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HEAT STRESS IN BEEF CATTLE: CLIMATE CHANGE AND THE GLOBAL SCENARIO – A REVIEW

Alok Khemraj Wankar[1♦], Gajendra Namdeo Bhangale[2], Sandeep Narayanrao Rindhe[3], Babu Lal Kumawat[4], Tawheed Ahmad Shafi[5]

[1]Department of Veterinary Physiology,
[2]Department of Veterinary Parasitology,
[3]Livestock Products and Technology,
[4]Department of Gynaecology,
[5]Department of Veterinary Medicine,
College of Veterinary and Animal Sciences, Parbhani-431402, Maharashtra,
Maharashtra Animal and Fishery Sciences University, Nagpur, Maharashtra, India
♦Corresponding author: wankaralok@gmail.com; alokwankar@mafsu.in

Abstract

With the increasing human population and urbanization, the demand for animal origin products is going to grow, especially in the developing nations till the 2050s and the production needs to be escalated and optimized with the changing climate. Heat stress is known to reduce the animal performance, production, shelf life and meat quality in all animals. The beef cattle are globally reared, following different managemental practices, so the usage of natural resources like land and water, manpower, fodders, production systems and the environmental impact also varies profoundly. Recent changes in the climate, global warming and depletion of resources have severely affected the production and heat stress is now a common constraint all over the world. Due to evolutionary diversification the tropical and temperate breeds are comparatively more thermotolerant, but the beef cattle in the colder regions are vulnerable to high environmental temperatures. Also, the production of beef increases the carbon footprint and is much less eco-friendly than growing plant-based protein. So, we comprehended the environmental temperature variation over the continents and impact of heat stress on beef cattle. Also, other factors like cattle population, land and pasture usage, livestock units in trade, methane emissions and gross beef production value were examined to evaluate the collective impact of all these on the beef sector. Our findings and predictions reveal that, in the advent of climate change, depleting natural resources and rise in the greenhouse gases, beef production will be a constant challenge, which can be only achieved by maintaining a healthy cattle population and optimum usage of natural resources. Only then can the beef sector be efficient, sustainable, and a profitable enterprise in future.

Key words: beef cattle, heat stress, climate change, sustainable production, carbon footprint

Livestock provide us 33% or more of our dietary protein (Rosegrant et al., 2009), support over 600 million farmers and employs 1.3 billion humans, globally (Thornton, 2010). Animal origin foods (AOF), such as red meat and other AOF, are in higher demand than ever in developing countries. The demand for animal products has increased by the growing world population, urbanisation, economic expansion, online marketing and delivery, favourable trade policies, and shifting consumer tastes (OECD, 2022). The consumption of beef worldwide is expected to increase by 0.75% by 2025 and double by 2050 from 460 to 570 million tonnes (OECD-FAO, 2021; OECD, 2022; World Consumption of Meat, 2023). Between 1990 and 2018, the per capita meat consumption increased tremendously, 88.1% for unprocessed meat and 152.8% for processed meat products (Miller et al., 2022). Studies have shown that the consumption of meat is directly proportional to its per capita disposable income, urbanization, and wealth of the nations, especially the developing nations (Ritchie et al., 2017; Miller et al., 2022).

This increase in AOF comes at a significant price, firstly majority of the agricultural and arable land is used for growing animal feeds, instead of using it for human food production. Currently, we grow cattle food on an area that is seven times larger than that of the European Union. Moreover, 90% of the soybeans farmed worldwide are used as animal feed. Secondly, producing meat consumes much more energy and natural resources than that required for agronomic operations. For example, producing 1 calorie of protein from beef requires 75 times more energy than producing the same amount of protein from maize, and 54 calories of fossil fuel are required instead of just 2–3 calories. And it takes 15500 litres of water to make 1 kg of beef as compared to 1600 litres to grow 1 kg of cereals (World Consumption of Meat, 2023). And lastly, it is the environmental impact and the greenhouse gases (GHG) emitted from the beef production systems. Presently, it is estimated that cattle are responsible for 77% of the emissions (direct emissions and from manure management) from agricultural sector, while monogastrics account just for 10% (Herreroa et al., 2013). The

projected GHG emission from the livestock by the 2050s might reach 114 gigatons of CO_2-equivalents ($GtCO_2$-eq) out of which 73 $GtCO_2$-eq, will be from cattle (World Consumption of Meat, 2023).

In the past two to three decades, the climate has undergone major changes and become more unpredictable, significantly affecting agri-animal husbandry. Extreme climatic events like sustained high environmental temperatures and humidity, heat waves, solar flares, scanty rainfall, droughts not only directly affect the livestock welfare and production systems, but also affect all food resources, food security, sustainability, and its supply in the same year and subsequent years (Lamy et al., 2012; Rojas-Downing et al., 2017). Several international agencies like Intergovernmental Panel on Climate Change (IPCC) and United States Environmental Protection Agency (USEPA) have predicted a steady increase in ambient temperatures (USEPA, 2016; IPCC, 2018). Numerous studies have confirmed that heat stress results in inferior performance, and production in cattle, culminating into billions of dollars of economic losses (St-Pierre et al., 2003; Nardone et al., 2010; Wankar et al., 2021; Mishra 2021).

Producing meat in the context of climate change is therefore a challenging task; however, cultural preferences, consumer preferences, and health considerations also have a role in determining how much beef is consumed (De Boer et al., 2014; Graca et al., 2016; Leroy and Barnard, 2020; Malek and Umberger, 2021). Still, it is speculated that the meat industry will continue to grow till the year 2030 and further increase by up to 70% or more in coming times (FAO, 2003; Datar and Betti, 2010; Gaughan et al., 2010), primarily driven by the population growth, modernization, operational optimization, and cleaner value-added meat production (Kristensen et al., 2014; Gokirmakli and Bayram, 2017).

Building on this background, we gathered data on "heat stress in beef cattle", global temperature variation and other associated factors like cattle population, land usage, livestock units in trade, methane emissions and beef production value. Different search engines, online platforms, national and international websites like Google Scholar, Science Direct, Microsoft Scientific Research Engine, PLOS ONE, CORE, ResearchGate, Semantic Scholar, Education Research Information Centre, science.gov, faostat.org were used for data mining. Finally, we collated the information to assess the influence of climate change and contributory factors on the global beef sector. Other meats, pork and chicken meats were excluded from the study as it is not possible to comprehend everything at once, and the present work is restricted to beef sector only.

Heat stress in animals and why high yielders are more affected due to heat stress?

Climate has a substantial impact on livestock systems (both intensive and extensive), with extensive or pastoral systems being more severely affected, resulting in poor animal growth, reproduction, performance and, in turn, productivity (Adams et al., 1998). Animals have evolved in a peculiar, eco-climatic zone with essential acclamatory adaptations, that allow them to be most comfortable and productive there. Extreme climatic events like high temperatures, humidity, or heat waves etc., compromise their thermoregulatory ability and they are unable to dissipate excess metabolic heat, making them vulnerable to deleterious effects of heat stress (Baumgard and Rhoads, 2012).

In order to maintain homeothermy, various homeostatic responses are immediately activated to decrease excess metabolic heat generation, store it, and promote dissipation (Wankar et al., 2014; Herbut et al., 2021; Vasconcelos et al., 2020). Animals' breed, stage of production and pregnancy, management, geographical location, physical attributes, and thermal plasticity, all collectively influence animals' acclimation, acclimatization, and adaptation capacity to heat stress (Robertshaw, 1985; Hansen, 2004; Brown-Brandl and Jones, 2011; Saizi et al., 2019).

High producing animals are already at the threshold of their maximum production and generate more heat energy which continues to accumulate, if the environmental conditions are adverse (Collier et al., 2019). Therefore, the more an animal produces, the more metabolic heat it generates and additional thermoregulatory pathways are triggered to maintain homeothermy, making the animal more vulnerable to heat stress (Ravagnolo and Misztal, 2000). Though, the selective breeding programs have multiplied production several fold over the past 3–4 decades, but it rendered livestock more vulnerable to changing climate, global warming, and heat stress (Renaudeau et al., 2012; Collier et al., 2019).

Heat stress in beef cattle

In contrast to the intensive dairy systems, beef cattle are primarily reared on pastoral (*viz*. feedlot, range) or semi-intensive facilities which provides them substantial access to shade, water, free movement, and behavioural expression. However, this also makes them easily susceptible to harsh environmental conditions (van den Pol-van Dasselaar, 2015; Magrin et al., 2017; Rojas-Downing et al., 2017).

Beef cattle respond differently to heat stress than dairy cows, owing to lower metabolic heat generation, breed variability, and their ability to withstand comparably higher temperature-humidity index (THI) (St-Pierre et al., 2003; Nardone et al., 2010). This does not imply that they are immune to heat stress and all the stress responses are activated once the THI exceeds the threshold (78–80, depending on the breed and geographical location). There is immediate reduction in feed intake which is more pronounced, especially if feed is of poor quality (Mitlöhner et al., 2002; Van Laer et al., 2014; Yadav et al., 2016; Wankar et al., 2017, 2019; Marchesini et al., 2018; Thornton et al., 2022). However, studies indicate that heat stress not only directly reduces feed

consumption, but it also has an indirect effect on energy metabolism, digestive processes, and nutrient assimilation. (Busby and Loy, 1997; Wheelock et al., 2010; Mahjoubi et al., 2014; Wankar et al., 2019). Soon after the decrease in feed intake, thermoregulatory processes like sweating, panting, increased water consumption, and behavioural changes are activated. The animals often prefer to move and feed during the cooler hours of the day (Magrin et al., 2017). All of these acclimatory responses divert the productive energy towards maintaining homeostasis resulting in poor growth rate, lower average daily weight gain, poor performance, and longer recovery periods in beef animals (Kadzere et al., 2002; Ravagnolo et al., 2002; Nardone et al., 2010; Marchesini et al., 2018).

Heat stress is more difficult to quantify in beef cattle since there are several phases *viz*. the gestational phase, growing phase, adult phase, and the finishing phase. The impact of heat stress during postnatal life is well documented, but prenatal exposure and its effects are still not very clear. Thermal stress during the embryonic period has been shown to cause irreversible changes in animal physiology, behaviour, and metabolism, resulting in poor birth weight, growth, and meat composition (Foxcroft et al., 2006; Tao and Dahl, 2013; Zhang et al., 2020). While, in growing and finishing cattle heat stress reduces the weight gain, protein gain, fat gain and carcass yield (Geraert et al., 1996; Marchesini et al., 2018; Summer et al., 2019). Other meat attributes like meat quality, tenderness, colour, and pH also alter, lowering the meat price and its acceptability to consumers (Mitlöhner et al., 2001; Sofos, 2008; Johnson et al., 2015; Sant'Anna et al., 2019; Abhijith et al., 2021).

A recent study (Bunning and Wall, 2022) reported poor growth rates, average daily carcass gain, carcass weight and 200-day weight gain in heat stressed beef calves, while the age at slaughter and production costs increased significantly. Similarly, another study has identified metabolic and molecular biomarkers, their expression in heat stressed beef cattle and how they alter the stress response, modulate animal performance, growth, and meat yield (Kim et al., 2022). Other researchers have mainly attributed poor growth and compositional changes in heat stressed livestock to down regulation of DNA, RNA and protein synthesis, protein deposition and elevated fat accumulation (Jacob, 1995; Geraert et al., 1996; Ronchi et al., 1999; O'Brien et al., 2010). Higher protein turnover and proteolysis for energy production via gluconeogenesis, exacerbates the protein turnover and deposition in heat stressed cattle (Danfar, 1994; Temim et al., 2000; Kuo et al., 2013; Gao et al., 2017).

Data analyses

Data was sourced from FAOSTAT website for the period 1961 till 2020 and changes in average environmental temperature, number of cattle (cattle and buffalo), land usage, area under meadows and pastures, total livestock units (LSU) percent share in trade, methane emissions and gross production value of beef were analysed, and comparisons were made for the last two decades, i.e., 2000–2010 and 2010–2020, respectively. Predictions for all the above variants were made by using Microsoft Windows, IBM Excel Package forecast functions, for the years 2025 and 2030. The results of analysis are presented as Tables 1–5 and Supplementary Tables 1–6, in the text, respectively. Similarly, Microsoft Windows, IBM Excel Package were used to plot maps for the current buffalo, cattle populations, country wise meat and per capita beef consumption, which are depicted in Figures 1, 2, 3 and 4 respectively.

Table 1. Continent-wise ambient temperature (°C)

Year	Africa	% Change	America	% Change	Asia	% Change	Europe	% Change	Oceania	% Change
2000	0.78		0.45		0.70		1.34		0.16	
2010	1.48	89.90	1.31	191.15	1.27	82.57	0.81	–39.22	0.69	308.88
2020	1.21	–18.11	1.33	1.52	1.53	20.11	3.35	311.78	1.38	99.86
2025	1.31	8.31	1.37	3.14	1.49	–2.61	2.13	–36.38	1.12	–18.39
2030	1.43	9.11	1.50	9.36	1.63	9.50	2.33	9.23	1.22	8.70

*Authors' own calculations based on FAOSTAT data.

Table 2. Global cattle population (millions)

Year	Africa	% Change	America	% Change	Asia	% Change	Europe	% Change	Oceania	% Change
2000	232.23		460.69		441.78		147.90		37.35	
2010	298.26	28.43	509.48	10.59	441.99	0.05	124.44	–15.86	37.34	–0.02
2020	376.31	26.17	531.12	4.25	465.67	5.36	116.12	–6.69	34.05	–8.82
2025	352.34	–6.37	568.15	6.97	488.34	4.87	107.11	–7.76	39.76	16.77
2030	372.20	5.64	587.54	3.41	501.70	2.74	95.38	–10.95	40.52	1.91

*Authors' own calculations based on FAOSTAT data.

Table 3. Global buffalo population (millions)

Year	Africa	% Change	America	% Change	Asia	% Change	Europe	% Change	Oceania	% Change
2000	3.53		1.11		159.35		0.23		0.00013	
2010	3.82	8.22	1.19	7.21	188.63	18.37	0.39	69.57	0.00015	15.38
2020	1.35	–64.66	1.92	61.34	197.38	4.64	0.48	23.08	0.000174	16.00
2025	3.83	183.70	1.96	2.08	212.41	7.61	0.23	–52.08	0.000181	4.02
2030	4.00	4.44	2.12	8.16	222.43	4.72	0.19	–17.39	0.000191	5.52

*Authors' own calculations based on FAOSTAT data.

Table 4. Land usage for cattle (LSU/ha)

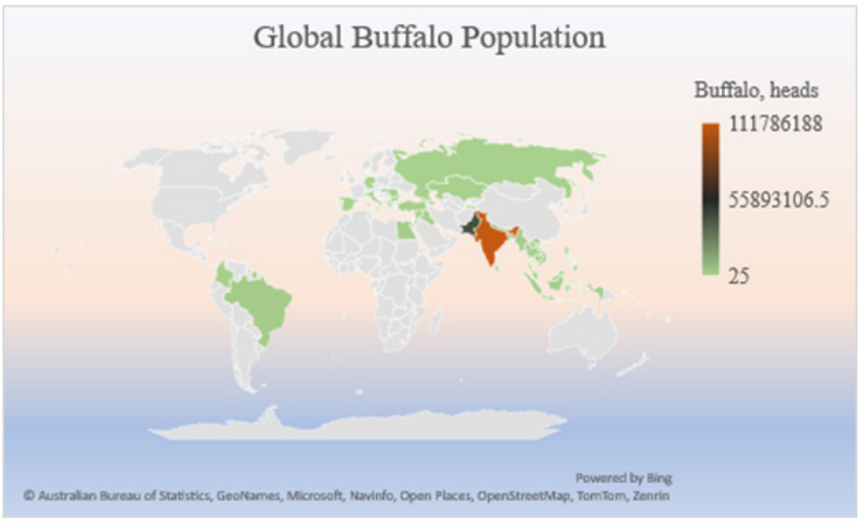
Year	Africa	% Change	America	% Change	Asia	% Change	Europe	% Change	Oceania	% Change
2000	0.11		0.31		0.20		0.24		0.07	
2010	0.14	27.27	0.34	9.68	0.20	5.00	0.21	–12.50	0.09	28.57
2020	0.17	21.43	0.36	5.88	0.22	4.76	0.20	–4.76	0.08	–11.11
2025	0.15	–6.47	0.37	3.06	0.20	–5.45	0.22	14.50	0.09	13.75
2030	0.16	5.03	0.38	2.96	0.20	–0.48	0.23	0.44	0.09	4.40

LSU = Total livestock units, ha = hectares.
*Authors' own calculations based on FAOSTAT data.

Table 5. Area under meadows and pastures (1000 ha)

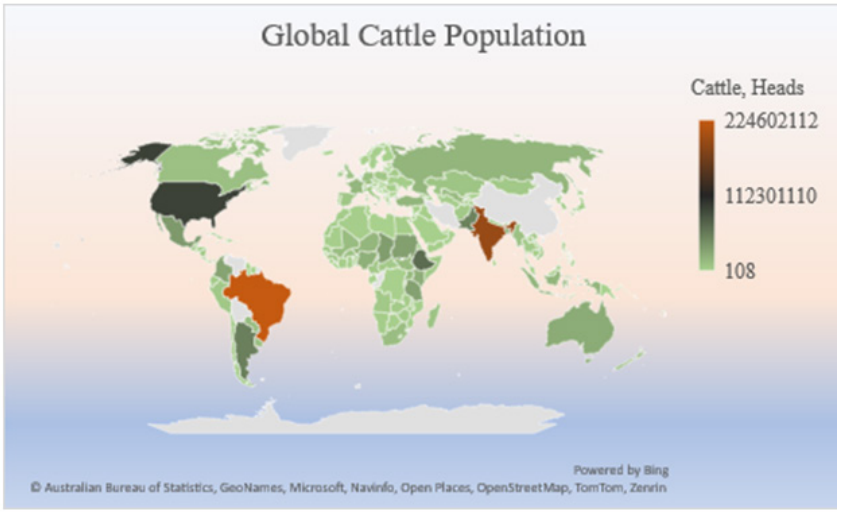
Year	Africa	% Change	America	% Change	Asia	% Change	Europe	% Change	Oceania	% Change
2000	21375.48		44897.58		56479.38		66442.22		42.29	
2010	21668.26	1.37	29034.41	–35.33	45958.70	–18.63	66303.17	–0.21	114.90	171.64
2020	22091.69	1.95	22624.27	–22.08	41354.79	–10.02	63578.61	–4.11	124.23	8.12
2025	21949.02	–0.65	11317.52	–49.98	34226.57	–17.24	62964.11	–0.97	137.92	11.02
2030	21976.75	0.13	4558.15	–59.72	29752.83	–13.07	62228.36	–1.17	147.85	7.20

ha = hectares.
*Authors' own calculations based on FAOSTAT data.



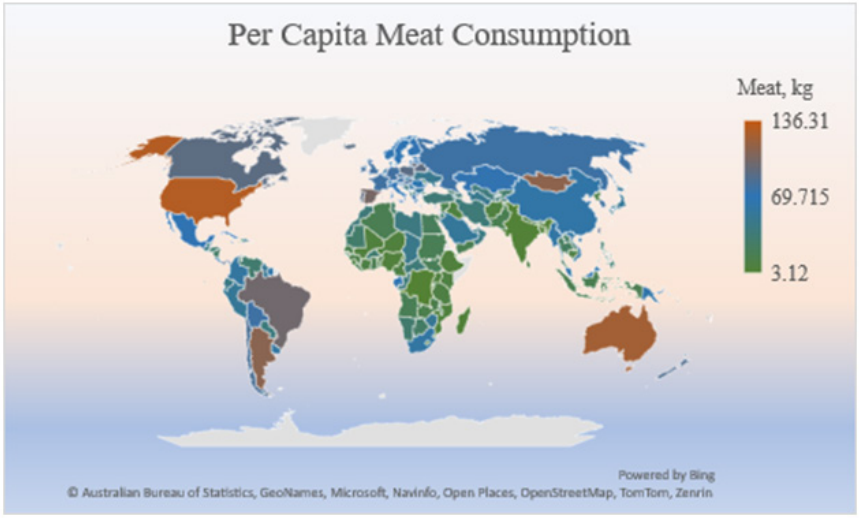
Sourced from FAOSTAT, 2020.

Figure 1. Global buffalo population



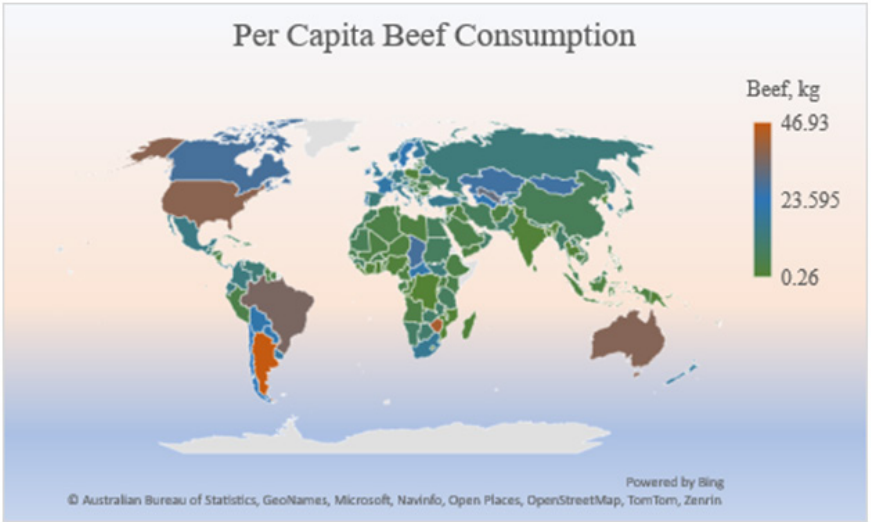
Sourced from FAOSTAT, 2020.

Figure 2. Global cattle population



Sourced from worldpopulationreview.com: Meat Consumption by Country 2023.

Figure 3. Global per capita meat consumption



Sourced from worldpopulationreview.com: Meat Consumption by Country 2023.

Figure 4. Global per capita beef consumption

The global scenario and consumption of beef

Global beef consumption significantly increased after World War II due to the start of industrialization, modernization, intensive cattle farming, food processing and urbanization. In addition, rising per capita income, consumer awareness, dietary preferences, and eating habits have accelerated the transformation of the food industry (OECD, 2022). Figures 3 and 4 show the current global status of beef consumption as well as the per capita consumption in different countries. The worldwide beef sector is driven by four key factors: 1. Increased consumption 2. Organized farming operations and distribution 3. Government policies, trade, and commerce 4. Climate change (Cerles et al., 2017; Hocquette et al., 2018). The per capita meat consumption (unprocessed or processed) increased tremendously in Southeast and East Asia, Latin America, Caribbean region, and sub-Saharan Africa during the period of 1990 to 2018. China, Japan, Brazil, South Africa, and Mexico topped the beef consumption. Contrarily, during the same period (1990–2018) beef consumption decreased in Central or Eastern Europe, Middle East, North Africa, other developed countries and central Asia, and the decline was between 14.0% and 47% for nations like Russia, Germany, Iran, and France (Miller et al., 2022).

Despite this, both in developed and developing countries, beef consumption is rising, with a 15% increase predicted by 2031 (Pohjolainen et al., 2016). The consumption of beef will increase by 10% in Asia and the Pacific region during the next ten years, but it will decrease (by between 2 and 15%) in the United States, Argentina, Canada, Brazil, and Oceania (Whitnall and Pitts, 2019; OECD-FAO, 2022). Depleting cattle herds, low- or poor-quality feed, saturated markets, growing awareness of environmental impact and carbon footprint, health concerns, and animal welfare are the main causes of this drop in beef consumption (Graca et al., 2016). Brazil and the United States are the major exporters of beef to the world in the present and in future also. Other countries for example Argentina, Australia, India, Pakistan, the European Union, Thailand, Paraguay, and Turkey will also contribute significantly in the global exports. China, the Middle East, and Indonesia will be the major importing nations (OECD-FAO, 2022). Looking at the scenario, it appears that demand and production for beef will increase until 2031, but the increasing proportion from chicken and pork cannot be overlooked, which are the two most popular meats in the world. Our quest to find an alternative environmentally friendly source of protein appears faraway and we are mostly dependent on AOF.

Climate change, the present status, and future implications on beef sector

Americas

The Americas can be sub-divided into the Northern and the Southern America, each of which have diversified beef producing systems. Feedlot system which primarily constitutes the cow-calf system, the stocker system and feedlot-finisher system dominates the United States (US) and Canada. While beef cattle are mostly raised extensively in the southern areas (Brazil, Argentina, and Mexico) (Galyean et al., 2011). Climate and environmental conditions directly affect the monsoons and the summers, grazing season, ecosystems, crops, and fodders grown for the livestock, which in turn influence the marketability of the beef cattle (Polley et al., 2013; Drouillard, 2018; Havstad et al., 2018). The feedlot systems will be impacted by the climate's rapid change, and vector-borne diseases will re-emerge as a result (Short et al., 2017). Also, the pastoral ecosystems, forage production, soil degradation, water scarcity and associated heat stress, animal death, decreased production and economic loss might be more pronounced (Havstad et al., 2018). The US uses roughly 41% of the total land area, whereas Mexico uses about 60% of it for livestock grazing on common or under-utilised pastoral land (Peel et al., 2010).

In terms of the natural resources consumed, beef production by feedlot method seems most efficient (Capper, 2011). Transformation of the beef industry began during late 1950s and in the last 2–3 decades, we witnessed an astonishing degree of mechanization and specialization, with bigger well organized production units. Another prominent driver was involvement of the world's largest corporations in the lucrative and ever-expanding food industry (MacDonald and McBride, 2009). However, the beef herds have seen decreasing patterns in the United States and Canada, and the size of the feedlot system has decreased from 34 million to 30.9 million heads (Galyean et al., 2011). In contrast, the cow herds in South America are stable and even growing slightly (Index Mundi, 2011).

The US carbon footprint also substantially decreased as a result of the sector's change, intensification, and development, increasing the value and environment-friendliness of the industry (Capper, 2011). The demand for beef is expanding rapidly both worldwide and in the south Americas, while the domestic US consumption is fairly stable and can remain same by the 2030s (OECD-FAO, 2017). New developing nations are now emerging as major exporters and competing with the giants like the United States, the European Union (EU) or Oceanic countries for the beef trade (OECD-FAO, 2017).

The Americas witnessed an astonishing 191.15% temperature rise during 2000–2010. Following then, the environmental temperatures are expected to grow consistently till 2023 (Table 1). Cattle populations grew marginally over the last two decades and a small increase is anticipated in the next decade as well (Table 2). While, the buffalo population increased from 2010, reached maximum till 2020 and thereafter only a minimal growth is expected by 2023 (Table 3). The land usage increased from 2000 to 2020, and the predicted growth by the 2030s looks stagnant (Table 4). Meadows and pastures have declined here, since the beginning of the 20th century and same trend is predicted till the 2030s (Table 5).

From supplementary tables, we can see that the share of cattle in the total trade is declining in Americas, while the methane emissions have increased steadily (Supplementary Tables 1, 3, 4). The value of beef production grew substantially during 2000 to 2010 (from 41,416,764.00 to 89,398,768.00, 1000 US$), however for the period 2010–2020 a major decrease was recorded but expected returns appear promising by 2025 and 2030 (Supplementary Table 5).

The production potential of cattle is fully exploited in the well-developed, organized American beef sector. The sector is equipped with well-established automation, processing, packaging, distribution, and supply chain. It is both a major beef importer and exporter nation. A major concern here are the already saturated domestic and international markets and the emergence of new players like Latin American nations, Australia, Africa, and India etc. The environmental temperatures ought to rise with time and maintaining a mature and maturing herd of thermotolerant beef cattle, is essential for sustained production. Shrinking usable lands, pastures and declining share in the trade are other issues to be critically addressed. For sustainable meat production immediate actions are required to reduce the GHG's emissions and the carbon footprint. For the south American beef producing nations, changing climate demands the need for improved management, distribution systems, beef quality, trade policies and curbing environmental impact for sustainable beef production in the future.

Africa

The Africa region is still to be fully explored, with rich natural resources and animal population. Africa will be one of the continents with the fastest population growth when it reaches 2.5 billion people by 2050, up from the current 1.5 billion. The meat business has grown quickly over the past 10 to 15 years as a result of the expanding human population, rising per capita GDP, changing agricultural and animal husbandry practices, consumer preferences, and consumer demands (AfDB, 2017; FAO, 2017; World Bank, 2017). Today Africa produces more than 6% of the total beef and the production has doubled in the last two decades from 11.59 to 19.88 million metric tons. Beef consumption also increased and some of the leading producers, consumers and exporters of beef are South Africa, Botswana, Namibia, Sudan, Nigeria, Egypt, Ethiopia, Kenya, Chad and Tanzania (Benson, 2022; Jenane et al., 2022). The African beef industry is nascent and still developing in comparison to the Americas, Europe, Australia, or Asia, but with supportive government policies and foreign or domestic investment, the potential for expansion here is infinite, and soon Africa can become a global beef exporting global zone (African Business, 2019).

A major constraint to the beef sector in Africa, is the hot climate and the effect of climate change is more pronounced in some of the vulnerable regions (Maplecroft, 2015). International climate agencies have already warned about a drastic decrease in annual rainfall, particularly over the Southern African region, which is the top beef producer and exporter (Serdeczny et al., 2016). Also, by the end of the 21st century the mean temperature can rise by 2°C or more, affecting the agriculture, water ecosystems and predisposing livestock to heat stress (Pereira, 2017). The need to reduce the greenhouse gases (GHG) emissions for sustainable, cleaner production remains another major concern for the beef units (Bogale and Temesgen, 2021). Despite having vast herds of thermotolerant beef cattle, if the policies, management, and trade in this region are not improved and optimised, Africa will become the world's largest importer rather than an exporter of beef (Christiaensen, 2020; Seleshi, 2021).

The geographical location makes the African continent inadvertently warmer, and during last two decades, the environmental temperatures increased rapidly and same trend is expected through the 2030s (Table 1). The total cattle population in Africa increased during 2000–2020, and our results show a minor decline by the year 2025 followed by a slight increase by the 2030s (Table 2). Like cattle, the buffalo population in Africa also increased till 2010, then decreased drastically by a 64.66% in 2020 and thereafter, it is expected to rise again by the year 2030 (Table 3). The land usage by the cattle was maximum till the 2020s, then a drop is seen until 2025, followed by a slight increase till the 2030s (Table 4). In Africa, the acreage used for pastures and meadows remained constant from 2000 to 2020, and no significant changes are anticipated by the year 2030 (Table 5). From Supplementary Table 1 and 2, we can see that the livestock share in the trade has substantially decreased between 2010 and 2020 and continued to fall until 2025 for cattle, unlike the buffalo. Further decline in the share is expected for both cattle and buffalo by the 2030s. Methane emissions from cattle were highest for the last three decades, and thereafter a minor decrease is predicted in 2025, and then again, the emissions are to elevate by the 2030s (Supplementary Table 3). Comparatively, the GHG emissions from the buffalo were low during 2000–2010, decreased significantly by 2020 and are expected to steeply rise by the 2030s (Supplementary Table 4). The value of gross production of meat increased significantly between the years 2000 and 2010, declined insignificantly in the 2020s, and will continue to maximize in the 2030s (Supplementary Tables 5 and 6).

The beef sector here is mainly extensive, pastoral, unorganized and so are the distribution systems. Still the growth of African beef industry is outstanding in the last decade. Selected African nations are major exporters of beef to the European Union. The cattle are average producers, but are fairly resistant to heat stress. Also, the increasing numbers of cattle and buffaloes is quite appreciable here. Here, the use of the land, meadows, and other natural resources can be greatly enhanced to increase productivity. The share of the beef in the trade and the revenue generated needs to be systematically boosted. Currently there is no recording of the GHG emissions

from the sector, but has to be critically monitored to reduce the environmental impact in future. Traditionally, as the summer heat intensifies, more and more farmers shift to rearing goats, sheep, and beef cattle, instead of dairy cattle. As Africa is naturally the warmest continent, this tradition needs to be combined with the modernization and production intensification in order to increase global distribution of high-quality meat and boost the continent's economy.

Asia

The Asian beef industry is currently expanding rapidly to accommodate the growing human population, industrialization, urbanization, and cultural transformations. China, Japan, Taiwan, Singapore, and Korean Republic are the major importers of beef from the US, Brazil, Argentina, Australia, and Europe (OECD-FAO, 2017). The demand for beef and veal is growing rapidly in India in last two decades, and here mostly the water buffalo is used for beef production as cow slaughter is banned (Landes et al., 2016). In Asia, China consumes the most beef and imports the most beef (Zhang et al., 2015). However, traditionally China has always been a major beef producer, but recent rise in beef imports is essential to match the increased beef consumption, population explosion and largescale migration of people from rural to urbanized regions (National Bureau of Statistics of the People's Republic of China, 2016; Wang et al., 2016).

Other Asiatic nations like Thailand, Malaysia, Indonesia, Vietnam, Philippines, Myanmar, Brunei, Laos, Cambodia, and the Association of South East Asian Nations (ASEAN) where the labour is still cheap and economy is growing, will be major beef consumer and producer markets globally (Bunmee et al., 2018; MLA, 2020). The Asian meat industry is predicted to grow at a rate of 5.10% and beef markets alone are to generate more than $33,382.50 million with additional $57,360.50 million from the packaged meat industry, by the year 2026 (Research and Markets, 2023). After the COVID-19 pandemic and other quality control issues, the recovery of the beef industry is slow here, preventing the exports to developed nations. Although the beef consumption has increased significantly in nations like China, Pakistan, and Turkey the exports remain low and most of the Asiatic nations are major beef importers (Global Trade Magazine, 2020).

In the advent of the changing climate, beef production is a challenge in itself and there has been an imbalance between the demand and supply equation for AOF in Asia. Asia's animal husbandry industry is under threat from progressively rising environmental temperatures, frequent droughts, and erratic rainfall. During the summer, a rise in ambient temperatures is already perceptible throughout all of northern Asia. While at the same time the rainfall has precipitously decreased in China, India, Indonesia, Japan, Philippines, and Pakistan (Cruz et al., 2007). The harsh climatic conditions, poor nutrition, and management, semi-intensive to extensive cattle rearing makes Asia one of the top GHG emitters on the global scale. In future, sustainable beef production under the climate change scenario, to supply the human population and to export the surplus meat will be a major challenge.

Table 1 shows that the environmental temperature increased rapidly in Asia till 2010 and continued to grow by 2020. Thereafter, it is expected to decrease in 2025 and again increased by 2023, respectively (Table 1). Only a modest increase in the population of cattle and buffalo was observed until the year 2020, and the same slow growth trend is anticipated to continue into the 2030s (Table 2 and 3). Land usage by cattle was optimum till the 2020s, and it can be seen that thereafter it will decline steeply by the year 2025 and 2030, respectively (Table 4). Similarly, there is a significant reduction in the total meadows and pasture area in Asia, since the year 2010 and our predictions show a similar trend till the year 2030 (Table 5). Despite the largest cattle population (cattle and buffalo) in the world, Asia's share in the trade is now small, has been dwindling in the previous 20 years, and is predicted to continue declining until the year 2030 (Supplementary Table 1–2). Since the beginning of the 20th century, a continuous increase in methane emissions is evident from the beef cattle and buffaloes, and they are expected to grow further by the end of the 2030s (Supplementary Table 3–4). The revenue generated by buffalo meat production continued to increase through the 2020s, but that of cattle meat production dropped by 2020 (Supplementary Table 5–6). Expected trends for cattle meat appear positive during 2025–2030, but buffalo meat will decrease slightly in 2025, and then increase again by the 2030s (Supplementary Table 5–6).

Asia has the world's largest populations of people, cattle, and buffalo. With the rapid growth in human population, urbanization, and economy in the entire region the demand for animal foods has also substantially increased. The animals in this area are average to elite yielders and evolved in hot temperate to tropical conditions, making them thermotolerant to heat stress. Here the major constraints are poor quality feed, management, pastoral or extensive rearing and prolonged harsh environmental conditions. The beef cattle often have infectious or zoonotic diseases which makes beef exports to developed nations impossible. Also, there is a direct conflict for natural resources like land and water resources for humans or livestock. Countries like China are the global importers of beef, although they also produce beef, but it is insufficient to fulfil the demands. The beef cattle and buffalo herd, seems to grow here, even with the climate change. However, the use of land and natural resources can be tightly optimized, for both humans and livestock. The prevalence of white meats has substantially reduced the cattle share in the trade, but the value of beef production and the potential for economic gains are rising, and still need to be fully explored. The steady increase in the GHG emissions from the beef systems will be a major constraint for future production in Asia. So, the beef

sector is currently blooming here and with optimization, futuristic planning, efficient use of resources and manpower, and supportive policy regulations, Asia will soon be a leading beef exporter and importer region.

Europe

In Europe, cattle rearing is mostly pastoral, semi-intensive as well as intensive systems (cow-calf-finisher) and there is great variation like, totally extensive or intensive, on permanent or temporary grasslands, fully feeders or breeders or a mix of breeder, feeder or finishing beef cattle. Presently, the EU is the third largest producer of beef, with more than 50% share coming from France (21.20%), Germany (17.80%) and Italy (11.10%) alone (FAPRI, 2012; Vinci, 2022). Despite the potential, EU barely contributes to a meagre 2% in beef exports and 3% in imports, globally. Contrastingly, trade of beef and live animal within the EU countries is quite healthy (Chatellier, 2016). The European beef production is being significantly impacted by the cow herds' ongoing decline (at a rate of 1.40% till 2021) (Buczinski, 2010; Clarke, 2021). In the future, production of dual-purpose cow breeds will be necessary to meet the rising demand for both milk and meat (Zehetmeier et al., 2012).

Also, the local demand for beef will decrease slightly by the year 2025 as other meats coming from poultry, sheep and goat are preferred over beef (FAPRI, 2011). In addition, the growing competition from developing nations, increasing feed and labour costs and concerns over environmental pollution have been a constant threat to European beef industry (Hermansen and Kristensen, 2011; Vinci, 2022). To stabilize the prices, the EU regulates the beef price fluctuations in their domestic markets as and when necessary and trading here is mainly by quota system, either open to all non-EU nations or a small number of specifically selected ones (Agriculture and Rural Development, European Commission, 2023).

European cattle are amongst some of the least thermotolerant breeds and primarily adapted to cold climates. But in recent years upsurge in the environmental temperatures and climatic fluctuations, led to a decline in animal performance. Here not only the livestock but even the grasslands are affected due to changing climate and soon might be converted into arable lands for sufficing the growing human demand (Havlík et al., 2012). People are becoming more aware of their health and the effects of livestock production systems on the environment, as well as their carbon footprint (Hocquette and Chatellier, 2011). Animal husbandry here is cleaner, emitting least amount of GHGs as compared to Asiatic or African regions.

Data analysis reveals fascinating temperature fluctuations and a drop was observed during 2000–2010. Afterwards an astonishing rise in environmental temperatures (311.78%) was noted during the next decade (2020), to be decreasing by 2025 followed by an increment again in the next five years (Table 1). Over the years, the cattle population here is steadily depleting and a substantial decline was seen between 2000 and 2010 and same declining trend is expected till the 2030s (Table 2). The buffalo population was at its peak till 2020, but there is a projected decrease for the period 2025 to 2030 (Table 3). We witnessed a decrease in land usage by the cattle in last two decades but by 2025–2030s a small rise is anticipated (Table 4). From Table 5, it can be seen that the meadows and pastures in Europe are constantly shrinking and significant reduction was noted in the 2020s and the trend will continue till the 2030s. The share of cattle in Europe's economy is continuously backsliding and it is expected to continue through the year 2030. Contrastingly, the buffaloes share was maximum till the late 2020s, and thereafter declined throughout the 2030s (Supplementary Table 1–2). The methane emissions from the cattle constantly decreased from 2000 to 2020 and are projected to fall further till the 2030s (Supplementary Table 3), but the GHG emissions from the buffalo were higher till 2020, which will drop by the 2030s (Supplementary Table 4). The production value and revenue generated for beef were maximum till 2010, then we noted a decrease in 2020 for cattle share, but the buffalo production grew significantly during the same period. Thereafter, for cattle a constant growth is expected till the 2030s, whereas for buffalo an initial decline of 16.35% (in 2025), followed by an increase is expected by the 2030s (Supplementary Table 5–6).

The impact of climate change in Europe is noteworthy and severe. Here the pastoral and extensive systems are diminishing, affecting the beef sector adversely. In general, the summers are now longer, more intense, and more stressful due to the heat. The local cattle breeds are mainly adapted to cold environment for thousands of years and are now suddenly to acclimatize to the high ambient temperatures. This has resulted in compromised production and animal deaths. The need for introduction of thermotolerant and dual-purpose cattle breeds cannot be stalled any further in the EU. It is also absolutely essential to increase the beef cattle herds to continue and upscale the demands. The beef produced is of high quality and exported in the EU and other countries, generating substantial revenue from the animal husbandry. The environmental impact is very less and the European systems are the cleanest and have least carbon footprint. Increasing the animal numbers (especially those that are adapted to higher ambient temperatures), production intensification, conservation and proper utilization of natural resources is pertinent for future growth and sustainability of the EU beef sector.

Oceania

Australia and New Zealand are the two major economies of the Oceania region and both nations export more than 60–70% of their beef (MLA, 2022). Previously, there were only pasture-based cow-calf finishing system and rangeland-based cow-calf systems; but in recent years, intensive feedlot beef cattle finishing like the US has gained popularity here (AgriFutures Australia, 2017). Australia

housed more than 11.5 million beef cattle, producing slightly over 2.07 million tonnes of beef (for the years 2016–2017). The beef produced and exported is of high quality and is disease free, increasing its demand all over the world and in 2021 Australia and New Zealand collectively contributed 13 and 7%, respectively, to the global beef exports (MLA, 2017, 2022). Still, the Oceania faces a steep competition for the large Asian beef markets from the emerging south American nations, US, and India (Bell et al., 2011; Hyde et al., 2017). Japan was a major importer of beef from Australia and New Zealand, but in the year 2021, Australian exports decreased by 44% while exports from New Zealand increased by 35%.

Although the beef sector is well established, the region's extensive geographic climatic zones are a constant challenge to the pastoral and rangeland systems and unpredictable rainfall patterns, severe droughts and heat stress is common (Poppi and McLennan, 2010; AgriFutures Australia, 2017). The Oceanic region has all the potential to grow even more, increase productions and exports and become global leaders by 2024 as the demand for beef is ever increasing in the Asiatic continents and all over the world (MLA, 2022; Marel, 2023).

During the first two decades of this century, the environmental temperatures drastically increased over the Oceanic region. The forecast for the year 2025 shows a decrease by 18.39% but the temperatures will once again rise by 2030 (Table 1). Both cattle and buffalo population declined here till the 2020s, thereafter the populations are expected to grow stably from 2025 to the 2030s (Table 2 and 3). As the Oceanic regions are sea-bound, expansion of land is difficult, still a 28.57% increase was seen in land use for livestock during 2000 to 2010, a reduction by the 2020s, and then a minimal increase by the 2030s (Table 4). Pasture utilization in the Oceanic nations increased significantly till 2010–2020, following then only small increments are expected in land utilization by the 2030s (Table 5). With the exception of 2020, the Oceanic regions have recorded a stable increase of share in the trade (Supplementary Table 1). From Supplementary Table 4, we can see that the methane emissions from the cattle were low till 2020 and then increased, while for the buffaloes' emissions in the Oceanic regions gradually increased over time (Supplementary Table 3). Beef production value and the revenue generated soared till the 2010s, followed by slight decline in the late 2020s and are again anticipated to grow steadily till the 2030s (Supplementary Table 5).

Although the beef breeds in this region are resistant to heat stress, the climate change not only predisposes them to heat stress but it also has a negative impact on the entire production system. Both Australia and New Zealand supply highest quality, disease free beef to the world. Here the beef cattle population and the amount of land, pasture and meadows utilization are all increasing gradually. Moreover, the well organised production, distribution systems and favourable trading policies give a genuine opportunity to improve the production, exports and increase the profitability even under the climate change scenario. Although clean meat production is not a constraint presently, soon pressure for cleaner beef might be a challenge for the Oceanic nations.

Conclusions and future outlook

Consistent with the growth in the human population and urbanization, the demand for animal origin foods will also rise across the globe. We have two major categories of nations, the super developed ones and the developing ones and the gap is constantly shrinking in the two. Demand for meat is stable in the developed worlds, but it keeps soaring continuously in growing economies. The sector uses the land, water, grains, pastures, meadows, grasslands, rangelands, and the feedlot intensive systems for producing the beef, which increase the GHGs and the environmental carbon footprint. Besides, in the context of global warming and climate change, the targeted increase in beef production has to be accelerated and achieved, making it more challenging, stressful, and questionable for its sustainability over plant-based foods. Presently the demand for beef and all types of meats, is rapidly increasing and is expected to grow for the next 2–3 decades, at which point we may need to look for alternative plant-based or lab-grown protein sources.

Future implications

- Do we really need to consume animal origin foods for nutrition, or can we search for better sustainable plant-based sources
- The beef sector has to be better organized; production should be intensified and global trade should be standardised and accessible to all nations
- Incorporation and conservation of native cattle, dual purpose, and crossbreeds suitable to local climatic conditions is essential to maintain a steady production and supply
- Cleaner beef production to reduce the methane, carbon dioxide, GHG footprint and overall ecological cost of the sector
- Regional amalgamation of traditional and modern scientific methods for rearing beef cattle
- Conservation of natural grasslands, pastures and rangelands while maintaining balance for the usable land
- Changing food preferences and consumption of white meats etc.

Author contributions

AKW and SNR conceived and conceptualized the study. AKW and GNB extracted the data and analysed it. TAS and BLK validated the data and prepared the tables. AKW prepared the figures and supplementary material. AKW and SNR drafted the manuscript, which was reviewed and edited by BLK, TAS and GNB. The manuscript was finalized by AKW and GNB, and AKW led the submission and all the correspondence. All the authors have agreed on the final version of the manuscript, and there is no conflict of interest.

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