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Abstract

The dairy buffalo industry in Asia is experiencing contrasting trends, with growth in South Asia yet declining in East and Southeast Asia. Despite global dominance by cattle milk, buffalo milks offer superior nutritional qualities, including lower cholesterol and higher protein content, making it an alternative for health-conscious consumers. This review highlights the current status of dairy buffaloes in Asia, focusing on their role in supplying essential animal protein and the potential for growth in the dairy sector. The key challenges affecting buffalo milk production include breed variability, health challenges, and environmental factors. Thus, to enhance the production, this review proposes several strategies such as targeted breeding initiatives, nutritional improvements, and policy support to enhance market competitiveness. As demand for sustainable livestock products increases, revitalizing the buffalo industry in East and Southeast Asia through innovative farming practices and regional collaboration can ensure food security while promoting climate-resilient agriculture.

Keywords (3 to 6): Dairy buffalo, Asian buffalo, milk composition, dairy production

Introduction

Currently, the human population in Asia has grown to approximately 47.7 billion people, which is equivalent to 59.22% of the total world population [1]. Meat and milk consumption in developing countries is expected to increase by approximately 37 kg and 21.2 kg per capita by 2030 [2]. The Asian "population explosion" coincided with an unusual economic growth that allowed an increment in purchasing power that changed food preferences and significantly influenced the demand for animal products, specifically milk and meat. Hence, it is crucial to produce sufficient animal protein for the increased population, especially in developing countries.

There was an increasing demand for livestock products in the world, with dairy production increasing by 1.1% to approximately 887 Mt in 2021. This growth has mainly been supplied by India and Pakistan due to the continuous increase in the dairy population and the availability of fodder following the monsoon rains [2]. Meanwhile, milk production by the major dairy exporters, particularly New Zealand, the United States, and the European Union, varied from a modest increase to a slight decline. Furthermore, expansion in the dairy trade market is primarily driven by the strong demand in the People's Republic of China, the largest global importer of dairy products [2].

World dairy production is dominated by cattle, which contributes 81% of milk production, 15% from buffaloes and the remaining 4% from a combination of goats, sheep and camels [2]. Despite global cattle milk domination, the milk industry in South Asian regions like India and Pakistan is dominated by dairy buffaloes, with 114.15 million and 38.85 million heads, respectively [3]. Dairy buffaloes are also present in other Asian countries, but are less popular than cattle and goats. Most consumers reject buffalo milk, leading to a smaller market in those countries. Fortunately, recent trends in healthy foods require milk to be low in cholesterol but high in protein. Hence, the non-traditional buffalo milk is becoming an important substitute for cattle milk, due to its low cholesterol level. The cholesterol of buffalo milk was in the range of 4 to 18.0 mg/100 mL milk, while in cattle milk, it was 13.1 to 31.4 mg/100 mL milk [38], making the buffalo milk a better choice for heart health. Given the potential of buffalo milk, many researchers have conducted studies to improve its production and quality to meet the targeted demand and requirements.

Our review paper focuses on the status of dairy buffalo in the Asia region, the potential of dairy buffalo to keep up with the demand in the dairy industry, and some critical factors limiting its growth and importance. Next, strategies and efforts at various national and international levels to boost buffalo production are highlighted.

Asian Water Buffalo

In Asia, buffalo plays a crucial role in supplying millions of people with essential animal protein. Buffalo supplies milk, meat, leather, bones, pharmaceuticals, dung and manure, in addition to draft power. Water buffaloes consist of two subspecies, the river (*B. bubalis bubalus*) and the swamp buffalo (*B. bubalis kerebau*), with chromosome numbers of 50 and 48, respectively. These subspecies exhibit distinct morphology and physiological characteristics, as well as productive and reproductive performances [3].

Morphologically, river buffaloes are larger and have a more elongated body, typically weighing between 450 and 1,000 kg [3]. Their tightly curled, compact horns and entirely black fur, along with smoother skin with fewer wrinkles, are common traits among river buffaloes. River buffalo have narrower, more refined heads with a less pronounced forehead. Their eyes are set closer together, giving a more "domesticated" appearance [3]. Their nostrils are smaller, as they are less adapted to prolonged submersion [3,5,39]. River buffalo also have longer, more slender legs with smaller, more compact hooves. They prefer to wallow in clean water and are found distributed in Pakistan, India, several European countries, western Asia, and America [4]. River buffaloes are purposely raised for milk production, particularly in South Asia and Europe, but are also used for draft and as a dual-purpose animal. River buffaloes have recently been used to improve local buffalo milk production in various countries, such as Egypt, Bulgaria and the Philippines [5].

Swamp buffaloes, on the other hand, weigh between 325 kg and 450 kg and are much smaller than river buffaloes [5]. They appear with ash or dark grey fur and a white chevron line on the neck and feet, giving the appearance of wearing white socks. Their horns are swept widely backwards. Contrary to river buffalo, swamp buffalo have broader, more robust heads with a pronounced forehead. Their eyes are wider apart, making them look wilder than river buffaloes. The legs of the swamp buffalo are shorter and sturdy, with larger and splayed hooves. Swamp buffaloes prefer to wallow in marshland and mud and are found largely concentrated in Southeast Asia and Southern China [5]. Swamp buffaloes in China can adapt to various climates, altitudes, and temperatures, allowing them to thrive in both lowland and highland regions. Swamp buffaloes are traditionally used for draught power, particularly in ploughing paddy fields and transporting oil palm fruits. They are usually raised for meat production. Even today, some oil palm estates continue to use them as draft animals to pull carts carrying oil palm bunches. The milk of swamp buffaloes is sometimes used to make dairy products such as yoghurt and mozzarella cheese [2]

Like other ruminants, buffalo can be exposed to microbial infections and parasitic infestations. Generally, buffalo are susceptible to the most common diseases and parasitic infection observed in cattle, with the prevalence and severity of these condition are vary significantly depending on the country, region, and farming practices [40] Diseases like brucellosis, tuberculosis, bovine viral diarrhea, fasciolosis, foot-and-mouth disease, and protozoal infections have crucial effects on the Asian water buffalo industry [3].

As mentioned above, the water buffalo comprises two subspecies, the swamp and river buffalo. Compared to river buffalo, swamp buffalo has a consistent phenotype, which is considered one type of subspecies; however, the separation in breeds still occurs, based on the geographic location. Meanwhile, according to data from the Food and Agriculture Organization (FAO), the river buffalo comprises various breeds, with 123 buffalo breeds, 90 local breeds from Asia, and only 15 breeds considered transboundary. Figure 1 illustrates some images of the morphological features and breeds of water buffalo.

Current Status of Buffaloes in Asia

Recent buffalo population and growth rates

Buffaloes are interesting animals referred to differently in various countries, such as *Majjh* or *Bhains* in India, *Karabue* or *Kwai* in Thailand, *Carabao* in the Philippines, *Al-jams* in Arabic countries, and *kerbau* in Malaysia [6]. Buffaloes hold significant importance as ruminant animals in various Asian nations, although for different purposes.

The current world population of buffalo is approximately 204 million heads [2], with 98% found in Asia, 0.62% in America, 0.22% in Europe, and 2.89% in Africa. In the Asian region, about 74.8% of buffaloes were in South Asia, 12.8% in East Asia, and 2.89% in Southeast Asia (Table 1) [2]. Between 2019 and 2022, the Asian buffalo population registered an average annual population growth rate of 0.56%, while within the Asian countries, South Asia showed the highest annual growth rate of 3.16%. (Table 2). The buffalo population in South Asia was dominated by India and Pakistan. In India alone, the buffalo population is 111.8 million, almost 53.75% of the total world buffalo population, and produces 67.78% of the world buffalo milk [39]. Pakistan is the second country in the world after India, with a buffalo population of 43 million [2], showing a 29.47% increase in the last decade. It can be noted that the buffalo population in Asia has had a constant increasing trend since 1968, in contrast with the buffalo population trend in Europe, which has been decreasing since 1998 till recently. This phenomenon could be attributed to the fact that in Europe, only Italy constantly increased its buffalo population because of its dairy breed, cheese industry, and a market with a strong economy.

Despite the positive increase in the buffalo population in South Asia, there was a significant decrease in Eastern Asia. In fact, between 2010 and 2022, buffalo populations in East and Southeast Asia had decreased dramatically, except for Myanmar and Hong Kong [2]. In Myanmar, in 2010, there were 2.97 million buffaloes, showing a 27.08% increase in 2020 [39]. Besides, the buffalo population in most East Asia countries like Japan, Korea, and North Korea is relatively limited compared to other livestock, due to differences in climate, agricultural practices, and economic priorities. At the same time, there are various reasons for the decline in buffalo populations in East and Southeast Asia, observed earlier in Malaysia and Taiwan. The intensive agriculture machines introduced since the 1970s for land tillage and transport have caused most buffaloes to end up in feedlots for fattening and slaughter until now [7]. The same situation was reported in Malaysia, where buffaloes were used as draft animals for land work and were replaced with farm tractors in the 1980s and early 1990s; the trend of buffalo herd keeping decreased [7; 8]. Besides, development and urbanization have reduced farms and paddy areas, ultimately reducing buffalo requirements. Furthermore, buffaloes are believed to have poor reproductive performance and response to current biotechnology techniques such as artificial insemination and embryo transfer technology, which was one of the reasons for the decline in buffalo population in the world, particularly in Asia. Above all factors, the neglect of buffalo industry development has subsequently led to a decrease in the buffalo population. Therefore, various stakeholders should start to focus on the growth of the buffalo industry, because buffalo can be one of the tools for the sustainability of the meat and milk industry.

Current trends of buffalo milk production in Asia

As reported by FAO, world milk production is estimated to increase by 1.8% p.a. over the next decade. In fact, the growth in the number of milk-producing buffaloes is expected to be strong (1.2% p.a.), particularly in South Asian countries [2]. In 2022, South Asia alone produced approximately 303,282,537.6 tons of milk, 45.7% was buffalo milk. Unlike other countries, buffaloes are an essential source of milk in the South Asia region, particularly Pakistan and India, which have contributed as much as 68.35% of the total milk production in Pakistan and 56.85% of the total milk production in India [2]. As mentioned before, the consistency of buffalo milk production in Pakistan and India is significantly correlated with the growth rate of the buffalo population and the performance of the animals. Meanwhile, the rates of buffalo milk production in other Asian regions like Southeast Asia, West Asia, and East Asia were dramatically declining (Table 3). Unlike South Asia, buffalo milk in other Asian countries has not been produced and consumed traditionally, except in parts of Southeast Asia. Here, farmers kept their animals for work, and only a tiny percentage of crossbred buffaloes were utilized for milk production. In Southeast Asia, Myanmar produces the highest buffalo milk since it has the highest dairy buffalo population [3,5,39]. Buffalo milk productions in other Southeast Asian countries are significantly influenced by the limited population of riverine and crossbred dairy buffaloes.

Many factors affect the milk production of dairy buffaloes in Asian countries: breed, genetic background, season and calving period, health status, and environmental factors, like feeding, climate, temperature, and animal welfare. The buffaloes with well-defined breeds in India and Pakistan could produce 4000 litres to 5000 litres and 1800 to 2500 litres per animal, respectively, with lactation length ranging between 300 days and 320 days [9, 10]. In contrast, the swamp-type buffalo in China has a very low milk yield, approximately 500 to 700 litres per animal, with a lactation period of 280 days [11]. In Southeast Asia, the native buffalo breed in the Philippines can only produce roughly 300 to 500 litres of milk per animal [12]; concurrently, in Indonesia, the milk yield of the dairy buffalo is only 2.40 litres per animal per day [13]. The production of dairy buffalo in Malaysia varies from 5 litres to 8 litres of milk per animal per day [10].

Overall, the trends of buffalo milk production in Asia indicate a steady increase, with countries like India and Pakistan leading the region and contributing significantly to the global buffalo milk supply. Concurrently, the continued investment in breeding programs, improved animal welfare, adaptation to climate change, and improved nutrition of the dairy buffalo remain crucial for dairy buffalo production in Asia.

Potentials of Dairy Buffalo in Asia

Buffalo milk quality and benefits

Buffalo milk consumption significantly impacts human nutrition, specifically the growth and development of human health. Buffalo milk contains less water but is high in total protein, medium-chain fatty acids, and conjugated linoleic acid (CLA). In fact, certain components, such as specific classes of gangliosides, may only be present in buffalo milk [14]. Therefore, buffalo milk appears thicker because it contains over 16% of total solids compared with between 11% and 14% of cow's milk. Moreover, the fat content in buffalo milk is usually higher, between 50% and 60% [15]. The comparative compositions between buffalo and cow milk are summarized in Table 4.

Buffalo milk contains more casein fractions, known as alpha-s and Kappa caseins, than cattle milk [16]. The high concentration of Kappa casein acts as a catalyst in enzymatic reactions in cheese manufacturing. Hence, it is more suitable for producing mozzarella cheese [17]. In terms of amino acid content, the breeds of buffalo can influence the concentration of amino acids. Generally, buffalo milk contains high concentrations of glutamic acid, ranging between 19.41 and 20.18 g/100g protein in the Nilli Ravi breed and 18.83 and 19.69 g/ 100 g protein in the Murrah breed. Glutamic acid is important in human nutrition, as it helps nerve cells in the brain send and receive information from other cells [18]. Buffalo milk also has a high proline value, followed by leucine and lysine [16]. The detailed amino acid contents of buffalo milk are summarised in Table 5.

The fatty acid profile of buffalo milk is displayed in Table 6. [16] reported that the primary fatty acids in buffalo milk are palmitic acid (C16:0; 31.7 - 34.4 %), oleic acid (C18:1; 24.59 - 27.22%), stearic acid (C18:0; 14.23 - 10.97%) and myristic acid (C14:0; 10.4 - 11%). In fact, [17] also reported that buffalo milk contains higher total saturated fatty acids, C16:0 and C12:0, compared to cow's milk. Interestingly, conjugated linoleic acid (CLA) of buffalo milk fat is more significant (15.5 mg/g fat) than cow milk fat (9.2 - 13.1 mg/g), and conjugated linoleic acid has potential health benefits, particularly for bone health, and acts as insulin resistance and diabetes [19]. Besides, buffalo milk fat contains the lowest (270.82 mg/100g fat) cholesterol level compared to cow (293.89 mg/100g fat), camel (315.62 mg/100g fat), and goat milk (325.18 mg/100g fat) [20]. Hence, the lower cholesterol content in buffalo milk should make it more popular with the health-conscious public.

Buffalo milk was found to contain more minerals. Studies by [17] and [14] revealed that buffalo milk has a high calcium content. [14] stated that most of the calcium found in buffalo milk is insoluble, which ranges between 67.6 and 82.6%, probably due to the high casein content in buffalo milk. Besides calcium, buffalo milk is also rich in phosphorus, magnesium, and citrate [14]. Moreover, there are essential trace elements in buffalo milk, especially zinc and iron. Compared to cow's milk, buffalo milk has only traces of carotene but is higher in vitamin A [20]. Nevertheless, there are variations in the level of vitamin A in buffalo milk based on the physiological status of the buffalo, environmental factors, and sensitivity of the analysis methods. According to Medhammar et al. (2012), the value of vitamin A in buffalo's milk is 69 mg/100g milk compared to 46 mg/100g of cow's milk [21]. Similarly, studies have shown that buffalo milk contains higher vitamin C when [17] reported approximately 20.3 ± 0.07µg/mL, while [21] reported 2.5mg/100g milk.

Like cow's milk, buffalo milk can be used in most dairy products. In India, ghee production accounts for approximately 45% of total buffalo milk [22]. Ghee, also known as butterfat, contains approximately 99% milk fat.

Unlike ghee from cattle, ghee from buffalo milk has no colour [10]. A previous study mentioned that the buffalo ghee scored significantly higher in all evaluated preferences. Buffalo ghee was tastier and had a finer and more uniform texture than cow ghee [50,51]. For cheese production, Mozzarella, paneer cheese (traditional cheese in India), and pickled cheese (traditional cheese in the Middle East) are best made from buffalo milk. Besides cheeses and ghee, buffalo milk can also be used for skimmed milk powder, ice cream, butter, and infant milk powder [10].

The socio-economic impact of dairy buffaloes in Asia

Milk is one of the essential proteins in the daily diet of many Asian countries, particularly among populations with high vegetarian diets, such as in India and Nepal. The buffalo population in India is approximately 100 million, representing 50% of the world's buffalo population. It is known as the top country in the world in terms of the number of buffalo and milk production. The Indian dairy sector has two most important roles: 1) addressing public health through milk, 2) developing wealth generation for rural areas. Among the livestock products in India, milk accounted for 67.2% of the livestock sector, which is the highest share compared to other sectors. Annually, 8.4 million farmers depend on the dairy sector for their livelihoods, out of which 71% are women. In recent years, the market size for the Indian dairy market has expanded to USD 124. 93 billion and is projected to grow to USD 227.53 billion by 2030, with a CAGR of 8.94% [23], which is around 49% of the total market supported by dairy buffalo production. In India, buffalo milk is used to make various products like ghee, butter, paneer, yoghurt, and traditional desserts and sweets [24]. Besides milk, India is also known as a major exporter of buffalo meat. India produces 1.63 million tonnes of meat, accounting for 21.1% of total meat production in the country [41]. It was recorded that India’s proportion of worldwide buffalo meat exports has increased from 3.34% in 2000 to 11.23% in 2020 [2,41]. At the same time, buffalo demonstrate significant work efficiency, especially in load pulling and ploughing activity during land cultivation. Notably, their milk yield remains stable even after 1 to 2 hours of continuous moderate labour [39]

According to statistical data from [2], China has the third-largest buffalo population in the world. However, most buffaloes in China are swamp buffaloes mainly used for draught power and as a source of meat, because their milk production is quite low, only 500 to 700 kg milk yield for lactation on average) [39]. Hence, China imported Murrah from India and Nili-Ravi buffaloes from Pakistan to improve buffalo milk production through crossbreeding and upgrading two breeds, Murrah F1, F2, and Nili-Ravi F1, F2 [8]. The crossbred buffaloes were used to supply milk and milk products to poor people in villages. In fact, few factories were established specifically to process buffalo milk to produce pasteurized milk, yoghurt, condensed milk, and crème. In 2020, the buffalo milk manufacturers Baifei Dairy and Huangshi Dairy from Guangxi produced buffalo milk products like buffalo yoghurt, buffalo fresh milk with high calcium, and buffalo fresh milk rich in selenium. From that product only, the sales of buffalo milk in that area and the company grew more than 400% yearly [25]. Besides the improvement in the dairy sector, China is also listed as one of the buffalo meat producing countries, contributing 15.7% of global buffalo meat production [41]. The buffalo meat production in China reaches 0.66 million tons, and mostly the primary part of the meat is sold directly to consumers, and the rest is processed as dried beef, sausages, and hams (Minervino et al., 2020).

Dairy buffalo production is also necessary in the Near East Asian countries like Turkey, Iran, and Iraq. Various buffalo-derived products, including fat skimmed from milk, are being produced in Iraq, which is utilized in producing butter, ghee, sweets, and cakes [42]. This skimmed milk can be consumed directly or used to make curd, fresh cheese, and sweets. Besides, Iraq also contributed to global buffalo meat production and produced at least 5.46 million kilograms of buffalo meat in 2022, an increase of 8% from the previous year [43]. The meat is also used for direct consumption or to produce meat products like salami and ham, as these products cannot come from pork, which is forbidden by the Islamic religion. In Iran, the price of buffalo milk was twice that of the cow [42]. Iranians develop highly valued products from buffalo milk, like yoghurt, fresh cream, cheese, butter, ice cream, rice pudding, churned yoghurt, dried whey, and ghee [42]. Besides, buffalo skin was used in the leather industry, while buffalo manure served as fuel in rural areas. In Turkey, the milk production of dairy buffalo is widespread, particularly for producing famous Turkish desserts [42]. The buffalo meat production is relatively low compared to milk. In 2023, buffalo meat accounted for only 0.6% of total red meat production compared to another ruminant [44]. A common strategy across these Asian countries to enhance milk production and product availability is the crossbreeding programs using semen from the Mediterranean Italian breed.

In Southeast Asia, buffaloes are usually raised by smallholder farmers and are focused only on draught power and partly on meat. The Philippines recorded a total of 28,49,006 buffaloes, of which 99% are managed by small farmers with few resources, low income, and less access to other economic opportunities. According to [6], the Philippines produces buffalo milk worth 300 million Philippine pesos (5,223,000.00 USD) and provides dairy products like pastillas de leche and white cheese or 'kesong puti'. Recently, the Carabao Development Program aimed to explore the halal market and invested in halal carabao meat products (Borghese, n.d.). Meanwhile, in

Indonesia, the milk was sold for 20,000-rupiah (1.25 USD)/1.25 litres of milk during the dry season; on the other hand, 15,000 rupiah (0.94 USD) in the rainy season when the water buffalo produces high milk yield [12,13]. Mainly, buffalo milk produces Indonesian desserts and candies like *dadih*, *sagon puan*, and *gulo puan* [12, 13]. Thai buffaloes are genetically the Swamp type and were raised by small farm holders as a multipurpose animal in agricultural production. Unfortunately, the local swamp buffalo have low production in both milk and meat; hence, these productions were not the main focus for the farmers.

Strategies for Dairy Buffalo Development in Asia

Development initiatives regarding buffalo production should be addressed by local agencies and international stakeholders, other than in cattle-related projects. It has been recognized that some Asian countries have experienced suboptimal growth in buffalo production, while others have seen noticeable declines. Substantial efforts are required to promote buffalo development in Asia, particularly in Southeast Asia. Persistent economic challenges in most Eastern Asian countries emphasize the crucial need for development in the agricultural sector, which cannot be achieved without including buffalo development and management. Realizing this need, various nations and international agencies have strategically enhanced buffalo production.

Government efforts to improve buffalo development

In India, the government initiated a research project that focused on buffalo breeding to improve the performance and quality of buffalo bulls. The project was started in 1972 [6]. Subsequently, a National Buffalo Research Centre, together with 27 State Agricultural Universities, started to perform research activities on various aspects of buffalo to improve buffalo productivity in India [6]. Meanwhile, research on the Nili-Ravi buffalo in Pakistan was initiated in 1981. Under this initiative, buffaloes were placed in five Government Livestock Farms, three military Dairy Farms, and some registered private farms for research and further improvements. Furthermore, the Pakistan Agricultural Council also started the National Coordinated Buffalo Research Program in 1992 to improve the productivity of the buffaloes in Pakistan via science and research [8].

In Thailand, a National Buffalo Breeding and Research Program was created to increase buffalo fertility and production, particularly in developing superior buffalo herds [6]. Various initiatives were introduced to attract the community towards buffalo rearing, including (1) a program called 'Buffalo Banks' that aimed at inducing self-sufficiency for small farmers; (2) the development of 'Model Buffalo Raising Villages' to promote best buffalo husbandry practices and (3) providing incentives to best-performing buffalo farmers. The authorities in Thailand also decided to celebrate National Thai Buffalo Conservation Day on May 14 each year to raise awareness about the importance of conserving native buffalo breeds [45]. The efforts are being made to encourage farmers to keep these animals, even if not for agricultural purposes. The Thai government also agreed to establish the International Buffalo Information Centre, which collects and keeps information on buffalo production and related issues. To improve dairy buffalo production, the Ministry for Agriculture and Cooperatives and Buriram Livestock Research in Thailand collaborated to develop dairy buffalo breeding in this country [46]. Besides, the Thai Department of Livestock Development has created initiatives to conserve the Thai swamp buffalo breed using full genome sequencing, and established a national genomic database center to identify important genomic markers and enhance the quality of the buffalo products like meat and milk [45,46]

Similarly, the government of the Philippines has established the Philippine Dairy Industry Roadmap for 2020 to 2025. The program aimed to improve the dairy value chain by covering efficiency, effectiveness, and inclusiveness in milk production and, subsequently, processing and marketing buffalo milk [26]. At the same time, the roadmap addresses systemic issues like herd build-up, promotion of interventions, and support for innovations in practical skills, feed and fodder supply, milk quality, and development of policy and regulatory environment. This program's key strategies and policies include: i) Enhancing the buffalo breeding system to improve the productivity of buffaloes, ii) Formulating proper and quality feed for dairy buffaloes, and iii) Providing incentives to the farmers to improve their knowledge and skills. Besides this program, the government of the Philippines also started the Caraboa-based Business Improvement Network (CBIN) Project. This project focuses on expanding the population of buffalo between regions around the country through processing and marketing facilities.

Improvement in the genetics and breeding of dairy buffaloes

Across the world, the genetic improvement in buffaloes is tailored to specific purposes, focusing on enhancing traits like milk and meat production, draft capabilities, or a combination of these, depending on the regional needs and utility of the products. As mentioned previously, most of the local buffalo breeds in Asia produce low milk and meat yield; hence, the crossbreeding between the local breed and imported breeds was one initiative to enhance the production of the local buffaloes. Generally, the crossbreeding occurs between River buffalo (50 chromosomes) and Swamp buffalo (48 chromosomes), producing fertile F1 and F2 with 49 chromosomes [27]. Generally, crossbreds show better growth and larger body sizes, which produce higher milk yields. The previous study stated that the crossbred buffaloes were significantly heavier in body weight compared to the pure breed from birth until 24 months [47]. Another study reported that the crossbred buffaloes' growth rate was advantageous, ranging from 10-31.1% compared to the swamp buffaloes [48]. Indeed, crossing swamp and river buffaloes improves all reproduction traits, including birthweight, age of maturity, age of first calving, and calving period.

To improve the genetics of local buffalo breeds in India, animal recording and selection systems are used to ensure the genetic quality of animals used for breeding [8]. Thus, India has the best dairy buffalo breeds in Asia, which include Murrah, Nili-Ravi, Surti, and Jaffarabadi. Besides being used for work and meat production, these breeds also have the potential to produce milk and fat. Similarly, Pakistan improves the genetics of Nili-Ravi and Kundhi buffalo breeds through animal recording, selection, and progeny testing trials [8]. Buffalo's performance was recorded in the seven institutional herds, specifically in the Livestock Research Institute and a few military farms. Meanwhile, buffaloes that the farmers raised were recorded under the progeny testing program.

The Carabao Development Program in the Philippines is a program that improves the local swamp buffalo, particularly in producing meat and milk. As a result, crossbreds between Bulgarian Murrah and local Swamp buffalo produced F1 with 1,100 kg and F2 with 1,350 kg of milk [8]. In addition, research in the Nueva Hecija area focuses on milk collection, organizing the smallholder dairy industry, and marketing buffalo products. The main purpose of this project was to detect and select the parents for future generations of buffalo [26]. Hence, evaluating the livestock performance and breeding management in that area is necessary. Similarly, buffalo play a crucial role in agriculture and the life of Vietnamese farmers. Buffaloes in Vietnam are mostly swamp buffaloes, and they are raised under traditional production systems. Therefore, the local buffaloes of Vietnam are small in size and show a slow growth rate and late maturity with long calving intervals and low milk yield. In the 1970s, Vietnam decided to import the dairy Murrah buffaloes from China, Bulgaria, and India to enhance the productivity of the local buffaloes [8]. The crossbreds have bigger body sizes and show better growth rates, draft power, and reproductive performance.

The Italian buffalo semen was introduced into Ilikpinar Village, Turkey, to improve the quality of genetic and milk productivity of the Anatolian buffalo in Turkey [8]. In the first trial, approximately a 45% pregnancy rate was achieved. This outcome suggests that the introduction of Italian semen was successful in terms of reproductive efficiency. This project was supported by the FAO Inter-Regional Cooperative Research Network and the Scientific and Technical Research Council of Turkey. Since 2011, the Republic of Turkey Ministry of Agriculture and Forestry has implemented the National Anatolian Water Buffalo Breeding Project, with the cooperation of different universities, research institutes, and water-buffalo-breeder associations. The result from that project is that the buffalo population in Turkey has increased by approximately 60,000 heads compared to the last decade [49]. Recent research has assessed the genetic diversity of the Turkish water buffalo population using microsatellite markers. The findings from this study can be implemented in formulating future strategies for conservation and breeding programs for water buffalo in Turkey [49].

Although artificial insemination and embryo transfer techniques for buffaloes have been developed successfully, the applications are limited. Consequently, buffalo performances have been poor in recent years. Hence, there is a need for international financial and technical support cooperation to improve this situation. More attention is needed to select breeds for dairy purposes and create a market for the buffalo dairy industry. In the future, buffalo development should focus on enhancing animal production to meet the growing population's demand for animal-derived food, which is currently inadequate in many countries.

Enhancing feeding management to improve the performance of dairy buffaloes

Feed and feeding directly influence buffalo production. In contrast to the common belief that buffalo can thrive on poor quality feed, dairy buffaloes require a balanced diet based on their physiological status, and an imbalanced diet affects their productivity. Lack of quality feeds, inadequate fodder or pasture land for grazing, and lack of feed supplements lead to poor buffalo production and reproduction. In Southeast Asia, buffaloes are fed rice straws that are highly lignified and contain low protein and energy [15]. However, various efforts have been made to improve the nutrient quality and utilization of rice straws in buffalo, including fermentation modifiers, rumen-protected dietary protein and fat, and industrial and agricultural by-products and vitamins. In fact, manipulating rumen microorganisms using metabolic and fermentation modifiers has significantly improved buffalo productivity [28]. Gaafar et al. (2009) [29], in their study, reported that the dairy buffaloes fed with 40% concentrate, 60% roughage, and 15g baker's yeast supplementation/head/day showed the best results in milk yield, feed conversion, and economic efficiency. In another study, [30] explained that supplementation of concentrate on the existing feed of lactating buffaloes can increase the milk yield and reduce the postpartum heat period, while metabolic alteration in the rumen can improve the buffalo's performance. This is in line with [28], who stated that the supplementation of bypass fat in the animal's diets could improve the growth performance of cows without any adverse effect on the rumen fermentation. Including 25% forage reap silage could improve microbial protein synthesis due to the dietary balance between carbon and ammonia, increasing the microbial protein content [31]. Therefore, modifications of feed and feeding regimens for dairy buffalo can enhance and improve their performance, leading to an increase in milk yield and milk composition.

Increasing farm economic efficiency

Identifying factors that optimize the production efficiency of dairy farms is essential to improve the productivity and profitability of the farms while protecting animal welfare and the environment. Good management practices, whether for individual or the whole herd, can improve the milk production per cow, raise the average milk yield per herd, enhance the dairy farm efficiency, reduce maintenance costs, and minimize environmental impact both at the level of a small-scale farm or at the commercial level [32].

In dairy farms, including dairy buffalo, the efficiency of the farms is evaluated through animal performance indicators such as calving rate, calving interval, and milk production [33]. Recently, some Asia countries have focused their evaluation on the profitability of the farms as an indicator by benchmarking specific indicators that measure the amount, cost, or marginal profit of a particular input per unit of output [32]. These indicators are also used as a benchmark of dairy farm performance for short-term farmers' decisions, even when complete economic balances are not calculated.

In the previous study in the Philippines, the researchers determined the performance efficiencies of the dairy buffalo using data envelopment analysis (DEA) [33]. DEA system considered three measures of efficiency: 1) technical efficiency (TE) or the ability of the decision-making unit (DMU); 2) allocative efficiency (AE); 3) Economic efficiency (EE), which measures the overall performance and is calculated as EE= TE x AE [34]. The study was done at Nueva Ecija in 2021 and involved 58 farms of smallholders (3-5 buffaloes), 12 family modules (6-10 buffaloes), and 5 semi-commercial farms (11-20 buffaloes). This study concluded that the dairy farms in Nueva Ecija were still not at their optimum value of AE, which is their potential to reduce the cost of inputs in the farm without affecting the output (liters of milk produced) [33]. Another study by [27] stated that the total factor productivity (TFP) of dairy buffalo milk production in Nueva Ecijia has the potential to improve, particularly through technological progress. Besides that, the Philippine Carabao Center (PCC) should continue investing in its Genetic Improvement and Research for Development Programs, consequently increasing the number of animals held per farmer and maximising the efficiency of their operation [27, 33].

Similar to the study in the Philippines, the study in Idgir Province, Turkey, also used DEA to analyse the efficiency of dairy buffalo farms. According to [34], the average technical efficiency of dairy buffalo farms in that area was 0.84, which shows that improving the inefficient farms by decreasing their input use by 16% is possible. In order to improve the efficiency of the farms, the farmers should manage their inputs efficiently by providing efficient extension services. Besides, they should manage to plant more quality roughage to improve the feed efficiency of the animals.

Precision livestock farming (PLF) is an artificial intelligence technology that monitors and manages animal production automatically. This technology can also be used to solve problems that may arise on the farm. At the same time, PLF also functions well in predicting reproductive outcomes at the individual animal or herd levels, optimizing resources and informing breeding strategies, which can lead to increased reproductive performance. This technology has been explored and implemented in various European countries, despite not focusing on buffalo farming. Accordingly, PLF should be applied to buffalo farming in the Asia region to upgrade the management system and increase buffalo production. In China and Japan, PLF technologies have been developed using artificial intelligence (AI) for smart livestock management. While these technologies are primarily used for other livestock, there is potential for adapting them to buffalo farming in the Asia region.

Conclusions

It is concluded that dairy buffalo has been and will remain an integral part of the agricultural economy, particularly for smallholder farmers in several developing Asian countries. While buffalo is known as a major milk contributor in South Asian countries, its role in Eastern Asian countries may shift from being primarily a draft animal to becoming primarily an important source of milk and meat. Therefore, it is necessary for most Asian countries to re-focus their buffalo industry from draft-related rearing to meat or dairy-related rearing. Enhancing the development of the buffalo population and production, several agencies should adopt an integrated approach combining breeding selection, nutritional optimization, sustainable management practices, providing training for the farmers, and collaboration with the universities and research institutions to always upgrade the system of the farms.

By prioritizing the breeding selection to improve productivity and resilience, optimizing nutrition with localized feed formulations, and implementing sustainable farming systems, stakeholders can significantly improve the growth rates and milk yield while reducing environmental impacts. Regional collaboration and policy support are crucial for scaling these innovations, ensuring that smallholders and large-scale producers alike benefit from precision farming technologies and premium market opportunities. As the global demand for sustainable livestock products grows, the strategic development of buffalo agriculture should focus on food security and position these animals as a model for climate-resilient livestock production in tropical regions.

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Tables

Table 1. Buffalo populations in Asian countries in 2023

Country	Buffalo population
Jordan	94
China Hong Kong	334
Armenia	727
Brunei Darussalam	1,209
Syria	6,564
Kazakhstan	9,452
Tajikistan	15,620
Georgia	19,384
Bhutan	55,413
Malaysia	64,733
Azerbaijan	119,900
Timor-Leste	127,352
Iran	132,644
Turkiye	171,835
Iraq	251,194
Sri Lanka	324,870
Cambodia	674,681
Thailand	735,248
Laos	1,208,634
Bangladesh	1,508,000
Myanmar	2,000,000
Vietnam	2,231,600
Philippines	2,774,471
Nepal	5,132,931
China Mainland	26,872,877
Pakistan	43,676,000
India	111,856,246

Table 2. Buffalo distributions and growth rates across Asian regions in 2022

Region	Population	Growth Rate (%)
Southeast Asia	10,988,136	0.8
Eastern Asia	26,875,125	-2.27
South Asia	162,686,104	3.16
Whole Asia	201,144,135	0.57
World	205,141,830	0.57

Table 3. Buffalo milk production between 2019 and 2022

Region	Milk Production (Thousand Tonne)				Average Annual Growth Rate (%)
	2019	2020	2021	2022	
Southeast Asia	223.23	222.16	221.25	222.50	-0.08
South Asia	132,140.44	132,642.38	144,504.06	138,690.57	1.21
West Asia	121.70	108.37	109.71	88.86	-7.56
East Asia	3,027.92	3,002.19	2,980.75	3,010.43	-0.14
Whole Asia	135,513.29	135,975.10	147,815.76	142,012.35	1.18
World	137,019.25	137,530.06	149,445.81	143,573.18	1.18

Table 4. Comparative milk compositions of buffalo and cow milk

Constituent	Buffalo milk	Cow milk
Total solids (%)	18.44 ± 0.71	11.81 ± 0.33
Lactose (%)	4.82 ± 0.15	4.28 ± 0.14
Protein (%)	4.91 ± 0.10	3.06 ± 0.06
Fat (%)	7.76 ± 0.48	3.35 ± 0.31
Solid Non-Fat (%)	10.52 ± 0.25	8.41 ± 0.42

Reproduced from [35, 36]

Table 5. Amino acid content (g/100 g protein) of milk from different buffalo breeds

Amino Acids	Buffalo Breeds	
	(Abdel-Hamid et al., 2023)	(Sun Q et al., 2014)
Aspartic acid	6.17 ± 0.22 - 7.0 ± 0.7	5.71 ± 0.17 - 7.2 ± 0.1
Methionine	2.30 ± 0.13 - 2.51 ± 0.2	2.15 ± 0.11 - 2.58 ± 0.1
Threonine	3.66 ± 0.19 - 4.19 ± 0.3	3.37 ± 0.17 - 4.21 ± 0.31
Serine	4.34 ± 0.21 - 4.65 ± 0.3	3.98 ± 0.18 - 4.76 ± 0.2
Valine	4.98 ± 0.22 - 5.84 ± 0.5	4.59 ± 0.20 - 5.84 ± 0.6
Phenylalanine	4.24 ± 0.29 - 4.34 ± 0.2	3.66 ± 0.12 - 4.41 ± 0.1
Leucine	3.72 ± 0.58 - 9.52 ± 0.6	3.52 ± 0.33 - 9.51 ± 0.6
Tyrosine	4.34 ± 0.22 - 4.87± 0.3	3.92 ± 0.16 - 5.03 ± 0.1
Lysine	5.78 ± 0.14 - 7.61± 0.5	5.73 ± 0.21 - 7.67± 0.1
Proline	8.66 ± 0.42 - 9.74 ± 0.5	8.29 ± 0.24 - 9.64 ± 0.2
Arginine	2.26 ± 0.09 - 2.74 ± 0.2	2.06 ± 0.02 - 2.78 ± 0.1
Histidine	2.02 ± 0.11 - 2.51 ± 0.2	1.83 ± 0.19 - 2.51 ± 0.1
Glycine	1.58 ± 0.14 - 1.74 ± 0.1	1.45 ± 0.09 - 1.8 ± 0.1
Alanine	2.65 ± 0.16 - 2.97 ± 0.2	2.40 ± 0.10 - 2.99 ± 0.1
Isoleucine	4.28 ± 0.21 - 5.33 ± 0.3	4.08 ± 0.18 - 5.43 ± 0.1
Glutamic acid	19.41 ± 0.6 - 20.18 ± 0.79	18.53 ± 0.57 - 19.69 ± 0.6

The data was adapted from [16, 37]

Table 6. Fatty acid (%) profile of buffalo milk

Fatty Acids	Dairy Buffalo	
	(Menard et al., 2010)	(Abdel-Hamid et al., 2023)
C4:0	2.8 ± 0.5	1.83 ± 0.2
C6:0	1.9 ± 0.3	0.92 ± 0.3
C8:0	1.1 ± 0.2	0.64 ± 0.1
C10:0	1.8 ± 0.3	1.5 ± 0.2
C11:0	-	0.05 ± 0.0
C12:0	2.3 ± 0.2	2.16 ± 0.2
C13:0	-	0.08 ± 0.0
C14:0	11.8 ± 0.2	10.4 ± 1.3
C14:1	0.7 ± 0.01	0.79 ± 0.1
C15:0	1.74 ± 0.08	1.08 ± 0.1
C15:1	-	0.26 ± 0.0
C16:0	36.0 ± 1.2	31.7 ± 1.8
C16:1	1.9 ± 0.02	2.07 ± 0.2
C17:0	0.8 ± 0.02	0.54 ± 0.0
C17:1	-	0.26 ± 0.0
C18:0	9.9 ± 0.2	14.23 ± 1.0
C18:1	20.3 ± 0.7	27.22 ± 1.7
C18:2T	-	0.87 ± 0.1
C18:2C	0.9 ± 0.1	1.70 ± 0.1
C18:3N6	-	0.14 ± 0.0
C20:1	-	1.59 ± 0.1
C18:3N3	0.7 ± 0.2	0.28 ± 0.0
C20:2	-	0.06 ± 0.0
C20:3	-	0.07 ± 0.0
C20:4	-	0.06 ± 0.0
C22:0	-	0.1 ± 0.0
C20:5	-	0.03 ± 0.0
C22:2	-	0.05 ± 0.0
C24:0	-	0.08 ± 0.0
C24:1	-	0.03 ± 0.0
C22:5N3	-	0.03 ± 0.0
USFA	-	36.155 ± 1.8
SFA	69.6 ± 1.7	64.561 ± 2.3

The data was resources from [37,52]

Figures 1 Certain types of buffaloes in Asia

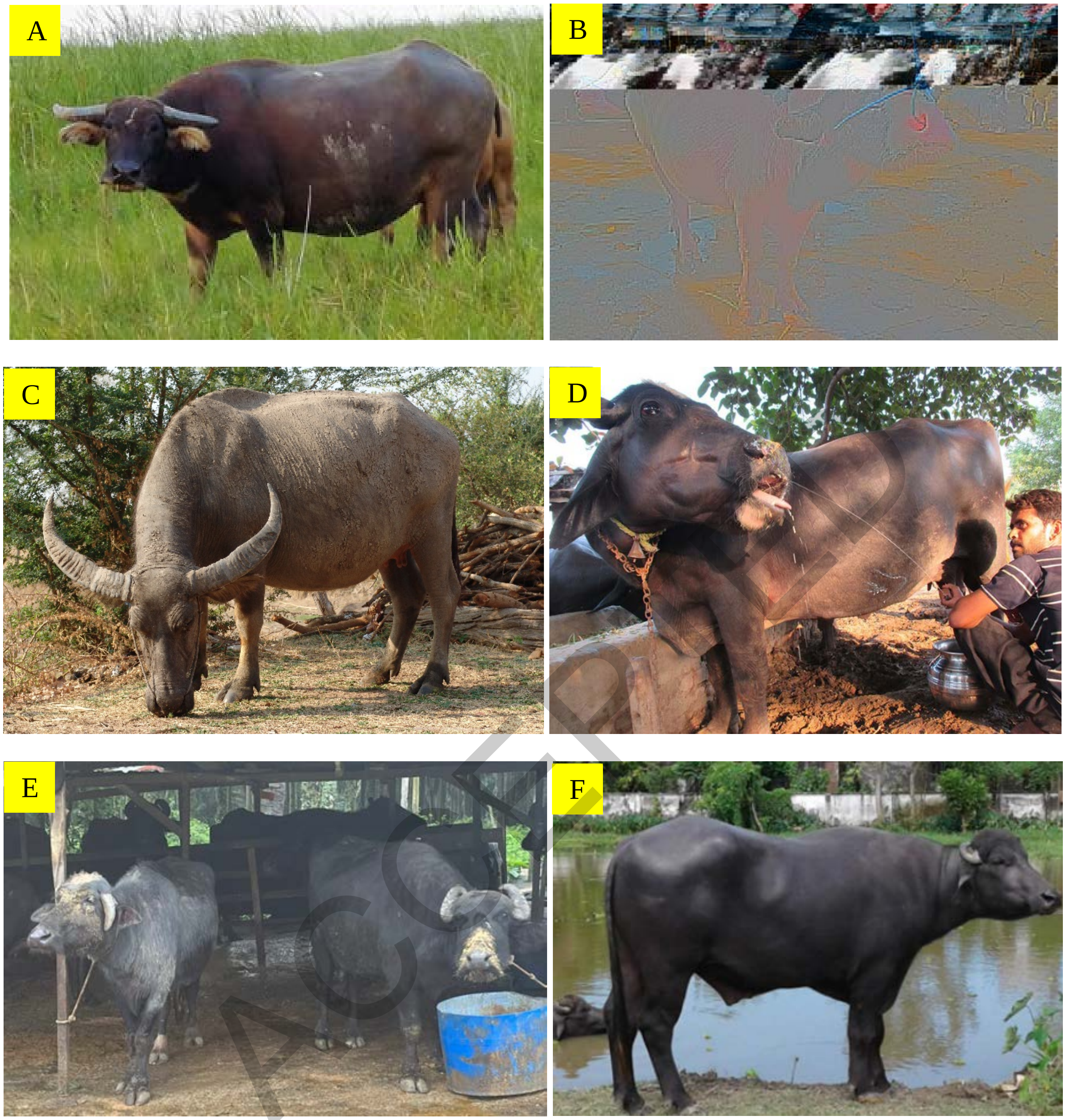

Figure 1: Variation of morphological and breeds in Asian water buffalo. (A) Shanghai swamp type of buffalo (China); (B) Toraja Spotted swamp type of buffalo (Indonesia); Caraboa swamp type of buffalo (Philippines); (D) Nili-Ravi riverine type of buffalo (Pakistan); (E) Murrah riverine type of buffalo (Malysia); (F) Murrah riverine type of buffalo (India). Images credits- (A) Zhang, (B) Sam Clark, (C) Boghese, (D) Md Omar Faruque, (E) Fadzlin Afiqah, (F) Yi Zhang