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Multi-view image-based phenotyping of body size and udder-related traits in water buffalo (Bubalus bubalis)

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Abstract

The objective of this study was to assess the performance of a multi-view image-based phenotyping approach for measuring body and udder morphometric traits in Khuzestani buffaloes and to evaluate its accuracy relative to conventional manual methods. A total of 106 female buffaloes were included in this study, and images were captured from side, rear, and top views. Measurements obtained in this study include body traits (withers height (WH), rump height (RH), body length (BYL), chest length (CL), hip–pin distance (HPD), hip width (HW), back length (BKL), chest width (CW), and rump width (RW)) and udder-related traits (fore teat length (FTL), rear teat length (RTL), fore teat–udder attachment distance (FTUAD), vulva–udder distance (VUD), and rear teat distance (RTD)). On average, body size traits showed higher correlation (88.3%) and lower ARE (3.55%) compared to udder-related traits (82.8% and 12.5%, respectively), indicating greater measurement accuracy for body dimensions. In addition, imaging perspective influenced different aspects of measurement accuracy, with certain views improving the ability to rank animals while others enhanced absolute measurement precision. Overall, the results demonstrate that image-based phenotyping provides a reliable and practical approach for measuring morphometric traits in buffalo, although careful selection of imaging perspective and consideration of trait-specific challenges—particularly for udder-related measurements—are essential to optimize accuracy.

Introduction

Water buffalo (Bubalus bubalis) are among the most economically important livestock species worldwide, contributing significantly to milk, meat, and draught production, particularly in Asia, the Middle East, and parts of Europe (AHH Minervino et al. 2020). Their ability to produce high-quality milk and efficiently utilize low-quality feed resources, combined with their adaptability to harsh environmental conditions, makes them a vital component of sustainable livestock systems and the livelihoods of millions of smallholder farmers (A Chiariotti et al. 2025, NB Maheswarappa et al. 2024). In Iran, buffaloes play a significant socioeconomic role in milk and meat production systems, and the national population consists of three ecotypes—Khuzestani, Mazandarani, and Azeri—of which the Khuzestani is the most numerous and economically important (M Rafiepour et al. 2021, J Rahmaninia et al. 2019, A Safari et al. 2018). This ecotype has been included in the first intensive management and breeding program established by the Ministry of Agriculture since 1994 at the Safiabad Agricultural and Natural Resources Research Center (Dezful), aimed at improving economic performance through structured genetic evaluation and selection Based on our previous study, this program has demonstrated promising results in improving milk production ability, as evidenced by a positive genetic trend of approximately 28.5 kg per year in estimated breeding values (K Karimi et al. 2026).

Previous studies have highlighted the critical role of body size and conformation traits in determining the economic efficiency of livestock production systems. These traits are closely linked to key performance indicators, including growth rate, feed utilization efficiency, metabolic capacity, carcass quality, reproductive performance, udder development, and milk production, making them essential components

in both beef and dairy production (ZJ Kőrösi et al. 2024, C Schmidtmann et al. 2023, M Sieber et al. 1988). Despite the importance of body measurements and conformation traits, accurately measuring these indices in buffalo remains challenging due to their relatively aggressive or reactive behavior, particularly when assessing udder-related traits. Therefore, image analysis has emerged as a promising alternative approach for measuring body size and conformation traits, offering a non-invasive and efficient solution that has been successfully applied across various livestock species (GP Freitag et al. 2021, K Kuchida et al. 1996, P Negretti et al. 2008, S Tasdemir et al. 2011, Ş Taşdemir et al. 2008, ALN Zhang et al. 2018). Previous study has demonstrated that image analysis can be effectively used for estimating body size and related traits (P Negretti, et al. 2008); however, these approaches have typically been limited to a small number of body measurements, and udder-related traits have not been evaluated using image-based methods. This lack of information makes it difficult to determine whether such approaches can be reliably extended to udder-related traits, which are critically important for assessing milking ability (S Poudel et al. 2022).

Given the importance of both body size and udder-related traits for evaluating productivity and functional performance, developing accurate and practical methods for measuring these traits is essential. Image-based phenotyping offers a promising approach to simultaneously capture body and udder morphometric traits in a non-invasive and safer manner, particularly in buffalo where direct handling can be challenging. If proven reliable, such approaches could facilitate large-scale data collection while improving animal welfare and measurement consistency. Therefore, the objective of this study was to assess the performance of a multi-view image-based analysis system for measuring body size and udder-related traits in Khuzestani buffaloes and to evaluate its agreement relative to traditional manual measurements.

Methods

Phenotypic data

Body and udder morphometric measurements were collected in 2025 from 106 female buffaloes belonging to the breeding herd maintained at the Department of Animal Science, Safıabad-Dezful Agricultural and Natural Resources Research and Education Center, Agricultural Research, Education and Extension Organization (AREEO), Dezful, Iran. The animals ranged in age from 18 months to 13 years, with an average age of 5.12 years. They represented different physiological and reproductive statuses, including milking (n = 42) and dry (n = 17) animals. The calving number ranged from 0 to 13, including nulliparous (n = 47), primiparous (n = 15), and multiparous (n = 44) individuals.

A set of body and udder morphometric traits was measured manually using standard livestock measurement techniques. All measurements were recorded in centimeters (cm), with animals standing on a flat surface and positioned properly to ensure accuracy. Body traits included withers height (WH), rump height (RH), body length (BYL), chest length (CL), hip–pin distance (HPD), hip width (HW), back length (BKL), chest width (CW), and rump width (RW), while udder-related traits included fore teat length

(FTL), rear teat length (RTL), fore teat–udder attachment distance (FTUAD), rear teat distance (RTD), and vulva–udder distance (VUD). To minimize measurement errors, all data were collected by trained personnel using consistent anatomical reference points.

Image acquisition and digital measurement

In addition to manual measurements, digital images were captured for each buffalo to enable image-based analysis. A multi-view imaging protocol was designed to extract different body and udder traits from three standardized perspectives, including side, rear (back), and top views. Images were captured inside a specially designed imaging box to properly restrain and position the animals, ensuring consistency in posture and camera alignment (Fig. 1). The lower part of the imaging box was equipped with calibrated scale markings, which were used as reference units for converting pixel-based measurements into real-world dimensions. For the rear-view images, the internal width of the box at the bottom—aligned with the position of the animal's feet—was used as the reference scale. Similarly, for the top-view images, the width of the box at the upper section served as the scaling reference for estimating measurements derived from image analysis.

<< Fig. about here>>

From the side view, images were used to extract longitudinal and vertical measurements, including WH, RH, BYL, CL, HPD, FTL, RTL, and FTUAD. The rear (back) view was used to capture traits related to udder structure and body width, including FTL, RTL, RTD, HW, and VUD. The top view was utilized to measure dorsal and width-related traits, including BKL, CW, RW, and HW.

All images were acquired under controlled conditions to ensure consistency and suitability for image processing. Animals were photographed in a standing position, and camera distance and angle were kept as constant as possible across all samples and views. Adequate lighting conditions were maintained, and background clutter was minimized to facilitate accurate segmentation and feature extraction. This integrated approach, combining phenotypic measurements with standardized multi-view imaging, provided a reliable dataset for subsequent image analysis and model development. Image processing and morphometric measurements from the captured images were performed using Digimizer software (version 5.7.5).

Accuracy evaluation of image-based measurements

To evaluate the performance of image-based body measurements, five statistical metrics were used, including average relative error (ARE), correlation coefficient (Cor), coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). These metrics were calculated to quantify the agreement between manually measured traits (considered as reference values) and image-derived measurements.

Two different evaluation scenarios were considered to assess the accuracy of the image-based approach. In the first scenario, accuracy metrics were calculated directly between manually measured values (M) and image-based measurements (I) without applying any correction. This represents the baseline performance of the image processing method using raw image-derived data.

In the second scenario, image-based measurements were corrected using a linear regression model combined with a leave-one-out cross-validation (LOOCV) strategy. In this approach, one observation was excluded from the dataset at each iteration, and the regression model was fitted using the remaining samples. The excluded sample was then predicted using the estimated regression parameters.

The regression model used in this study is expressed as:

$$M_i = \beta_0 + \beta_1 I_i + \epsilon_i$$

where M_i represents the manually measured traits for the *i*th animal, I_i denotes the corresponding image-based measurement for the *i*th animal, β_0 is the intercept, $\beta_1$is the regression coefficient, and ϵ_i is the random error term assumed to be normally distributed with mean zero and constant variance. For the top-view images, the width of the imaging box at the upper section was used as a fixed scaling reference for converting pixel measurements into real-world dimensions. However, due to variation in body height among buffaloes, the distance between the animal and the camera was not constant, which may have introduced scaling distortion in the image-based measurements. To account for this potential source of error, animal height-related variation was implicitly incorporated into the prediction model used for top-view traits.

The predicted values obtained from the leave-one-out procedure were then compared with the corresponding manual measurements, and the evaluation metrics (ARE, Cor, R^2, RMSE, and MAE) were calculated. All statistical analyses were conducted using the R programming language (R R Core Team 2020).

Results

Uncorrected image measurements

The accuracy of image-based measurements without any correction is presented in Table 1. Overall, the results indicate a moderate to high level of agreement between manual and image-derived measurements across most traits (Supplementary Figures S1–S3).

Table 1

Accuracy of raw image-based measurements for body and udder traits across different imaging views. Average relative error (ARE), correlation coefficient (Cor) with p-values (in parentheses), coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE) are presented along with the number of records (No.). Values in parentheses indicate the significance level (p-value) of the correlation.

Image view	Trait[1]	No.	ARE (%)	Cor (%)	R2	RMSE (cm)	MAE (cm)
Side	WH	106	3.91	90.67 (8.72e-41)	0.835	5.943	5.311
	RH	106	3.31	80.89 (9.93e-26)	0.651	5.387	4.489
	BYL	101	3.99	85.01 (2.48e-29)	0.721	7.207	5.677
	CL	105	2.71	91.63 (9.81e-43)	0.862	2.482	1.959
	HPD	99	7.57	71.29 (1.26e-16)	0.462	3.72	2.928
	FTL	62	9.15	87.25 (2.55e-20)	0.8	0.618	0.494
	RTL	56	12.06	77.34 (2.8e-12)	0.605	1.132	0.831
	FTUAD	61	18.63	76.11 (1.08e-12)	0.509	2.245	1.817
Rear	FTL	95	18.52	92.42 (1.16e-40)	0.834	1.015	0.833
	RTL	95	18.93	89.03 (1.55e-33)	0.831	1.37	1.018
	RTD	74	14.81	84.24 (5.14e-21)	0.701	1.229	0.952
	HW	98	9.76	91.65 (5.58e-40)	0.895	3.462	2.968
	VUD	79	14.14	76.11 (3.97e-16)	0.626	2.111	1.527
Top	BKL	94	3.89	89.83 (1.29e-34)	0.847	5.696	4.458

[1]WH: Wither Height; RH: Rump Height; BYL: Body Length; CL: Chest Length; HPD: Hip–Pin Distance; FTL: Fore Teat Length; RTL: Rear Teat Length; FTUAD: Fore Teat–Udder Attachment Distance; RTD: Rear Teat Distance; HW: Hip Width; VUD: Vulva–Udder Distance; BKL: Back Length; CW: Chest Width; RW: Rump Width.

Image view	Trait[1]	No.	ARE (%)	Cor (%)	R2	RMSE (cm)	MAE (cm)
	CW	100	5.79	92.31 (1.83e-42)	0.869	2.872	2.414
	RW	100	4.23	96.72 (3.79e-60)	0.947	2.815	2.32
	HW	84	4.25	95.61 (1.77e-45)	0.948	1.552	1.302

[1]WH: Wither Height; RH: Rump Height; BYL: Body Length; CL: Chest Length; HPD: Hip–Pin Distance; FTL: Fore Teat Length; RTL: Rear Teat Length; FTUAD: Fore Teat–Udder Attachment Distance; RTD: Rear Teat Distance; HW: Hip Width; VUD: Vulva–Udder Distance; BKL: Back Length; CW: Chest Width; RW: Rump Width.

For the side-view traits, the highest accuracy was observed for CL and WH, with correlation coefficients of 91.63% and 90.67%, and R^2 values of 0.862 and 0.835, respectively, which were also associated with relatively low ARE values. BYL also showed relatively high agreement (Cor = 85.01%, R^2 = 0.721) and low ARE, whereas HPD exhibited lower accuracy (Cor = 71.29%, R^2 = 0.462) and comparatively higher ARE. Udder-related traits such as FTL showed strong agreement (Cor = 87.25%, R^2 = 0.800) with moderate ARE, while RTL and FTUAD showed comparatively lower accuracy and higher ARE values.

For the rear-view traits, high correlations were observed for FTL, RTL, and HW, with correlation values exceeding 89%, although these traits exhibited relatively higher ARE values compared to body traits. HW showed the highest R^2 (0.895), indicating strong predictive capability with moderate ARE. RTD showed moderate accuracy, while VUD had relatively lower agreement and higher ARE.

For the top-view traits, the highest accuracy was obtained for RW and HW, with correlation coefficients of 96.72% and 95.61%, and R^2 values of 0.947 and 0.948, respectively, accompanied by low ARE values. CW and BKL also showed strong agreement with manual measurements and relatively low ARE.

In terms of error metrics, lower RMSE, MAE, and ARE values were generally associated with traits showing higher correlation and R^2, confirming consistency across evaluation criteria. Overall, width-related traits, particularly from the top view, showed higher accuracy compared to some length-based and udder-related traits, likely due to more stable geometric projection in the imaging setup.

Corrected image-based measurements

The results obtained after applying linear regression correction with LOOCV (Table 2 and Figure S4-6) were generally consistent with those observed for the uncorrected image-based measurements, while demonstrating improved calibration of predictions relative to manual observations. In most cases, correlation coefficients and R^2 values remained comparable, with only minor variations, whereas RMSE, MAE, and ARE showed slight decreases for several traits, indicating improved absolute and relative

precision. Overall, the correction step enhanced the alignment between image-based predictions and manual measurements, resulting in estimates that more closely reflect the true scale and distribution of the observed traits.

Table 2

Accuracy of corrected image-based measurements for body and udder traits across different imaging views using linear regression with leave-one-out cross-validation. Average relative error (ARE), correlation coefficient (Cor) with p-values (in parentheses), coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE) are presented along with the number of records (No.). Values in parentheses indicate the significance level (p-value) of the correlation.

Image view	Trait[1]	No.	ARE (%)	Cor (%)	R^2	RMSE (cm)	MAE (cm)
Side	WH	106	1.73	90.45 (2.75e-40)	0.832	2.995	2.33
	RH	106	2.44	80.79 (1.26e-25)	0.647	4.341	3.311
	BYL	101	3.98	84.7 (6.38e-29)	0.716	7.177	5.636
	CL	105	2.67	91.44 (2.99e-42)	0.86	2.442	1.928
	HPD	99	7.5	71.06 (1.75e-16)	0.456	3.684	2.91
	FTL	62	8.71	87.15 (3.16e-20)	0.794	0.595	0.472
	RTL	56	12.28	76.64 (5.81e-12)	0.594	1.154	0.845
	FTUAD	61	16.71	75.68 (1.71e-12)	0.496	2.181	1.636
Rear	FTL	95	11.53	92.33 (1.99e-40)	0.829	0.664	0.507
	RTL	95	13.18	88.78 (4.27e-33)	0.826	0.95	0.687
	RTD	74	13.46	83.93 (9.81e-21)	0.694	1.17	0.835
	HW	98	4.61	91.59 (7.65e-40)	0.893	1.775	1.384
	VUD	79	11.6	75.31 (1.19e-15)	0.616	1.711	1.328
Top	BKL	94	3.26	89.52 (4.66e-34)	0.837	4.823	3.701

[1]WH: Wither Height; RH: Rump Height; BYL: Body Length; CL: Chest Length; HPD: Hip–Pin Distance; FTL: Fore Teat Length; RTL: Rear Teat Length; FTUAD: Fore Teat–Udder Attachment Distance; RTD: Rear Teat Distance; HW: Hip Width; VUD: Vulva–Udder Distance; BKL: Back Length; CW: Chest Width; RW: Rump Width.

Image view	Trait[1]	No.	ARE (%)	Cor (%)	R^2	RMSE (cm)	MAE (cm)
	CW	100	3.84	92.02 (1.02e-41)	0.867	2.016	1.587
	RW	100	2.29	95.76 (8.96e-55)	0.938	1.588	1.199
	HW	84	3.15	95.49 (5.39e-45)	0.944	1.187	0.94

[1]WH: Wither Height; RH: Rump Height; BYL: Body Length; CL: Chest Length; HPD: Hip–Pin Distance; FTL: Fore Teat Length; RTL: Rear Teat Length; FTUAD: Fore Teat–Udder Attachment Distance; RTD: Rear Teat Distance; HW: Hip Width; VUD: Vulva–Udder Distance; BKL: Back Length; CW: Chest Width; RW: Rump Width.

Despite these variations, the overall pattern of trait performance remained consistent across imaging views. Top-view traits, particularly width-related measurements such as RW and HW, continued to exhibit the highest accuracy and robustness, with consistently high Cor and R^2 values and low ARE values. In contrast, some side-view and udder-related traits, including HPD and FTUAD, showed comparatively lower accuracy and higher ARE values compared to other traits. Following correction, slight reductions were observed in ARE, RMSE, and MAE for both traits—particularly for FTUAD—indicating improved absolute and relative precision, although minor decreases in Cor and R^2 suggest that the overall strength of linear association remained largely unchanged. Overall, the regression-based correction preserved the relative ranking of traits while improving the calibration of predictions, supporting the reliability of image-based measurements, particularly for width-related traits derived from the top view.

Discussion

This study evaluated the potential of a multi-view image-based phenotyping system for estimating body and udder morphometric traits in buffaloes and assessed the effectiveness of a regression-based correction approach. The results demonstrated that image-derived measurements showed moderate to high agreement with manual measurements across most traits, confirming the feasibility of using digital imaging as a reliable alternative to traditional phenotyping methods.

An important observation from this study is that imaging perspective appears to influence different aspects of measurement accuracy. For traits such as FTL and RTL, the rear view resulted in higher correlation coefficients, indicating improved ability to correctly rank animals; however, this was accompanied by increases in ARE, RMSE, and MAE, suggesting reduced absolute precision of the measurements. This indicates that while the rear-view perspective may better capture relative differences among animals, it may also introduce greater deviation from true measurement values, potentially due to scaling differences, perspective distortion, or challenges in landmark identification. In contrast, width-related traits such as HW showed higher accuracy when derived from the top view, as reflected by consistently high correlation and low error metrics, suggesting that this perspective provides

a more stable geometric representation for such measurements. These findings highlight the distinction between relative and absolute accuracy in image-based phenotyping, where correlation-based metrics are particularly important for ranking animals in genetic evaluation, whereas error-based metrics such as ARE provide a more direct measure of measurement precision. These findings are consistent with previous work in livestock phenotyping, where imaging perspective has been shown to influence prediction accuracy. For example, studies using 3D camera systems in cattle have reported substantial differences between lateral and dorsal views, with certain perspectives providing more accurate representations of body traits due to improved visibility and reduced distortion (BM Martins et al. 2020). Therefore, the choice of imaging perspective may depend on the intended application, although further validation across different conditions is warranted.

Body morphometric measurements are essential for evaluating conformation score (CS), as they provide objective and quantitative descriptors of structural and functional traits. This relationship has been confirmed in previous study, which reported significant correlations between body measurements and CS, highlighting their importance for improving the accuracy and consistency of phenotypic evaluation (C Buranakarl et al. 2013). Additionally, body morphometric and conformation traits are also critical for the economic evaluation of livestock production systems, as they are strongly associated with key performance indicators such as growth, feed efficiency, reproductive performance, carcass value, and milk yield in both cattle and buffalo (BA de Melo et al. 2020, MA Gutiérrez-Reinoso et al. 2023, S Poudel, et al. 2022, C Schmidtmann, et al. 2023, M Sieber, et al. 1988). Therefore, achieving high measurement accuracy is essential; however, it can be more challenging in buffalo due to their relatively more aggressive temperament—particularly in Khuzestan buffalo—making handling and precise measurements more difficult. Despite these challenges, the strong agreement observed between image-based and manual measurements—reflected by correlation coefficients generally ranging from approximately 0.71 to 0.97—demonstrates that image-based approaches provide a reliable and effective method for morphometric measurement in this buffalo population. On average, body size traits showed higher correlation (88.3%) and lower ARE (3.55%) compared to udder-related traits (82.8% and 12.5%, respectively), indicating greater measurement accuracy for body dimensions and highlighting the increased difficulty associated with udder-related traits. A high degree of similarity in measurement accuracy for comparable traits was observed when compared with a previous study in dairy cattle using non-contact 3D imaging systems, where average relative errors for traits such as WH, BYL, and CW were reported within a similar range (G Yang et al. 2022). In addition, for certain traits, the present study achieved even lower relative errors, indicating improved accuracy under the proposed imaging framework. For comparable traits such as WH, BYL, and RH, the correlation coefficients obtained in the present study (approximately 0.84–0.91) are consistent with those reported in horses, where analogous traits including withers height, body length, and croup height showed correlations ranging from approximately 0.80 to 0.89 (GP Freitag, et al. 2021). These results indicate a comparable level of accuracy for key morphometric traits across species, with the present study achieving similar—and in some cases slightly higher—agreement for structurally well-defined traits.

Previous studies using computerized image analysis in livestock have reported very high agreement between image-derived and manual morphometric measurements under controlled conditions (P Negretti, et al. 2008, S Tasdemir, et al. 2011). For example, P Negretti, et al. (2008) reported correlations ranging from 0.91 to 0.99 between traditional Lydtin stick measurements and Visual Image Analysis (VIA) measurements in Mediterranean buffaloes, with measurement differences below 1.6%. However, those experiments were conducted under highly standardized imaging conditions and involved a limited number of animals for direct morphometric validation. In contrast, the present study evaluated image-based phenotyping under more variable and realistic production conditions, including multiple imaging perspectives and greater biological diversity. Consequently, although some traits exhibited lower absolute accuracy metrics, the proposed framework may provide improved scalability and external applicability for practical livestock phenotyping applications.

Despite these promising results, several limitations should be considered. First, the study was conducted exclusively on female animals, primarily to enable the evaluation of udder-related traits that are closely associated with milk performance; therefore, the applicability of the proposed approach to males requires further investigation. Second, although a diverse set of morphometric traits was included, the number of measurable traits was constrained by practical challenges in image acquisition and landmark identification; nevertheless, efforts were made to capture a broad range of body dimensions across different views, including vertical and horizontal height, depth, and length measurements, as well as both body and udder-related traits. Third, data were collected from a single herd representing a breeding nucleus for Khuzestani buffaloes, which may limit the generalizability of the findings. Evaluating the method in additional herds, particularly under traditional management systems with fewer environmental controls, would provide a more comprehensive assessment of its robustness under real-world conditions. Furthermore, factors such as animal posture, movement, lighting conditions, and partial occlusion may have introduced additional variability in image-based measurements, potentially affecting accuracy across traits. Addressing these limitations in future studies will be important for improving the robustness and wider applicability of image-based phenotyping systems in buffalo.

Conclusion

In conclusion, this study demonstrated that image-based measurement is an effective approach for quantifying body size and udder-related traits in Khuzestani buffaloes, achieving acceptable levels of accuracy and strong agreement with manual measurements, with generally higher accuracy observed for body traits compared to udder-related traits. The use of a multi-view imaging framework further highlighted that measurement accuracy depends on imaging perspective, indicating that selecting the most appropriate view for each specific trait is critical for optimizing both precision and reliability. These findings support the potential of image-based phenotyping as a practical and scalable alternative to traditional measurement methods. Future studies should focus on validating this approach across different herds and management systems, including more diverse populations, and exploring advanced techniques such as automated feature extraction and machine learning to further improve measurement accuracy and applicability under real-world conditions.

Declarations

Financial support

Agricultural Research, Education and Extension Organization (AREEO), Tehran, Iran.

Statement of Animal Rights

This experiment was conducted under the supervision and approval of the Ethics Committee of Animal Welfare of Agricultural Research, Education and Extension Organization (AREEO), Karaj, Iran.

Conflict of interest

The authors declare that they have no conflict of interest.

Author contribution

Mahmoud Amiri Roudbar contributed to the study conception and design, performed data analysis, and wrote the first draft of the manuscript. Hamid-Reza Seyedabadi contributed to the conception and design of the study and interpreted the results. Alireza Jolazadeh contributed to the study conception and design and prepared the data. Zeinab Amiri Ghanatsaman contributed to the study conception. Mahmoud Amiri Roudbar were responsible for data collection and preparation. All authors commented on previous versions of the manuscript and read and approved the final manuscript.

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Data availability

Data will be made available on request.

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Figures

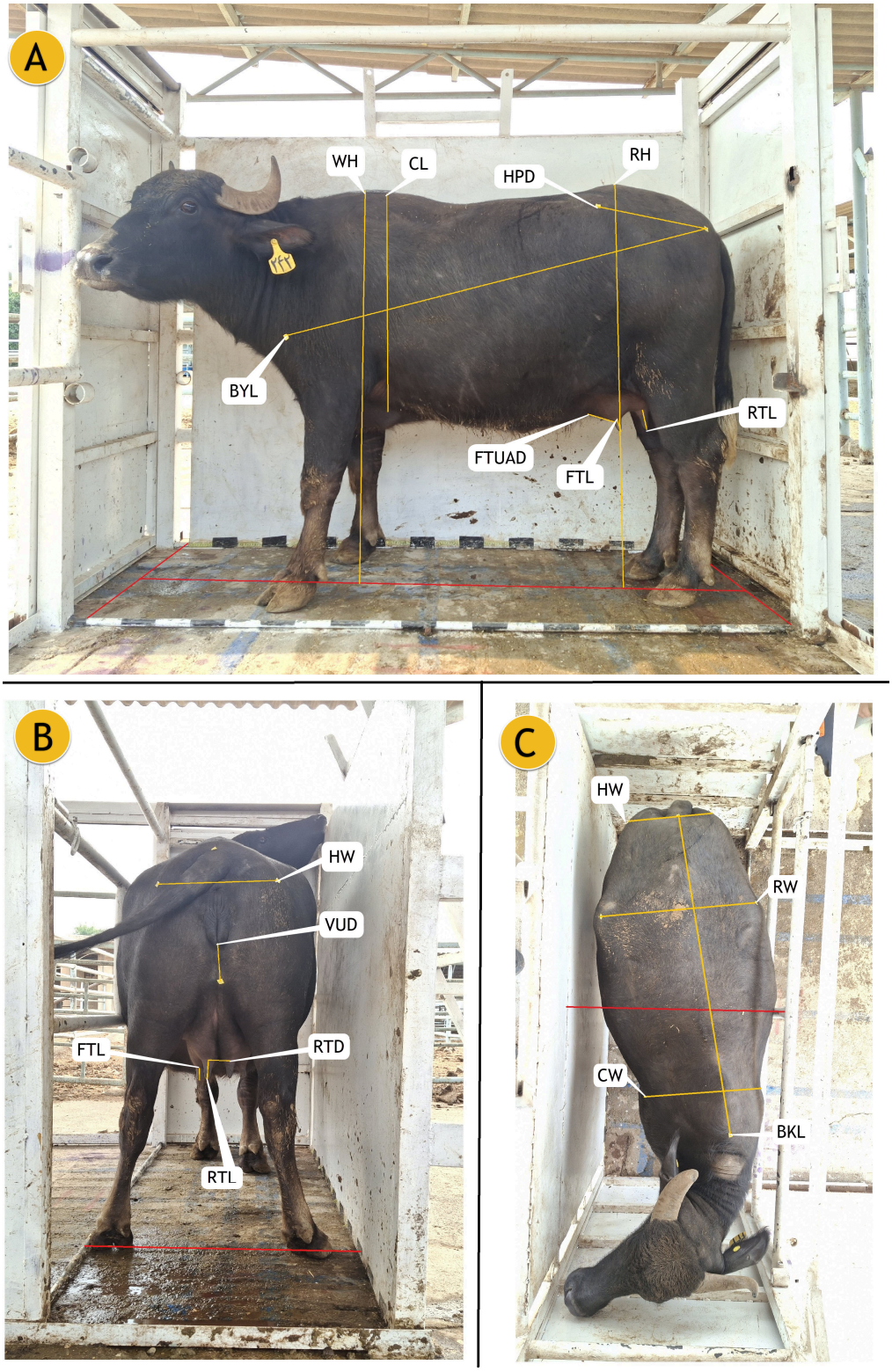


Figure 1

Representative examples of image-based body and udder measurements extracted from different imaging perspectives. (A) Side view showing linear body and udder traits, including withers height (WH), rump height (RH), body length (BYL), chest length (CL), hip–pin distance (HPD), fore teat length (FTL), rear teat length (RTL), and fore teat–udder attachment distance (FTUAD). (B) Rear view illustrating udder and width-related traits, including hip width (HW), Vulva–Udder Distance (VUD), RTL, rear teat distance

(RTD), and FTL. (C) Top view showing body width and length traits, including HW, rump width (RW), chest width (CW), and back length (BKL). Yellow lines indicate the locations and directions of measurements used for image-based phenotyping, while red reference lines were used for image scaling in Digimizer software.

Supplementary Files

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