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Review Article

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Assisted reproductive technologies and genetic improvement strategies for enhancing livestock production and food security in Tropical East Africa: A review

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ABSTRACT

Despite an increase in global food availability, food insecurity remains a pressing global challenge affecting millions across developed and developing nations. This issue is particularly severe in developing countries in tropical regions, where harsh climatic conditions, low agricultural productivity, and limited access to resources intensify the challenge of food insecurity. Africa exemplifies these challenges, with approximately 20% of the total population undernourished. East Africa is no stranger to these statistics with 31.8% of the country's children under 5 years old being malnourished. Many livestock production systems in tropical East Africa operate significantly below their potential due to constraints including climate vulnerability, endemic diseases, and low genetic production capacity of indigenous breeds. Improving livestock productivity has been an area of focus for improving food security for many years. Applying our knowledge of environmental adaptations such as heat tolerance mechanisms like the SLICK gene in cattle and fat tails in sheep and disease resistance traits like trypanotolerance is a foundational step in the development of breed improvement programs for the tropics. Crossbreeding programs have utilized this knowledge for decades resulting in great success stories such as the Girolando cattle of Brazil, which are responsible for producing 80% of the country's milk today. With the development and use of assisted reproductive technologies (ARTs) like artificial insemination, in vitro fertilization & embryo transfer we have the ability to achieve genetic gain at an unprecedented speed. Many cases have demonstrated promising applications of these technologies, with one such study reporting IVF and ET implementation in Kenyan dairy herds could increase monetary gain by 184% while reducing generation intervals by 47%. Overall, strategic implementation of genetic improvement programs, when adapted to the diverse livestock production systems of the developing tropics hold the key to significantly enhancing livestock productivity, improving food security, and overall contributing to more sustainable agricultural systems in East Africa.

KEYWORDS: Assisted Reproductive Technologies, Livestock Productivity, Tropical Agriculture, Food Security

INTRODUCTION

Despite an increase in global food availability, food insecurity remains a pressing global challenge affecting millions across developed and developing nations. The 1996 World Food Summit defines food security as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). It is driven by multiple factors including population growth, climate change, and socioeconomic disparities, and typically impacts regions highly dependent on agriculture (Shaw, 2007; Godfray *et al.*, 2010). This issue is particularly severe in tropical regions, where harsh climatic conditions, low agricultural productivity, and limited access to resources intensify the challenge of food insecurity. Current world events such as the COVID-19 pandemic, the war in Ukraine, and ever- rising food prices have only further exacerbated this issue, resulting in projections of nearly 600 million people to be chronically undernourished by 2030 (FAO, 2023).

Though Asia accounts for the largest number of people facing hunger, the proportion of the population facing these issues in Africa is more than doubled (8.5% and ~20% respectively) (FAO, 2023). East Africa, and more specifically Tanzania (TZ), are no strangers to this statistic. Home to nearly 60 million people, the World Food Program reports 31.8% of the country's children under 5 years old are malnourished (WFP, 2024b). With rural populations relying heavily on agriculture for both sustenance and income, significant challenges including climate variability, outdated agricultural practices, and insufficient infrastructure which have further intensified food insecurity in this region.

Lack of dietary diversity is often a major factor for children living in areas where they are unable to meet daily nutrient requirements. Because of strong ties to malnutrition, dietary diversity has been used as both an indicator of food insecurity and a predictor of nutritional status (Antwi *et al.*, 2022). A study in Kenya reported a correlation between household dietary diversity and diversity in animal species kept by the family (Muthini *et al.*, 2020). Though often tied to rural, agriculturally dependent regions, improvements and diversifications in agricultural practices within an operation can increase access to both the quantity and quality of animal- source foods. Addressing food insecurity in these regions will require varied and innovative approaches. Promising solutions may include precision livestock management practices and assisted reproductive technologies (ARTs) such as artificial insemination (AI), embryo transfer (ET), and genomic selection to stabilize access to animal source foods and management of livestock production systems.

This literature review explores the application of livestock genetic improvement programs to mitigate food insecurity in the tropics by enhancing animal productivity, specifically in East Africa and Tanzania.

GLOBAL PERSPECTIVE ON FOOD INSECURITY

Food insecurity has been on the rise since 2015 (UN, 2023). and is challenging nearly 783 million people across the globe as of 2022 (FAO, 2023). The 2021 Global Nutrition Report notes that despite progress in some areas, malnutrition remains a significant challenge, with millions of people lacking access to sufficient, safe, and nutritious food (Global Nutrition Report, 2021). Climate change, conflict, and disease have only exacerbated this problem. In developing countries, particularly those in tropical regions, food insecurity is often more acute due to a combination of many factors such as low agricultural productivity, climate vulnerability, and a variety of socioeconomic factors. Insufficient governmental support (often due to political volatility and lack of funds) in the form of policy, research, and infrastructure development within the agricultural sector are also contributing factors. These factors are further explored in Table 1.

Food Insecurity in East Africa

Many countries in East Africa face challenges such as those previously mentioned when addressing food insecurity. A meta-analysis performed on the drivers of food security in southern Africa revealed that 17 direct drivers held most of the impact (Misselhorn, 2005). These are as follows: climate and environmental stressors, poverty, increase in food prices, absence of property rights and land access, unavailability of employment, lack of education, poor market access, pests and diseases of crops and livestock, poor human health, low regional cereal availability, poor distribution networks and infrastructure, in- and out- migration, inflation, social and political unrest or war, sale of assets, insufficient agricultural inputs, and formal and informal government policies. These drivers are quite comparable to the drivers of food security observed in East Africa. The study went on to describe 67% of these drivers as being chronic or ongoing, supporting the known endemic state of food insecurity in these regions. The short-term drivers described, such as increasing food prices, further exacerbate the already critical issue.

Ranking 100th out 127 countries for food insecurity by global hunger index scores in 2024 (Wiemers *et al.*, 2024) food insecurity is a challenge faced by an estimated 1.8 million people in Kenya (WFP, 2024a). A study analyzing food security across the country revealed that 52% of households were food secure based on a combination of calorie deficiency and food expenditure indicators (Mutea *et al.*, 2022). These numbers vary across geographical regions, with rural regions still being disproportionately food insecure. With many inhabitants of rural regions relying heavily on animal source foods for nutrition it is unsurprising that death of livestock was found to have severe impacts on food security. An interesting finding of this particular study was that households headed by women experienced a 21% increase in likelihood of achieving food security over male headed households (Mutea *et al.*, 2022).

Table 1: Factors exacerbating food insecurity in tropical regions

Climate Vulnerability	Tropical regions are particularly susceptible to climate change impacts, including increased frequency of droughts, floods, and extreme heat events, which can devastate both crop yields and livestock production. Climate change poses many challenges to animal agriculture, providing conditions for heat stress, affecting water availability, and production of forages and crops used as livestock feeds.	Eguiguren-Velepucha *et al.,* 2016; Ortiz-Colón *et al.,* 2018
Low Agricultural Productivity	Many tropical countries struggle with low agricultural yields due to poor soil quality, limited access to modern technologies, and inadequate infrastructure. The inability to access improved genetics (for both crops and livestock), fertilizers, and modern farming techniques also contributes to production yields well below global averages.	Spencer, 1996; Gallup & Sachs, 2000; Te Pas & Rees, 2014
Socioeconomic Factors	Poverty, lack of education, and limited access to markets and resources are major contributors to persistent food insecurity in many tropical regions.	Misselhorn, 2005; Bogale & Abebaw, 2009; Assenga & Kayunze, 2020; Hemerijckx *et al.,* 2022

A study in the Chamwino District of Tanzania reported general causes of national food insecurity to be a result of the low-level use of technology, dependency on rainfall, and lack of proper inputs (Mbwana *et al.*, 2017). Similar to 96% of the agricultural land in sub-Saharan Africa (Burney *et al.*, 2013), agricultural production of food crops within this district is predominantly dependent upon rainfall, with distinct rainy and dry seasons creating particular vulnerability to climate variability and change. As a result, food crops like maize, beans, and pigeon pea are imported during deficient months and are sold for more than three times their typical price. Other important determinants of food security in Chamwino are land size cultivated, household size, age and income. In addition, a survey of caregivers within the study reported 89% had never received any kind of nutrition training or education and the district reported 41% of children under the age of five years old had experienced stunting.

In contrast with the rural Tanzanian district of Chamwino, urbanization in Kampala, Uganda is occurring rapidly with a population increase of greater than 5% every year (Vermeiren *et al.*, 2012). Though research suggests rapid urbanization often goes hand in hand with an increase in market development, Kampala's food system is still heavily reliant on small retailers and street vendors (Wanyama *et al.*, 2019). In Uganda as a whole, moderate to severe food insecurity is experienced by nearly 70% of the population (Cafiero *et al.*, 2016). Psychological distress often accompanies the physical health impact of food insecurity (Myers, 2020). Further studies in Uganda reveal an association between severe food insecurity and an increase in severe depression symptoms further supporting these findings (Perkins *et al.*, 2018).

Addressing challenges in food security requires a multifaceted approach, including improvements in education, infrastructure, and agricultural productivity. An examination of the current state of livestock production in the tropics may reveal how ARTs can contribute to improving food security in these regions.

CURRENT STATE OF LIVESTOCK PRODUCTION

Global livestock production, valued at more than $1.4 trillion, occupies approximately 30% of the globe's ice-free landmass and accounts for 60-70% of agricultural economy (Steinfeld *et al.*, 2006; Thornton, 2010; Kadzere, 2018). The livestock sector and its extensive market chains employ more than 1.3 billion people across the globe. Involvement in this directly supports the livelihoods of approximately 600 million impoverished smallholder farmers living in developing countries (Thornton *et al.*, 2006). Animal source foods are a prominent component of diets around the world. These foods account for 33% of global protein consumption, though it should be noted that there is significant variability between countries of varying levels of poverty (Thornton, 2010). Though meat consumption appears to have peaked in some countries, there is strong evidence of consumption increases in developing countries (Whitton *et al.*, 2021). Overall, this sector has been widely labeled as invaluable for public health, social equity and economic growth (WorldBank, 2009).

Global Trends & Challenges

The global livestock sector has seen significant improvements in production throughout recent decades, driven by technological advancements, better management practices, and genetic improvements. According to the Food and Agriculture Organization (FAO), global meat production has more than quadrupled since the mid-1960s, reaching 370 million tons in 2023 (FAO, 2024). Today, global meat production is projected to observe a marginal increase, with poultry production currently being the driving force due to its affordability and low feed costs (FAO, 2024). Mutton and beef production is projected to see a similar slight increase, though consumer demand is constrained by purchasing costs. Contrary to the growth observed in other areas of meat production, pork production is expected to decline by 1.2 million tons (nearly 1%) (FAO, 2024). Similarly to global meat production, milk production has more than doubled, projected to reach 979 million tons in 2024 (FAO, 2024). Asia is expected to drive the increase through both expanding herd size and an increase in contributions from large-scale farms with higher output per animal unit (FAO, 2024).

Key drivers of improvements within the global livestock sector include advancements in selective breeding, animal nutrition, disease control, and technology. Assisted reproductive technologies such as artificial insemination and embryo transfer have significantly enhanced animal productivity, particularly in dairy cattle (Rabel *et al.*, 2024). The U.S. dairy industry has dramatically reduced herd size by 65% since 1944, while increasing milk production by more than 80% (Mueller & Van Eenennaam, 2022). Innovations in animal nutrition through alternative feed sources, feed processing methods, and diet formulation have led to greater production by increasing feed efficiency (Opadoyin, 2018). Enhanced veterinary care and the eradication or prevention of major diseases such as rinderpest (Hamilton *et al.*, 2017), foot-and-mouth disease (FMD) (Rweyemamu *et al.*, 2008), and brucellosis, have further reduced livestock mortality and improved herd health. The most recent developments in the sector have been advancements in precision agriculture and modern technologies (Kleen & Guatteo, 2023). A prime example of the contribution of these modern technologies can be observed with the automated milking systems. These systems significantly reduce human labor (by 20-50%) and generally increase milk yield, while retaining the milk quality seen with non-automated milking systems (Jiang *et al.*, 2017).

Though the sector continues to grow and improve, it is still facing several obstacles. One of these obstacles is climate change. Over the last several years, there has been a strong push toward the reduction of greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide) from agriculture and livestock production systems. It has been estimated that between 7-18% of greenhouse gasses come from livestock production systems (via enteric fermentation, manure production, feed transport, etc. (Kadzere, 2018). This frame of reference has moved Denmark to implement climate mitigation policies in which a tax is placed on greenhouse gasses produced by livestock. The policy, beginning in 2030, will cost livestock owners $43 per metric ton of carbon dioxide equivalent produced by their livestock (IER, 2024). By implementing this policy,

legislators strive to incentivize livestock owners to make the shift toward more sustainable practices. Consumers, primarily those residing in more developed nations, are not blind to this campaign. As a result, there has been a slight market shift observed as the popularity of plant- based meats and vegetarian diets have begun to rise in the name of sustainability (Safdar *et al.*, 2022).

On the other hand, climate vulnerability is continuing to put stress on production outputs, especially within the tropics. Heat stress is an increasing concern across the globe. Modeling scenarios have estimated that by the end of the 21st century production losses related to heat stress could amount to nearly $40 billion (Thornton *et al.*, 2022). To survive these changing times, livestock owners must be proactive and innovative in finding solutions. Overall, in the next 50 years, agricultural production will be increasingly constrained by human competition for land and water, and climate change. Food prices will likely continue to rise as a result of the aforementioned production constraints, opening the door for the strategic use of biotechnologies to play a significant role in feeding the future.

Tropical Livestock Production in East Africa

The global livestock sector is poised for continued success and advancements as technology, genetic improvements, and management practices further evolve. However, many geographic regions, particularly tropical regions, face persistent challenges in areas where the more developed world has seen dramatic improvements. Disparities in several key areas such as genetic potential and productivity, feed quality and availability, and overall disease burden are particularly evident. Addressing these challenges is crucial for unlocking the full potential of livestock systems in developing regions.These challenges are particularly pronounced in East Africa's livestock sector, where the industry plays a crucial role in economies, contributing significantly to food security, livelihoods, and cultural practices. In many African countries, livestock ownership is regarded as a sign of wealth, especially in regions lacking stable government currency backing (Herrero *et al.*, 2013). The diverse agro-ecological zones of East Africa, ranging from arid and semi-arid lands to highlands, support various livestock production systems, including traditional nomadic/pastoral systems, integrated crop-livestock farming systems, and some more intensive market-oriented systems which implement modern management practices and improved genetics (Rewe *et al.*, 2009).

Historically, countries in this region have relied on indigenous breeds that are well- adapted to local conditions, sacrificing the improved production potential of breeds that have undergone intensive genetic selection and are more typically used in developed countries. For example, as of 2015, approximately 3% of Tanzania's national cattle herd was comprised of improved dairy breeds. However, these cattle contributed 30% of the nation's annual milk production (Lunogelo *et al.*, 2020). Indigenous breeds have strong potential for many benefits from extensive genetic selection, but realizing the monumental progress seen with this technology will require a substantial long-term commitment. Crossbreeding and the use of ARTs are both tools that have been implemented to combat the current low potential for productivity.

Tropical regions often face challenges in providing feeds that meet the animal's nutritional requirements for both nutrients and dry matter, particularly during dry seasons, which further hinders productivity. The high temperatures, seasonal rainfall patterns, and prolonged dry seasons, pose significant obstacles in procuring feeds of high quality with consistent availability. Scarcity of food for human consumption has led to the consumption of things typically conceived as by-products (ex. potato leaves) in more developed countries, leaving even less for livestock consumption. Feed is considered a major cost of production in most livestock systems. This is exacerbated in tropical livestock rearing by low productivity, poor diets, and extremely high feed conversion ratios for products like milk and meat (Paul *et al.*, 2020).

Native, and most commonly grazed forages are often not highly nutritious or digestible. Some of which is a result of poor soils. For example, in the Mpwapwa region on Tanzania, commonly grazed vegetation supported by these poor soils includes *Chloris gayana*, *Themeda* spp, *Cynodon dactylon*, and *Hyperrhenia rufa* (Kabuni, 2017). Improving forage quality and utilization is crucial for enhancing livestock productivity in tropical regions. Survey reports suggest that only approximately 20% of livestock owners purchase supplemental fodder to help get through seasons of scarcity (Hikuepi Katjiuongua, 2014).

Nutritional obstacles combined with the increased prevalence of diseases such as trypanosomiasis, East Coast fever, and FMD maintaining livestock health and optimal production levels can be serious challenges. An example of the severity of livestock health issues in Tanzania, can be observed where Tick Born Diseases (TBD), FMD, Contagious Bovine Pleura Pneumonia (CBPP), trypanosomiasis and helminthiosis, were reported as the most common diseases affecting large and small ruminants. Government reports from 2019-20 found 4,359,545 cattle were infected with TBD; 4,297,145 infected with FMD; 3,872,491 infected with helminthiosis and 3,516,887 infected with CBPP (Mkenda, 2021). In these reports, the Kusini region reported the most livestock owners practicing deworming in their livestock herds at a meager 27.4%. Similarly, no region reported greater than 50% of livestock owners to have vaccinated their herds for FMD, rabies, black leg, anthrax, or CBPP. Other disease concerns affecting production in the tropics include brucellosis, anthrax, blackleg, rabies, East Coast fever, Rift Valley fever, and lumpy skin disease. Disease prevention in areas like sub-Saharan Africa can prove to be quite difficult for a variety of reasons. Often, the two most common methods to prevent disease are vaccination and quarantine or movement control, both of which have been proven difficult to accomplish in sub-Saharan Africa.

The Narok district of Kenya presents one of many cases in which vaccination proved difficult. Many of the livestock owners in this region of Africa are pastoralists. Pastoralism is a highly traditional livestock production system in which livestock are raised using mobility to adapt to dry environments with low productivity (Tessema *et al.*, 2014). In this case, regarding CBPP, authors found that though pastoralists generally perceived vaccination to be a solution to the disease, vaccination was irregular due to inadequate access to the vaccine. Education about disease treatment and prevention was also a concern with approximately 13% of participants unaware of any prevention methods and 10% who did not know what to do or would do nothing in the event of a CBPP outbreak (Kairu-Wanyoike *et al.*, 2014). Furthermore, because of the traditional pastoralist lifestyle, movement control of livestock is difficult. Livestock may travel upwards of 20 km per day or every other day in search of forage, especially during dry seasons when forages and water may be scarce (Turner & Schlecht, 2019).

Heat stress, traditionally defined as a condition in which animals are unable to dissipate an adequate quantity of heat whether generated internally (by the body) or externally (by the environment), further compounds these challenges (Bernabucci *et al.*, 2014; Habimana *et al.*, 2023). With negative effects spanning from growth and development to production, reproduction, and health (Figure 1), it is unsurprising that heat stress plays a dramatic role in the reduction of tropical livestock productivity and a similar reduction in profits. Heat stress indicators include increased core and rectal temperatures, heart and respiration rates, as well as increases in panting, drooling, and sweating (Mader *et al.*, 2006; Dalcin *et al.*, 2016; Osei-Amponsah *et al.*, 2020). Using early identification of indicators and removal of animals with higher levels of susceptibility to heat stress, livestock owners can mitigate the financial loss associated with the disease.

Even with these challenges, the livestock sector plays a crucial role in East African economies. Tanzania's agricultural sector plays a pivotal role in the nation's economy, contributing approximately 30% to the national GDP in 2020 (Mkenda, 2021), with the livestock sector alone accounting for 5% (Hikuepi Katjiuongua, 2014). The country maintains the third- largest cattle herd in Africa, with the 2019/20 National Sample Census of Agriculture reporting approximately 34 million cattle, 24.5 million goats, 5.65 million sheep, and 3.2 million (Hikuepi Katjiuongua, 2014; Mkenda, 2021). Despite this substantial livestock population, productivity across all species remains markedly below global standards, highlighting significant potential for improvement in both meat and dairy production systems.

Ultimately, despite its challenges, the East African livestock industry shows great potential for growth and improvement. Genetic improvement of the livestock herd in East Africa, with consideration for environmental adaptability, is vital for the region to reach its production potential. Further, integrating modern technologies, including assisted reproductive technologies, offers promising avenues for enhancing productivity and addressing food insecurity in the region.

LIVESTOCK GENETIC DEVELOPMENT IN THE TROPICS

Importation of European breeds with high genetic potential to improve production is not an uncommon practice in many tropical countries. In the Philippine Islands, reports as early as 1589 have been found referring to the importation of livestock (Sarao, 1922). Unfortunately, despite adequate rations and disease prevention measures, these temperately adapted *Bos taurus* animals experience significant difficulty reaching their full production potential under tropical conditions. In 1910, the Philippine Bureau of Agriculture remarked "The American and Australian cattle kept at this farm have not done well although they received a liberal ration of concentrated feed. The amount of milk given by the cows is about one half what it would have been in the United States under similar circumstances" (Sarao, 1922). Similarly to the cows, *Bos taurus* bulls have difficulties successfully breeding females under tropical conditions (Contreras *et al.*, 2021). Instances around the globe like that of the Philippines have helped establish the framework for research pertaining to the identification of environmental adaptations and development of crossbreeding programs for improvements in genetic production potential.

Environmental Adaptations

It has been well established that *Bos indicus* cattle are well adapted to tropical climates, parasite loads, and prevalent

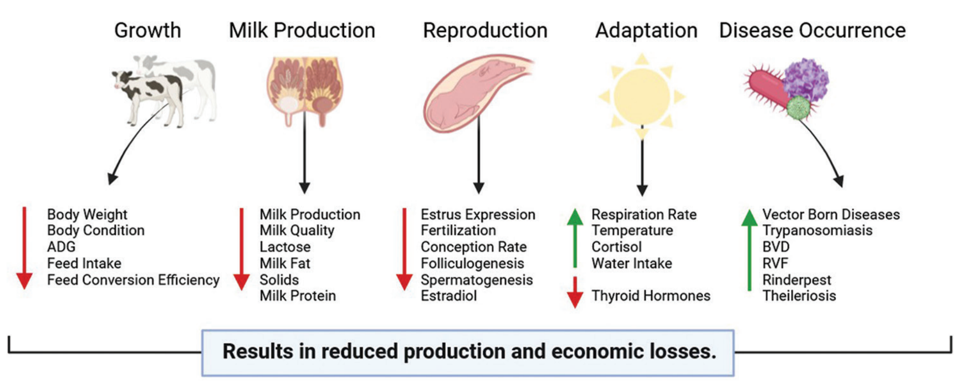

Figure 1: The impacts of heat stress on livestock production. Adapted from Kadzere (2018)

diseases. However, in comparison to *Bos taurus* cattle they have been found to be inferior in feed efficiency, production, and reproduction. Overall, due to their relative inefficiencies, they result in a larger carbon footprint and are therefore less economical (Madalena, 2002; Cooke *et al.*, 2020; Marchioretto *et al.*, 2023). In tropical regions, livestock face numerous environmental challenges, including heat stress, high humidity, and increased disease pressure. Selecting and breeding animals that can thrive in these conditions is essential for sustainable livestock production (Table 2). The importance of heat tolerance in cattle breeds has been emphasized around the world. *Bos indicus* breeds and their crosses generally exhibit better heat tolerance than *Bos taurus* breeds. This adaptation is crucial for maintaining productivity in hot climates, as heat stress can significantly impact growth rates, milk production, and reproductive performance. A notable development in climate-adapted cattle is the emergence of SLICK cattle. This genetic trait, originally identified in Senepol cattle found in the Caribbean Island of St. Croix, is being introduced through cross breeding and genome editing into other breeds to improve heat tolerance without sacrificing productivity. The SLICK mutation, a mutation in the prolactin receptor gene, results in a coat that is short and smooth with increased opportunity for heat dissipation, increasing the animal's thermotolerance (Rodriguez-Villamil *et al.*, 2021). P.Leu18del, observed in Japanese Brown cattle, is a mutation in the pre-melanosomal protein 17 gene which results in a coat that is lighter colored, but has similar effects on heat dissipation and thermotolerance (Kimura *et al.*, 2022). Breeding programs have been developed using Holstein cattle to produce a dairy animal with superior thermoregulation from the SLICK gene. The result of these matings in Florida presented Holsteins with slick coats and the ability to outproduce their long-haired counterparts under warm environmental conditions (Dikmen *et al.*, 2014). The marginal production drop in response to temperature stress was not the only evidence of improved thermotolerance. Observations including rectal temperature, skin temperature, sweating and respiration rates all further support the contribution of the SLICK mutation to thermotolerance in cattle. As a result of this, many countries are employing the SLICK mutation in their breeding programs to mitigate economic losses from heat stress.

Similarly to cattle, sheep indigenous to tropical regions have often developed adaptations to survive the harsh environmental conditions. These adaptations adapted traits include thinner skin, shorter hair, carpet type wool, and fat tails (McManus *et al.*, 2009). Research has shown both fleece type (Leite *et al.*, 2018) and color (Kay, 1997) are contributing factors in minimizing water loss and protection from the heat. The fat tail is a more notable morphological characteristic. These fat-tailed or fat-rumped sheep account for approximately 25% of the global sheep herd (Elbeltagy, 2017). Their unique ability to localize fat storage to the tail decreases overall body insulation, allowing animals with this characteristic to dissipate heat more efficiently (Degen & Shkolnik, 1978). Aside from thermoregulation, this fat store can be mobilized for use in times of hydration and nutritional deficiency (Chilliard *et al.*, 2000; Naziha *et al.*, 2004). Genome-wide scans of fat and thin-tailed Iranian sheep revealed three novel chromosomal regions located on *Oar* 5, *Oar* 7, and *Oar* X were associated with fat deposition (Moradi *et al.*, 2012). Aside from thermotolerance, disease resistance is another critical trait for livestock in tropical regions. Trypanosomiasis accounts for estimated annual losses of billions of dollars in sub-Saharan countries (Mekonnen *et al.*, 2019). Numerous control methods have been applied to this disease, transmitted by infected tsetse flies, but successful eradication has not occurred (Leak *et al.*, 1996; Giordani *et al.*, 2016). Certain breeds have been identified as significantly more resistant to trypanosomiasis than most *Bos indicus* cattle, such as the N'Dama and West African Shorthorn (Murray & Trail, 1984). Mekonnen *et al.* (2019) highlights the importance integrating of breeding for trypanotolerance and vector control in Ethiopia, where trypanosomiasis is a major constraint on livestock production (Mekonnen *et al.*, 2019).

Crossbreeding Programs

Unfortunately, animals with these environmental adaptations often have reduced production potential when compared to breeds less adapted to tropical environments. To achieve high productivity yet retain adaptability crossbreeding programs are often put into play. Widely practiced across species, crossbreeding plays a significant role in tropical dairy production. Local breeds have slowly been replaced over the years by crossbred *Bos taurus* x Bos indicus animals.

A notable success story in crossbreeding to improve tropical livestock productivity is that of the Girolando cattle in Brazil. The ideal Girolando composition is 5/8 Holstein and 3/8 Gyr, balancing productivity with adaptability to tropical conditions. This breed, developed by crossing Gyr (a *Bos indicus* breed) with Holstein (a *Bos taurus* breed), has become the backbone of the Brazilian dairy industry. The industry has grown nearly 4% each year across the last decade to reach its present state as the fifth largest cattle milk producer in the world with 80% of milk production attributed to animals of Gyr x Holstein descent (Madalena, 2012; Daltro *et al.*, 2019). Today, there are more than 20 million *Bos taurus* x *Bos indicus* crossbreds in South America alone (Madalena, 2012).

Success of tropical crossbred livestock is not limited to South America. One of the earliest documented efforts to develop a thermotolerant composite breed began in Jamaica around 1910. Breed development was riddled with obstacles, but the resulting Jamaica Hope breed was declared some 40 years later (Wellington & Mahadevan, 1977). Other similar composite breeds focused on thermotolerance include the Australian Milking Zebu (AMZ), Australian Friesian Sahiwal (AFS), and Guzerat. ARTs such as AI and ET have played a significant role in the development of such breeds. Table 3 details a variety of crossbred cattle developed for production in tropical and subtropic regions.

One challenge with crossbreeding programs in developing countries is the lack of consistency within breeding programs, resulting in never reaching a fixed phenotype. One tale of these struggles is the Mpwapwa breed in Tanzania. The Mpwapwa

Table 2: Environmental adaptations of livestock breeds and their importance

Adaptation	Breed	Importance	References
SLICK or light colored hair coats	Senepol Japanese Brown Carora Criollo Limonero Romosinuano	Enhances heat dissipation to reduce heat stress in hot climates.	Huson *et al.,* 2014; UF, 2020; Rodriguez-Villamil *et al.,* 2021; Kimura *et al.,* 2022
Trypanotolerance	N'Dama West African Shorthorn West African Dwarf	Increases resistance to Trypanosoma parasites and reduces subsequent trypanosomiasis infections.	Murray *et al.,* 1982, 1984; Hanotte *et al.,* 2003
Fat-Tail or Fat- Rump	Awassi Damara Karakul Tunis Tunisian Barbarin Nejd Hajaz Arabi Red Maasai Karakas Norduz Afshari	Stores fat in the tail/rump to increase thermotolerance. This store can be mobilized to aid in survival during droughts and periods of low forage availability.	Epstein, 1957; Degen & Shkolnik, 1978; Naziha *et al.,* 2004; Almeida, 2011; Pourlis, 2011; Elbeltagy, 2017; Mohapatra & Shinde, 2018
Tick, Parasite, and Nematode Resistance	Katahdin Red Maasai St. Croix Barbados Blackbelly Gulf Coast Native Small East African Garole Namaqua Afrikaner West African Dwarf	Reduces incidence of tick-borne diseases, especially in humid, tick-prone areas.	Stear & Murray, 1994; Baker, 1998; Stear *et al.,* 2007; Bishop, 2012

Table 3: Details crossbreeds of cattle and their component breeds used for production in tropical and sub tropic environments (Porter *et al.,* 2016)

Composite Breed	Breed Components	Developed In
Australian Milking Zebu (AMZ)	Sahiwal, Red Sindhi, Jersey	Australia
Brangus	Brahman, Angus	Louisiana, USA Australia
Jamaica Hope	Sahiwal, Jersey, Holstein	Jamaica
Murray Grey	Guzerat, Roan Shorthorn, Angus	Australia
Santa Gertrudis	Brahman, Shorthorn	Texas, USA
Sunandini	Zebu, Brown Swiss, Jersey, Holstein	India
Girolando	Gyr, Holstein	Brazil
Australian Friesian Sahiwal (AFS)	Sahiwal, Holstein	Australia
Mambi de Cuba Siboney de Cuba	Cuban zebu, Holstein	Cuba

breed was originally developed from the concept of an Indo-African breed. This concept originated with Dr. H. G. Hutchison and his cross of local Tanganyika Zebu cows with Red Sindhi and Sahiwal bulls (Ojango, 2020). The development of the Mpwapwa intended to produce a dual-purpose breed that was adapted to the semiarid environment of central Tanzania. The breeding programs began in 1935 with the aim of producing a new synthetic breed. At its origin, the program used *Bos taurus* bulls (mainly Ayrshires from the UK) to breed local cattle (Wilson, 2021). Around 5 years into the breeding program, it was noted that the crosses with Bos taurus were not achieving the desired production parameters, so modification of the breeding program began and Bos indicus species (Red Sindhi & Sahiwal) were introduced to the developing breed to replace (in part) the Bos taurus genetics. Unfortunately, in the 1940s this breeding program was cancelled altogether, but a new breeding program began shortly thereafter in 1944 (Syrstad, 1990). The goal of the new program was to conserve 30% of the genetics from the final animals from the original breeding program (*Bos indicus* Indo-African zebu with traces of *Bos taurus* genetics) and combine with 60% Sahiwal/Red Sindhi and 10% Ayrshire to develop the new breed (Syrstad, 1990). More current breeding programs have implemented embryo transfer with the goal of improving milk production for human consumption. Altogether the breeding program has changed drastically at multiple points. Little is known about the true breed composition of current animals, but the production parameters envisioned for this breed have still not yet been met (Table 4).

All in all, crossbreeding programs have proven to be quite beneficial over the years.

However, caution should be taken against indiscriminate crossbreeding and an emphasis put on the need for well-designed breeding programs that consider local production systems and environmental conditions. Sustainable crossbreeding programs should aim to optimize, rather than maximize, exotic blood levels to maintain an appropriate balance between productivity and adaptability.

POTENTIAL AND LIMITATIONS OF ARTS IN THE TROPICS

Assisted reproductive technologies have played a critical role in improving livestock production in many countries around the world. An example of this exemplary success can be found in "Toystory", a bull that fathered more than 500,000 offspring using AI (Zuidema *et al.*, 2021). The use of AI around the globe has grown exponentially. Today, countries such as the Netherlands, Denmark, and the UK utilize AI to breed more than 90% of their dairy herd (Ombelet & Van Robays, 2015). Timed AI alone has been estimated to return over $ 0.5 billion/year to the Brazilian beef industry (Baruselli *et al.*, 2019; Mueller & Van Eenennaam, 2022). Reproductive technologies offer opportunities to enhance the genetic quality of livestock thus increasing both productivity and resilience to environmental challenges, allowing tropical regions to experience the same tidal wave of benefits that the US has seen. In the tropics, ARTs can also be used to select desirable traits observed in indigenous breeds and multiply them at an exponentially faster rate than possible with conventional mating. The most common ARTs used in livestock production include artificial insemination and embryo production and transfer.

Artificial Insemination (AI)

Artificial insemination, often referred to as the "gateway tool," is one of the oldest and most widely adopted ARTs (Rabel *et al.*, 2024) (Figure 2). By collecting semen from elite males, processing it, and inserting it into the uterus of selected females, AI allows livestock owners to make selective breeding decisions and disseminate superior male genetics within their herds. It allows for the selective breeding of livestock without the need for live animal transport, thus reducing the opportunity for disease transmission. In some cases, AI was able to even surpass reducing risk of disease and essentially eliminate venereal pathogens. The UK observed this level of success in the 1940s using AI to virtually wipe out *Tritrichomonas foetus* and *Campylobacter fetus* subsp. *Venerealis* (Parkinson & Morrell, 2019). Reducing or eliminating live animal transport is a huge benefit for countries like Tanzania, with a high prevalence of communicable diseases (Mkenda, 2021). In comparison to other ARTs, the AI process is relatively cheap and easy to implement, though it is important to note that skilled labor is still required. Additionally, AI is cost-effective in comparison to owning and maintaining high- quality sires, especially for smallholder farmers which represent the majority of livestock owners in developing countries (Cabrera, 2022).

Table 4: Desired vs actual breed characteristics and production parameters of the Mpwapwa breed in Tanzania

Characteristic or Parameter	Desired	Actual
Withers Height	119 cm	~115-130 cm
Mature Male Weight	520 kg	~ 280 kg
Mature Female Weight	400 kg	~250 kg
Calving Interval	380 days	~730 days
Milk Production in 305 Days*	2300 kg	~210-630 kg

*Calculated based on the assumption of 1-3 liters milk produced per day for a 7-month lactation period

Unfortunately, the benefits of AI are accompanied by a significant number of challenges when implementing a tropical AI program. AI requires skilled technicians for proper execution, which can be scarce in the rural areas in which many livestock owners are located. A reliable cold chain for semen storage and transport is also crucial and can be difficult to maintain in regions with unreliable electricity or limited infrastructure. Furthermore, accurate estrus detection can be challenging in the extensive farming systems common in many tropical countries, The failure to detect heat is the most common problem of AI programs around the world and the major limiting factor of their success (Nebel & Jobst, 1998). Estrus detection is overall more difficult with *Bos indicus* cattle and their crosses as they exhibit a significant reduction in estrus behaviors (such as mounting). With reduced estrus behaviors and commonly used traditional breeding, it is not unlikely that many pastoralists and livestock owners lacking a formal education would not be familiar with identifying estrus, thus establishing the requirement for further education or training to aid livestock owners in effectively identifying estrus and determining when to use AI. Educational exercises should extend to liquid nitrogen use and semen handling. Improper usage of liquid nitrogen can result in minor to severe burns and even death (Kernbach-Wighton

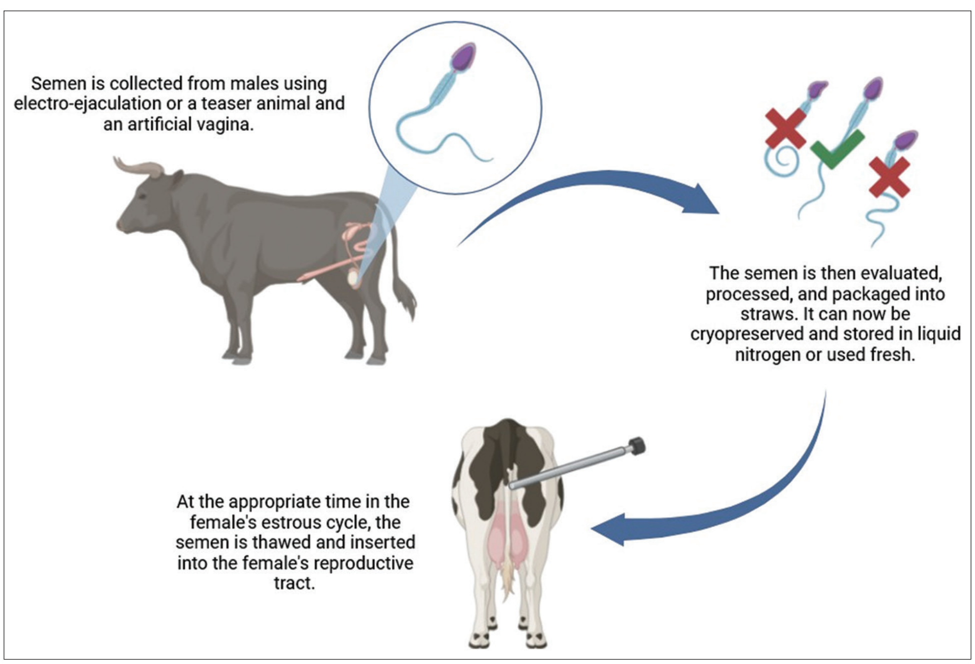

Figure 2: A graphical representation of the artificial insemination process

et al., 1998). Likewise, incorrect handling of cryopreserved semen can cause recrystallization to occur in which small ice crystals transform or reorganize into larger crystals resulting in the potential invasion of cell membranes and organelles (Stroud, 2013). This invasion can damage or even destroy sperm cells. Similarly, cryopreserved embryos may experience these negative effects if improperly handled.

Despite the obstacles it faces, AI is not a foreign concept to many of the developing countries in East Africa. In fact, there is evidence of significant efforts to establish AI programs. In Tanzania, the Ministry of Livestock and Fisheries established a National Artificial Insemination Centre {NAIC} in 1972 with Swedish aid (Anonymous, 2024). Prior to this in 1968, the government declared AI to be a free service offered by institutions functioning under the Ministry of Livestock and Fisheries, effectively putting dairy cattle societies which offered three inseminations for 12.50 Tanzanian shillings (equivalent to $0.0046 USD) out of business (Anonymous, 2024). Today, the NAIC is very well equipped, boasting automated equipment for freezing, straw labeling, and processing as well as a computer-aided semen analysis system {CASA} (van der Horst, 2018). The NAIC does offer training, but there is evidence of inadequate trainee skills resulting in exceptionally low pregnancy rates, and therefore, a low adoption rate of this technology.

Kenya has taken a similar route to Tanzania, implementing the Kenyan National Artificial Insemination Service {KNAIS}. The KNAIS was also preceded by breeder's associations offering insemination service, though their breeder's associations services are now linked to those provided by KNAIS (Duncanson, 1975). Based in Kabete, the Central Artificial Insemination Station {CAIS} was established in 1946 (KAGRC, 2025) with more than 125 bulls, consisting of the following breeds: Ayrshire, Friesian, Guernsey, Jersey, Sahiwal, Simmental, Boran, Charolais and Hereford (Duncanson, 1975). Although semen for dairy cattle is still being provided, the beef breeds were phased out by 1992 due to a lack of demand (Juma, 2020). Today, after its transformation into a state corporation, this station is known as the Kenya Animal Genetic Resources Centre {KAGRC} and it offers both bovine and caprine semen.

In collaboration with government institutions, NGO funding and partnerships with private institutions are continuing to help drive progress within this sector. A recent example of this is a grant proposal from URUS, an agricultural and genetics holding company, funded by the Bill and Melinda Gates Foundation. Their objectives are to increase AI adoption by small-scale producers, build a network of reliable AI technicians, increase participation of women in the dairy value chain, and develop partnerships with local genetic centers for the benefit of livestock owners and AI technicians (URUS, 2021). The program, known as the Africa Dairy Genetics Multiplication program, will focus on providing genetics (both local and exotic) that will thrive in East African environmental conditions and contribute to a more sustainable production system.

Embryo Transfer (ET) and Embryo Production

Similarly to AI, embryo transfer allows for rapid dissemination of superior genetics from the male, but also incorporates selection of elite female genetics, thus offering the greatest promise for advances in genetic gain. It is one of the most common reproductive technologies used in modern breeding programs in developed countries (Rabel *et al.*, 2024). Embryos used for ET can be produced either *in vivo* or *in vitro* (Figure 3).

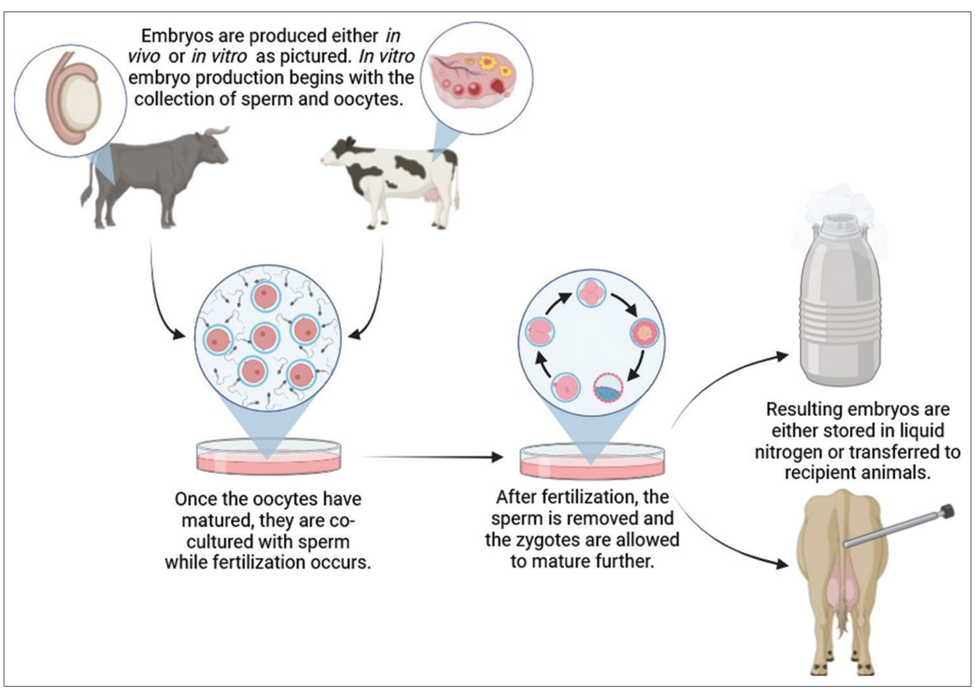

Figure 3: A graphical representation of the *in vitro* embryo production and transfer process

In vivo conventionally produced embryos are produced by super ovulating a donor animal, breeding the donor using artificial insemination, and flushing the resulting embryos from the uterus for transfer to recipient animals. In contrast, *in vitro* or IVF embryos are produced from oocytes aspirated from slaughterhouse ovaries or oocytes collected using transvaginal ultrasound-guided ovum pickup. The matured oocytes are fertilized and incubated until they have developed to the blastocyst stage. This technique allows for more frequent embryo production from a donor herd when compared to *in vivo* methods. It also facilitates the application of other biotechnologies like embryo sexing or genetic testing, offering more control over breeding outcomes. Additionally, IVF can be used to produce embryos from valuable females that may have reproductive issues preventing natural pregnancy. However, *in vivo* embryos have higher survival rates than those of their *in vitro* counterparts.

Though often we see more temperate countries trailblazing new ARTs, Brazil leads the world in *in vitro* produced embryos, accounting for 37% of the market as of 2022 (Viana, 2023). As the third largest cattle producer in the world, with 48.5 million head of cattle, it is unsurprising how the market for embryos has flourished there (Aquino, 2023). Contributing to this success is the zebu breed that is superior in terms of oocyte production when compared to European breeds. With the largest commercial zebu herd in the world, Brazil has become the global supplier of zebu genetic material (Rodrigues, 2014). Embryo technologies are prominent in Brazil throughout both the beef and dairy industries and have been used to drive the development of breeds like the Girolando.

Bovine embryo transfer activities in Kenya commenced in the 1980's, some 30 years after the first live calf had been produced using ET (Willett *et al.*, 1951). In the early years, embryos had to be imported. One of these original cases occurred in 1986 when N'Dama embryos were imported from Gambia and transferred into Boran heifers (Jordt *et al.*, 1986). These 29 *in vivo* embryos resulted in 10 calves. The success of this study allowed the trypanotolerant N'Dama cattle to travel greater than 5,000 miles without risk of contracting communicable diseases to increase productivity in an area where trypanosomiasis is endemic. In 2019, M'lkiugu *et al.* (2015) achieved success rates with *in vitro* embryo production similar to those observed in proficient embryo production systems. The transfer of embryos from this study resulted in a 46.5% conception rate, supporting the viability of using this technology to improve genetic potential. Furthermore, a 2019 study reported that using IVF and ET within Kenyan dairy herds could increase monetary gain by 184% and reduce the generation interval by 47% (Gicheha *et al.*, 2019). At present, large-scale farms, government operations, and research organizations are carrying out the majority of embryo transfer programs in the country (Kios, 2019).

Similarly to Kenya, reports of Ugandan ET began in the 1990's, where Holstein *in vivo* embryos were imported and transferred to indigenous recipients (Cumming *et al.*, 1994). This study reported conception rates similar to what is expected (58.5%), and a slightly lower live birth rate (41.2%). It is suspected that this was due to poor recipient management. Even with these challenges, the calving rate achieved reduced costs of exporting live animals by nearly 20% (Cumming *et al.*, 1994). ET activities in several other East African countries began much later, with the first ET calf in Ethiopia being produced in 2010 (Mebratu *et al.*, 2020). Several attempts have been made in Tanzania to implement ET, but success rates have been low (Bangert *et al.*, 2024).

As with artificial insemination, embryo production technologies face numerous challenges, attributing to lower success rates. There can be considerable variability in superovulation response

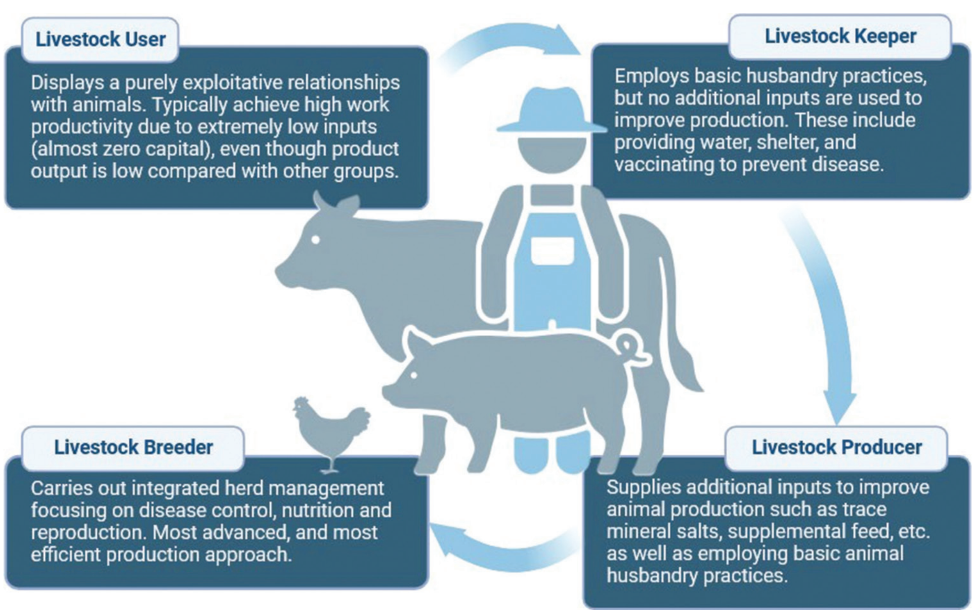

Figure 4: A graphical representation of the four different categories of livestock owners adapted from descriptions from (Neidhardt *et al.*, 1996; Rewe *et al.*, 2009)

among donors, especially those of varying breed compositions. These variations may be further exacerbated by environmental and nutritional stressors in tropical climates. Like AI, the process requires skilled technicians who may be in short supply in some areas. IVF requires specialized laboratory equipment and highly skilled technicians, which may be expensive, scarce, or unavailable in many countries. Success rates are strongly affected by both donor and recipient management, which can be more challenging in extensive farming systems or resource-limited settings. This is particularly a concern as average success rates are already significantly lower than observed with natural mating or AI. Success rates observed with *in vitro* produced embryos are even lower than those observed with *in vivo* derived embryos and can be further compromised by heat stress and other environmental factors common in tropical regions. Using embryo technologies is generally more expensive than AI without the assistance of a government program or incentives, often reducing economic feasibility for small-scale producers, which account for more than 150 million farming households worldwide (Hemme & Otte, 2010; Contreras *et al*., 2021). A 2010 study estimated the average costs of preparing an embryo donor at $600 (Alarcón *et al*., 2010). Considering these costs, opportunities for widespread ET in the tropic is limited, but as success rates improve, the economic prospects for tropical embryo production and transfer programs is subject to change.

CONCLUSIONS

Food insecurity remains one of the most pressing challenges in tropical regions, particularly in East Africa. The complex interplay between climate vulnerability, low agricultural productivity, and socioeconomic constraints demands innovative solutions that can enhance both food availability and accessibility. As animal source foods play a crucial role in providing essential nutrients and supporting household income in these regions, improving livestock productivity represents a key pathway to addressing food insecurity. Neidhardt *et al.* (1996) broke livestock owners into 4 distinct groups: users, keepers, producers, and breeders. These groups are briefly defined in Figure 4. Acknowledgement of these distinctions in the development and implementation of genetic improvement strategies is often an overlooked factor leading to failure. This review has demonstrated that assisted reproductive technologies, when properly implemented and combined with strategic genetic improvement programs, can play a crucial role in enhancing livestock productivity and food security in tropical regions and improving the economic viability of livestock production systems.

While ARTs alone cannot solve the complex challenges of food insecurity, they represent a valuable tool in the broader effort to enhance livestock productivity and food security in tropical regions. Success will depend on coordinated efforts to address both technical and socioeconomic barriers to implementation, while ensuring that solutions are appropriate and sustainable for local conditions. As efforts to improve tropical livestock productivity progress, future studies should focus on developing cost-effective approaches to implementing ARTs in resource-limited settings, improving the success rates of embryo technologies under tropical conditions, and identifying genetic markers for enhanced environmental adaptation and disease resistance. Additionally, more attention should be given to developing comprehensive dissemination and support systems that enable smallholder farmers to access and benefit from these technologies.

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