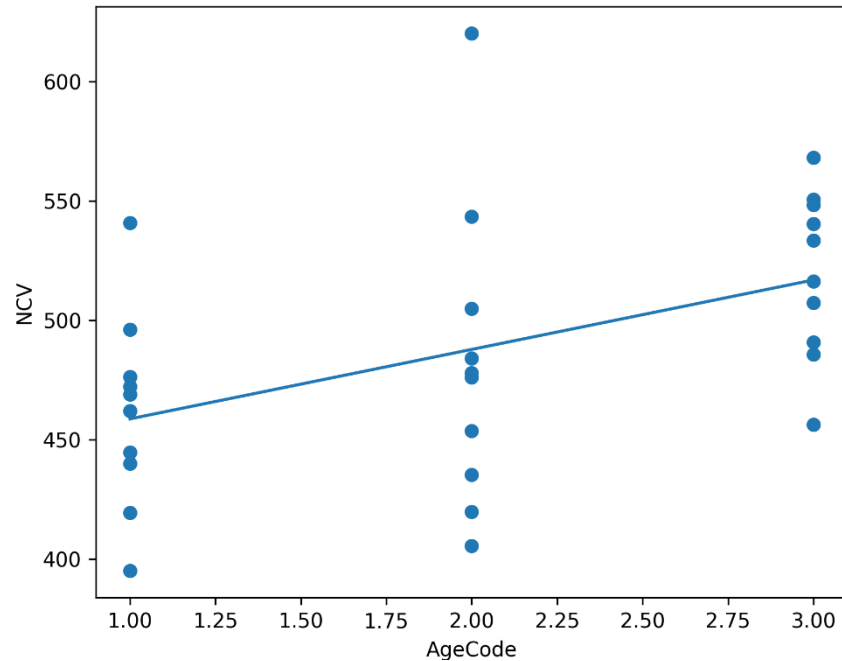


Figure 5. Regression scatter plot illustrating relationships among caudal skull morphometric parameters in Kuri cattle across age groups.

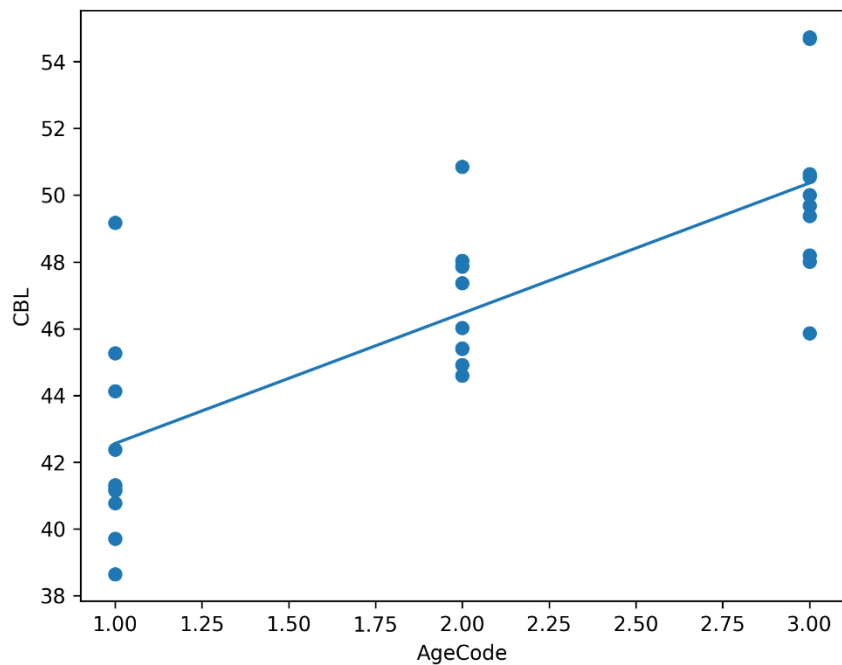


Figure 6. Regression scatter plot illustrating relationships among ventral skull morphometric parameters in Kuri cattle across age groups.

according to their contribution to overall skull variation, with longitudinal and transverse measurements contributing substantially to age-related separation among individuals.

The correlation heatmaps in Figures 9 and 10 further revealed strong positive associations among several occipital and ventral skull measurements, indicating

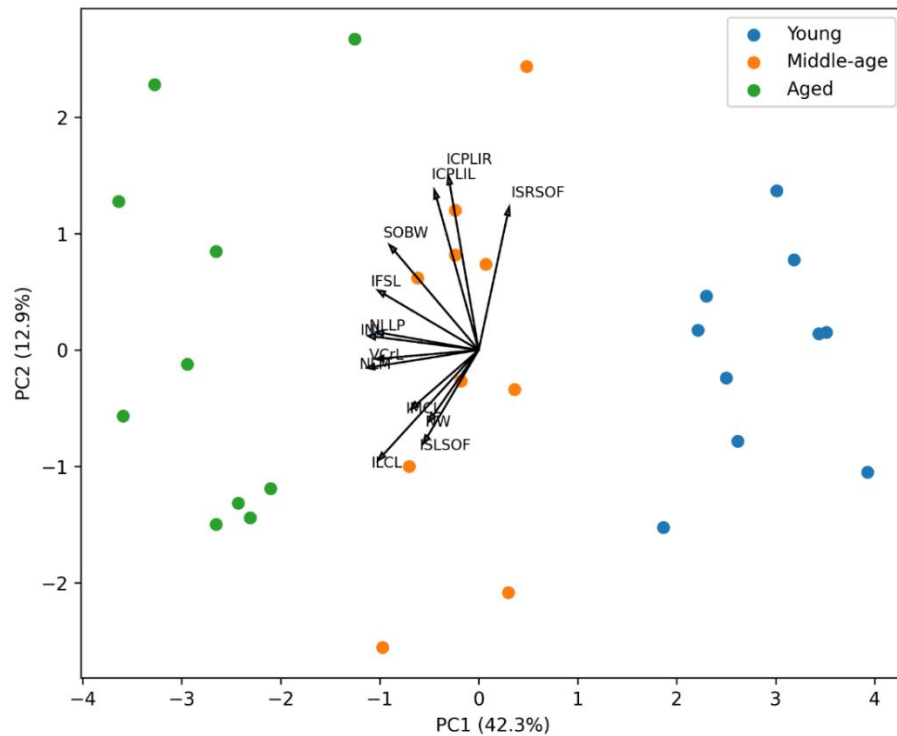


Figure 7. Principal component analysis (PCA) biplot showing the contribution and clustering of caudal (occipital) skull morphometric parameters across age groups in Kuri cattle.

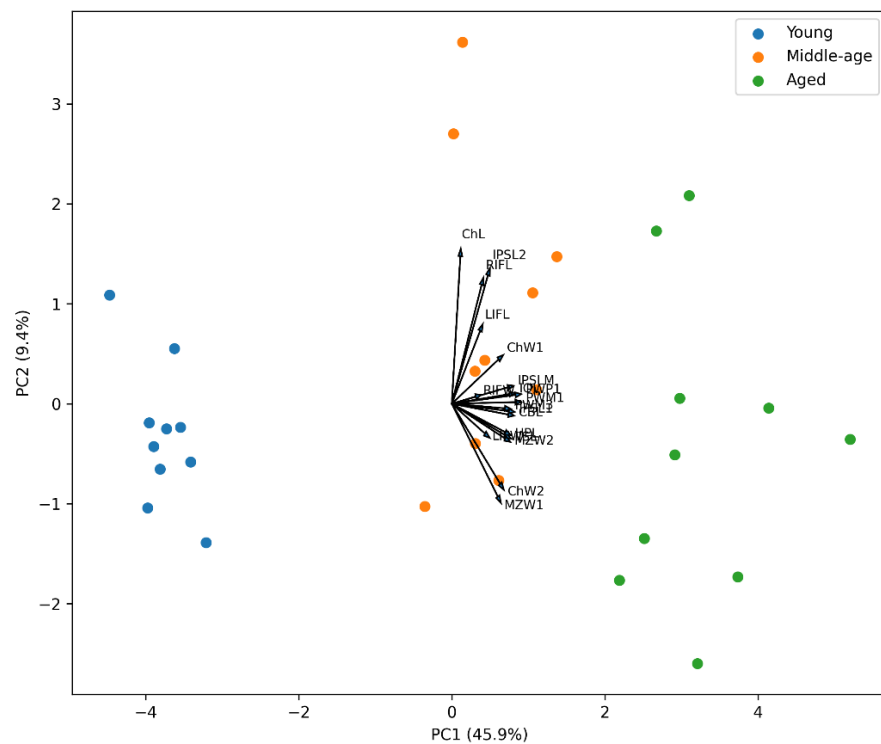


Figure 8. Principal component analysis (PCA) biplot showing the contribution and clustering of ventral skull morphometric parameters in Kuri cattle.

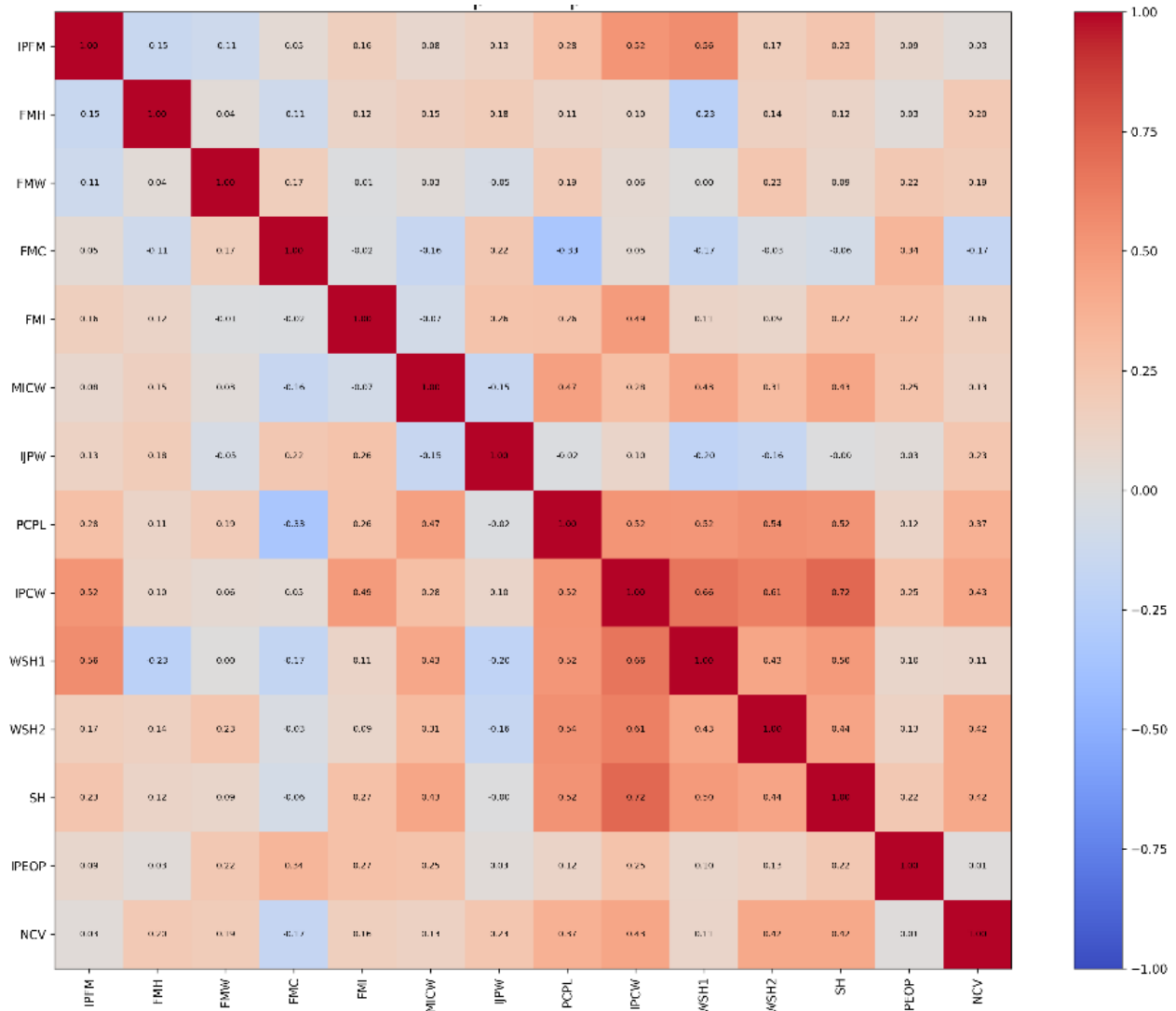


Figure 9. Correlation heatmap showing patterns of morphometric integration among caudal (occipital) skull structures in Kuri cattle. Intercornual protuberance to external occipital protuberance (IPEOP), Intercornual Protuberance to Foramen magnum (IPFM), Foramen magnum height (FMH), Foramen magnum width (FMW), Maximum intercondylar width (MICW), Interjugular process width (IJPW), Paracondylar process length (PCPL), Interparacondylar width (IPCW), Whole skull height 1 (WSH1), and Whole skull height 2 (WSH2).

coordinated growth of anatomically related structures. Such interrelationships suggest that enlargement of one cranial component is accompanied by proportional changes in adjacent structures, thereby preserving overall skull architecture throughout maturation. These findings suggest that both the occipital and ventral skull regions undergo coordinated morphological changes during postnatal growth rather than independent enlargement of isolated structures.

The negative allometric relationships recorded for FMH and FMC indicate that these structures increased at a relatively slower rate than overall skull length, as represented by CBL. In contrast, the positive allometry

observed for IJPW, WSH1, and SH indicates that these structures underwent proportionally greater growth relative to CBL. These differences further demonstrate that cranial development in Kuri cattle involves region-specific growth patterns rather than a uniform increase in skull dimensions. The relatively high R^2 values obtained for MZW1, SH, IPSL1, LIFW, IPCW, and IPSLM indicate strong associations between these measurements and CBL. This suggests that variation in these facial, palatal, and masticatory dimensions can be reliably explained, to a considerable extent, by changes in overall skull length. The strong relationships may therefore reflect coordinated growth among these cranial components during postnatal

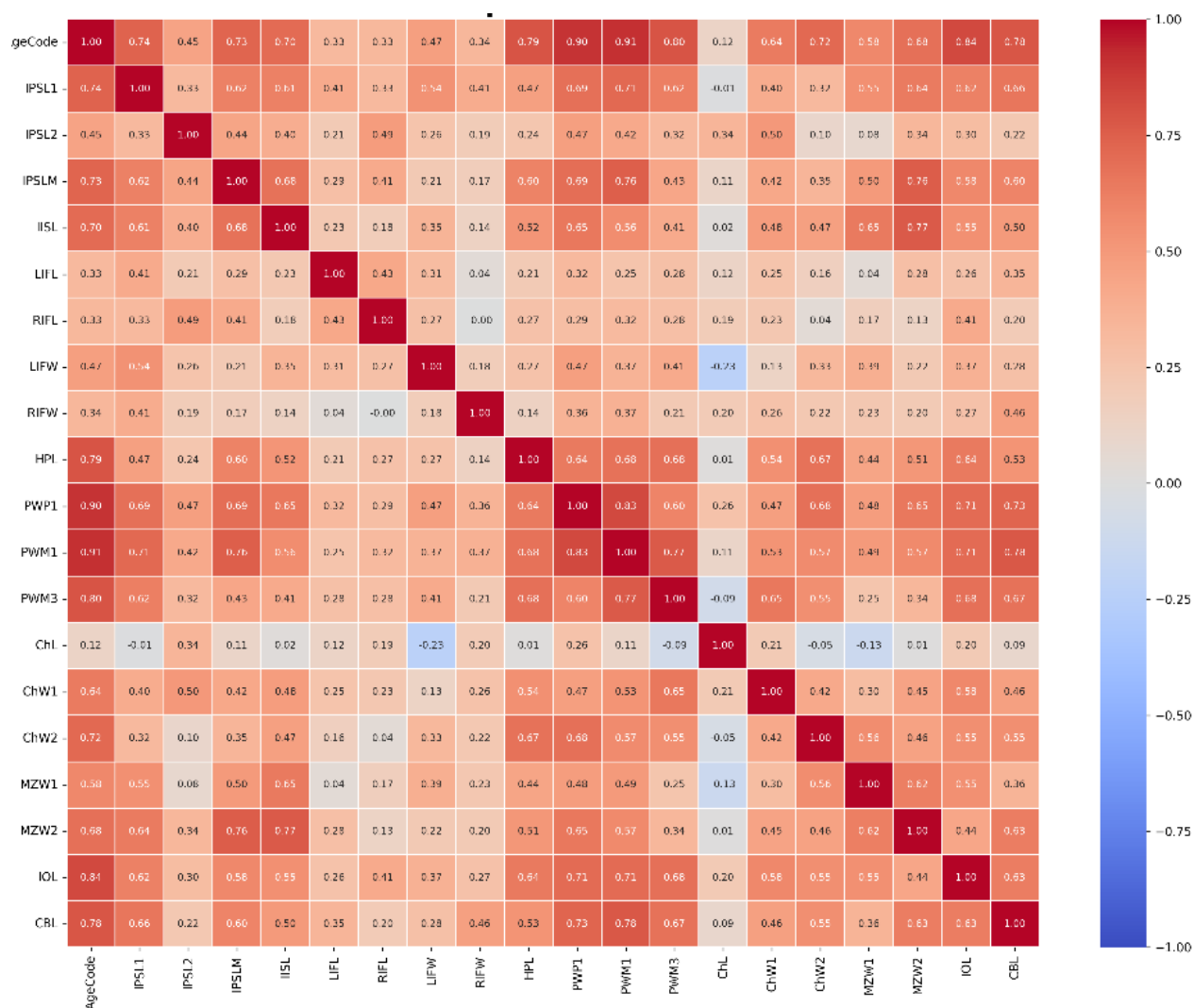


Figure 10. Correlation heatmap showing patterns of morphometric integration among ventral skull structures in Kuri cattle. Left Incisive fissure length (LIFL), Right Incisive fissure length (RIFL), Left Incisive fissure width (LIFW), Right Incisive fissure width (RIFW), Palatine width at premolar 1 (PWP1), Palatine width at molar 1 (PWM1), Palatine width at molar 3 (PWM3), Choana width 1 (ChW1), Choana width 2 (ChW2), Hard palate length (HPL), Choana length (ChL), Maximum zygomatic width 1 (MZW1), Maximum zygomatic width 2 (MZW2), Interincisive suture length (IISL), Interpalatine suture length 1 (IPSL1), Interpalatine suture length 2 (IPSL2), Interpalatine suture length (IPSLM), Incisivo-occipital length (IOL), and Condylbasal length (CBL).

development.

Overall, the allometric findings indicate that cranial growth in Kuri cattle is predominantly expressed within the facial, palatal, and masticatory regions, while structures associated with the foramen magnum and neurocranium exhibit comparatively slower growth and earlier developmental stabilisation. This regional variation in growth rates highlights the heterogeneous nature of skull development in Kuri cattle and may reflect functional adaptations associated with feeding, mastication, and facial development.

The present study also possesses important clinical

implications. Accurate morphometric information on the occipital condyles, jugular processes, basioccipital region, palatine region, and associated foramina provides essential anatomical reference data for regional anaesthesia, surgical planning, computed tomography, and radiographic interpretation. Previous studies in cattle (Turgut, 2025), buffaloes (Monfared, 2013a), and Kuri cattle (Gambo *et al.*, 2015; Gambo *et al.*, 2016) have demonstrated the importance of cranial morphometry for locating neurovascular structures and improving the accuracy of clinical procedures. The baseline measurements generated in the present study therefore

provide valuable anatomical information for veterinary clinicians, anatomists, zooarchaeologists, and conservation biologists working with indigenous African cattle.

The findings of this study should be interpreted with caution due to several limitations. The relatively small sample size and purposive abattoir-based sampling approach may restrict the generalizability of the reference values to the wider Kuri cattle population. Age estimation was based on dentition, and animals were classified into broad age categories, which may have masked subtle age-related variations. Although males and females were represented across age groups, the independent effect of sex on cranial morphometry was not statistically assessed. Furthermore, body weight and other indicators of body size were not included in the analyses, limiting evaluation of allometric relationships. Future studies should incorporate larger sample sizes, known-age animals, and body-size measurements to improve the accuracy and applicability of cranial morphometric reference data in Kuri cattle.

Conclusion

The present study provides comprehensive morphometric evidence of age-related variation in several caudal and ventral skull dimensions of Kuri cattle, particularly measurements associated with the occipital, palatal, zygomatic, facial, and longitudinal regions. In contrast, several foramen magnum and neurocranial measurements exhibited limited age-related variation, suggesting earlier attainment of mature dimensions in these structures. Allometric and regression analyses revealed coordinated growth patterns among anatomically related cranial components, supporting the maintenance of overall skull architecture during maturation. These findings establish useful baseline morphometric data for Kuri cattle that may enhance understanding of their cranial developmental pattern. Furthermore, it may provide useful anatomical reference data for future studies involving regional anaesthesia, surgical planning, diagnostic imaging and radiographic interpretation in Kuri cattle.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

- Ari, H. H., Duro, S., Alpak, H., Tulobaev, A., Ceylan, N., Ashyk, A., Salykov, R., Djordjevic, M., & Gündemir, O. (2026). Skull morphometry and sexual dimorphism in the Kyrgyz horse: A multivariate size-corrected analysis. *Research in Veterinary Science*, 210, 106288. <https://doi.org/10.1016/j.rvsc.2026.106288>
- Çakar, B., Tandir, F., Güzel, B. C., Bakıcı, C., Ünal, B., Duro, S., & Gündemir, O. (2024). Comparison of skull morphometric characteristics of Simmental and Holstein cattle breeds. *Animals*, 14(14), 2085. <https://doi.org/10.3390/ani14142085>
- Chipping, E. (2024). *The functional morphology of British cattle: Biomechanical and shape analysis of aurochs and domestic cattle* (Doctoral dissertation, University of York, York, United Kingdom).
- Choudhary, O. P., Priyanka, Kalita, P. C., Dalga, S., Kalita, A., Doley, P. J., & Keneisenuo (2022). Morphological studies on the skull bones of Indian Mithun (*Bos frontalis*). *Indian Journal of Animal Research*, 56(1), 91-96. <https://doi.org/10.18805/IJAR.B-4279>
- Choudhary, O. P., & Singh, I. (2015). Applied Anatomy of the Maxillofacial and Mandibular Regions of the Indian Blackbuck (*Antelope cervicapra*). *Journal of Animal Research*, 5(3), 497-500.
- da Silva, G. M. D., Stipp, A. C. M., Oliveira, L. R., Heupa, T. C., & de Souza, R. A. M. (2024). Descriptive skull morphology of Subulo gouazoubira and Mazama nana (Artiodactyla, Cervidae). *Ciência Rural*, 55(2), e20230692. <https://doi.org/10.1590/0103-8478cr20230692>
- Dalga, S., & Aslan, K. (2025). Principal component and discriminant function analysis of cranium and mandible in domestic buffalo (*Bos bubalis*). *Ankara Üniversitesi Veteriner Fakültesi Dergisi*, 72(3), 345-355. <https://doi.org/10.33988/auvfd.1544641>
- Dias, F. G. G., Pessinato, M. G., de Oliveira, A. R., de Castro Sasahara, T. H., de Freitas Pereira, L., Carrijo, M. S., ... & de Castro Capoa, I. (2023). Anatomics comparative aspects of head bones of domestic animals and adult human. *Cuadernos de Educación y Desarrollo*, 15(9), 9731-9744. <https://doi.org/10.55905/cuadv15n9-092>
- Fostowicz-Freluk, Ł., & Tseng, Z. J. (2023). The mammalian skull: development, structure and function. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 378(1880), 20220077. <https://doi.org/10.1098/rstb.2022.0077>
- Gambo, B. G., Yahaya, A., & Olopade, J. O. (2016). Morphological studies of the facial tuberoses and infraorbital, supraorbital and mental foramina in Kuri cattle. *Global Veterinaria*, 17(2), 99-104.
- Gambo, B. G., Yahaya, A., Girgiri, I., & Olopade, J. O. (2015). Morphometric studies of the mandibular and maxillofacial regions of the Kuri cattle and the implications in regional anaesthesia. *Folia Morphologica*, 74(2), 183-187. <https://doi.org/10.5603/FM.2015.0028>
- Gündemir, O., & Szara, T. (2025). Morphological patterns of the European bison (*Bison bonasus*) skull. *Scientific Reports*, 15(1), 1418. <https://doi.org/10.1038/s41598-025-85654-3>
- Gündemir, O., Manuta, N., Güzel, B. C., Bakıcı, C., Duro, S., Ünal, B., Çakar, B., & Szara, T. (2025). Skull morphology in native and non-native cattle breeds in Türkiye. *Journal of Anatomy*, 247(1), 179-188. <https://doi.org/10.1111/joa.14234>
- Güzel, B. C., Çakar, B., Manuta, N., Ünal, B., & Duro, S. (2025). Exploring skull morphology in East Anatolian Red cattle and

- South Anatolian Red cattle breeds through 3D modelling. *Veterinary Medicine and Science*, 11(5), e70521. <https://doi.org/10.1002/vms3.70521>.
- Karimi, I., Onar, V., Pazvant, G., Hadipour, M., & Mazaheri, Y. (2011). The cranial morphometric and morphologic characteristics of Mehraban sheep in Western Iran. *Global Veterinaria*, 6(2), 111-117.
- Kobryńczuk, F., Krasieńska, M., & Szara, T. (2008, August). Sexual dimorphism in skulls of the lowland European bison, *Bison bonasus bonasus*. In *Annales Zoologici Fennici* (Vol. 45, No. 4, pp. 335-340). Finnish Zoological and Botanical Publishing Board.
- König, H. E., & Liebich, H. G. (2007). *Veterinary anatomy of domestic mammals: Textbook and colour atlas* (3rd edition). Schattauer GmbH.
- Mansour, M., Wilhite, R., Rowe, J., & Hafiz, S. (2023). *Guide to Ruminant Anatomy: Dissection and Clinical Aspects* (2nd edition). Wiley-Blackwell.
- Monfared, A. L. (2013a). Craniometrical and gross anatomical studies on the skull of the Iranian buffaloes and their clinical value for regional anesthesia. *Global Veterinaria*, 10(4), 427–431.
- Monfared, A. L. (2013b). Gross anatomical measurements of the head region of the Iranian native cattle and their clinical value for regional anesthesia. *Global Veterinaria*, 10(2), 219–222.
- Nourinezhad, J., Heidarinejad, S., Mazaheri, Y., & Khazaeel, K. (2016). Morphological and morphometrical features of the occipital area of male Khouzestan river buffalo. *Veterinary Research Forum*, 7(2), 197-204. Retrieved from <https://www.cabidigitallibrary.org/doi/full/10.5555/20163241113>
- Olopade, J. O., & Onwuka, S. K. (2005). Some aspects of the clinical anatomy of the mandibular and maxillofacial regions of the West African dwarf goat in Nigeria. *International Journal of Morphology*, 23(1), 33-36.
- Özkan, E., Siddiq, A. B., Kahvecioğlu, K. O., Öztürk, M., & Onar, V. (2019). Morphometric analysis of the skulls of domestic cattle (*Bos taurus* L.) and water buffalo (*Bubalus bubalis* L.) in Turkey. *Turkish Journal of Veterinary & Animal Sciences*, 43(4), 532-539. <https://doi.org/10.3906/vet-1903-66>.
- Özüdoğru, Z., Özdemir, D., Teke, B. E., & Kırbaş, M. (2023). A study on morphological and morphometrical parameters on the skull of the Konya merino sheep. *Turkish Journal of Veterinary Research*, 7(2), 59-66. <https://doi.org/10.47748/tjvr.1189675>.
- Pasquini, C. (1982). *Atlas of bovine anatomy*. Sudz Publishing.
- Rajathi, S. (2015). Morphometric measurements of the skull of the cross bred cattle of Tirunelveli district with reference to anatomical landmarks. *Indian Journal of Veterinary and Animal Sciences Research*, 44(2), 116-119.
- Sarma, K. (2006). Morphological and craniometrical studies on the skull of Kagani goat (*Capra hircus*) of Jammu region. *International Journal of Morphology*, 24(3), 449-55.
- Sathapathy, S., Dhote, B. S., Bharti, S. K., & Singh, I. (2022). Morphometrical Studies on Skull Bones of Adult Blue Bull (*Boselaphus tragocamelus*). *Indian Journal of Animal Research*, 56(11), 1351.
- Turgut, N. (2025). Morphometric Analysis of the Skull in the Holstein Cow: A Computed Tomography Study. *Kocatepe Veterinary Journal*, 18(1), 61-74.
- Yahaya, A., Olopade, J. O., Kwari, H. D., & Wiam, I. M. (2012). Osteometry of the skull of one-humped camels. Part I: immature animals. *Italian Journal of Anatomy and Embryology*, 117(1), 23-33. <https://doi.org/10.36253/ijae-1109>.
- Zehtabvar, O., Masoudifard, M., Abbasi, J., Modarres Tonekabony, S. H., & Zamani, A. (2024). Normal CT Anatomy, Morphometry, and Volumetry of the Skull in Urial Sheep (*Ovis vignei*). *Veterinary Medicine International*, Volume 2024, Article ID 5547865, 10 pages. <https://doi.org/10.1155/vmi/5547865>.