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Spectrum analysis of buffaloes acoustic signature for their individuality identification

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Abstract
The vocal behavior of animals holds promise as an indicator of their physiological and psychological states, offering insights that can enhance livestock management and welfare assessment. With this conjecture, a study was planned to explore whether the bio-acoustic features of Murrah buffaloes' vocal signature could serve as markers of individuality. 25 buffaloes were selected for vocal signal recording, and their vocalizations were analyzed using PRAAT software. The analysis of 1250 voice samples from the buffalo subjects uncovered notable distinctions across a range of bio-acoustic characteristics, including amplitude (minimum, maximum, and mean), total energy, pitch (minimum, maximum, range, and mean), intensity (mean, minimum, and maximum), formants (F1, F2, F3, and F4), number of pulse, number of periods, unvoiced frames, degree of voice breaks, jitter, shimmer, mean noise/harmonic ratio, and mean harmonic/noise ratio ($p<0.001$). Upon further scrutiny, it became evident that only a specific subset of acoustic features demonstrated statistically significant differences ($p<0.05$) among individual buffaloes. These included the number of pulses, pitch, jitter, shimmer, degree of voice breaks, and formants (F1, F2, F3, and F4). This finding suggests that these particular features hold promise for noninvasively distinguishing the individual identities of buffaloes based on their vocal signatures, even within a sizable herd. In summary, the study highlights the potential of leveraging vocal signatures for individual identification in Murrah buffaloes, paving the way for improved livestock management practices and welfare assessment techniques.

Keywords: Behavior, buffalo, identification, vocalization

Introduction
Vocal behavior serves as a crucial form of communication among animals, it is widely believed that animal vocalizations serve as a vital means of interaction with their environment. These vocalizations are thought to convey a wealth of valuable information pertaining to the mental and physical well-being of the animals. In the current landscape of industrialization, the transformation from small-scale dairy farming to large commercial operations underscores the necessity for precise animal identification. This is essential for evaluating individual performance and recognizing productive conditions accurately. While various tools have been devised for assessing animal individuality and physiological status separately, vocalization emerges as a non-invasive, remote sensing tool capable of identifying animal individuality and discerning conditions such as pain, separation from herds and their estrus phase. Vocalizations convey valuable insights into the age, sex, dominance status, and reproductive condition of the caller (Watts and Stookey, 2000) [14]. Animals possess the ability to discern the calls of their offspring and vice versa, as demonstrated by Clemins *et al*. (2005) [1] and Lee *et al*. (2006) [10]. Moreover, when confronted with multiple vocal signals, recipients can effectively gather simultaneous details about the caller's identity, motivational state, and the context of communication (Karin *et al*., 2021) [8]. Notably, there are consistent and distinctive variations in vocalizations among individuals of the same species (Yin and McCown, 2004) [15]. Despite the wealth of research on vocal communication in wild vertebrates, particularly birds and primates, studies on auditory communication in domestic animals, including cattle, remain limited. Surprisingly, given that vocal responses can be easily recorded and analyzed non-invasively with simple equipment, the vocal behavior of cattle has not received adequate

attention. Hence, the primary objective of the present study was to identify acoustic features within vocal signals that effectively discriminate individual dairy animals. By uncovering characteristic and stable differences in vocalizations, this research aims to leverage vocal signals alone or in conjunction with other evidence as a means of identifying individuals within dairy herds.

Materials and Methods

25 apparently healthy lactating Murrah buffaloes were chosen from the livestock research complex of the National Dairy Research Institute, Karnal, for the purpose of recording their vocalizations. The recordings were conducted in the morning after separating the animals from their herd. Sufficient time was allocated to ensure the collection of at least 50 clips, each containing a complete vocal signal produced in a single attempt, from each buffalo. All management practices, including feeding, breeding, and housing, were carried out according to the normal schedule of the farm, with no external interference. Sound recording was conducted using a biosensor equipped with a high-quality microphone to ensure optimal signal capture. Subsequently, the recorded audio underwent filtration to extract complete voice clips. Using MATLAB (2014), audio files were extracted from the Avi files at a sampling frequency of 16 kHz. Spectral analysis, crucial for understanding the frequency content of discontinuous signals like sound, was performed. This analysis, relying on classical Fourier Transform-based methods and modern parameter estimation techniques, provides detailed frequency-domain information (Semmlow J. L., 2008) [7]. Particularly, the power spectrum density (PSD) was computed by squaring the magnitude of the Fast Fourier Transform (FFT) of the waveform. Approximately 50 complete vocalizations were extracted from each buffalo for feature extraction. These features (Call Duration, Pulse, Pitch, Intensity, Amplitude, Total Energy, Jitter, Shimmer, Harmonic-to-noise ratio, Fraction of locally unvoiced frames, Voice break, Mean autocorrelation and Formants frequency) essential for acoustic analysis, were extracted using PRAAT version 6.0.17. The data were analyzed using the least squares technique outlined by Harvey (1987) [4]. To assess the significance of differences among various subclasses, Duncan's Multiple Range Test as Modified by Kramer (1957) [9] was employed. Least squares model $Y_{ij} = \mu + A_i + e_{ij}$ was utilized to examine significant differences between the different acoustic features of voice signals produced by individual animals. Where Y_{ij} is the voice signal of ith animal; μ is the overall mean; A_i is the effect of ith animal; e_{ij} is the residual error.

Result and Discussion

A least squares analysis was conducted on data comprising various bioacoustic features extracted from a total of 1250 voice samples obtained from 25 Murrah buffaloes to identify significant differences among these features.

1. Call duration, Total Energy, Number of Pulse and Number of periods of Vocal Signals

The least squares analysis of variance indicated highly significant differences in vocal signals among Murrah buffaloes for call duration, total energy, number of pulses, and number of periods (Table 1 and Table 2; $p<0.001$). The overall means for call duration, total energy, number of pulses, and number of periods in the present study were calculated as 1.80±0.05 seconds, 0.082±0.006 Pascal².sec, 168.67±4.35, and 139.24±8.32, respectively. The findings regarding call duration and total energy align with those reported by Singh *et al*. (2013) [13]. Specifically, Murrah buffalo 6441 exhibited the most periodic vocalization, with a periodicity of 98.99% (244.80 periodic pulses out of 247.3 pulses), while Murrah buffalo 6255 produced the least periodic sound at 25.39% (35.60 out of 140.2). Notably, these results parallel those observed by Zhang *et al*. (2017) [16] in the vocalization of frogs (Odorrana tormota).

2. Amplitude, Pitch and Intensity of Vocal Signals

The least squares variance analysis revealed significant differences in vocal signals among the 25 Murrah buffaloes for mean ($p<0.001$), minimum ($p<0.01$), maximum ($p<0.001$), and range ($p<0.001$) amplitudes (Table 1 and Table 3). While noteworthy variations in amplitudes were observed across many Murrah buffaloes, this variability wasn't uniformly significant across all individuals, consistent with the findings of Ozmen *et al*. (2022) [12]. Moreover, pitch in vocal signals demonstrated significant differences ($p<0.001$) for mean, minimum, maximum, and range subclasses (Table 1). Particularly, mean pitch values exhibited significant differences among all individual Murrah buffaloes, echoing the results reported by Mielke and Zuberbuhler (2013) [11] in blue monkeys. Additionally, the least squares variance analysis unveiled significant differences ($p<0.001$) in mean, minimum, maximum, and range intensity of vocal signals among Murrah buffaloes (Table 1). This observation aligns with the findings of Green *et al*. (2019) [3]. Notably, buffalo 6286 showed the greatest intensity fluctuation (ranging from 73.33±0.87 dB to 82.66±0.09 dB), whereas buffalo 6185 exhibited the least fluctuation (ranging from 77.14±0.39 dB to 81.70±0.19 dB), indicating that the vocal signals from buffalo 6185 were the least stable in nature. This variability in intensity values among the animals reflects the results observed by Singh *et al*. (2013) [13] during individual discrimination experiments.

3. Fraction of locally unvoiced frames, Number of voice break, Degree of voice break and Jitter of Vocal Signals

The least squares analysis of variance uncovered significant differences ($p<0.001$) in vocal signals among Murrah buffaloes across various acoustic features, including Fraction of locally unvoiced frames, Number of voice breaks, Degree of voice breaks, and Jitter (Table 1 and Table 4). This finding corroborates the results reported by Singh *et al*. (2013) [13]. Notably, Murrah buffalo 6621 demonstrated the lowest value of unvoiced frames (16.23±3.07), while Murrah buffalo 6619 exhibited the lowest degree of voice breaks (9.75±0.20). The minimal value of unvoiced frames suggests that the vocalization of that specific animal was more periodic compared to others, echoing findings in Cercopithecus mitis stuhlmanni by Mielke and Zuberbuhler (2013) [11] for individual identification. Additionally, buffalo no. 6871 displayed notably low jitter values (0.92±0.01 %), indicating reduced nervousness in this individual. Conversely, buffalo 6204 showed the highest jitter (7.27±0.07 %), suggesting heightened nervousness compared to other individuals. With significant differences observed in the mean degree of voice breaks and jitter % across all 25 individuals, it can be inferred that these acoustic features offer potential for pattern recognition in identifying individual buffaloes.

4. Shimmer, Autocorrelation, Noise-to-Harmonics Ratio (NHR) and Harmonics-to-Noise Ratio (HNR) of Vocal Signals

The least squares analysis of variance indicated significant differences ($p<0.001$) in vocal signals among Murrah buffaloes for Shimmer, Autocorrelation, NHR, and HNR (Table 1 and Table 5). Notably, Murrah buffalo 6231 exhibited the highest value of Shimmer (27.42±0.10), while Murrah buffalo 6668 showed the highest value of Autocorrelation (0.844±0.010). The elevated Shimmer value suggests that the vocalization of the specific animal was softer compared to others, while the high Autocorrelation value indicates greater coordination among all acoustic features of the vocal signal. Moreover, buffalo 6204 displayed the highest NHR (0.86±0.02 %) and the lowest HNR (1.07±0.09 dB), indicating that its voice was less harmonic compared to other animals. Given that Shimmer % and HNR exhibited significant differences among most individual buffaloes, these features could serve as indicators for pattern recognition in identifying the individuality of dairy animals. Similar findings were reported by Green *et al*. (2019) [3] and Ozmen *et al*. (2022) [12] in dairy cattle.

5. Formants (Resonant Frequency) of Vocal Signals

The resonant frequency, defined as the frequency at which the power reaches its local maximum value, was analyzed for the first four lowest resonant frequencies or formants (F1, F2, F3, and F4) in Murrah buffaloes. The least squares variance analysis (Table 1, Table 6, and Figure 1) revealed significant differences ($p<0.001$) in vocal signals among Murrah buffaloes for all four formants. The overall mean of formants suggested that F2, F3, and F4 frequencies appeared to be one-fold integer multiples of the fundamental frequency (F1), indicating potential harmonic overtones. This observation aligns with the findings of Ikeda and Ishii (2008) [5] for identifying individual cows and is supported by previous studies by Singh *et al*. (2013) [13] and Green *et al*. (2019) [3]. The least squares mean table and Figure 1 clearly demonstrate that all four formants significantly differ for each individual, indicating their potential utility as robust acoustic features for individual identification through vocal signal processing. The relative elevation or reduction of the formants (F1, F2, F3, etc.) is contingent upon factors such as the length of the vocal tract, the configuration of pharyngeal regions, and the oral and nasal cavities, as well as the opening of the mouth. Increased mouth opening tends to elevate F1 closer to F2. Conversely, pharyngeal constriction and mouth retraction typically lead to a rise in F1 and a decline in F2 and F3. Additionally, protrusion of the lips extends the length of the vocal tract, thereby lowering all formant frequencies (Fitch and Hauser, 1995) [2].

Table 1: Least squares analysis of variance (mean squares only) for various acoustic features of Murrah buffalo

Source of variation		Individual Animals	Error
d f		24	225
Call duration, Seconds		2.431***	0.487
Amplitude, Pascal	Mean	0.00001***	0.0000028
	Minimum	0.013**	0.005
	Maximum	0.021***	0.006
	Range	0.057***	0.016
Total energy, Pascal² sec		0.027***	0.006
Intensity, dB	Mean	17.935***	2.160
	Minimum	10.954**	6.808
	Maximum	19.861***	0.359
	Range	18.747***	7.171
Pitch, Hz	Mean	45278.919***	39.730
	Minimum	18046.002***	4287.133
	Maximum	58272.770***	12033.458
	Range	54390.264***	12753.275
Number of pulses		48717.661***	27.008
Number of periods		45237.452***	14332.330
Fraction of locally unvoiced frames (%)		1155.162***	420.619
Number of voice breaks		19.496***	5.431
Degree of voice breaks		4446.828***	1.025
Jitter %		24.955***	0.099
Shimmer %		206.276***	0.128
Autocorrelation		0.062***	0.002
Noise-to-Harmonics Ratio		0.216***	0.048
Harmonics-to-Noise Ratio dB		45.04***	224.55
F1, Hz		141256.939***	892.461
F2, Hz		103720.760***	1195.368
F3, Hz		96373.461***	1357.076
F4, Hz		149628.919***	1454.177

**$p<0.01$

***$p<0.001$

Table 2: Least squares means (±SE) for Call duration, Total Energy, Number of Pulse and Number of periods of individual Murrah buffaloes

S. No	Animal No.	Call duration (Second)	Total energy (Pascal² sec)	Number of pulse	Number of periods
		Mean±SE	Mean±SE	Mean±SE	Mean±SE
1	MU 6617	1.86^{bcde}±0.15	0.080^{bc}±0.015	116.3^{p}±2.20	109.10^{cde}±32.35
2	MU 6871	1.78^{cde}±0.07	0.059^{bc}±0.006	71.7^{r}±1.41	59.60^{de}±13.67
3	MU 5317	2.09^{abcde}±0.19	0.088^{bc}±0.008	128.9^{o}±1.87	107.20^{cde}±18.30
4	MU 5743	2.18^{abcd}±0.15	0.087^{bc}±0.007	278.3^{c}±1.90	253.40^{ab}±60.98
5	MU 5881	1.36^{efg}±0.25	0.062^{bc}±0.014	128.7^{o}±1.89	116.70^{cde}±30.68
6	MU 5914	1.74^{cde}±0.16	0.071^{bc}±0.012	139.8^{m}±1.69	127.60^{bcde}±23.10
7	MU 5946	1.52^{defg}±0.22	0.063^{bc}±0.010	197.1^{g}±2.00	181.40^{abcd}±37.51
8	MU 6105	2.07^{abcde}±0.28	0.069^{bc}±0.013	190.2^{hi}±2.00	178.10^{abcd}±65.10
9	MU 6151	2.26^{abcd}±0.17	0.078^{bc}±0.009	117.4^{p}±1.83	110.40^{cde}±17.87
10	MU 6185	2.59^{a}±0.28	0.085^{bc}±0.010	212.5^{f}±1.90	194.50^{abc}±64.47
11	MU 6204	1.76^{cde}±0.30	0.062^{bc}±0.009	152.8^{l}±1.47	136.50^{bcde}±24.63
12	MU 6231	0.91^{gh}±0.18	0.029^{c}±0.005	289.1^{b}±1.68	79.60^{cde}±32.18
13	MU 6255	0.70^{h}±0.11	0.027^{c}±0.003	140.2^{m}±1.21	35.60^{e}±8.25
14	MU 6286	1.01^{fgh}±0.16	0.035^{bc}±0.006	57.7^{s}±1.51	40.60^{cde}±20.71
15	MU 6349	1.85^{bcde}±0.23	0.067^{bc}±0.008	164.1^{k}±1.53	95.80^{cde}±15.06
16	MU 6438	2.45^{abc}±0.21	0.078^{bc}±0.007	178.9^{j}±1.93	140.00^{abc}±24.84
17	MU 6441	2.25^{abcd}±0.40	0.238^{a}±0.045	247.3^{e}±1.78	244.80^{ab}±62.64
18	MU 6442	2.02^{abcde}±0.22	0.060^{bc}±0.013	192.9^{gh}±1.37	163.50^{abc}±32.42
19	MU 6614	1.63^{def}±0.30	0.245^{a}±0.108	267.3^{d}±1.16	245.40^{ab}±59.32
20	MU 6618	2.25^{abcd}±0.26	0.086^{bc}±0.016	186^{i}±1.35	176.00^{abcd}±32.19
21	MU 6619	1.61^{defg}±0.12	0.071^{bc}±0.005	79.5^{q}±0.97	70.60^{cde}±13.48
22	MU 6621	2.58^{ab}±0.23	0.117^{b}±0.012	309.4^{a}±2.19	298.50^{a}±35.52
23	MU 6630	1.56^{defg}±0.20	0.076^{bc}±0.011	135.2^{n}±0.98	110.60^{cde}±45.84
24	MU 6668	1.39^{efg}±0.19	0.054^{bc}±0.009	162.9^{k}±1.21	132.80^{bcde}±47.87
25	MU 6869	1.68^{def}±0.18	0.060^{bc}±0.007	72.7^{r}±0.99	65.80^{cde}±24.46
	Overall mean	1.80±0.05	0.082±0.006	168.67±4.35	139.24±8.32

Data with different superscript in the same column differs significantly from each other (p<0.05)

Table 3: Least squares means (±SE) for Amplitude of individual Murrah buffaloes

S. No	Animal No.	Amplitude (Pascal)*	Pitch (Hz)	Intensity (dB)
		Mean±SE	Mean±SE	Mean±SE
1	MU 6617	-0.43±0.45	124.91^{o}±0.94	80.08^{bcd}±0.34
2	MU 6871	0.07±0.72	87.15^{r}±0.24	78.77^{de}±0.52
3	MU 5317	0.87±0.38	110.03^{p}±0.56	80.23^{bcd}±0.25
4	MU 5743	-0.61±0.61	231.8^{f}±0.68	79.98^{bcd}±0.33
5	MU 5881	0.87±1.30	132.2^{m}±0.61	80.12^{bcd}±0.30
6	MU 5914	-0.25±0.96	96.7^{q}±0.42	79.85^{bcd}±0.37
7	MU 5946	0.18±0.93	183.5^{i}±0.98	80.13^{bcd}±0.23
8	MU 6105	0.50±0.62	243.3^{e}±1.62	78.85^{de}±0.47
9	MU 6151	0.40±0.70	169.4^{k}±1.54	79.17^{bcde}±0.47
10	MU 6185	-0.04±0.72	134.9^{m}±1.29	79.03^{cde}±0.40
11	MU 6204	0.73±3.27	208.5^{h}±4.57	79.70^{bcde}±0.32
12	MU 6231	0.68±2.44	235.2^{f}±2.48	79.03^{cde}±0.36
13	MU 6255	0.66±1.15	164.76^{k}±2.57	80.07^{bcd}±0.33
14	MU 6286	-0.52±0.86	214.4^{g}±3.03	79.32^{bcde}±0.35
15	MU 6349	-0.32±0.89	208^{h}±2.37	79.34^{bcde}±0.23
16	MU 6438	-0.26±0.28	213.6^{gh}±2.71	78.94^{cde}±0.25
17	MU 6441	0.51±0.10	230.18^{f}±2.84	84.20^{a}±0.71
18	MU 6442	0.10±0.21	268.56^{c}±2.53	78.16^{e}±0.50
19	MU 6614	2.73±1.03	328.92^{a}±1.94	83.44^{a}±1.15
20	MU 6618	0.37±0.78	143.39^{l}±1.72	79.33^{bcde}±0.71
21	MU 6619	1.42±0.64	130.62^{n}±1.47	80.46^{bc}±0.29
22	MU 6621	1.22±0.89	317.9^{b}±1.40	80.50^{bc}±0.22
23	MU 6630	-1.12±0.43	177.1^{j}±1.81	80.76^{b}±0.32
24	MU 6668	-0.43±1.02	91.2^{qr}±1.28	79.49^{bcde}±0.66
25	MU 6869	0.43±0.60	252.3^{d}±1.85	79.00^{cde}±0.36
	Overall mean	0.31±0.21	187.94±4.20	79.92±0.12

Data with different superscript in the same column differs significantly from each other (p<0.05)

Table 4: Least squares means (±SE) for Fraction of locally unvoiced frames, Number of voice break, Degree of voice break and Jitter of individual Murrah buffaloes

S. No	Animal No.	Fraction of locally unvoiced frames (%)	Number of voice break	Degree of voice break (%)	Jitter (%)
		Mean±SE	Mean±SE	Mean±SE	Mean±SE
1	MU 6617	35.45^{abcdef}±7.50	2.50^{cdefghi}±0.70	24.42^{n}±0.21	2.66^{l}±0.13
2	MU 6871	45.14^{abc}±6.80	2.00^{cdefghi}±0.45	32.23^{k}±0.13	0.92^{o}±0.01
3	MU 5317	28.97^{bcdef}±4.19	4.20^{abcd}±0.70	39.11^{i}±0.13	3.69^{j}±0.10
4	MU 5743	31.07^{bcdef}±5.87	6.10^{a}±1.31	35.18^{j}±0.13	4.43^{gh}±0.10
5	MU 5881	27.65^{bcdef}±7.23	1.30^{ghi}±0.37	18.79^{p}±0.11	3.64^{j}±0.06
6	MU 5914	20.34^{ef}±6.89	1.80^{defghi}±0.51	27.56^{m}±0.17	1.77^{n}±0.08
7	MU 5946	18.22^{f}±5.69	2.50^{cdefghi}±0.82	11.27^{r}±0.11	4.99^{ef}±0.10
8	MU 6105	45.00^{abc}±7.56	3.50^{bcdefgh}±1.13	43.13^{h}±0.12	6.17^{c}±0.14
9	MU 6151	46.10^{ab}±7.48	3.00^{cdefgh}±0.68	31.04^{l}±0.08	4.72^{fg}±0.10
10	MU 6185	43.87^{abcd}±8.89	4.10^{abcde}±0.91	71.15^{b}±0.11	3.99^{i}±0.12
11	MU 6204	32.14^{bcdef}±3.61	3.20^{cdefgh}±0.73	63.46^{d}±0.30	7.27^{a}±0.07
12	MU 6231	44.05^{abcd}±4.81	2.30^{cdefghi}±0.76	14.09^{q}±0.19	5.64^{d}±0.09
13	MU 6255	44.51^{abc}±5.54	1.70^{defghi}±0.37	6.56^{t}±0.28	4.46^{h}±0.12
14	MU 6286	29.39^{bcdef}±5.66	3.60^{bcdefg}±0.85	57.66^{e}±0.28	5.74^{d}±0.07
15	MU 6349	50.04^{ab}±3.82	2.80^{cdefghi}±0.49	42.85^{h}±0.24	5.52^{d}±0.09
16	MU 6438	33.50^{bcdef}±6.32	3.90^{abcdef}±0.89	78.34^{a}±0.39	3.96^{i}±0.11
17	MU 6441	29.05^{bcdef}±9.39	1.60^{efghi}±0.37	14.46^{q}±0.27	3.95^{i}±0.09
18	MU 6442	31.87^{bcdef}±8.15	1.00^{hi}±0.33	54.53^{f}±0.56	3.28^{k}±0.09
19	MU 6614	31.86^{bcdef}±3.98	2.00^{cdefghi}±0.52	24.81^{n}±0.45	6.69^{b}±0.07
20	MU 6618	22.06^{cdef}±6.56	4.40^{abc}±1.06	20.10^{o}±0.44	3.22^{k}±0.12
21	MU 6619	40.79^{abcde}±5.87	3.10^{cdefgh}±0.60	9.75^{s}±0.20	2.57^{l}±0.11
22	MU 6621	16.23^{f}±3.07	5.80^{ab}±1.15	48.20^{g}±0.57	5.13^{e}±0.10
23	MU 6630	47.07^{ab}±8.10	3.40^{cdefgh}±0.76	69.86^{c}±0.47	5.11^{e}±0.09
24	MU 6668	23.08^{cdef}±7.98	0.50^{i}±0.22	10.90^{r}±0.49	2.25^{m}±0.10
25	MU 6869	55.71^{a}±5.71	1.50^{fghi}±0.31	30.45^{l}±0.54	6.10^{c}±0.12
	Overall mean	34.92±1.40	2.87±0.16	35.20±1.31	4.30±0.10

Data with different superscript in the same column differs significantly from each other ($p<0.05$)

Table 5: Least squares means (±SE) for Shimmer, Autocorrelation, Noise-to-Harmonics Ratio (NHR) and Harmonics-to-Noise Ratio (HNR) of individual Murrah buffaloes

S. No	Animal No.	Shimmer (%)	Autocorrelation	Noise-to-Harmonics Ratio (NHR)	Harmonics-to-Noise Ratio (HNR)
		Mean±SE	Mean±SE	Mean±SE	Mean±SE
1	MU 6617	12.38^{r}±0.14	0.604^{fg}±0.012	0.58^{def}±0.08	4.34^{e}±0.10
2	MU 6871	9.816^{t}±0.11	0.703^{b}±0.015	0.45^{efg}±0.07	5.16^{d}±0.11
3	MU 5317	15.19^{n}±0.11	0.600^{fgh}±0.011	0.57^{def}±0.06	3.89^{f}±0.10
4	MU 5743	20.13^{g}±0.18	0.578^{ghi}±0.006	0.69^{abcde}±0.05	2.40^{i}±0.08
5	MU 5881	13.74^{p}±0.10	0.674^{bc}±0.015	0.52^{ef}±0.10	4.98^{d}±0.09
6	MU 5914	8.69^{u}±0.09	0.830^{a}±0.014	0.30^{g}±0.05	9.44^{a}±0.51
7	MU 5946	18.11^{i}±0.06	0.653^{cde}±0.014	0.62^{cdef}±0.07	4.07^{ef}±0.12
8	MU 6105	21.73^{e}±0.08	0.540^{ij}±0.008	0.84^{abc}±0.04	1.07^{k}±0.09
9	MU 6151	15.92^{m}±0.14	0.628^{def}±0.014	0.66^{abcde}±0.05	2.86^{gh}±0.14
10	MU 6185	15.27^{n}±0.10	0.685^{bc}±0.011	0.57^{def}±0.08	5.05^{d}±0.10
11	MU 6204	22.91^{c}±0.13	0.554^{ij}±0.006	0.86^{a}±0.02	1.12^{jk}±0.11
12	MU 6231	27.42^{a}±0.10	0.564h^{ij}±0.010	0.79^{abcd}±0.04	1.42^{jk}±0.09
13	MU 6255	17.61^{j}±0.10	0.603^{fg}±0.015	0.57^{def}±0.08	4.01^{ef}±0.12
14	MU 6286	20.52^{f}±0.09	0.620^{def}±0.006	0.66^{abcde}±0.02	2.64^{hi}±0.12
15	MU 6349	18.48^{h}±0.10	0.562^{hij}±0.014	0.78^{abcd}±0.07	1.53^{j}±0.10
16	MU 6438	15.77^{m}±0.09	0.615^{defg}±0.021	0.62^{bcdef}±0.09	3.28^{g}±0.10
17	MU 6441	12.72^{q}±0.12	0.678^{bc}±0.011	0.50^{efg}±0.09	5.88^{c}±0.08
18	MU 6442	16.25^{l}±0.09	0.613^{efg}±0.012	0.64^{abcde}±0.11	3.89^{f}±0.08
19	MU 6614	20.65^{f}±0.10	0.528^{j}±0.006	0.86^{a}±0.05	1.22^{jk}±0.09
20	MU 6618	16.58^{k}±0.12	0.688^{bc}±0.015	0.46^{efg}±0.09	6.09^{c}±0.11
21	MU 6619	14.38^{o}±0.13	0.655^{cd}±0.014	0.64^{abcde}±0.07	2.87^{gh}±0.10
22	MU 6621	22.11^{d}±0.12	0.622^{def}±0.015	0.67^{abcde}±0.05	2.96^{gh}±0.11
23	MU 6630	17.89^{ij}±0.11	0.630^{def}±0.013	0.65^{abcde}±0.06	2.83^{h}±0.08
24	MU 6668	11.01^{s}±0.13	0.844^{a}±0.010	0.40^{fg}±0.11	7.89^{b}±0.11
25	MU 6869	23.32^{b}±0.10	0.548^{ij}±0.012	0.85^{ab}±0.04	1.35^{jk}±0.07
	Overall mean	17.14±0.28	0.633±0.005	0.63±0.02	3.69±0.13

Data with different superscript in the same column differs significantly from each other ($p<0.05$)

Table 6: Least squares means (±SE) for Formants Frequency of individual Murrah buffaloes

S. No	Animals No.	F1 (Hz)	F2 (Hz)	F3 (Hz)	F4 (Hz)
		Mean±SE	Mean±SE	Mean±SE	Mean±SE
1	MU 6617	1215.8^{a}±14.38	1612.2^{gh}±11.38	2540.9^{m}±13.73	3558.3^{j}±26.47
2	MU 6871	1178.6^{b}±15.31	1582.5^{hi}±10.93	2536.7^{m}±19.43	3665.4^{fg}±9.17
3	MU 5317	909^{hi}±16.37	1696.6^{ef}±15.31	2722.8^{ef}±20.57	3635.8^{gh}±10.13
4	MU 5743	873^{jkl}±5.00	1754.4^{bc}±8.70	2803.4^{b}±11.33	3732.2^{de}±14.15
5	MU 5881	1022^{d}±8.26	1597.5^{ghi}±7.36	2685.1^{hi}±7.19	3785.9^{c}±12.02
6	MU 5914	971.7^{ef}±7.30	1518.5^{kl}±11.86	2713.5^{ef}±10.21	3772.8^{c}±13.22
7	MU 5946	846.1^{l}±10.62	1453.3^{n}±12.16	2623.8^{k}±13.51	3724.4^{e}±13.45
8	MU 6105	894.5^{ij}±15.15	1687.4^{ef}±14.71	2746^{cd}±9.32	3792.2^{c}±11.21
9	MU 6151	1073.8^{c}±15.24	1536.6^{k}±7.40	2701.5^{gh}±10.92	3600.6^{i}±12.94
10	MU 6185	1070.3^{c}±8.51	1585.2^{hi}±9.34	2735.7^{de}±10.71	3476.5^{k}±17.05
11	MU 6204	738.8^{n}±1.11	1708.7^{de}±16.24	2745.8^{cd}±14.56	3734.6^{de}±5.42
12	MU 6231	803.9^{m}±7.36	1729^{cd}±4.84	2711.6^{fg}±8.98	3771.9^{c}±6.88
13	MU 6255	875.3^{jk}±9.61	1571.1^{ij}±6.30	2576.7^{l}±11.19	3621.9^{hi}±12.01
14	MU 6286	859.73^{kl}±8.83	1499.8^{lm}±14.93	2642.3^{jk}±7.84	3631.4^{hi}±14.19
15	MU 6349	915.4^{hi}±9.87	1775.7^{b}±10.18	2741.1^{de}±10.26	3919^{b}±12.29
16	MU 6438	927.2^{gh}±4.90	1849.2^{a}±9.57	2951.1^{a}±8.34	4064.6^{a}±10.24
17	MU 6441	1058.31^{c}±11.25	1666.7^{f}±9.10	2689.12^{hi}±8.24	3762.67^{cd}±7.40
18	MU 6442	949.84^{fg}±9.51	1533.61^{k}±9.68	2527.4^{m}±8.38	3671.6^{f}±9.00
19	MU 6614	936.17^{gh}±5.56	1630.55^{g}±9.13	2691.33^{hi}±9.00	3642.4^{fg}±9.35
20	MU 6618	896.52^{ij}±1.52	1540.85^{jk}±14.37	2630.63^{k}±12.69	3730.52^{de}±6.19
21	MU 6619	1186.6^{b}±7.89	1629.9^{g}±8.79	2519.1^{m}±11.78	3664.2^{fg}±8.04
22	MU 6621	888.2^{ijk}±2.49	1755.4^{bc}±9.28	2750.4^{cd}±6.79	3634.2^{gh}±11.38
23	MU 6630	1024.7^{d}±7.81	1543.2^{jk}±10.52	2767.3^{c}±12.63	3647.9^{fg}±9.91
24	MU 6668	985.6^{e}±0.83	1483.9^{m}±11.41	2670.1^{ij}±11.31	3530.7^{j}±9.57
25	MU 6869	951.2^{fg}±0.95	1610.1^{gh}±10.60	2624.6^{k}±10.46	3784.6^{c}±11.83
	Overall mean	962.09±7.60	1622.07±6.66	2681.91±6.49	3702.25±7.93

Data with different superscript in the same column differs significantly from each other (p<0.05)

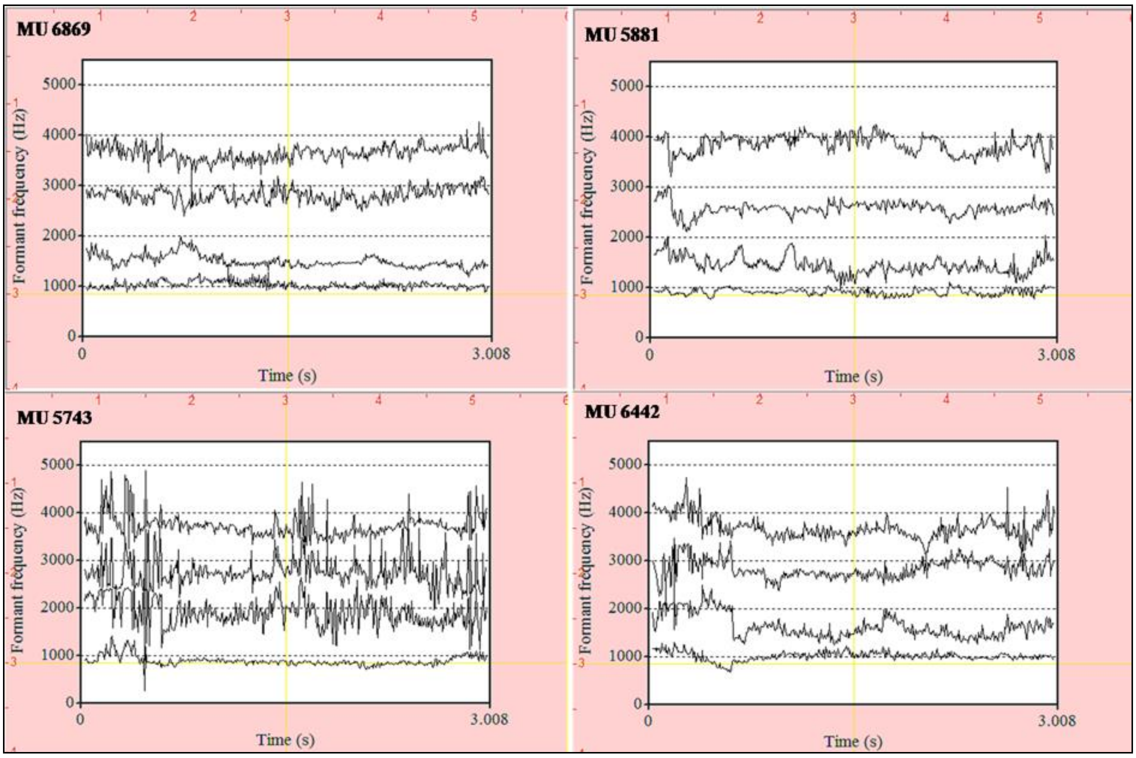

Fig 1: Comparison of Formant frequency (F1, F2, F3 and F4) contour in four Murrah buffaloes for discrimination of their individuality

Conclusion

The study findings suggest that analyzing vocalizations could serve as a reliable indicator of individuality among Murrah buffaloes within large herds. Among the various acoustic features examined; Pulse, Intensity, Jitter, Shimmer, HNR, and Formant frequency were emerged as the most distinctive acoustic features for context-independent speaker identification in buffalo. Consequently, Formant frequency appears to be particularly effective in discriminating between individual animals based on their vocal signals.

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