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Invited Review Article

Climate change trends and their impacts on bovine productivity: Precision livestock farming for Sustainable Development Goals and One Health

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Abstract

Rise in ambient temperature due to climate change influencing livestock production system and its efficiency by impacting growth, milk production and reproduction of bovines under tropical conditions. Natural environments are much more complex, with far more environmental factors varying both spatially and temporally, so it is likely that global warming and climate variability will amplify the complexity of genotype environment interaction. Projected temperature rise is likely to impact livestock productivity (milk, meat, wool, and draught power), particularly in non-adapted livestock. The temperature rise will also cause a change in composition of species, breeds (quantity, quality) and their mix at farm level due to availability of resources. Inadequate resources and infrastructure make Indian farmers and their livestock highly susceptible to extreme weather events and climate change. Livestock production system is likely to suffer greater losses due to substantial increase (160%) in stressful days by the year 2100 due to global warming. The reduced availability of livestock products will increase risk of malnutrition, hunger and imbalance in vegetarian diets. The global imperative to achieve Sustainable Development Goals (SDGs) has intensified the need for innovative technological interventions in animal resource management. The innovations in technology can enhance sustainability in this sector, particularly under changing climatic scenarios and One Health approach, which links human, animal, and environmental health. In this review, recent developments in precision farming, biotechnology, digital monitoring systems, and sustainable feed innovations are presented. It also examines the integration of these technologies within the broader framework of climate adaptation strategies and public health.

Keywords: Climate change, Livestock, Production, Sustainable development goals, Thermal stress

Highlights

- Temperature rise due to global warming threatens livestock productivity and welfare.
- Livestock are vulnerable to temperature variability due to inadequate resources and infrastructure.
- By 2100, increase in stressful days due to global warming could impact livestock production.
- To achieve SDGs requires innovative technological interventions.
- Precision farming, biotech, digital monitoring, etc, can boost sustainability amid climate change.

INTRODUCTION

Agriculture and allied sectors contribute nearly 18 per cent of India's Gross Domestic Product. About 70 per cent of the population is dependent on agriculture for their livelihoods (FAO in India, 2021). Indian Livestock sector provides sustainability and stability to the national economy by contributing to farm energy and food security. The livestock sector consists of about 192.52 million cattle, 109.85 million buffaloes, 74.26 million sheep, 148.88 million goats and 10.27 million other animals making a total of 535.78 million (Twenty Livestock Census, 2019). Approximately 16 percent of the world's cattle and 57% of its buffalo are found in India. India has the largest number of buffaloes, second-largest population of cattle and goats, and third-largest population of sheep worldwide (Twenty Livestock Census, 2019).

During the last decade, the annual growth rate for livestock production has maintained a steady growth of 4.8 to 6.6%. The sector has registered a compounded growth rate of more than 5.0% during the last decade, in spite of the fact that a majority of the animals continue to be reared under sub-optimal conditions and milk productivity per animal is low. On the other hand, agricultural production either barely increased or remained the same. Energy demands and livelihood security are met by an estimated 440 million livestock heads spread across 100 million households in roughly 600,000 localities (Jack *et al*., 2021).

Climate change is defined as the significant variation of average weather conditions becoming warmer, wetter, and drier over decades or longer. It is the long-term development that differentiates climate change from natural weather variability. According to NOAA's (2023)

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Annual Climate Report the combined land and ocean temperature has increased at an average rate of 0.06°C per decade since 1850. Since 1982, the rate of warming has increased by more than three times, or 0.20°C per ten years. As the warmest summer on record, the summer of 2023 was 1.2°C warmer than the average summer from 1951 to 1980 and 0.23°C warmer than any previous summer in NASA's record. (NOAA/NASA – Annual Global Analysis for 2023).

Livestock production systems in India

Several studies have been done to characterize the farming systems in different agro-climatic zones in India, not much have been done to characterize and represent the milk production systems (Saha, 2001). In India, livestock farming systems are mainly classified as-

- Arid, semi-arid tropics and subtropics rain-fed system
- Humid and sub-humid tropics and subtropics mixed system
- Arid and semi-arid tropics and subtropics mixed system

The most popular method of rearing livestock is generally an arid rain-fed system, in which livestock do a number of tasks at once, such as producing meat and milk, producing manure, and serving as a currency reserve. The humid and sub-humid tropics and subtropics mixed system is characterized by intensive crop production, especially water-intensive crops such as paddy twice a year due to increasing population pressure and demand for food crops (Saha, 2001; Amejo *et al.*, 2018).

Over the years, smallholder livestock production systems have gained very high significance, and milk has emerged as the major food commodity in mixed farming systems. The majority of milk (>90%) and the largest portion of total meat (53.9%) are produced in mixed-farming systems, which are followed by landless systems. Grazing systems have only a small share (<10%). The significance of mixed systems as providers of animal products is expected to increase further in the future (Saha, 2001; Amejo *et al.*, 2018).

Climate change may have substantial effects on Indian livestock farming system in various ways, and changes in productivity are expected. Increasing climate variability will increase livestock production risks as well as reduce the ability of farmers to cope up. Many tropical and subtropical regions, including India, will be severely impacted by climate change (Dinar, 1998).

Climate of India

The climate of India comprises a wide range of weather conditions, from deserts in the west to alpine tundra in the north to humid tropical regions that support rain forests in the southwest and the island territories. India experiences four distinct seasons: winter (January and February), summer (March to May), the monsoon or rainy season (June to September), and a post-monsoon period (October to December), covering a vast area with diverse topography. The country's unique geographical location and geological features play a key role in shaping its climate. The Himalayas to the north serve as a barrier against the cold winds from Central Asia, while the Thar Desert in the northwest helps keep India warm or only mildly cool in winter; this same influence contributes to the country's high temperatures in summer. With the Tropic of Cancer running through the centre, India falls within the tropical zone. Similar to the tropical phenomenon, monsoonal and other weather conditions in India are unstable: major droughts, floods, cyclones and other natural disasters are sporadic and kill and displace millions of humans and livestock species.

Global warming and extreme weather events

India contributes a substantial share of global carbon dioxide (CO_2) and greenhouse gases (GHG) emissions, largely due to its expanding population and industrial growth (Ahmed *et al.*, 2022; Pathak, 2023). From 1970 to 2021, India experienced 573 climate-related disasters, causing 138,377 fatalities (IMD Annual Report, 2021). India has recorded unprecedented high temperatures and prolonged dry spells (Panda *et al.*, 2009), and is now listed on the UN's Global Drought Vulnerability Index, with recurring droughts in key rice-producing states such as Uttar Pradesh, Bihar, Jharkhand, and West Bengal (Amrit *et al.*, 2021). Meanwhile, episodes of intense, short-duration rainfall have led to flooding, including notable events in Uttarakhand (2013), Kashmir (2014), and Kerala (2018) (Akram *et al.*, 2023). Now the world's most populous country with 1.4 billion people, or 17.7% of the global population (Salunke, 2022), India's carbon footprint is expected to rise. Under a business-as-usual (RCP6.0–RCP8.5) scenario, Coupled Model Intercomparison Project Phase 5 (CMIP5) projections predict a temperature rise of 1.7–2°C by 2030 and 3.3–4.8°C by 2080, relative to pre-industrial levels (Cionni *et al.*, 2011). In this scenario, all-India precipitation is also projected to increase by 4-5% by 2030 and 6-14% by the end of the century. Sector-specific CO_2 emissions reveal that electricity (35.05%), agriculture (23.18%), manufacturing (15.92%), and transportation (8.64%) are primary contributors, driven by economic and development demands (Tiseo, 2023a). Despite per capita CO_2 emissions being relatively low (1.82 metric tons) compared to the global average (4.55 metric tons) (World Bank, 2021), India ranked as the fourth-largest emitter in 2017 due to its large population (UNEP, 2019). Per capita emissions have increased from 0.39 metric tons in 1970 to a peak of 1.91 metric tons in 2022 (Tiseo, 2023b), with CO_2 emissions from fossil fuel and industrial activity increasing by 6.5% in 2022, reaching 2.7 billion metric tons (Tiseo, 2023c). Annual anthropogenic emissions are estimated at 47,000 million metric tons of CO_2, 570 million metric tons of CCl4, and 9 million metric tons of N_2O (Basha and Reddy, 2022). Other pollutants include 2.144 tons/capita of GHGs, 69.4 kg/capita of CO, 20.36 kg/capita of NOx, and 9.51 kg/capita of SOx (OECD, 2023). Climate change-driven events, such as forest fires, exacerbate pollution. Globally, land-use and land-cover changes contribute about 4.3–5.5 $GtCO_2e$/year. Between 2003 and 2017, India experienced over 520,861 forest fires (Sannigrahi *et al*., 2020), with the Uttarakhand fires increasing CO and NOx levels by 52% and O_3 by 11% during the High Fire Activity Period (HFAP). Vulnerability index highlight that the upper Himalayas, northern and central Western Ghats, and parts of central India are particularly vulnerable to climate impacts, whereas North-eastern forests show greater resilience (Chaturvedi *et al*., 2011).

Thermal stress during the year

Thermal stress on livestock is a major concern in India as it adversely affects livestock production. The upsurge in temperature and humidity, individually or jointly, adversely affects the livestock species. A temperature higher than 25°C with a relative humidity of more than 50% has a negative impact on animal health and productivity (Habeeb *et al*., 2018). Temperature Humidity Index (THI) has been extensively used to indicate environment comfort/discomfort worldwide and in India also. THI variations at different locations in India have been determined based on dry bulb temperature and relative humidity to express the level of stress on livestock.

The THI was calculated for different months of the year for 103 places in India on the basis of temperature and humidity during the day at 7:20 h and 14:20 h. Animals remain comfortable when THI ranges between 65 and 72, under mild stress from 72 to 78 and under severe stress above 80. The data showed that during the morning (7:20 h) from October to March, THI remained less than 80 all over India, and from April, THI started increasing and was observed to be more than 80 during the morning (Aggarwal and Upadhyay, 2013). More than 30% of places in India experienced THI in the range of 80-85 from May to July. During August and September, more than 15% of places had THI in the range of 80-85 during the forenoon. In the afternoon (14:20 h), THI remained less than 80 from November to February and started increasing from March onwards, and THI exceeded 80 at 15% places. In September, more than 45% of places experience THI between 80 and 85. In May and June, the heat stress on livestock is very high, and 25% of places in India experience THI more than 85. The analysis of THI at the regional levels indicated that northern and western India experienced THI of more than 85 during May and June, mainly on account of dry heat, often referred to as “loo”. Coastal parts of India observe heat stress during March and April, and THI is more than 80. The study concluded that in India, there is a huge difference in the THI throughout the year, and in most agro-climatic zones, the average THI throughout the year is in the range of mild to severe stress. Therefore, the livestock production system requires proper infrastructure development for animal protection, amelioration of thermal stress and productivity improvement (Aggarwal and Upadhyay, 2013). In 2022-23, the per capita milk availability in India reached 459 g per day, significantly higher than the global average of 322 g per day (Food Outlook, 2023).

Productivity trends

The livestock productivity per animal, when considered on the basis of their multi-utility (milk, meat, work, etc.), is much higher than that of single-utility livestock (meat or milk). However, milk productivity per non-descript/indigenous cow is low in different agro-climatic regions of India. The non-descript/indigenous cows maintained under sub-optimal stressful tropical conditions produce around 2-3 kg of milk whereas Murrah buffaloes kept in optimal managemental conditions produce between 6-8 litres of milk per day. The livestock of different states have large potential for milk production and have scope for increasing milk production not only in terms of yield (kg/ animal/day) but also productivity (kg/lactation) of cattle and buffaloes.

India’s milk production reached an estimated 230.58 million tonnes in 2022-23, marking a 22.81% growth over the last five years, up from 187.75 million tonnes in 2018-19. Year-over-year, production increased by 3.83% from 2021-22 to 2022-23. Annual growth rates were notable in previous years: 6.47% in 2018-19, 5.69% in 2019-20, 5.81% in 2020-21, and 5.77% in 2021-22.

Among states, Uttar Pradesh led milk production in 2022-23, contributing 15.72% of the total, followed by Rajasthan (14.44%), Madhya Pradesh (8.73%), Gujarat (7.49%), and Andhra Pradesh (6.70%). In terms of annual growth rate (AGR), Karnataka saw the highest increase at 8.76%, with West Bengal at 8.65% and Uttar Pradesh at 6.99% over the previous year (https://pib.gov.in/PressReleasePage.aspx?PRID=1979950).

Temperature trends in India and level of thermal stress

The annual average temperature for the country as a whole has risen to 0.7°C since 1900. The annual mean temperature has been consistently above normal (normal based on the period 1961-1990) since 1993, and warming is chiefly due to the rise in maximum temperature across the country. However, since 1990, minimum temperature is steadily rising, and rate of its rise is slightly more than that of maximum temperature. Spatial patterns of trends in the mean annual temperature have shown significant positive increasing trends over the majority of regions across the country except over parts of Rajasthan, Gujarat and Bihar, where significant negative decreasing trends have been observed. Seasonally, the highest increase in mean temperature has been recorded during the post-monsoon season (0.77°C), followed by the winter season (0.677°C), pre-monsoon season (0.506°C), and monsoon season (0.330°C) (Kothawale and Kumar, 2002). Since 1991, winter seasons in the northern plains have shown a notably greater rise in minimum temperatures compared to maximum temperatures, accompanied by frequent occurrences of fog. All India's summer monsoon season (June to September) rainfall, as well as the rainfall for all four monsoon months, does not show any significant trend. During the season, three subdivisions viz. Jharkhand, Chhattisgarh, and Kerala show a significant decreasing trend and eight subdivisions viz. Gangetic West Bengal, West Uttar Pradesh, Madhya Maharashtra, Konkan and Goa, Jammu and Kashmir, Rayalaseema, Coastal Andhra Pradesh and North Interior Karnataka show significant increasing trends. June rainfall has shown a significant increasing trend for the western and southwestern parts of the country, whereas a significant decreasing trend is observed for the central and eastern parts of the country. July rainfall has significantly decreased for most parts of central and peninsular India, but has increased significantly in the North-eastern parts of the country. August rainfall has shown a significant increase in the region of Konkan and Goa, Marathwada, Madhya Maharashtra, Vidarbha, West Madhya Pradesh, Telangana and West Uttar Pradesh. September rainfall has shown significantly decreasing trend for subdivisions Vidarbha, Marathwada and Telangana and increasing trend (95%) for the subdivision Sub Himalayan Gangetic West Bengal (ICAR publication, 2009).

Future changes in extreme temperatures and precipitation

The PRECIS (Providing Regional Climates for Impacts Studies) regional climate modeling system, developed by the Hadley Centre for Climate Prediction and Research, has been applied in India to create high-resolution climate change scenarios (Rupa *et al.*, 2006). Projections for A2 and B2 scenarios showed an overall increase in both temperature and precipitation across India. The spatial patterns suggest the highest rainfall increase along the west coast and north-eastern regions in both scenarios. PRECIS predicts a 20% rise in all-India summer monsoon rainfall in future projections compared to present levels, with rainfall increases expected in most states, except for slight decreases in Punjab, Rajasthan, and Tamil Nadu. The simulation for 2071–2100 indicates widespread warming over the Indian subcontinent due to rising greenhouse gas concentrations. The annual mean surface air temperature rise by the end of the century ranges from 3 to 5ºC in A2 scenario, whereas the rise lies between 2.5 and 4ºC in the B2 scenario. The warming seems to be more pronounced over the northern parts of India. In order to assess thermal comfort levels and changes due to global warming in India, the scenarios for HadCM3 A2 and B2 scenarios for different months were constructed using temperature and precipitation changes. The temperature rise during different months are likely to increase number of stressful days as assessed by THI and number of stress hours during different months beyond the threshold for temperature changes particularly from March to October for different time slices. The results indicated that number of days THI >80 will increase from 40 at present to 104 (160%) by 2100 (Upadhyay *et al.*, 2008).

Thermal stress during different months and animal productivity

Ambient temperature higher than 25ºC with relative humidity of more than 50% has a negative impact on performance and productivity. Different individuals have different tolerance levels for temperature and humidity.

Temperature Humidity Index (THI) has been used to monitor the stress levels of the animals. Stress levels determined based on the hourly THI on different days of the years 2005 and 2006 at Karnal and other places in Northern India revealed that for 160-165 days average THI was below 65 in northern India, and for about 50 days, the THI ranged between 66 and 70. The THI remained more than 70 for 40-42 days, and THI ranged between 75 and 80 for 95-100 days during the year. The uncomfortable THI (>80) due to high temperature was observed for about 40 days. The average THI for different places in India were also calculated on the basis of temperatures and humidity. The climate change scenario constructed for India revealed that temperature rise of about or more than 4°C is likely to increase uncomfortable days (THI >80) from existing 40 days

(10.9%) to 104 days (28.5%) for HadCM 3 - A2 scenario and 89 days for B2 scenario for time slices 2080-2100 (Upadhyay *et al.*, 2012).

Harmful effect of temperature increase on total milk production in India has been estimated to be more than 15 million tonnes in 2050. Northern India is likely to experience further negative effects of climate change on the milk yield of bovines due to a rise in ambient temperature during the years 2040-2069 and 2070-2099. An unexpected change in ambient temperature, either an increase in T max during summer (heat wave) or a decrease in T min during winter (cold wave), is also likely to impact a decline in milk yield. The deviation in T max (>4°C above normal) during summer and T min (>3°C than normal) during winter impacted the milk production of crossbred cattle and buffaloes negatively. The drop in milk yield was up to 30% in the first lactation and around 20% in the second and third lactation (ICAR publication, 2009). Therefore, global warming and variability in climate are likely to impact the availability of milk, milk products and other food items of animal origin for human consumption. The non-availability of livestock products will increase the risk of malnutrition, hunger and imbalance in diets.

Climate change and milk production, its availability

A small rise in temperature towards climate change is not likely to impact the physiological functions of animals due to their adaptive capacity. The temperature changes are likely to affect the normal reproductive rhythm of animals. The reproductive cycles of seasonally breeding domestic animals are closely linked to the rhythmicity of the seasons; climatic changes are likely to cause desynchronization of such events due to responses of pineal- hypothalamo- hypophyseal-gonadal axis that may lead to interdependent pairs of hormonal events. Alterations in temperature and photoperiodicity could lead to reproductive malfunctioning, affecting many other physiological functions, such as milk production and reproduction.

Dairy is the largest agricultural commodity in India, accounting for 5% of the national economy and directly employing over 8 crore farmers. India ranks first globally in milk production, contributing 23% of the world's total milk output. Milk production has increased by 57.60% over the past 8 years from 146.3 million tons in 2014-15 to 230.58 million tons during 2022-23. Milk production in India has been growing at an annual rate of 6.4% over the past eight years, significantly outpacing the global milk production growth rate of 1.2% per year. The sector utilizes crop residues and agricultural by-products for animal feeding that are unfit for human consumption. The sector has registered a compounded growth rate of more than 5.0% during the last decade, in spite of the fact that a majority of the animals continue to be reared under sub-optimal conditions and milk productivity per animal is low. For the reduction and alleviation of poverty remarkable progress in this sector should therefore be a national priority with emphasis on scientific livestock management, animal feeds and their feeding, water quality etc. to compete globally. The demand-driven growth in livestock products and foods of animal origin in future is likely to stretch the existing production and distribution systems in India.

Climate change: growth and reproduction

The rise in temperature negatively impacts growth and time to attain puberty. The adverse effect of THI rise on animals growing at higher rates will be more than slow growing. The change in temperature with changes in photoperiodicity could lead to reproductive problems due to hormonal imbalance mediated through pineal-hypothalamo- hypophyseal- gonadal axis. Heat stress due to high ambient temperature with limited access to feed and water affect buffaloes' estrus expressions particularly from March to June, when these animals have relatively non-functional gonads with less number of sperms in the semen of males and poor expression of estrus in females- mainly due to animals are unable to dissipate the extra heat. ACTH is released from the anterior pituitary during heat stress, which triggers the release of cortisol and other glucocorticoids from the adrenal cortex, and ultimately, the secretion of luteinizing hormones is inhibited. Thermal stress also causes hyperprolactinaemia, which inhibits the secretion of both FSH and LH from the anterior pituitary (Singh *et al.*, 2013). Heat stress impacts the endocrine system during the dry period, leading to shorter gestation lengths, higher rates of fetal abortions, reduced calf birth weights, and impaired follicle and oocyte maturation. It also reduces conception and pregnancy rates by 20-30% (Khan *et al.*, 2013). The scrotal circumference, size and weight are decreased during heat stress due to degeneration in the germinal epithelium (Chou *et al.*, 1974). Further higher ambient temperature negatively affects the thermoregulatory mechanism of the testes, sexual desire, ejaculate volume, live sperm percentage, sperm concentration, viability and motility (Gamcik *et al.*, 1981).

Climate change and animal diseases

Elevated temperature and humidity will favour spread and growth of insects/vectors. Incidences of diseases affecting livestock species will spread in susceptible

Table 1. Climate change impact on livestock health, production and reproduction

Climate change factor	Direct and indirect effect	Reference
Rise in ambient temperature	● Decrease availability of water ● Decrease feed intake and feed conversion efficiency ● Age of puberty and maturity ● Decrease milk and meat production ● Decrease reproduction efficiency ● Decrease semen quality ● Increased mortality	Rojas-Downing *et al.*, 2017; Cheng *et al.*, 2022
Rise in relative humidity	● Increase diseases by: i. Increase of pathogens ii. Increase of parasites iii. Increase of disease spreading/transmission iv. Spreading of vector-born diseases faster ● Following forage parameters will be affected: i. Forage quality ii. Forage growth ● Biodiversity	Rojas-Downing *et al.*, 2017; Cheng *et al.*, 2022
Increase CO_2 level affects	● Composition and forage production ● Forage quality	Cheng *et al.*, 2022

populations. The frequency of diseases like FMD, HS and tick fever are most likely to be higher because of climate change (Table 1).

Sustainable Development Goals (SDGs)

The United Nations' SDGs provide a blueprint for addressing global challenges, including poverty, inequality, climate change, environmental degradation, and health. (United Nations, Department of Economic and Social Affairs). In India, a particular ambitious and all-encompassing plan for global development by 2030 is outlined in the SDGs. As the country's premier organisation for accomplishing the SDGs, NITI Aayog is driving the 2030 Agenda with a competitive yet cooperative federalism mindset. A number of tools, including the SDG India Index and Dashboard, Multidimensional Poverty Index: Progress Review 2023, North Eastern Region Index and Dashboard, and others, track progress at the national and subnational levels. Since localising the SDGs is essential to catching those who are far behind first, it is a vital vertical mandate. Through these efforts, the data systems have been enhanced and a monitoring framework spanning all 17 Goals and over 100 indicators nationwide has been constructed (An Overview of SDGs / NITI Aayog). Among these, SDG 13 (Climate Action), SDG 14 (Life below Water) and SDG 15 (Life on land) are particularly relevant to animal and aquaculture resource management.

As per the SDG Goal 13, in 2023, global climate records were broken, and the world witnessed the climate crisis play out in real time. Extreme weather has a devastating effect on communities all over the world, ruining lives and livelihoods on a regular basis. There can be no room for the international community to procrastinate, waver, or take half-hearted action in the fight to keep the rise in global temperature to 1.5°C and prevent the worst-case scenario. In order to attain net zero emissions by 2050 and drastically cut global greenhouse gas emissions this decade, swift action is required (Goal 13a). Climate change is mostly caused by GHG emissions from human activity, which are also increasing. They have never been higher than they are right now. Since 1990, carbon dioxide emissions have increased globally by about 50%. Methane, nitrous oxide, and CO_2 concentrations in the atmosphere have reached levels not seen in the previous 800000 years. Since pre-industrial times, the concentration of CO_2 has increased by 40%. This increase is mostly due to production from fossil fuels, with emissions from net land use change coming in second. Ocean acidification is the result of the ocean absorbing roughly 30% of the CO_2 that humans have generated (Goal 13b). As per SDG Goal 14, considering more than 70% of the planet's surface is made up of oceans, contain 97% of the total earth water and represent 99% of the living space on the planet by volume, these bodies of water are vital to both mitigating the consequences of climate change and supplying food and livelihoods for over 3 billion people. However, worrying phenomena, including diminishing fish stocks, pollution in the water, acidification of the ocean, and degradation of habitat, pose a threat to marine ecosystems and the way of life for coastal communities around the globe. In order to solve these issues and guarantee the ocean's long-term health and sustainability, immediate action is required. This action can be taken through global cooperation, pollution reduction, sustainable fishing methods, and marine conservation initiatives to protect ecosystems and marine life for future generations (Goal 14a, b). The market value of marine and coastal resources and industries worldwide is projected to be \$3 trillion annually or around 5% of the worldwide GDP. About 30% of the CO_2 that people emit is absorbed by the oceans, mitigating the effects of global warming. Over 3 billion people rely on the oceans as their main supply of protein, making them the world's largest source. Over 200 million people are employed by marine fishing, either directly or indirectly. Fishing subsidies are making it harder to save and rebuild global fisheries and related jobs, which is leading to the fast extinction of many fish species and reducing the annual revenue generated by ocean fisheries by US\$ 50 billion (Goal 14b).

As per SDG Goal 15, an annual loss of thirteen million hectares of forest occurs. Approximately 1.6 billion people get their living from trees. About 70 million indigenous people are included in this. Over 80% of terrestrial animal, plant, and insect species live in forests. Although 52% of the area utilised for cultivation is moderately to severely damaged by soil degradation, 2.6 billion people directly depend on agriculture. Every year, 12 million hectares (or 23 hectares per minute) of land that could have produced 20 million tonnes of grain are lost to drought and desertification. Of the 8,300 known breeds of animals, 22% have been threatened with extinction, and 8% are extinct. India is home to many species that are unique to its region, accounting for 8% of the world's biodiversity (Goal 15). These technological interventions can help meet these goals, with a focus on adapting to climate change and promoting the One Health concept.

Challenges and demands of the livestock sector

Lack of awareness among the farmers regarding the latest technological advancements related to improving productivity, breeding, and vaccination is the major reason for the low productivity of livestock. High incidence of animal disease also contributes to lower livestock production. Shortage of veterinary infrastructure, i.e. veterinary hospitals, polyclinics, veterinarians and other skilled staff in veterinary services, leads to a lack of health and welfare of animals. The rapid growth of the human population, together with economic and urban development, has a substantial impact on livestock production, particularly due to the increasing demand for animal products. The growing demand for affordable and high-quality meat, eggs, and dairy products has driven the rapid intensification and industrialization of animal production, with significant economic, social, and environmental implications on a global scale. The livestock sector plays a crucial role in the socio-economic development of rural households, contributing around 6% to the Gross Domestic Product (GDP) and 25% to the Agricultural GDP. According to the 20th Livestock Census, the total livestock population has increased by 4.6% compared to the 2012 Census (Twenty Livestock Census, 2019).

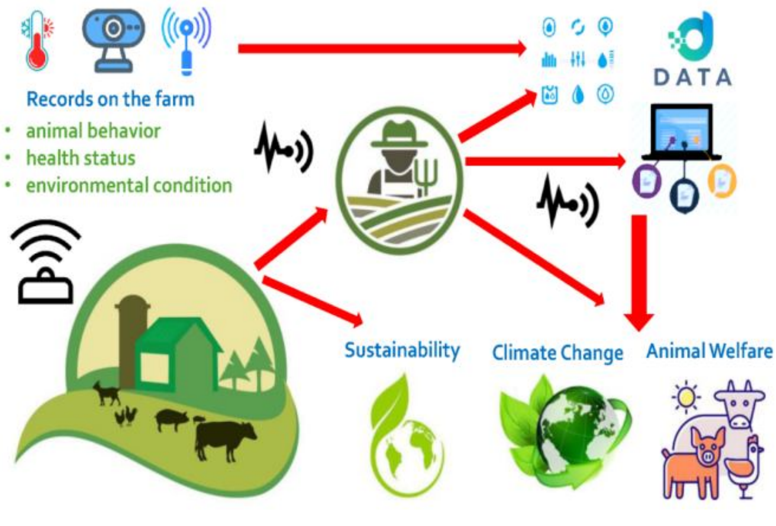

Fig. 1. The concept of precision livestock farming in modern livestock production (Papakonstantinou *et al*., 2024)

Technological interventions in animal resource management

Precision livestock farming (PLF): The term "PLF technology" describes the use of cutting-edge tools and data analytics in livestock production system management to enhance animal productivity, welfare, and health while reducing environmental impact and making the most use of available resources (Fig. 1). PLF usually refers to the application of technology that enables continuous, automated, real-time livestock monitoring. These technologies enable data collecting and analysis through the use of cameras, sensors, and acoustic devices that are increasingly combined with artificial intelligence (Banhazi *et al.*, 2012; Hostiou *et al.*, 2017). With the help of this tactic, farmers may make informed decisions on the sustainability of agricultural techniques, animal welfare, and health (Berckmans *et al.*, 2017; Werkheiser, 2020; Papakonstantinou *et al.*, 2024).

The PLF involves the use of advanced technologies such as sensors, IoT (Fig. 2) and AI to monitor and manage livestock health, welfare, and productivity. Key applications include, animal monitoring, Animal health and welfare monitoring: Wearable sensors and smart collars can track vital signs, behaviour, and movement patterns to detect diseases early.

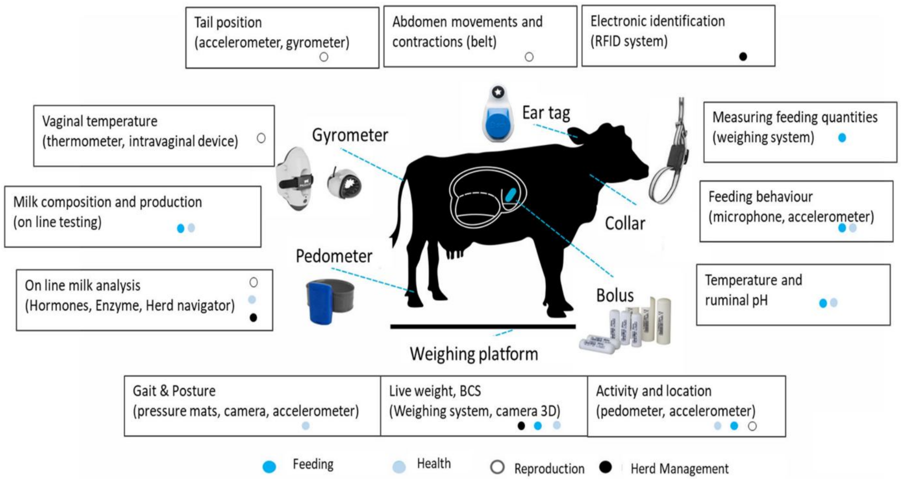

Fig. 2. Overview of currently used devices to capture biological data from animals. All these sensors are interconnected, making it an application of the "Internet of Things" (IoT) in the dairy cattle sector (Kleen and Guatteo, 2023).

Feed optimization: Automated feeding systems and smart feeders ensure optimal nutrition and reduce waste.

Automatic milking system, environmental control: Automated systems control barn climate, enhancing animal comfort and reducing stress-related issues. These technologies not only improve animal welfare but also enhance productivity and sustainability by optimizing resource usage and reducing environmental impacts.

Climate change adaptation and mitigation: *Climate-resilient breeds and species:* Developing and promoting breeds and species that are resilient to climate-related stressors, such as heat, drought, and disease, is crucial. Genetic research and breeding programs play a crucial role in this effort.

Sustainable feed and resource use: Alternative Feed Sources: Innovations in feed, such as insect-based proteins and algae, offer sustainable alternatives to traditional fishmeal and soybean meal. Resource-efficient practices: Precision farming techniques optimize resource use, thereby reducing the carbon footprint and minimizing the environmental impact of animal production.

Carbon footprint reduction: Renewable energy: Incorporating renewable energy sources, such as solar and wind, into farm operations reduces reliance on fossil fuels.

Methane mitigation: Technological solutions for methane capture and reduction in livestock operations contribute to lower greenhouse gas emissions.

One Health Approach

The One Health paradigm promotes equal, all-encompassing collaborations across various sectors of health, including animal, plant, environmental, and human health. This approach brings together a wide range of professionals, such as chemical, engineering, and social scientists, dentists, nurses, agricultural and horticultural experts, food producers, wildlife and environmental health specialists, among others.

US Centres for Disease Control and Prevention (CDC) and One Health Commission (OHC) definition: One Health is a collaborative, multisectoral, and trans-disciplinary approach working at local, regional, national, and global levels to achieve optimal health (and well-being) outcomes recognizing the interconnections between people, animals, plants and their shared environment.

The previous OHC definition described One Health as the collective effort of multiple health science professions, along with their related disciplines and institutions, working locally, nationally, and globally to achieve optimal health for people, domestic animals, wildlife, plants, and the environment.

WHO (2017) definition: "One Health' is an approach to designing and implementing programmes, policies, legislation and research where multiple sectors communicate and collaborate to achieve better public health outcomes".

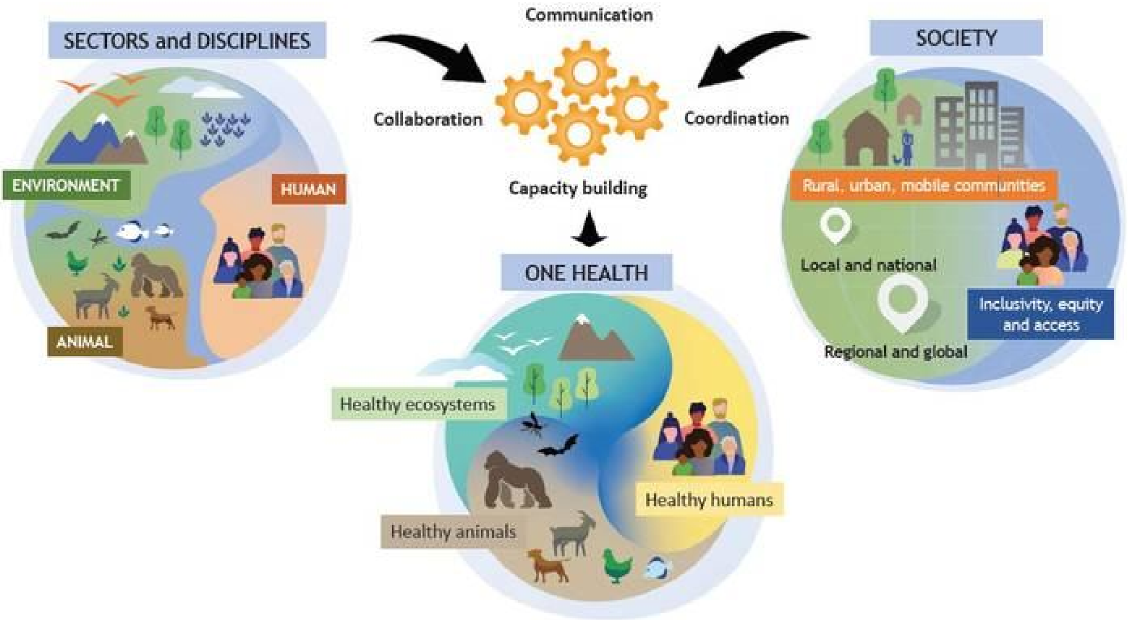

Fig. 3. One Health approach (One Health High-Level Expert Panel *et al.*, 2022)

One Health High-Level Expert Panel define it as an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and the ecosystem. It recognizes the wellness of humans, domestic and wild animals; plants and the wider environment (including ecosystems) are closely interconnected and interdependent.

This approach mobilizes multiple sectors, disciplines, and communities at different levels of society to collaborate in promoting well-being, addressing health threats, and safeguarding ecosystems. It also focuses on meeting the collective needs for healthy food, water, energy, and air, tackling climate change, and contributing to sustainable development (Fig. 3).

Key principles including

Equity between sectors and disciplines: Socio-political and multicultural parity (Upholding the belief that all people are equal and deserve equal rights and opportunities) and inclusion and engagement of communities and marginalized voices. The socio-ecological equilibrium aims to acknowledge the importance of biodiversity while achieving a harmonious balance between interactions between humans, animals, and the environment. Insuring access to appropriate natural resources and space, as well as the inherent worth of all living organisms in the ecosystem. Stewardship and acknowledging humanity's responsibility to change behaviour and adopt sustainable solutions that recognize the importance of animal welfare and the integrity of the whole ecosystem, securing the well-being of current and future generations, and trans-disciplinary and multisectoral collaboration, which includes all relevant disciplines, both modern and traditional forms of knowledge and incorporating a broad representative array of perspectives to foster comprehensive solutions (One Health High-Level Expert Panel *et al.*, 2022).

Challenges and future directions

Technological adoption and accessibility: *Cost and scalability:* High initial costs and scalability issues can hinder the widespread acceptance of advanced technologies. Strategies to reduce costs and enhance scalability are essential.

Training and education: Providing training and support to farmers is critical for effective technology implementation.

Policy and Regulatory Frameworks: *Supportive policies:* Governments must develop policies that support innovation and the implementation of sustainable technologies.

Regulatory standards: Establishing and enforcing standards for animal welfare, environmental protection, and food safety is crucial.

Research and innovation: Continuous research and innovation are needed to develop new technologies and improve existing ones. Collaboration between academia, industry, and government is essential to drive progress.

Conclusion

Precision livestock farming offers significant potential to advance SDGs in animal resource management. By enhancing productivity, boosting animal welfare, and reducing environmental impacts, these technologies contribute to a more sustainable and resilient food system. Addressing challenges related to adoption, policy, and innovation will be key to realizing their full potential, particularly in the situation of changing climatic scenarios and the One Health approach.

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