Meat and Muscle Biology™

Establishing Water Buffaloes as a Promising Source of Red Meat in Pursuit of Sustainable Animal Proteins for a Better World

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Abstract: Water buffaloes (*Bubalus bubalis*) are distributed in 46 countries across 5 continents and hold significant importance within the livestock production system in various South Asian countries. Water buffaloes are native to Asia and Mediterranean regions and have a significant impact on the economic profitability of producers due to their valuable contributions through milk, meat, leather, and draught power. The production of buffalo meat plays a significant role in safeguarding global food security by meeting the growing demand for high-quality proteins. Buffaloes provide consumers with an unmatched blend of low-fat, low-cholesterol, conjugated linoleic acid and other bioactive peptide-rich meat with a lower atherogenic index and health advantages. Multiple utility, climate-smart nature, reduced food miles, suitability under a small-holder production system, and contribution to UN Sustainable Development Goals promise water buffaloes as a sustainable source of red meat. This comprehensive depiction emphasizes the pivotal position that buffaloes are expected to assume in the future of meat technology. The current review serves as an essential reference for stakeholders engaged in the dynamic domain of buffalo meat production, processing, import and export agencies, standard-setting bodies, and policymakers.

Key words: water buffalo, meat quality, value addition, beef, sustainability
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Introduction

The domestic water buffalo, scientifically known as *Bubalus bubalis*, is a large-sized, cloven-footed ruminant animal of the family Bovidae. It is closely related to domestic cattle on the phylogenetic tree (Maheswarappa et al., 2022). This species is indigenous to the Asian and African subcontinents. The Food and Agriculture Organization of the United Nations (FAO) has identified buffalo as an "undervalued" strategic asset (Nanda and Nakao, 2003). After cattle, water buffaloes rank as the second most significant large-ruminant species in the world, and they are primarily raised for milk, meat, hides, and draught purposes. Water buffaloes that are no longer useful for draught work or dairy production (spent animals) are typically used to produce buffalo meat in India, which is generally known as "cara beef," whereas it is marketed as "beef" in the international market, mainly Vietnam, United Arab Emirates, Saudi Arabia, Malaysia, Indonesia, and Iraq (Naveena et al., 2011). The contribution of water buffalo meat to food security in Asia and the Middle East is substantial (Naveena and Kiran, 2014). The increasing demand for affordable buffalo meat effectively addresses a significant issue pertaining to food security in these regions. The growing demand presents equitable prospects for small-scale and landless agricultural workers to engage in global food markets, consequently fostering a conducive atmosphere for poverty alleviation and the enhancement of rural livelihoods in developing nations, in accordance with the UN

Sustainable Development Goals (SDG; United Nations, 2015; Shehata et al., 2022). Their significance within the global food sector has demonstrated a consistent upward trajectory, as evidenced by a multitude of scholarly publications (e.g., Naveena et al., 2004; Borghese and Mazzi, 2005; Neath et al., 2007a, 2007b; Minervino et al., 2020; Maheswarappa et al., 2022). Currently, water buffalo meat is available in economical segments of food markets, and water buffalo milk has a noteworthy function within the culinary domain, as demonstrated by its usage in the production of mozzarella cheese (Brescia et al., 2005; López-Calleja et al., 2005). Moreover, they function as a fiscally viable means of obtaining animal protein that offers nutritional advantages.

Water buffalo meat, known for its exceptional nutritional profile and environmentally friendly production methods, plays a crucial role in addressing the increasing protein needs of a rapidly expanding global population (Tamburrano et al., 2019; Minervino et al., 2020). As per the United Nations (2019), it is projected that the world's human population will attain 9.7 billion by 2050. This significant increase in population size is expected to result in a notable rise in the need for quality proteins. With the evolution of diets, particularly in developing nations, there arises a growing demand for protein sources that are both affordable and sustainable. The utilization of water buffalo meat is a feasible alternative owing to its advantageous nutritional composition, widespread accessibility, and reduced ecological impact in comparison to other large ruminants (Maheswarappa et al., 2022). The water buffalo population, which is predominantly concentrated in places such as Asia, Africa, and South America, plays a large role in global meat production (FAOSTAT, 2021). According to recent findings (Guerrero-Legarreta et al., 2020), consumers' acceptance of buffalo meat is changing as they become more aware of its nutritional advantages. The export market for buffalo meat has witnessed significant expansion, with nations such as India, Brazil, and Vietnam emerging as notable contributors to the export trade (FAOSTAT, 2021). The increasing popularity of buffalo meat is observable not only in its consumption within the domestic circle but also in its recognition and escalating requests in global markets. The increasing body of research and ongoing market trends suggest that buffalo meat is poised to play a more prominent role in satisfying the changing demands of consumers on a global scale (Wanapat et al., 2011). The current review provides a comprehensive overview of the water buffalo origin, distribution, slaughter, carcass and meat quality, composition, processing, and advances in the area of buffalo meat research to foster innovation and possible global collaborations for shaping the sustainable animal protein sector.

Geographical Distribution and Characterization of Major Water Buffalo Breeds

Domestic cattle (*Bos taurus* or *Bos indicus*) and water buffalo (*Bubalus bubalis*) are 2 distinct species; however, they both belong to the same family Bovidae and are phylogenetically related. Cattle is a primary bovine species, which is widely utilized for meat production in most parts of the world; however, there are other species—like the domestic water buffalo—belonging to the Bovidae family that are extensively utilized for meat production in Asia and to a lesser extent in Africa, South America, and Europe. The domestic buffalo, often referred to as the water buffalo, is distinct from the American bison (*Bison bison*), a wild animal that is often mistaken and incorrectly identified as a buffalo (Maheswarappa et al., 2022).

The water buffalo, also referred to as domestic Asian buffaloes, are divided into 2 subspecies: the river buffalo (*Bubalus bubalis bubalis*) and the swamp buffalo (*Bubalus bubalis carabanesis*). These types have 25 and 24 pairs of chromosomes, respectively. Although the precise evolutionary relationship between these species is yet unknown, the fusion of chromosomes 4 and 9 in swamp buffalo (Yavasoglu et al., 2014) demonstrates the genetic heterogeneity that exists among these 2 types. Another lesser-known buffalo species, the African buffalo, can be classified into 2 distinct subspecies, specifically the cape buffalo (*Syncerus caffer caffer*) and the forest buffalo (*Syncerus caffer nanus*). The cape buffalo is characterized by its possession of 26 pairs of chromosomes, while a forest buffalo exhibits 27 pairs (El-Debaky et al., 2019). Researchers must rely on genomic data from cattle because the genome sequence of both types of water buffalo are available in scaffolds on the National Center for Biotechnology Information (NCBI) platform. This highlights the need for high-resolution sequencing of the buffalo genome using cutting-edge research tools like transcriptomics, proteomics, metabolomics, and lipidomics (El-Debaky et al., 2019). The genetic populations of river buffalo exhibit global distribution patterns that can be attributed to many migration events occurring at different

Table 1. The global demographic distribution of water buffaloes in major buffalo-producing countries with % change over the last 20 years (year 2000 to 2020)

		Buffalo Population Distribution				
Continent	Country	Year 2000	Year 2020	% Change	Total Livestock Population	% Buffalo Population
Africa	Egypt	3530000	1348000	−61.81	9179562	14.68
America	Brazil	1102551	1502482	36.27	304065477	0.49
	Trinidad and Tobago	5450	6246	14.61	148699	4.20
Asia	Bangladesh	890000	1493000	67.75	87069565	1.71
	Burma	2441240	1983014	−18.77	21868285	9.07
	India	93831000	109736433	16.95	541313250	20.27
	Pakistan	22669000	41191000	18.17	229266938	17.96
	Indonesia	2405277	1154226	−52.01	66441564	1.74
	Philippines	3024403	2865715	−5.25	22483275	12.75
	Thailand	1711573	890078	−48.00	34283622013	0.00
	Vietnam	2897220	2332754	−19.48	34058649	6.85
	China	22595017	27247992	20.59	829920391	3.28
	Bhutan	2200	52365	2280.23	34283622013	0.00
	Iran	490600	171156	−65.11	79121244	0.22
	Iraq	115000	233453	103.00	10947067	2.13
	Nepal	3525952	5257591	49.11	27937127	18.82
USSR and EU		232499	480088	106.49	454234846	0.11
World		164254815	201181520	22.48	71056033027	0.28

Source: FAOSTAT, available online at: http://www.fao.org/faostat/en/#data/QCL (Accessed October 07, 2023).

historical and spatial scales (Colli et al., 2018). The river buffalo is the prevailing species, encompassing a range of breeds including Murrah, Nili-Ravi, Mediterranean, and Carabao (Olivatto et al., 2013). The majority of these demographics, comprising more than 80%, are concentrated in India, Pakistan, and China, while a minority of less than 5% are dispersed over non-Asian regions. According to FAOSTAT (2021), the current distribution of the world buffalo population is predominantly concentrated in Asia, accounting for around 97% of the total population. The buffalo herds in Asia frequently depend on low-quality roughages and leftover crops that have little nutritional value, leading to decreased productive and reproductive performances (Qureshi, 2009). However, water buffaloes are very good at converting poor-quality feed into high-quality milk and meat (Deb et al., 2016). Differences in production capacity give rise to discernible production systems in river and swamp buffaloes (Aziz et al., 2014).

Buffaloes predominantly inhabit tropical and subtropical climates, exhibiting adaptability to diverse grasses and vegetation. The global demographic distribution of buffaloes in major buffalo-producing countries is shown in Table 1. The prominent nations engaged in buffalo production globally include India, Pakistan, China, Nepal, Myanmar, Egypt, the Philippines, and Vietnam. India is widely recognized as the primary global producer of buffalo meat, with Pakistan and China occupying subsequent positions in terms of production. Globally, there has been a 22.48% increase in the buffalo population between the years 2000 and 2020; however, buffaloes still account for only 0.28% of the total livestock population. The Murrah breed, which has its origin in India, is widely recognized for its exceptional capacity for meat production, characterized by well-developed musculature and high-quality meat (Mello et al., 2017). The Nili-Ravi breed, originating from India and Pakistan, is known for its exceptional meat yield and marbling, rendering it a very desirable choice within the meat market (Mahkdoom et al., 2009). The Mediterranean buffalo breed, which is commonly found in Italy, Romania, and Egypt, is mostly exploited for dairy production; however, it also exhibits favorable meat qualities such as tenderness and juiciness (Hassan et al., 2018). The Carabao breed, which is indigenous to the Philippines, is highly esteemed for its meat characteristics. It possesses lean and palatable meat that is well-suited for a wide range of culinary uses (Ortega et al., 2021). The breeds exhibit variation in terms of their geographical distribution. The Murrah and Nili-Ravi buffalo breeds are mostly distributed in the Indian subcontinent, whereas the Mediterranean buffalo breed is more commonly found in the Mediterranean region and certain areas of Africa. The Carabao, however, is primarily found in Southeast Asia, with a specific concentration in the Philippines (Dehkordi et al., 2014; Colli et al., 2018).

Augmenting Meat Quality and Nutritional Characteristics

Breeding strategies

The use of various breeding strategies to augment water buffalo productivity and meat quality has received substantial attention in recent years from researchers and breeders (Safari et al., 2018); however, significant obstacles, such as the lack of efficient methods for determining oestrus and ensuring timely insemination, as well as innate reproductive problems unique to buffaloes, have yielded little success for traditional reproductive technologies (Purohit et al., 2003). Yet it is possible to select animals with higher genetic potential for meat yield, marbling, and tenderness by incorporating genomic data into the breeding program (Borghese and Mazzi, 2005). The field of genetic improvement in meat quality has witnessed accelerated advancements due to the implementation of genomic selection. This approach empowers breeders to make more accurate and informed selections when selecting desirable traits (Hayes et al., 2013). The quality of buffalo meat has been positively impacted by conventional breeding strategies such as selection based on phenotypic characteristics (Safari et al., 2018). The integration of conventional breeding techniques with genomic information has demonstrated its efficacy as a beneficial instrument for breeders in discerning buffaloes that display desirable meat attributes, ultimately leading to enhanced meat quality results (Ghoreishifar et al., 2020; Saravanan et al., 2022).

Feeding strategies

Buffaloes exhibit a remarkable ability to adjust to various rearing systems, ranging from extensive systems that depend on low-quality feeds with a high fiber content (Guerrero-Legarreta et al., 2020) to intensive systems that involve the provision of diets rich in protein and energy (Masucci et al., 2016). Buffalo production in tropical and subtropical regions exceeds that of other cattle species mostly as a result of the abundance of low-quality pastures (Ranjhan, 1992). The transformative and digestive capabilities of buffaloes have been mostly attributed to their capacity to process and extract nutrients from low-quality foods (Ranjhan, 1992).

A diet that is carefully formulated to meet specific nutritional requirements is of utmost importance in supporting the development of muscle, stimulating an increase in body weight, and improving reproductive efficacy (Ramadan, 2018). Diets that are rich in energy and protein sources, such as grains, oilseed meals, and high-quality forages, have been found to promote enhanced meat yield and improved feed efficiency (Iqbal et al., 2017). The use of traditional feeding techniques such as the practice of grazing on natural pastures results in limited accessibility of nutrients, leading to slower growth rates and decreased meat output (Cruz, 2007; Röös et al., 2018). In contrast, research indicates that intensive feeding systems utilizing well-balanced diets consisting of cereals, forages, and protein-rich concentrates have the potential to improve growth rates and optimize carcass characteristics (Lambertz et al., 2014; Conto et al., 2022). These diets enhance meat yield and quality by increasing lean meat content, promoting muscle growth, and decreasing fat deposition (Ekiz et al., 2018; Conto et al., 2022). The taste and flavor profile of buffalo meat can be significantly impacted by the feeding regimen employed. Numerous research studies have been conducted to examine the effects of various dietary interventions on fatty acid composition, carcass characteristics, and meat quality in ruminants that may be adopted in water buffaloes. These interventions include the utilization of bypass fat (Azmi et al., 2021), supplementation of vegetable oil (Wanapat et al., 2011), incorporation of unconventional feed sources such as spineless cactus and cottonseed (Beltrão et al., 2021), and the supplementation of sugarcane-based diets with spineless cactus (Borges et al., 2022). The growth and performance under similar rearing conditions in water buffaloes have been well reviewed recently (Rodas-González and Huerta-Leidenz, 2023a). Previous studies on other ruminant species offer insights for future feeding strategies in water buffalo meat production to enhance meat quality; however, further research is needed to specifically evaluate the effects of suggested feeding strategies on water buffalo. These studies highlight the significance of employing appropriate feeding techniques to achieve the best buffalo meat production outcomes, ensuring the satisfaction of consumers' sensory preferences and meeting their nutritional demands.

Slaughter, Carcass Traits, Composition, and Meat Quality

Slaughtering and carcass traits

After proper preslaughter care and antemortem examination, water buffaloes are moved to a slaughter hall and restrained using a stunning box, which is designed in such a manner to effectively restrict the free movement of animals, with the primary objective of ensuring the precise stunning and bleeding. A double rotary type killing box with motorized rotation and pneumatic/hydraulic operated doors, fully constructed of hot dip galvanized iron (SS304 grade), is employed in several buffalo slaughterhouses in India and other countries (Figure 1). Restrained water buffaloes are either stunned using captive bolt stunning or electrical stunning or directly bled using a sharp knife by severing the major neck blood vessels, namely the carotid artery and jugular vein at the C1–C3 (cervical vertebra) level. After bleeding, carcasses are subjected to electrical stunning with either low-voltage or high-voltage electric current (Muthukumar and Thulasi, 2006) followed by dehiding, head removal, evisceration, postmortem inspection, carcass trimming, washing, chilling, and fabrication (Figure 2). Dressed carcasses can undergo 3 primary methods of processing such as processed whole, split into halves (sides), or cut into quarters (fore quarter and hind quarter). Routinely, buffalo carcasses are fabricated into primal cuts. Primal cuts are frequently split into sub-primal cuts, which are typically vacuum sealed, frozen, or packaged fresh. Subsequently, portion cuts will be produced by sub-primal cuts as required.

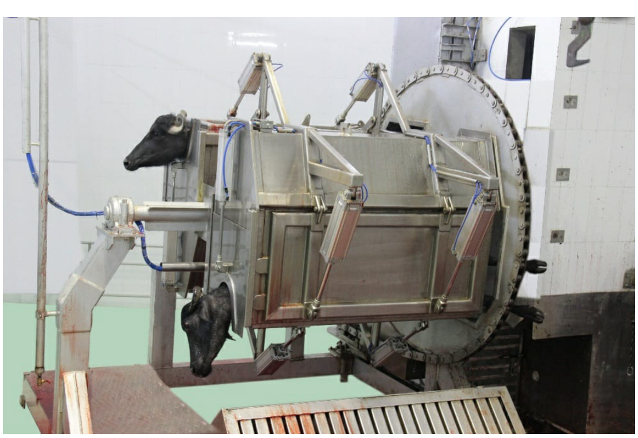

Figure 1. Double rotary stunning/killing box for water buffaloes (photo courtesy of MEATEK Food Machineries India Private Limited, India).

The average weight of a commercial water buffalo carcass in India is 62 kg to 139 kg (Singh et al., 2013); however, in a few countries, carcass weights ranging from 150 kg and 290 kg have been reported (Lambertz et al., 2014). Several studies have indicated that the dressing percentage of buffalo carcasses is similar to that of beef, ranging from 45% to 68% (Kumagai et al., 2012; Lambertz et al., 2014; Naveena and Kiran, 2014; Di Stasio and Brugiapaglia, 2021). Larger head and skin weight of Murrah buffaloes (21.0 kg and 53.2 kg) relative to Bulgarian cattle (19.0 kg and 47.0 kg) have been reported at 24–25 mo of age (Valin et al., 1984). Water buffaloes have shorter body and carcass lengths than cattle at 10 mo with a larger rump due to their thick and short quadriceps (Spanghero et al., 2004). Buffalo carcasses produce a greater yield of primal cuts, such as round cuts with a high commercial value relative to cattle carcasses (Mello et al., 2017). The variation in the ribeye area of water buffaloes, ranging from 40 to 70 cm^2, has been documented. In general, a lower ribeye area of 50.92 cm^2 was reported in water buffalo carcasses compared to 62.16 to 76.90 cm^2 in beef cattle at 24 mo of age (Latimori et al., 1997; Irurueta et al., 2008).

Composition

The composition of buffalo meat is often comparable to that of beef and contains an average of 74.2% moisture, 20.4% protein, 1.4% fat, and 1.0% ash (Tamburrano et al., 2019). Several factors, including age, gender, muscle type, slaughter weight, and feeding practices, have the potential to impact the fat content of an animal. In a comparative study, researchers examined the lipid profiles of water buffalo and zebu cattle that were raised in natural pasture conditions. The findings revealed that the buffalo meat lipid had a higher concentration of conjugated linoleic acid (CLA) at 1.83 mg/g, in contrast to the cattle lipid, which contained 1.47 mg/g (Giuffrida-Mendoza et al., 2015). Compared to other meats, the cholesterol content of buffalo meat is considerably lower at 50 mg/100 g (Naveena et al., 2022). The reported fatty acid values are within the range of several European cattle breeds with oleic, stearic, palmitic, and linoleic acids being the most prevalent. Andrade et al. (2022) have reported that the analysis of beef and buffalo meat has facilitated the detection of key volatile chemicals, including alcohols, aldehydes, and ketones. The results of earlier studies have shown that buffalo meat contains a higher concentration of unsaturated fatty acids than beef (Spanghero et al., 2004; Giuffrida-Mendoza et al., 2015). Analysis

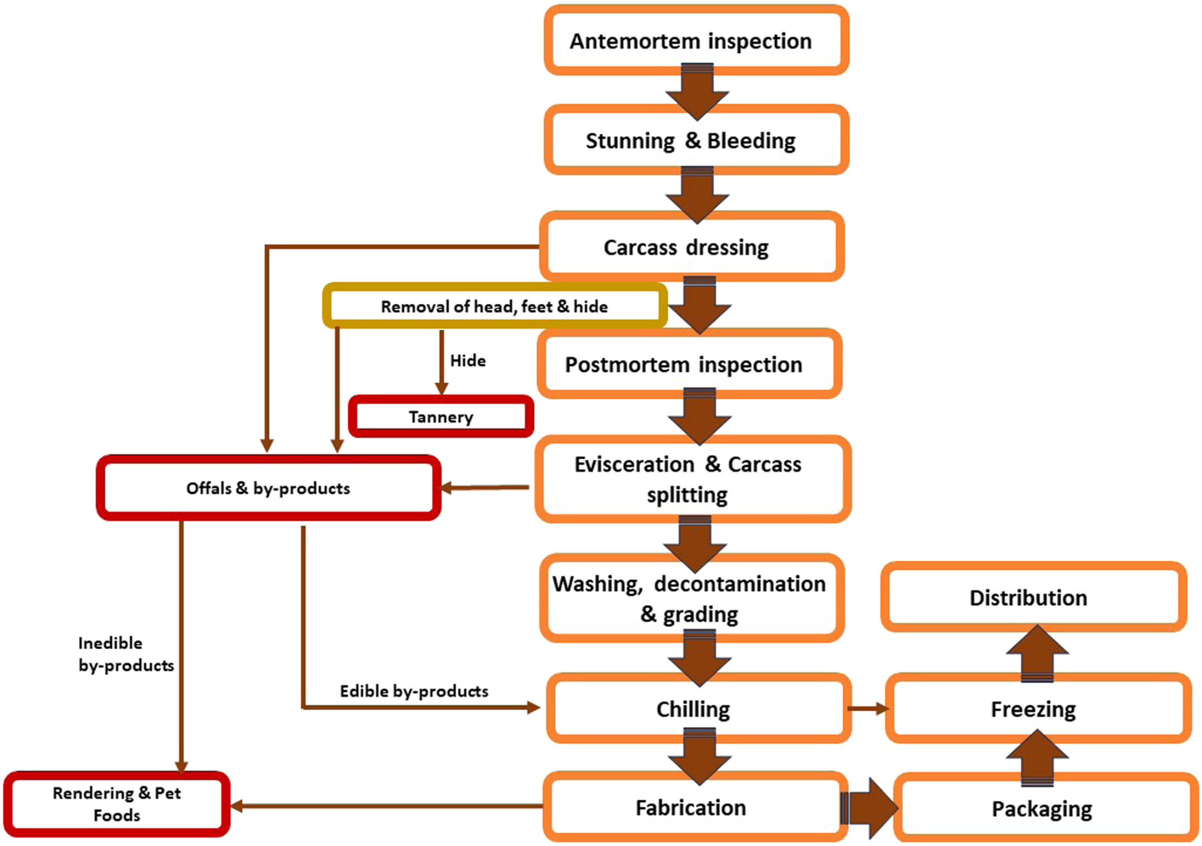

Figure 2. Primary processing steps in water buffalo slaughter, dressing, and fabrication.

of *Longissimus dorsi* muscles from male water buffaloes of the Campania region in Italy revealed 8.52 to 10.36 mg/100 g of essential amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, valine, and tryptophan) (Landi et al., 2016). Ilavarasan et al. (2016) analyzed the amino acid content of 12 male Toda buffaloes in India and reported 1.80 to 2.22 g/100 g of glutamic acid, followed by lysine (0.84–1.07 g/100 g) and aspartic acid (0.89–1.05 mg/100 g). Buffalo meat has abundant quantities of iron, zinc, phosphorus, sodium, potassium, magnesium, and other minerals. Buffalo meat was reported to contain higher iron content than beef (2.55 mg vs. 2.13 mg/100 g) at 24 mo of age, making it more nutritionally valuable (Infascelli et al., 2009). The nutritional composition of water buffalo meat in comparison with cattle meat produced under similar conditions has been recently reviewed (Rodas-González and Huerta-Leidenz, 2023b).

Meat quality

Water buffalo meat exhibits a large similarity to beef in terms of its composition, quality, and organoleptic characteristics while demonstrating comparatively higher iron content (Rodas-González and Huerta-Leidenz, 2023b). An overview of water buffalo meat quality and factors influencing different attributes has been depicted in Figure 3. The inherent characteristics of buffalo meat, including its color, tenderness, flavor, and juiciness, have a significant impact on customer preferences and the dynamics of the meat market. Buffalo meat is still regarded by the FAO (FAO, 2000) as a valuable and under-appreciated commodity. The color of buffalo meat, which serves as a visual indicator of its freshness and quality, is determined by the status and concentration of the myoglobin (Mb) pigment. The deep and intense red color of buffalo meat is related to its increased Mb concentration and oxygen-binding capacity. A higher Mb content in the *Longissimus* muscles, ranging from 2.36 mg/g to 3.59 mg/g, was linked to the darker color of the buffalo meat (Kiran et al., 2016). Variations of Mb content ranging from 2.7 mg/g to 9.4 mg/g depending upon the type of the muscle and age and an increase in darkness of meat with age have been reported (Valin et al., 1984). Maheswarappa et al. (2016) evaluated the molecular mass (17,043.6 daltons) and isoelectric point (6.77) of isolated Mb using matrix assisted laser desorption ionization-time of flight mass spectrometry

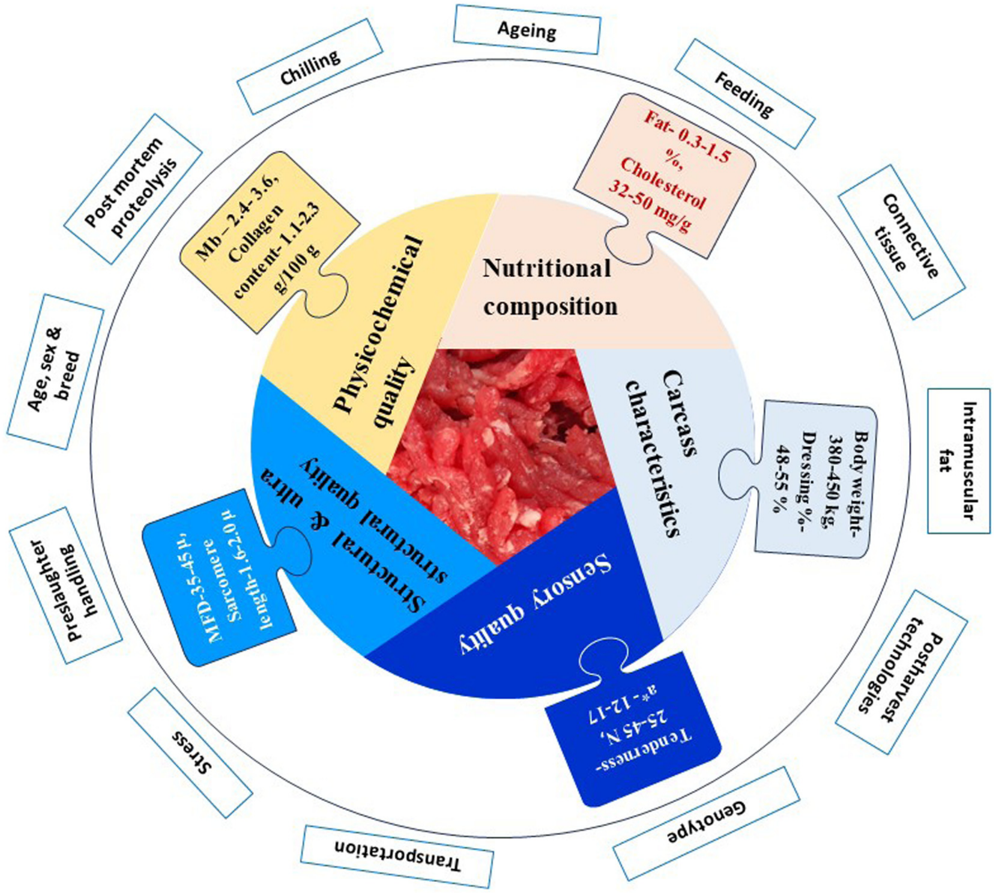

Figure 3. An overview of buffalo meat quality and factors influencing different attributes.

(MALDI-TOF MS) and an OFFGEL fractionator and concluded that buffalo Mb had greater redox stability than caprine (goat) Mb. After comparing the O_2 dissociation curves of purified bovine and buffalo Mb at pH 7.2 under the same experimental conditions, Dosi et al. (2006) came to the conclusion that the higher discoloration rate of buffalo Mb might be caused by larger Mb concentrations compared to beef as well as other species-specific variables. Fresh and frozen buffalo meat from various age groups were observed to have redness scores (*a** values) ranging from 12.0 to 20.0 (Tateo et al., 2007; Irurueta et al., 2008; Naveena et al., 2011).

The palatability of meat is significantly influenced by tenderness, which is particularly pronounced in buffalo meat. This can be attributed to the distinctive composition of buffalo muscle fibers, which possess a finer structure and relatively low levels of collagen (Naveena et al., 2011; Kiran et al., 2016). The pH range of buffalo meat is commonly observed to fall within the values of 5.4 and 5.6. Previous research has indicated that buffalo meat has a lower pH compared to beef (Valin et al., 1984; Spanghero et al., 2004; Lapitan et al., 2008; Kiran et al., 2016). Neath et al. (2007a) observed a relatively higher pH of water buffalo meat during the first 48 h postmortem, resulting in significantly higher calpain activity, and no discernible differences in calpastatin activity were seen between water buffalo meat and beef (Neath et al., 2007b). Sarcoplasmic and myofibrillar protein extractabilities have been found to be 65–68 mg/g protein and 148–160 mg/g protein, respectively, whereas the average water-holding capacity (WHC) has been reported to be between 14% and 23% (Kiran et al., 2015). The *Biceps femoris* muscles of spent female buffaloes were found to contain 0.67 mg/g of collagen with a 45% solubility (Naveena et al., 2011).

Warner-Bratzler shear force (WBSF) readings varying from 22.95 N to 33.45 N (*Longissimus dorsi*), 40.35 N to 41.64 N (*Biceps femoris*), 25.93 N to 27.13 N (*Gluteus medius*), 29.0 N to 32.03 N (*Gastrocnemius*), 38.08 N to 41.28 N (*Semimembranosus*), and 40.52 N to 44.98 N (*Semitendinosus*) were reported in castrated male buffaloes subjected to postmortem aging for 25 d (Irurueta et al., 2007). Kiran et al. (2015) have observed an average muscle fiber diameter of 44.22 μ and a sarcomere length of 1.70 μ in *Longissimus lumborum* (LL) muscles in spent female buffaloes of more than 10 y of age. Numerous investigations have identified several markers pertaining to tenderness, marbling, and muscle growth in different food animals. These include the calpain gene, calpastatin gene, calpain I gene (Warner et al., 2010), leptin gene, thyroglobulin gene, myogenic regulatory factors (Hernández-Hernández et al., 2017), and IGF1R polymorphisms (Hoopes et al., 2012). An in-depth investigation into the genetic markers associated with the economically important characteristics of buffalo meat has been reviewed by El-Debaky et al. (2019).

Buffalo Meat Proteomics

An overview of the application of proteomic tools in buffalo meat quality and authenticity is depicted in Figure 4. Proteins that influence the tenderness or toughness of buffalo meat that serve as potential biomarkers have been identified (Kiran et al., 2016). Proteomic studies allowed the identification of proteins including calcium/calmodulin-dependent 3, calcium-transporting ATPase type 2C, vitamin K-dependent protein Z precursor, and 5-cyclic nucleotide phosphodiesterase type 1B related to buffalo meat texture (Kiran et al., 2016). Potential biomarkers for buffalo meat quality include heat shock protein beta-1, Aspartate aminotransferase, Uroplakin-1b, Glycogen phosphorylase, Complement C1q subcomponent subunit B, Myosin-IIIa, Cytosolic carboxypeptidase 3, and Phosphatidylinositol transfer protein beta isoform (Kiran et al., 2015). Buffalo meat from young (<2 y) and old (>10 y) animals were studied to determine the biochemical, ultrastructural, and proteomic profile of *Longissimus dorsi* muscles (Kiran et al., 2015). Using two-dimensional gel electrophoresis (2-DE), these researchers have identified 93 proteins that differed between aged and young buffalo meat samples. The 2-DE proteome studies of buffalo meat from young and old after 6 d of aging showed 191 and 95 differentially expressed protein spots, respectively. A MALDI-TOF/TOF MS analysis was conducted on a subset of gel spots in order to identify structural

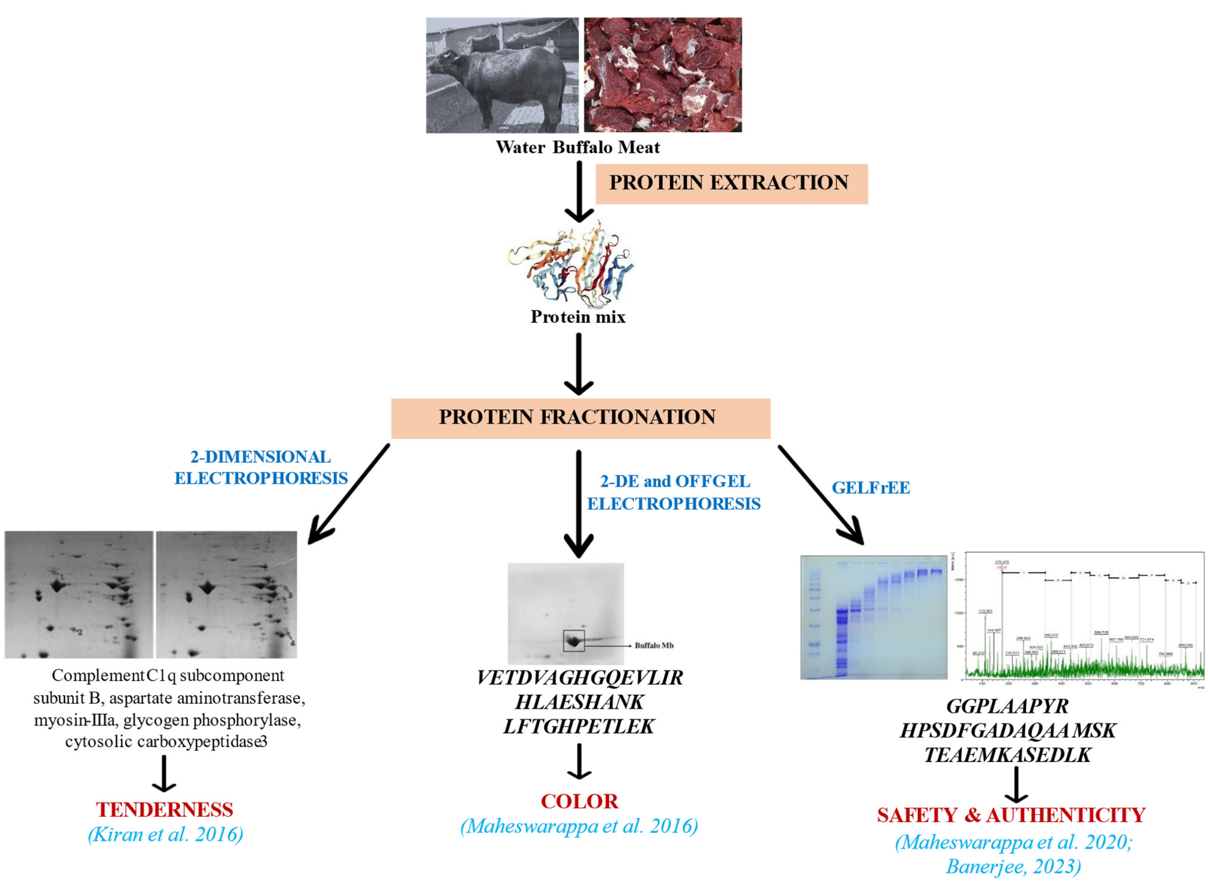

Figure 4. Illustration of proteomic tools and their applications for understanding water buffalo meat quality and safety.

proteins, which are molecular indicators for tenderness (Kiran et al., 2015). In another study, Kiran et al. (2016) examined the variations in meat quality between the less tender (LL) and more tender (*Psoas major* [PM]) muscles in Indian water buffaloes. The 2-DE proteome analysis of PM and LL yielded 123 proteins that differed in abundance between the 2 samples. There was a significant difference in the MALDI-TOF-TOF MS analysis of selected protein spots from LL and PM with substantial changes in protein composition. Research has shown that the 2-DE characteristics of buffalo and goat Mb differ, which was determined using OFFGEL electrophoresis. Covalent alteration of 7 and 9 histidine residues in water buffalo and goat Mb further supports the possibility of interaction with a lipid-derived aldehyde (HNE) by water buffalo Mb. The results indicate that water buffalo Mb is less susceptible than goat Mb to the redox destabilizing action of HNE (Maheswarappa et al., 2016).

Proteomics can also be efficiently employed for meat authenticity studies. The study conducted by Naveena et al. (2017) demonstrated the ability to detect the presence of buffalo meat adulteration in sheep meat at levels as low as 0.5% in meat mixes. The identification of the species was accomplished by employing species-specific peptides obtained from MLC-1, namely EAFLLFDRTGECK (water buffalo) and EAFLLYDRTGDGK (sheep), respectively, and MLC-2, namely FSKEEIK (water buffalo) and FSQEEIR (sheep). Using 2-DE (in-gel) and OFFGEL electrophoresis in conjunction with MALDI-TOF MS, up to 1.0% substitution of sheep and goat meat in buffalo meat was detected using the in-gel method, while the OFFGEL approach detected up to 0.1% substitution of sheep and goat meat in buffalo meat (Naveena et al., 2018). Researchers reported that OFFGEL and gel-eluted liquid fraction entrapment electrophoresis (GELFrEE) procedures may be used to separate proteins that are relatively low in abundance. It has been found that the GELFrEE 8100 cartridges can effectively fractionate entire buffalo meat proteins within a mass range of 10–240 kDa, 10–140 kDa, and 5%–12% GELFrEE 8100 cartridges (Maheswarappa et al., 2020). A peptidomic approach using simple GELFrEE and MALDI-TOF MS was developed for authentication of adulteration of water buffalo meat with pork under raw and cooked conditions up to 0.5% w/w (Banerjee et al., 2023). These researchers have demonstrated the heat stability of water buffalo-specific peptide markers derived from Mb (HPGDFGADAQGAMSK) and carbonic anhydrase-3 (GGPLTAAYR).

Interventions to Enhance Water Buffalo Meat Quality

Water buffalo meat color, tenderness, flavor, and juiciness play a crucial role in determining consumer acceptance. Researchers have reported the effect of postmortem aging/conditioning, muscle and pH effect, marination, and electrical stimulation for improving the tenderness of buffalo meat. Improved tenderness of buffalo carcasses subjected to high-voltage electrical stimulation (700 V, 1400 V peak, 60 Hz, 2 A) at 24 h postmortem was reported (Soares et al., 1995). These researchers have observed an acceleration of the aging process in electrically stimulated carcasses to 3 d compared to 6 d in non-stimulated carcasses. Similarly, the application of electrical stimulation after the slaughter process was reported to expedite the pH reduction, thereby facilitating enzymatic breakdown that plays a role in the tenderization of meat that has been reported (Neath et al., 2007a). Postmortem aging of *Longissimus thoracis* muscles from 32- to 36-month-old water buffalo during 21 d was reported to significantly reduce the WBSF values from 85.91 N to 48.64 N (Luz et al., 2017). However, in younger buffaloes of 20 to 24 mo of age, these researchers have reported a reduction in WBSF values from 59.62 N to 26.38 N during 21 d of aging in *Longissimus thoracis* muscles. The study concluded that 7 d of aging is optimum for younger (20 to 24 mo) buffaloes relative to 21 d of aging for older (32 to 36 mo) male Murrah buffaloes from Brazil. Similarly, Irurueta et al. (2008) observed a reduction in WBSF from 33.45 N to 22.95 N during 25 d of aging in water buffalo meat. Rajagopal and Oommen (2015) observed a strong correlation between myofibrillar fragmentation index (MFI) and WBSF in *Longissimus dorsi* muscles from 4- to 5-year-old male water buffalo aged at 2–4°C for 8 d and concluded that MFI is an immediate postmortem predictor of buffalo meat tenderness, and significant tenderization occurs during the first 24 h of postmortem aging. Pressure cooking of *Semimebranosus* muscles from spent female buffalo was reported to cause loss of integrity in the endomysium and perimysium layers (Vasanthi et al., 2007). Ginger rhizome (*Zingiber officinale*) marinade mixed with buffalo meat cubes was reported to reduce the shear force from 40.52 to 21.70 N while improving the cooking yield (Naveena and Mendiratta, 2005). Proteolytic enzymes from *Cucumis trigonus Roxb* (Kachri), ginger rhizome, and papain in *Biceps femoris* muscle chunks of spent buffaloes were reported to increase in sarcoplasmic and myofibrillar protein extractability and collagen solubility and reduce the shear force values relative to distilled water treated control (Naveena et al., 2004). Marination of *Biceps femoris* muscle chunks with 0.1%, 0.5%. and 1.0% v/w solution of ammonium hydroxide for 48 h at 4 ± 1°C has been reported to increase the WHC, total and salt soluble protein extractability, and collagen solubility and significantly reduce the WBSF values from 140 to 80 N (Naveena et al., 2011).

Value Addition of Buffalo Meat and Sensory Attributes

A significant number of buffaloes in the Asian continent undergo slaughter once they become infertile and stop producing milk, thereby resulting in tough and coarse meat (Naveena et al., 2011). Water buffalo meat is normally consumed in Asia as hot meat without subjecting it to further processing. Hence, converting into value-added meat products offers better opportunities for economic utilization. The 2% NaCl and 0.5% polyphosphate pre-blend into minced buffalo meat was reported to improve the emulsion stability, emulsifying capacity (EC), and cooking yield (Anjaneyulu et al., 1990). These researchers have evaluated different polyphosphates and concluded that the use of sodium pyrophosphate was highly effective in improving the pH, WHC, emulsion stability, protein extractability, cooking yield, and moisture content when used at 0.3 to 0.7% level. It has been reported that pre-blending minced buffalo meat with α-tocopherol acetate, sodium ascorbate, and sodium tripolyphosphate, followed by vacuum packaging and storage at 4°C, improves the meat's quality, shelf life, and color stability (Sahoo and Anjaneyulu, 1997). The processing of emulsion and restructured buffalo meat nuggets and their quality evaluation have been reported by Thomas et al. (2006).

The addition of buffalo fat to comminuted meat products has been found to have an impact on palatability due to increased saturation and inadequate fat distribution within the emulsion, leading to tongue coating (Pati et al., 1992). Hence, researchers have suggested the use of fat pre-mixes (Pati et al., 1992), refined mustard oil (Sahoo and Verma, 1999), and hydrocolloid fat substitutes like 0.1% sodium alginate and 0.75% carrageenan (Suman and Sharma, 2003). A low-fat burger made from comminuted buffalo meat has been successfully produced, incorporating several decorticated legume flours such as soya bean, Bengal gram, green gram, and black gram as binders with satisfactory quality (Modi et al., 2003). Ripening sausages from buffalo meat by adding pork fat (Luccia et al., 2003) and semi-dry fermented sausages containing different levels of buffalo heart and buffalo fat (Ahmad and Srivastava, 2007) have been reported. Curing and salting rump cuts from water buffalo hindquarters produced Bresaola, an Italian cold-cut food designated as a Geographic Protected Indication (GPI) (Paleari et al., 2000). Buffalo meat cubes that were shelf-stable were processed by adding sorbic acid, glycerol, sodium nitrite, sorbide, propylene glycol, and honey. They were then heated to 80°C for 20 min and then dried for 150 min at 80°C (Malik and Sharma, 2014). Due to its leanness, lower intramuscular fat, cholesterol, and calories, higher units of essential amino acids, biological value, and iron content, water buffalo meat has become more popular as the demand for lean red meat has increased (Anjaneyulu et al., 1990). It has been observed that water buffalo meat and beef from similar age groups have almost identical palatability traits, shear force values, and taste panel ratings (Ognjanovic, 1974). According to Lapitan et al. (2007), the marbling score, firmness, tenderness, and WHC of buffalo meat were all similar to those of cattle beef.

Valorization of Water Buffalo Co-Products

The utilization of buffalo slaughter co-products has emerged as a noteworthy economic and public health issue. Processing of various carcass by-products encompasses around 15 unique industries, covering areas such as food, pharmaceuticals, leather, biochemicals, sports, dairy, cosmetics, animal feed, detergents, handicrafts, and fat refining. Water buffalo slaughter co-products and a few commercially available value-added products have been depicted in Figure 5. The proportion of edible co-products (head, liver, feet, heart, stomach, kidney, and fat) and inedible co-products (blood, skin, intestine, and lungs) in relation to the live weight of buffalo ranges from 25% to 30%. The gastrointestinal tract (25–27%) was found to contribute the highest percentage of co-products, followed by the skin (9–11%) (Muthukumar et al., 2017; Singh et al., 2018). The liver of water buffalo could be employed commercially for the preparation of acceptable minced meat products (Devatkal et al., 2004). Buffalo hide is excellent, robust, and reasonably priced leather that may be processed into shoe soles and other leather goods. Acid pre-treatment of buffalo hide and production of industry-standard gelatin has been

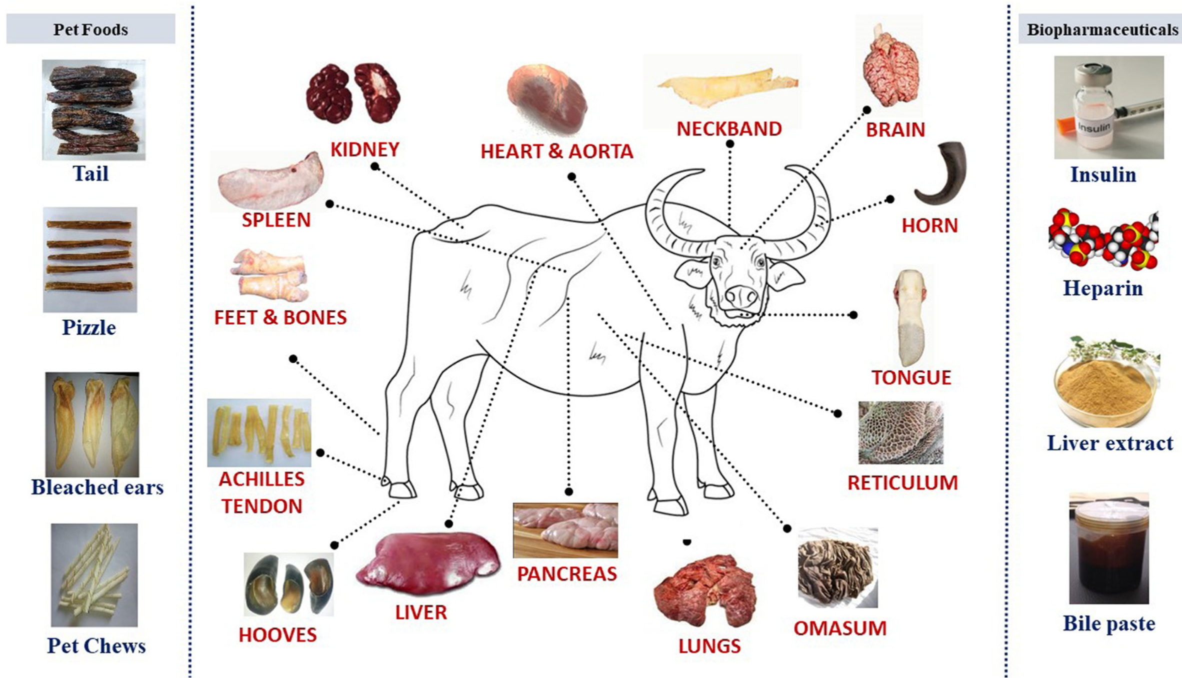

Figure 5. Buffalo meat industry co-products and their valorisation approaches.

reported by Mulyani et al. (2017). Extraction and characterization of chondroitin sulfate (CS) from buffalo tracheal, nasal, and joint cartilages have been reported by Sundaresan et al. (2018). Buffalo skin strips that have been softened with inedible fat can be woven into robust, attractive, and durable ropes. Buffalo hides are utilized in certain regions of Indonesia, Thailand, and Nepal to produce delicious buffalo chips. Massive buffalo horns are used to create a range of ornamental and decorative items. A musical instrument named tetuag is made in Malaysia using buffalo horns (Maheswarappa et al., 2022). Different varieties of pet treats were made from bleached ears, food pipes, dried tails, dried udder, bladder flat, hooves, neckband, Achilles tendon, pizzle, etc. Besides these, bleached braided skin, bleached head skin roll, bleached head skin, bleached press bone, bleached twisted stick, metatarsal bone bleach, etc., were also made from buffalo slaughter co-products. Rendering of offals and slaughter waste produces meat and bone meal with 48–52% protein, 33–35% ash, 8–12% fat, and 4–7% moisture, which is mainly used in the formulation of poultry and aquaculture feed. Extraction and characterization of angiotensin converting enzyme (ACE)-inhibitory peptides from water buffalo liver has been recently reported by Maheswarappa et al. (2022). The optimal utilization of co-products from the buffalo sector is imperative in order to satisfy the increasing need for animal proteins and extraction of high-value hydrolysates and biostimulants will offer great scope in food supplements, nutraceuticals, and human nutrition.

Water Buffaloes—Promising Candidates for Sustainable and Circular Production

An expanding cohort of conscientious consumers places an emphasis on ethical and environmentally responsible food selection, thereby guiding the industry to adopt sustainable and circular practices. To a large extent, Asiatic water buffaloes are reared under free-range, natural conditions, mostly feeding on locally available feed resources like coarse feed, sugar cane waste, straw, and crop residues. Because of their capacity to convert and digest low-quality feed, buffaloes have been shown to yield higher milk/meat than other bovine species in tropical or subtropical areas with poor pasture quality (Ranjhan, 1992). This suggests that buffaloes are climate-friendly animals that can produce excellent meat and milk from low-quality feed without the need for supplement concentrates (Hamid et al., 2016). Buffalo production is dominated by marginal farmers, small-holders, and women who contribute primarily to small-scale operations, and buffaloes as a species have desirable qualities (Choudhary and Sirohi, 2019). The local production and consumption practices and preference for hot meat followed in India and many other Asian countries ensure reduced water footprints and lower food miles. Buffaloes exhibit remarkable adaptations to thrive in hot and humid floodplain environments, hence assuming a significant economic role in numerous tropical and subtropical nations. These animals are highly adaptable under resource-poor tropical conditions, exhibit a higher degree of resistance to diseases, and survive with minimal housing and managemental conditions (Cockrill, 1981). Buffaloes serve multiple purposes, including the provision of milk, meat, manure, and draught power, hence making a substantial contribution towards the attainment of several SDG. The water buffalo sector contributes to fulfilling social benefits (zero hunger, good health, and well-being), economic resilience (no poverty, quality education, gender equality, decent work, and economic growth), and environmentally responsible (responsible consumption and production, climate action) objectives of SDG. Buffaloes exhibit a range of desirable traits that contribute to sustainable livestock production, including disease resistance, enhanced digestibility of low-quality pasture, adaptability to diverse climatic conditions, and rapid growth and weight gain, highlighting the versatility and positive impact of buffaloes in the context of sustainable livestock production (Maheswarappa et al., 2022). Sustainable production methods can be fostered by boosting the use of water buffalo meat from spent and unproductive animals, which will improve the ecological balance and resilience of agricultural landscapes. Adoption of scientific practices and disruptive technologies, improved breeding and feeding practices, optimal realization of both meat and dairy commodities with control, and eradication of transboundary animal diseases through one-health approaches may further enhance the role of buffaloes in fulfilling SDG.

There is great potential for male buffalo calf (MBC) salvaging and rearing for meat in India. There are about 18–20 million MBC available per annum, and most of them perish without their full economic potential being realized. Buffalo calf mortality is abnormally high, as farmers do not provide adequate milk to calves and do not give adequate health care such as deworming and management of calves. Due to the age restrictions by various state governments in India on the slaughter of steers for meat purposes, raising the male calves until 10 y is non-remunerative. With positive slaughter-policy interventions, even if 50% of these MBC are salvaged and grown to a live weight of 200–300 kg, they would produce an additional 1.0 million tonnes (MT) boneless meat, which is worth Rs 30,000 crores (~5 billion USD). However, exclusive government schemes to support these activities must be launched, and state governments must amend the existing rules to slaughter male buffalo steers (Naveena et al., 2021). This will further enhance the sustainability of water buffalo production in India.

Conclusion

The strategy for meeting the burgeoning global demand for animal proteins in the coming years involves the integration of nutrition, economics, and culture. Water buffaloes, with their multiple uses and versatility, may serve as sustainable and circular alternatives to other red meat sources. From an economic standpoint, it wields substantial influence inside rural communities, fostering the advancement of livelihoods and aiding economic expansion. The trajectory of buffalo meat in the future is characterized by a complex journey that involves various problems, possibilities, and transformational advancements. The utilization of genomic selection as a breeding strategy presents a prospective approach to selectively enhance the meat and milk characteristics of buffaloes while concurrently preserving their inherent adaptability to hotter and more humid climates. The development of desired meat qualities must be furthered through advanced omics research while remaining consistent with sustainability standards. The integration of sustainable practices, salvaging of MBC, disruptive technologies, and innovative research will reshape the industry's environment, establishing a domain in which buffalo meat emerges as a high-quality, ethically conscious, and environmentally sustainable option for conscientious consumers. The future prospects of buffalo meat are contingent upon the intersection of research and innovation.

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Literature Cited

Ahmad, S., and P. K. Srivastava. 2007. Quality and shelf life evaluation of fermented sausages of buffalo meat with different levels of heart and fat. Meat Sci. 75:603–609. https://doi.org/10.1016/j.meatsci.2006.09.008

Andrade, B. F., M. M. D. O. Paula, J. D. D. S. Carneiro, P. R. Fontes, R. D. A. T. Filho, E. M. Ramos, and A. D. L. S. Ramos. 2022. Influence of intrinsic and extrinsic factors on the sensory perception and intention to purchase buffalo meat by consumers in Southeast Brazil. Brazilian Journal of Food Technology 25:e2022002. https://doi.org/10.1590/1981-6723.00222

Anjaneyulu, A. S. R., N. Sharma, and N. Kondaiah. 1990. Specific effect of phosphate on the functional properties and yield of buffalo meat patties. Food Chem. 36:149–154. https://doi.org/10.1016/0308-8146(90)90098-O

Aziz, A., A. H. Shah, I. Haq, M. Khaskheli, M. Salman, and A. R. Talpur. 2014. Comparative studies on nutritional quality of cattle and buffalo meat. International Journal of Science and Research 3:524–531.

Azmi, A. F. M., F. M. Amin, H. Ahmad, N. M. Nor, G. Y. Meng, M. Z. Saad, M. Z. A. Bakar, P. Abdullah, A. Irawan, A. Jayanegara, and H. A. Hassim. 2021. Effects of bypass fat on buffalo carcass characteristics, meat nutrient contents and profitability. Animal 11:3042. https://doi.org/10.3390/ani11113042

Banerjee, R., N. B. Maheswarappa, S. Biswas, S. Dasoju, K. Mohan, and R. Ramanathan. 2023. Peptidomics approaches for meat authentication employing rapid in-solution GELFrEE fractionation and MALDI-TOF MS. J. Food Compos. Anal. 121:105349. https://doi.org/10.1016/j.jfca.2023.105349

Beltrão, E. S., A. M. D. A. Silva, J. M. P. Filho, J. F. P. D. Moura, J. P. F. D. Oliveira, T. P. Dias-Silva, and L. R. Bezerra. 2021. Effect of different blend levels of spineless cactus and Mombasa hay as roughage on intake, digestibility, ingestive behavior, and performance of lambs. Trop. Anim. Health Pro. 53:140. https://doi.org/10.1007/s11250-021-02585-7

Borges, C. R. D. A., F. F. R. D. Carvalho, M. L. M. W. Neves, J. D. P. Neto, G. H. P. Vieira, and R. A. S. Pessoa. 2022. Carcass and meat traits of bubaline finished on sugarcane-based diets supplemented with spineless cactus as a replacement for wheat bran. Animal Bioscience 35:47. https://doi.org/10.5713/ab.20.0825

Borghese, A., and M. Mazzi. 2005. Buffalo population and strategies in the world. In: A. Borghese, editor, Buffalo Production and Research. FAO Regional Office for Europe Inter-Regional Cooperative Research Network on Buffalo. pp. 1–39. http://www.fao.org/docrep/010/ah847e/ah847e00.htm

Brescia, M. A., M. Monfreda, A. Buccolieri, and C. Carrino. 2005. Characterisation of the geographical origin of buffalo milk and mozzarella cheese by means of analytical and spectroscopic determinations. Food Chem. 89:139–147. https://doi.org/10.1016/j.foodchem.2004.02.016

Choudhary, B. B., and S. Sirohi. 2019. Sensitivity of buffaloes (*Bubalus bubalis*) to heat stress. J. Dairy Res. 86:399–405. https://doi.org/10.1017/S0022029919000773

Cockrill, W. R. 1981. The water buffalo: A review. Brit. Vet. J. 137:8–16. https://doi.org/10.1016/s0007-1935(17)31782-7

Colli, L., M. Milanesi, E. Vajana, D. Iamartino, L. Bomba, F. Puglisi, M. D. Corvo, E. L. Nicolzzi, S. S. E. Ahmed, J. R. V. Herrera, L. Cruz, S. Zhang, A. Liang, G. Hua, L. Yang, X. Hao, F. Zuo, S.-J. Lai, S. Wang, R. Liu, Y. Gong, M. Mokhber, Y. Mao, F. Guan, A. Vlaic, L. Ramunno, G. Cosenza, A. Ahmad, I. Soysal, E. Ünal, M. Ketudat-Cairns, J. F. Garcia, Y. Utsunomiya, P. S. Baruselli, M. E. J. Amaral, R. Pampai, M. G. Drummond, P. Galbusera, J. Burton, E. Hoal, Y. Yusnizar, C. Sumantri, B. Moioli, A. Valentini, A. Stella, J. L. Williams, and P. Ajmone-Marsan. 2018. New insights on water buffalo genomic diversity and post-domestication migration routes from medium density SNP chip data. Frontiers in Genetics 9:53. https://doi.org/10.3389/fgene.2018.00053

Conto, M., G. F. Cifuni, M. Iacurto, and S. Failla. 2022. Effect of pasture and intensive feeding systems on the carcass and meat quality of buffalo. Animal Bioscience 35:105. https://doi.org/10.5713/ab.21.0141

Cruz, L. C. 2007. Trends in buffalo production in Asia. Ital. J. Anim. Sci. 6:9–24. https://doi.org/10.4081/ijas.2007.s2.9

Deb, G. K., T. N. Nahar, P. G. Duran, and G. A. Presicce. 2016. Safe and sustainable traditional production: the water buffalo in Asia. Frontiers in Environmental Science 4:38. https://doi.org/10.3389/fenvs.2016.00038

Dehkordi, F. S., F. Khamesipour, and M. Momeni. 2014. Brucella abortus and Brucella melitensis in Iranian bovine and buffalo semen samples: The first clinical trial on seasonal, senile and geographical distribution using culture, conventional and real-time polymerase chain reaction assays. Kafkas. Univ. Vet. Fak. 20:821–828. https://doi.org/10.9775/kvfd.2014.10827

Devatkal, S. K., S. K. Mendiratta, and N. Kondaiah. 2004. Quality characteristics of loaves from buffalo meat, liver and vegetables. Meat Sci. 67:377–383. https://doi.org/10.1016/j.meatsci.2003.11.006

Di Stasio, L., and A. Brugiapaglia. 2021. Current knowledge on river buffalo meat: A critical analysis. Animals 11:2111. https://doi.org/10.3390/ani11072111

Dosi, R., A. D. Maro, A. Chambery, G. Colonna, S. Costantini, G. Geraci, and A. Parente. 2006. Characterization and kinetics studies of water buffalo (Bubalus bubalis) myoglobin. Comp. Biochem. Phys. B. 145:230–238. https://doi.org/10.1016/j.cbpb.2006.07.006

Ekiz, B., A. Yilmaz, H. Yalcintan, A. Yakan, I. Yilmaz, and I. Soysal. 2018. Carcass and meat quality of male and female water buffaloes finished under an intensive production system. Ann. Anim. Sci. 18:557. https://doi.org/10.1515/aoas-2017-0036

El-Debaky, H. A., N. A. Kutchy, A. Ul-Husna, R. Indriastuti, S. Akhter, B. Purwantara, and E. Memili. 2019. Potential of water buffalo in world agriculture: Challenges and opportunities. Applied Animal Science 35:255–268. https://doi.org/10.15232/aas.2018-01810

FAO. 2000. Water buffalo: An asset undervalued. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. 1–6.

FAOSTAT. 2021. Food and Agriculture Organization of the United Nations Statistical Database. Retrieved from http://www.fao.org/faostat/en/#data/QA. (Accessed 13 September 2021).

Ghoreishifar, S. M., H. Moradi-Shahrbabak, M. H. Fallahi, A. Jalil Sarghale, M. Moradi-Shahrbabak, R. Abdollahi-Arpanahi, and M. Khansefid. 2020. Genomic measures of inbreeding coefficients and genome-wide scan for runs of homozygosity islands in Iranian river buffalo, Bubalus bubalis. BMC Genomic Data 21:1–12. https://doi.org/10.1186/s12863-020-0824-y

Giuffrida-Mendoza, M., L. A. D. Moreno, N. Huerta-Leidenz, S. Uzcátegui-Bracho, K. Valero-Leal, S. Romero, and A. Rodas-González. 2015. Cholesterol and fatty acid composition of longissimus thoracis from water buffalo (Bubalus bubalis) and Brahman-influenced cattle raised under savannah conditions. Meat Sci. 106:44–49. https://doi.org/10.1016/j.meatsci.2015.03.024

Guerrero-Legarreta, I., F. Napolitano, R. Cruz-Monterrosa, D. Mota-Rojas, P. Mora-Medina, J. E. Ramírez-Bribiesca, A. B. Mendoza, J. Berdugo, and A. Braghieri. 2020. River buffalo meat production and quality: Sustainability, productivity, nutritional and sensory properties. J. Buffalo Sci. 9:159–169. ISSN: 1927-5196/E-ISSN: 1927-520X/20.

Hamid, M. A., M. N. A. Siddiky, M. A. Rahman, and K. M. Hossain. 2016. Scopes and opportunities of buffalo farming in Bangladesh: A review. SAARC Journal of Agriculture 14:63–77. https://doi.org/10.3329/sja.v14i2.31246

Hassan, M. A., H. H. Abdel-Naeem, H. M. Mohamed, and N. A. Yassien. 2018. Comparing the physico-chemical characteristics and sensory attributes of imported brazilian beef meat and imported Indian buffalo meat. Journal of Microbiology, Biotechnology and Food Sciences 8:672. https://doi.org/10.15414/jmbfs.2018.8.1.672-677

Hayes, B. J., H. A. Lewin, and M. E. Goddard. 2013. The future of livestock breeding: Genomic selection for efficiency, reduced emissions intensity, and adaptation. Trends Genet. 29: 206–214. https://doi.org/10.1016/j.tig.2012.11.009

Hernández-Hernández, J. M., E. G. García-González, C. E. Brun, and M. A. Rudnicki. 2017. The myogenic regulatory factors, determinants of muscle development, cell identity and regeneration. Semin. Cell Dev. Biol. 72:10–18. https://doi.org/10.1016/j.semcdb.2017.11.010

Hoopes, B. C., M. Rimbault, D. Liebers, E. A. Ostrander, and N. B. Sutter. 2012. The insulin-like growth factor 1 receptor (IGF1R) contributes to reduced size in dogs. Mamm. Genome 23:780–790. https://doi.org/10.1007/s00335-012-9417-z

Ilavarasan, R., R. J. J. Abraham, V. A. Rao, S. W. Ruban, and R. Ramani. 2016. Effect of age on meat quality characteristics and nutritional composition of Toda buffalo. Buffalo Bull. 35:215–223.

Infascelli, F., M. Roscia, and F. Buffardi. 2009. La carne di bufalo. Edizioni Pubblicita Italia.

Iqbal, Z. M., M. Abdullah, K. Javed, M. A. Jabbar, N. Ahmad, Y. A. Ditta, H. Mustafa, and F. Shahzad. 2017. Effect of varying levels of concentrate on growth performance and feed economics in Nili-Ravi buffalo heifer calves. Turk. J. Vet. Anim. Sci. 41:775–780. https://doi.org/10.3906/vet-1702-1

Irurueta, M., A. Cadoppi, L. Langman, G. Grigioni, and F. Carduza. 2008. Effect of aging on the characteristics of meat from water buffalo grown in the Delta del Paraná region of Argentina. Meat Sci. 79:529–533. https://doi.org/10.1016/j.meatsci.2007.12.010

Irurueta, M., A. J. Pordomingo, G. Grigioni, F. Carduza, A. B. Pordomingo, and G. V. Lagreca. 2007. Effects of pasture grazing vs feedlot feeding on meat quality of young steers. 53rd Proceedings of Intl. Congress of Meat Sci., Beijing, China.

Kiran, M., B. M. Naveena, K. S. Reddy, M. Shahikumar, V. R. Reddy, V. V. Kulkarni, and T. H. More. 2016. Understanding tenderness variability and ageing changes in buffalo meat: Biochemical, ultrastructural and proteome characterization. Animal. 10:1007–1015. https://doi.org/10.1017/S1751731115002931

Kiran, M., B. M. Naveena, K. S. Reddy, M. Shashikumar, V. R. Reddy, V. V. Kulkarni, and T. H. More. 2015. Muscle-specific variation in buffalo (Bubalus bubalis) meat texture: biochemical, ultrastructural and proteome characterization. J. Texture Stud. 46:254–261. https://doi.org/10.1111/jtxs.12123

Kumagai, H., B. R. Baral, T. Shiino, N. R. Devkota, K. Oishi, and H. Hirooka. 2012. Effects of plane of nutrition on slaughtering traits and meat characteristics in Murrah graded male buffalo (Bubalus bubalis) calves in Nepal. Anim. Sci J. 83:434–438. https://doi.org/10.1111/j.1740-0929.2011.00970.x

Lambertz, C., P. Panprasert, W. Holtz, E. Moors, S. Jaturasitha, M. Wicke, and M. Gauly. 2014. Carcass characteristics and meat quality of swamp buffaloes (Bubalus bubalis) fattened at different feeding intensities. Asian Austral. J. Anim. 27:551. https://doi.org/10.5713/ajas.2013.13555

Landi, N., A. M. A. D. Giuseppe, S. Ragucci, and A. D. Maro. 2016. Free amino acid profile of Bubalus bubalis L. meat from the Campania region. Rev. Bras. Zootecn. 45:627–631. https://doi.org/10.1590/S1806-92902016001000008

Lapitan, R. M., A. N. D. Barrio, O. Katsube, T. Ban-Tokuda, E. A. Orden, A. Y. Robles, T. Fujihara, L. C. Cruz, H. Homma, and Y. Kanai. 2007. Comparison of carcass and meat characteristics of Brahman grade cattle (Bos indicus) and crossbred water buffalo (Bubalus bubalis). Anim. Sci. J. 78:596–604. https://doi.org/10.1111/j.1740-0929.2007.00480.x

Lapitan, R. M., A. N. D. Barrio, O. Katsube, T. Ban-Tokuda, E. A. Orden, A. Y. Robles, L. C. Cruz, Y. Kanai, and T. Fujihara. 2008. Comparison of carcass and meat characteristics of Brahman grade cattle (Bos indicus) and crossbred water buffalo (Bubalus bubalis) fed on high roughage diet. Anim. Sci. J. 79:210–217. https://doi.org/10.1111/j.1740-0929.2008.00519.x

Latimori, N., A. Kloster, F. Carduza, and C. Margaria. 1997. Producción de novillos para exportación en sistemas pastoriles intensificados. Revue d'Intelligence Artificielle 28: 87–98.

López-Calleja, I., I. G. Alonso, V. Fajardo, M. A. Rodríguez, P. E. Hernández, T. García, and R. Martín. 2005. PCR detection of cows' milk in water buffalo milk and mozzarella cheese. Int. Dairy J. 15:1122–1129. https://doi.org/10.1016/j.idairyj.2004.12.003

Luccia, A. D., A. Satriani, C. Barone, P. Colatruglio, S. Gigli, M. Occidente, E. Trivellone, A. Zullo, and D. Matassino. 2003. Effect of dietary energy content on the intramuscular fat depots and triglyceride composition of river buffalo meat. Meat Sci. 65:1379–1389. https://doi.org/10.1016/S0309-1740(03)00060-3

Luz, P. A. C. D., A. M. Jorge, C. D. L. Francisco, J. L. M. D. Mello, C. T. Santos, and C. Andrighetto. 2017. Chemical-physical characteristics of buffalo (Bubalus bubalis) meat subjected to different aging times. Acta Scientiarium-Animal Sciences 39: 419–428. https://doi.org/10.4025/actascianimsci.v39i4.36799

Maheswarappa, N. B., R. Banerjee, M. Muthupalani, S. Barbuddhe, S. Dasoju, and P. Varakumar. 2020. Optimization of novel GELFrEE fractionation for molecular weight–based in-solution protein separation from buffalo meat, pork, and chicken. Food Anal. Method 14:88–97. https://doi.org/10.1007/s12161-020-01839-8

Maheswarappa, N. B., M. Muthupalani, K. Mohan, R. Banerjee, A. R. Sen, and S. B. Barbuddhe. 2022. Buffalo slaughtering, dressing, and carcass fabrication. In: Asiatic water buffalo: A sustainable and healthy red meat source. Springer Nature Singapore, Singapore. p. 35–48. https://doi.org/10.1007/978-981-19-2619-8

Maheswarappa, N. B., K. U. Rani, Y. P. Kumar, V. V. Kulkarni, and S. Rapole. 2016. Proteomic-based approach for characterizing 4-hydroxy-2-nonenal induced oxidation of buffalo (Bubalusbubalis) and goat (Capra hircus) meat myoglobins. Proteome Sci. 14:1–16. https://doi.org/10.1186/s12953-016-0108-7

Mahkdoom, A. J., A. Rehman, M. Fiaz, A. H. Gilani, T. N. Pasha, and I. B. Marghazani. 2009. Comparative performance of calves of buffalo and different breeds of cattle on feedlot fattening. Pak. J. Zool. Supplementary Series 9:401–407.

Malik, A., and B. D. Sharma. 2014. Shelf-life study of hurdle treated ready-to-eat spiced buffalo meat product stored at 30±3 °C for 7 weeks under vacuum and aerobic packaging. J. Food Sci. Tech. 51:832–844. https://doi.org/10.1007/s13197-011-0592-9

Masucci, F., G. D. Rosa, C. M. A. Barone, F. Napolitano, F. Grasso, P. Uzun, and A. D. Francia. 2016. Effect of group size and maize silage dietary levels on behaviour, health, carcass and meat quality of Mediterranean buffaloes. Animal 10:531–538. https://doi.org/10.1017/S1751731115002359

Mello, J. L. M., A. B. B. Rodrigues, A. Giampietro-Ganeco, F. B. Ferrari, R. A. Souza, P. A. Souza, and H. Borba. 2017. Characteristics of carcasses and meat from feedlot-finished buffalo and Bos indicus (Nellore) bulls. Anim. Prod. Sci. 58:1366–1374. https://doi.org/10.1071/AN16556

Minervino, A. H. H., M. Zava, D. Vecchio, A. Borghese. 2020. Bubalus bubalis: A short story. Frontiers in Veterinary Science 570413:1–15. https://doi.org/10.3389/fvets.2020.570413

Modi, V. K., N. S. Mahendrakar, D. Narasimha Rao, N. M. Sachindra. 2003. Quality of buffalo meat burger containing legume flours as binders. Meat Sci. 66:143–149. https://doi.org/10.1016/S0309-1740(03)00078-0

Mulyani, S., F. M. C. S. Setyabudi, Y. Pranoto, U., and Santoso. 2017. Physicochemical properties of gelatin extracted from buffalo hide pretreated with different acids. Korean J. Food Sci. An. 37:708–715. https://doi.org/10.5851/kosfa.2017.37.5.708

Muthukumar, M., G. Kandeepan, V. Pathak, K. S. Rathod, R. K. Ambadkar, and V. V. Kulkarni. 2017. Carcass traits and value of meat and byproducts of buffalo. Indian J. Anim. Sci. 88: 95–100. https://doi.org/10.56093/ijans.v88i3.78306

Muthukumar, M., and Thulasi, G. 2006. Effect of electrical stimulation on biochemical characteristics and tenderness of buffalo meat. Indian J. Anim. Sci. 76:971–973. https://epubs.icar.org.in/index.php/IJAnS/article/view/4483

Nanda, A. S., and Nakao, T. 2003. Role of buffalo in the socioeconomic development of rural Asia: Current status and future prospectus. Anim. Sci. J. 74:443–455. https://doi.org/10.1046/j.1344-3941.2003.00138.x

Naveena, B. M., and M. Kiran. 2014. Buffalo meat quality, composition, and processing characteristics: Contribution to the global economy and nutritional security. Animal Frontiers 4:18–24. https://doi.org/10.2527/af.2014-0029

Naveena, B. M., D. S. Jagadeesh, A. J. Babu, T. M. Rao, V. Kamuni, S. Vaithiyanathan, V. V. Kulkarni, and S. Rapole. 2017. OFFGEL electrophoresis and tandem mass spectrometry approach compared with DNA-based PCR method for authentication of meat species from raw and cooked ground meat mixtures containing cattle meat, water buffalo meat and sheep meat. Food Chem. 233:311–320. https://doi.org/10.1016/j.foodchem.2017.04.116

Naveena, B. M., D. S. Jagadeesh, V. Kamuni, M. Muthukumar, V. V. Kulkarni, M. Kiran, and S. Rapole. 2018. In-gel and OFFGEL-based proteomic approach for authentication of meat species from minced meat and meat products. J. Sci. Food Agr. 98:1188–1196. https://doi.org/10.1002/jsfa.8572

Naveena, B. M., M. Kiran, K. S. Reddy, C. Ramakrishna, S. Vaithiyanathan, and S. K. Devatkal. 2011. Effect of ammonium hydroxide on ultrastructure and tenderness of buffalo meat. Meat Sci. 88:727–732. https://doi.org/10.1016/j.meatsci.2011.03.005

Naveena, B. M., and S. K. Mendiratta. 2005. The tenderization of buffalo meat using ginger extract. J. Muscle Foods 15: 235–244. https://doi.org/10.1111/j.1745-4573.2004.06403.x

Naveena, B. M., S. K. Mendiratta, and A. S. R. Anjaneyulu. 2004. Tenderization of buffalo meat using plant proteases from Cucumis trigonus Roxb (Kachri) and Zingiber officinale roscoe (Ginger rhizome). Meat Sci. 68:363–369. https://doi.org/10.1016/j.meatsci.2004.04.004

Naveena, B. M., M. Muthukumar, B. G. Kumar, C. S. Rao, N. Kondaiah, S. Vaithiyanathan, and S. B. Barbuddhe. 2021. Policy issues and stakeholder requirements in Indian meat sector [Policy Paper]. ICAR-National Academy of Agricultural Research Management and ICAR-National Research Centre on Meat, Hyderabad, India.

Neath, K. E., A. N. D. Barrio, R. M. Lapitan, J. R. V. Herrera, L. C. Cruz, T. Fujihara, S. Muroya, K. Chikuni, M. Hirabayashi, and Y. Kanai. 2007a. Difference in tenderness and pH decline between water buffalo meat and beef during postmortem aging. Meat Sci. 75:499–505. https://doi.org/10.1016/j.meatsci.2006.08.016

Neath, K. E., A. N. D. Barrio, R. M. Lapitan, J. R. Herrera, L. C. Cruz, T. Fujihara, S. Muroya, K. Chikuni, M. Hirabayashi, Y. Kanai. 2007b. Protease activity higher in postmortem water buffalo meat than Brahman beef. Meat Sci. 77:389–396. https://doi.org/10.1016/j.meatsci.2007.04.010

Olivatto, L. M., N. B. Stafuzza, B. C. M. Naressi, H. Tonhati, and M. E. J. Amaral. 2013. Allelic variant analysis of the DRB3 gene by PCR-RFLP in Mediterranean buffaloes breed. Buffalo Bull. 32:680.

Ognjanovic, A. 1974. Meat and meat production. In: Cockrill, W. R., editor, The husbandry and health of domestic buffalo (pp. 633–657). FAO, Rome.

Ortega, A. D. S., M. A. Mujitaba, S. Xayalath, W. Gutierrez, A. C. Soriano, and C. Szabó. 2021. Perspectives of the livestock sector in the Philippines: A review. Acta Agraria Debreceniensis 1:175–188. https://doi.org/10.34101/actaagrar/1/9101

Paleari, M. A., G. Beretta, F. Colombo, S. Foschini, G. Bertolo, and S. Camisasca. 2000. Buffalo meat as a salted and cured product. Meat Sci. 54:365–367. https://doi.org/10.1016/s0309-1740(99)00111-4

Pati, P. K., A. S. R. Anjaneyulu, and N. Kondaiah. 1992. Effect of buffalo fat premix on the quality of patties. J. Food Sci. Tech. 29:167–169.

Purohit, G. N., G. P. Duggal, D. Dadarwal, D. Kumar, R. C. Yadav, and S. Vyas. 2003. Reproductive biotechnologies for improvement of buffalo: The current status. Asian Austral. J. Anim. 16:1071–1086. https://doi.org/10.5713/ajas.2003.1071

Qureshi, M. 2009. Nutritional and management support to reproduction in dairy buffaloes under tropical conditions. Pak. J. Zool. 895–909.

Rajagopal, K., and G. T. Oommen. 2015. Myofibril fragmentation index as an immediate postmortem predictor of Buffalo meat tenderness. J. Food Process. Pres. 39:1166–1171. https://doi.org/10.1111/jfpp.12331

Ramadan, S. I. 2018. Effect of some genetic and non-genetic factors on productive and reproductive traits of Egyptian buffaloes. Journal of Advanced Veterinary and Animal Research 5:374. https://doi.org/10.5455/javar.2018.e287

Ranjhan, S. K. 1992. Nutrition of river buffaloes in Southern Asia. In: J. H. G., Tulloh, and H. D. Holmes, editors, Buffalo production. Elsevier, Amsterdam, the Netherlands. p. 111–134.

Rodas-González A., and N. O. Huerta-Leidenz. 2023a. Water buffalo versus cattle under similar rearing condition. I. Growth and carcass performance. Animal Frontiers. 13: 33–41. https://doi.org/10.1093/af/vfad060

Rodas-González A., and N. O. Huerta-Leidenz. 2023b. Water buffalo versus cattle under similar rearing condition. II. Eating and nutritional quality. Animal Frontiers 13: 43–52. https://doi.org/10.1093/af/vfad061

Röös, E., A. Mie, M. Wivstad, E. Salomon, B. Johansson, S. Gunnarsson, and C. A. Watson. 2018. Risks and opportunities of increasing yields in organic farming. A review. Agron Sustain. Dev. 38:1–21. https://doi.org/10.1007/s13593-018-0489-3

Safari, A., N. G. Hossein-Zadeh, A. A. Shadparvar, and R. A. Arpanahi. 2018. A review on breeding and genetic strategies in Iranian buffaloes (Bubalus bubalis). Trop. Anim. Health Pro. 50:707–714. https://doi.org/10.1007/s11250-018-1563-1

Sahoo, J., and A. S. R. Anjaneyulu. 1997. Quality improvement of ground buffalo meat by preblending with sodium ascorbate. Meat Sci. 46:231–241. https://doi.org/10.1016/S0309-1740(97)00018-1

Sahoo, J., and S. P. Verma. 1999. Oxidative problems in meat and meat products and use of antioxidant vitamins. J. Food Sci. Tech. 36:487–499.

Saravanan, K. A., D. Rajawat, H. Kumar, S. S. Nayak, B. Bhushan, T. Dutt, and M. Panigrahi. 2022. Signatures of selection in riverine buffalo populations revealed by genome-wide SNP data. Anim. Biotechnol. 1–12. https://doi.org/10.1080/10495398.2022.2145292

Shehata, N., K. Obaideen, E. T. Sayed, M. A. Abdelkareem, M. S. Mahmoud, A. H. R. El-Salamony, H. M. Mahmoud, and A. G. Olabi. 2022. Role of refuse-derived fuel in circular economy and sustainable development goals. Process Saf. Environ. 163:558–573. https://doi.org/10.1016/j.psep.2022.05.052

Singh, G. S., A. K. Hazra, S. R. Ruchira, S. Koli, B. Bhardwaj. 2013. Overview of the Indian buffalo meat value chain. Federation Indian Chamber of Commerce and Industry, New Dehli, India.

Singh, P. K., S. S. Ahlawat, D. P. Sharma, and A. Pathera. 2018. Carcass characteristics of male buffalo calf and meat quality of its veal. Buffalo Bull. 37:129–144.

Soares, G. J., J. Arêas, and J. Batistuti. 1995. Effect of high voltage electrical stimulation on buffalo meat conditioning. Current Agricultural Science and Technology 1.

Spanghero, M., L. Gracco, R. Valusso, and E. Piasentier. 2004. In vivo performance, slaughtering traits and meat quality of bovine (Italian Simmental) and buffalo (Italian Mediterranean) bulls. Livest. Prod. Sci. 91:129–141. https://doi.org/10.1016/j.livprodsci.2004.07.013

Sundaresan, G., J. J. A. Robinson, V. A. Rao, V. Narendra Babu, V. Govind, and M. F. Meti. 2018. Established method of chondroitin sulphate extraction from buffalo (*Bubalus bubalis*) cartilages and its identification by FTIR. Journal of Food Science and Technology 55:3439–3445. https://doi.org/10.1007/s13197-018-3253-4

Suman, S. P., and B. D. Sharma. 2003. Effect of grind size and fat levels on the physico-chemical and sensory characteristics of low-fat ground buffalo meat patties. Meat Sci. 65:973–976. https://doi.org/10.1016/S0309-1740(02)00313-3

Tamburrano, A., B. Tavazzi, C. A. M. Callà, A. M. Amorini, G. Lazzarino, S. Vincenti, T. Zottola, M. C. Campagna, U. Moscato, and P. Laurenti. 2019. Biochemical and nutritional characteristics of buffalo meat and potential implications on human health for a personalized nutrition. Italian Journal of Food Safety 8:174–179. https://doi.org/10.4081/ijfs.2019.8317

Tateo, A., P. D. Palo, N. C. Quaglia, and P. Centoducati. 2007. Some qualitative and chromatic aspects of thawed buffalo (*Bubalus bubalis*) meat. Meat Sci. 76:352–358. https://doi.org/10.1016/j.meatsci.2006.12.003

Thomas, R., A, S. R. Anjaneyulu, and N. Kondaiah. 2006. Quality and shelf life evaluation of emulsion and restructured buffalo meat nuggets at cold storage (4 ± 1 °C). Meat Sci. 72: 373–379. https://doi.org/10.1016/j.meatsci.2005.03.022

United Nations. 2015. Global Sustainable Development Report 2015 (Advance United Version) (GSDR 2025), publisher UNDESA.

United Nations (2019). World Population Prospects 2019, Volume I: Comprehensive Tables (ST/ESA/SER.A/426). Department of Economic and Social Affairs, Population Division.

Valin, C., A. Pinkas, H. Dragnev, S. Boikovski, and D. Polikronov. 1984. Comparative study of buffalo meat and beef. Meat Sci. 10:69–84. https://doi.org/10.1016/0309-1740(84)90032-9

Vasanthi C, V. Venkataramanujam, and K. Dushyanthan. 2007. Effect of cooking temperature and time on physicochemical, histological and sensory properties of female carabeef (buffalo) meat. Meat Sci. 76:274–280. https://doi.org/10.1016/j.meatsci.2006.11.018

Wanapat, M., C. Mapato, R. Pilajun, and W. Toburan. 2011. Effects of vegetable oil supplementation on feed intake, rumen fermentation, growth performance, and carcass characteristic of growing swamp buffaloes. Livest. Sci. 135:32–37. https://doi.org/10.1016/j.livsci.2010.06.006

Warner, R. D., P. L. Greenwood, D. W. Pethick, and D. M. Ferguson. 2010. Genetic and environmental effects on meat quality. Meat Sci. 86:171–183. https://doi.org/10.1016/j.meatsci.2010.04.042

Yavasoglu, N. U. K., C. Koksal, Y. Yaman, and C. Un. 2014. Karyotype of Anatolian water buffalo (*Bubalus bubalis*). Buffalo Bull. 33:337–342.