Asia Pacific Academy of Science Pte. Ltd.

Advances in Modern Agriculture 2024, 5(2), 2362.
https://doi.org/10.54517/ama.v5i2.2362

Review

Crossbreeding and its implication for small-scale animal agriculture in Africa: Outcomes, both positive and negative, and future prospects

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CITATION

Assan N, Muteyo E, Masama E, et al. Crossbreeding and its implication for small-scale animal agriculture in Africa: Outcomes, both positive and negative, and future prospects. Advances in Modern Agriculture. 2024; 5(2): 2362. https://doi.org/10.54517/ama.v5i2.2362

ARTICLE INFO

Received: 31 October 2023
Accepted: 18 February 2024
Available online: 19 April 2024

Abstract: African animal genetic resources are diverse and have been the subject of crossbreeding for decades to improve local livestock and poultry populations. However, the literature on crossbreeding performance has been inconsistent, with many projects failing due to various reasons. This has led to mixed support and criticism for crossbreeding in small-scale animal agriculture. The review examines the achievements, problems, and future prospects for livestock and poultry genetic improvement through crossbreeding in Africa's small-scale animal agriculture. Community-based Breeding Practices (CBBP) can be seen as a community livestock development strategy that mobilizes local animal genetic resources and boosts smallholder livestock producers' ability to collaborate in resource-scarce communities. Genome sequencing is seen as the future cornerstone of promoting crossbreeding in Africa, but it should be based on consideration of the socioeconomic context of small-scale animal husbandry and local livestock production conditions. Smallholder farmers, who are the major custodians of local animal biodiversity, have faced challenges such as genotype and environmental interaction, lack of funding, poor laws, and lack of farmer participation. In conclusion, the review highlights the importance of phenomics and genomic prediction in improving animal genetic resources in Africa, but it also emphasizes the need for further research and development in this area. The study suggests that modern breeding technologies (genomics and phenomics) and training of smallholder livestock farmers in improved animal husbandry management practices can be used to enhance food and nutrition security for African rural households. This review examines the effects of crossbreeding through the decades on small-scale livestock farming in Africa, including positive and negative outcomes as well as future implications.

Keywords: crossbreeding; smallholder; animal agriculture; local animal genetic resources; community based breeding program; genomics; phenomics; Africa

1. Introduction

The African animal genetic resources show astonishing diversity, which might be the product of over a million years of animal evolution on the continent. There have been efforts over the years to raise the standard of animal production, which in Africa mostly depends on local animal genetic resources, in order to enhance the quality of the livelihoods of the rural majority [1]. The use of crossbreeding as one option to improve the performance of livestock and poultry in small-scale animal agriculture has received both enthusiastic public support [2,3] and harsh criticism [3–5].

On the African continent, small-scale livestock farming, enabled by local animal genetic resources, is a vital part of rural livelihood [6]. The majority of the rural poor own a significant proportion of the livestock population, which has several uses. It is crucial to focus on this sector in order to solve challenges related to food security and poverty reduction and ensure the survival of the larger population. In this case, crossbreeding is expected to continue to be a crucial tool for enhancing livestock production in the tropics despite multiple obstacles [7].

Crossbreeding speeds up genetic development by utilizing both breed complementarity and genotype compatibility with the environment [8]. However, crossbreeding does not seem to be a one-size-fits-all solution because of Africa's different agro-ecological features, extensive livestock system practices, and increased genetic biodiversity of domesticated animal breeds. Marchioretto et al. [9] found that crossbred animals' relative advantage over native animals in terms of production characteristics under difficult circumstances is limited by frequent and significant genetic and environmental interactions. Both uncontrolled crossbreeding and subpar management have been held responsible for the genetic decline of Africa [10]. Improper crossing and poor management techniques for some animal genetic resources are endangering the present conservation effort [11]. This study reviews the successes and failures of crossbreeding indigenous cattle, goats, and poultry with improved exotic breeds in small-scale animal agriculture in Africa.

The vast genetic diversity of the local animal genetic resources makes them good resources for the development of livestock and poultry since these animals may be raised in a range of environments and be used for a variety of purposes. Significant genetic resources contained in indigenous livestock and poultry still need to be properly utilized in order to create breeds that are adapted to local conditions for the benefit of farmers, particularly in developing nations [12]. What is the most effective strategy for boosting the production of indigenous animal genetic resources in Africa? Heterosis (hybrid vigor) is more significant in unfavorable environments than in ones that have a wider genetic distance [13,14] pointed out that the main objective of crossbreeding in commercial animal production is to take advantage of the heterosis effect on the crossed animals. This review examines the effects of crossbreeding on small-scale livestock farming in Africa, including positive and negative outcomes, as well as future implications.

2. Overview of the utility of African indigenous animal genetic resources in Africa

Nearly one billion animals are raised by more than 800 million poor livestock keepers in peri-urban, rural, and peripheral areas of developing countries [15]. According to AU-IBAR [16], Africa has one-third of the world's livestock, and its agricultural sector contributes about 40% of the continent's GDP. This percentage varies from 10% to 80% in different countries [17]. Africa is home to a large number of indigenous animal genetic resources that are highly prized for their capacity to adapt to the challenging agro-ecological conditions of the continent [18]. However, due to a number of issues, such as poor animal nutrition and disease prevalence, a lack of strong institutional support, and a lack of proper government policies and funds to promote this sector, local animal genetic resources typically perform below par.

In Africa, there are 150 different cattle populations and breeds, including diverse conglomerations of the taurine and indicus lines as well as pure taurine and indicus lines [19]. Indian cattle, which currently come in 75 different breeds and are spread out across the African continent, make up the bulk of cattle on the continent. There are around 61 of these in East Africa. While Sanga cattle breeds are widespread in eastern and southern Africa, Zenga breeds, which are a stable cross between the Sanga and Bos indicus, have a comparable geographic distribution to the Sanga [20].

Chickens being the most populous animal species ahead of goats and sheep, they will account for over 2.1 billion heads of livestock in Africa by 2020, and several studies [21,22] claim that raising hens helps to alleviate poverty and improve household food security. Rural poultry, dominated by village fowl, accounts for more than 80% of all poultry holdings in many developing countries [23]. In many developing nations, village hens play a key role in poverty reduction and household food security [24]. Family poultry is well established as a starting point for addressing the issues of malnutrition, food insecurity, and poverty for the rural poor [25].

Goats and sheep were the next most common livestock species on the continent, with 490 million and 420 million heads, respectively. Goats are estimated to number around 1 billion worldwide, with the majority of them living in Asia and Africa [26]. Africa is home to around 35% of the world's goat population [27]. Goats account for 30% of the domestic ruminants currently found on the African continent [28]. In Africa, goats play a critical role in improving livelihoods and food security. In rural locations across Africa, the majority of indigenous and regionally adapted goats are kept in small-scale production systems. Goat meat production in Africa increased from 1.1 million tons in 2008 to 1.3 million tons in 2017 [29], with the bulk of goat meat being produced and consumed locally (within households) [30,31].

3. The concept of cross-breeding in animal agriculture

Wu and Zhao [32] reported that cross-breeding is an effective way to increase animal production. In contrast to purebred animals, crossbred animals perform better because crossbreeding takes advantage of heterosis effects and breed complementarity [33]. In terminal crossbreeding systems, selection of purebred animals to increase their crossbreed performance is the ultimate aim [34,35]. Purebred productivity pursuant to nucleus environments might not serve as the best indicator of crossbred efficiency because of the possibility that genotype-by-environment interaction impacts non-additive genetic effects and distinctive allele frequencies in different breeds [33]. Nevertheless, the long-term viability of crossbreeding is usually jeopardized by obstacles like inadequate adaptability to the local environment or a lack of logistical assistance.

By reducing inbreeding and enhancing fertility, survival, and other desirable qualities, crossbreeding is a desirable method for proactively enhancing animal breeding sustainability [36]. It has been one of the most important livestock and poultry genetic improvement tools for decades. For many years, production techniques for beef cattle, pigs, and poultry have heavily utilized crossbreeding to improve the performance of these species of livestock. Falconer and Mackay [37] described the mating of individuals from various lineages, breeds, or populations as known as crossbreeding.

The use of crossbreeding in livestock is motivated by two basic factors. The first is to make use of the various additive genetic levels seen in different breeds to produce progeny with improved economic propensity brought on by new additive genetic component combinations. Second, heterosis is expressed in crosses between pure lines or breeds. Mäki-Tanila [38] reported that, in comparison to their mother breeds, crossbred animals are more robust and economically efficient. Crossbreeding must be lucrative if systematic breeding techniques are consistently applied, and breeds that are comparable in terms of overall merit should be used [39].

Systematic crossbreeding programs involving temperate and tropical breeds have proven to be quite beneficial when carefully designed. In comparison to selective breeding, crossbreeding has been shown to have a number of benefits, such as the potential to create the desired productivity in a shorter period of time [40]. However, it has also been found to have a number of disadvantages. Due to the extent of the depletion of domestic animal resources, it is increasingly questionable whether breeding highly productive introduced genotypes with domestic animal genetic resources will be viable in the long run [41].

3.1. Crossing village chicken in African small-scale animal agriculture

In Africa, native African chickens make up around 80% of the chickens reared there. The majority (60%) of African families' employ backyard methods to rear native African chickens [42]. Indigenous chicken genotypes have low egg production and growth performance despite their better adaptability to the low input scavenging/semi-scavenging system [43]. Improved exotic chickens, on the other hand, produce more eggs and meat than indigenous chicken ecotypes, but a tropical environment is a significant barrier [44]. As a result, the genetic diversity of indigenous and exotic chicken breeds could be exploited through cross breeding to create a new breed or synthetic that is resistant to unfavorable tropical climate conditions while producing an intermediate level of egg and meat production [45]. Crossing indigenous chickens with selected, but still robust exotic breeds could improve their genetic potential [43].

Based on both qualitative and quantitative features, local African chickens have a high genetic diversity [46–48]. Local African chicken ecotypes show phenotypic variability in terms of physical and morphological characteristics such as plumage color and type, body shape and size, and productive performance [49,50]. In most African nations, including Sudan [51], Ethiopia [52], Botswana [53], Nigeria [54], and Algeria [55], variation in phenotypic characteristics both within and across native African chickens has been documented.

Crossbreeding in poultry could result in birds with increased growth rates, greater feed conversion rates, and improved reproductive capacities without compromising the birds' capacity to adapt to their environment, which would lower production costs. However, selection and crossbreeding have to be properly designed and developed to suit existing cultural and socio-economic conditions [56]. Khawaja et al. [57] observed that the ideal crossbred animal would perform better in terms of growth rate, feed conversion efficiency, reproduction, and carcass quality; however, increasing the genetic potential of native chickens and carrying out a planned breeding program take time or are time-consuming.

3.2. Crossing indigenous chickens with exotic breeds to improve growth traits

Kgwatalala and Segokgo [58] observed that, compared to their more exotic relatives, they grow more slowly and weigh less when they are fully mature. By utilizing breed complementarity and heterosis, crossbreeding indigenous Tswana chickens with exotic chicken breeds can be used as an alternate technique to enhance the growth performance of indigenous. Hence in order to increase the growth performance of indigenous Tswana chickens raised using an intensive management method, crossbreeding can be ideal strategy. Crossbreeding can can enhance the overall genetic diversity by introducing new genes and genotypes in the targeted population [59].

Figure 1 lists a few of Ethiopia's native chicken ecotypes. In Rwanda in accordance with morphobiometric analysis of both quantitative and qualitative features, it was discovered that the IC ecotypes are diversified [60]. Oke et al. [2] evaluated the hatching egg characteristics, embryonic development, hatching parameters, and juvenile growth of Nigerian indigenous chickens in crosses with exotic broiler chickens. It was concluded that there could be a positive improvement in embryonic development and post-hatch growth of the local chicken by crossbreeding using the same genotype ratio (50:50). The results of the present study therefore indicate that FE chickens were more fecund than those of the other crosses, while TE birds were intermediate. An increase in hatchability is advantageous, and crossbreeding has been reported to influence the hatchability of chicken eggs.

Figures 2 and **3** show the African naked neck and frizzled feather indigenous chickens. A lot of characterization work have been done on African naked neck and frizzled feather chickens and results have shown their potentiality in some of the productive traits.

Figure 1. Indigenous chicken ecotypes in Ethiopia. **(a)** Ahun Tegegn ("Gutena"); **(b)** Muffed ("Gugut"); **(c)** Sekela ("Solola"); **(d)** Gelego ("Angete melata"); **(e)** Bakelit ("Feathered"); **(f)** Silky feathered ("Gumaidea") [59].

Figure 2. African naked neck indigenous chickens.

In their study of crossbred chickens raised in backyard systems employing both exotic and native breeds, Padhi et al. [61] found that the crossbred chickens outperformed their purebred counterparts in terms of growth performance attributes, indicating substantial differences among the chicks studied. Amao [62] discovered significant differences in growth performance characteristics between pure and crossbred chickens, including Rhode Island Red and indigenous Nigerian chickens. These distinctions serve as the basis for dividing chickens into breeds (**Figure 2**). African naked neck indigenous chickens.

According to Fisinin and Kaytarashvili [63], the naked neck gene has also been found to be resistant to significant environmental changes like high temperatures. Due to more feathers on the skin, the naked neck gene reduces feather mass by up to 40% and decreases the likelihood of heat insulation [64,65]. In comparison to birds with regular feathers, studies show that fowl with Na gene perform better while under heat stress. Lin et al. [66] reported that the Na chicken line has improved immunity and production performance. Lack of feathers on the neck creates greater area for heat dissipation and inhibits heat insulation, allowing birds to withstand the extreme temperatures.

The Na gene plays a significant beneficial effect in avian immunity and production efficiency. Additionally, it reduces fat formation in the breast area, enhancing heat dissipation and enhancing heat tolerance. Raju et al. [67] and Darwin [68] noted the existence of a particular phenotypic known as "frizzled feather" (**Figure 3**) which is characterized by curled feathers that wave beyond the body. It was suggested that this breed of chicken provides the highest defense against harsh environments, and many chicken breeds express the unique gene displaying such traits [69].

Figure 3. African frizzled feather indigenous chickens.

Figures 2 and **3** show the African naked neck and frizzled feather indigenous chickens, which have been studied for their production traits in different agroecological regions of Africa. [70] (Nigeria); [71] (Botswana); [72] (Kenya); [73] (Uganda); [74] (Malawi). FAO [75] states that the generation interval, selection criteria, intensity, and population's genetic diversity all affect the rate of genetic gain. In order to plan breeding programs and make informed decisions about the sustainable use of animal genetic resources, it is essential to assess the genetic diversity of indigenous chickens [76]. Crossbreeding can also be used to produce the foundation for new breeds, synthetics, or composites. Synthetic chicken breeds were developed by crossbreeding local genetic resources with exotic breeds in Africa (**Table 1**).

Table 1. Synthetic chicken breeds developed by cross breeding in Africa [29].

Synthetic breeds	Their crosses	Origin
Dokki 4	Fayoumi × Barred Plymouth Rock	Egypt
Golden Montazah	Dokki 4 × Rhode Island Red	Egypt
Mandarah	Dokki 4×Alexandria	Egypt
Matrouh	Dokki 4×White Leghorn	Egypt
Alexandria	White Leghorn×Barred Plymouth Rock×Rhode Island Red×Fayoum Egypt	Egypt
Potchefstroom koekoek	Black Australorp×White Leghorn×Barred Plymouth Rock	South Africa

3.3. Crossing indigenous chickens with exotic breeds to improve egg production

Amao [77] discovered considerable changes in the fertility and hatchability features of backcrossed chickens made up of Rhode Island Red and indigenous Nigerian birds. Significant differences were found between pure and crossbred F1 chicken progenies [78]. Significant effects were also discovered among Nigerian indigenous chickens [79]. The enhanced fertility and hatchability qualities displayed by NFRIR × NF birds were consistent with another study [80]. The genetics of individuals with normal feather genes performed better in terms of fertility and hatchability. In comparison to exotic poultry breeds, it was found that native chickens had superior fertility and hatchability features.

Adedeji et al. [78] studied the pattern of fertility and hatchability performance traits and revealed significant differences among the genotypes involved. In the same study, the genetic backgrounds of the chickens used in their various investigations varied significantly, which led to variances in the fertility and hatchability features. Significant body weight differences between genotypes at day old may be due to DRB chickens having larger egg weights than other genotypes, and it demonstrates the observed impact of the heterosis effect on crossbred chicks. The potential to improve genetics without compromising the quality of the offspring's products was demonstrated by Szalay et al. [81] utilizing two "indigenous and rare" Hungarian chicken breeds. Crossing could be viewed as an additional technique for the conservation of low-yielding and critically endangered breeds.

3.4. Crossbreeding in goat production for small scale farming sector

For some years, smallholder farmers have used planned crossbreeding as a foundation for goat production in order to boost the productivity of indigenous goat breeds [82]. By joining indigenous goat breeds with exotic goat breeds, the genetic potential of local goat breeds was boosted. Crossbreeding has long been employed, and it has a proven track record of enhancing goat meat yield [83]. The output of goat meat has increased significantly around the world as a result of crossbreeding.

African goats have a wide range of native robust genotypes that make them desirable and considerably contribute to the continent's meat industry, but their medium size is thought to be a drawback for meat production. The crossbred animals have a substantially greater genetic level of meat output than most tropical goats in a circumstance where improved goat types have been mixed with indigenous goats and given better nutrition [84]. **Figure 4** shows some indigenous goats from southern Africa.

Figure 4. Some of the indigenous goats of Southern Africa [85].

Boer goats have a number of exceptional phenotypic traits that are plainly seen in their hybrid progeny [4]. Through cross breeding, Boer goats have successfully increased the productivity of indigenous breeds due to their desired genetic features for meat production [4]. Hass [86] studied the growth rates of Boer goat crossings and native Small East African goats in Kenya and discovered that the Boer crosses had greater birth, weaning, and average daily gains than the native Small East African goats. There have also been reports of Boer crossbred goats having higher average daily growth and birth weights than other goat breeds [87].

According to Merlos-Brito [88], Boer, Nubian, and local goats were crossed with local goats to boost productive qualities in Guerrero, Mexico's arid tropics. Additionally, crossbreeding with Boer goats had similar favorable impacts on growth rates in India and China [89]. Waldron et al. [90] found higher fertility in crossbreds in addition to improved weight gains in Spanish-Boer crosses. The mode of crossing indigenous genetic goat blood takes many forms, and one of the main purposes is upgrading with purebred bucks (**Figure 5**).

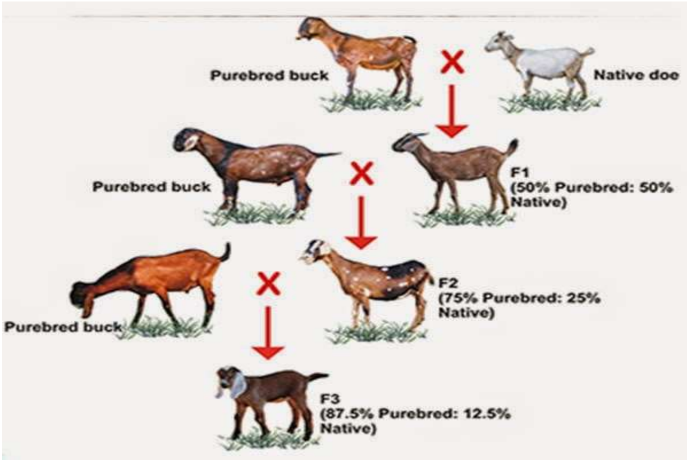

Figure 5. Upgrading of indigenous goats in Africa.

Rhone [91] revealed that F1 Boer-Spanish and Spanish females had improved reproductive productivity and progeny growth differences; higher weights at maturity for blended kids might be explained by this advantage and the favorable association between weaning weight and mature weight. Kassahun et al. [92] found that crossbred Saanen* and Adal goat youngsters had greater crossbred birth weights and weaning weights than Adal goats in Ethiopia and those reported for Sudanese goats [93]. Feeding the concentrate containing molasses led to lower dry matter intake, while the crossbreds showed higher dry matter intake than pure Mubende [94].

3.5. Crossbreeding for high milk yield in small scale dairy farming sector in Africa

Crossbred cattle with the production capabilities of Taurine cattle and the tropical adaptability of Zebu cattle have been established in subtropical nations [14]. In order to utilize breed complementarity and preserve some heterosis (hybrid vigor) in subsequent generations, composite cattle are created by mating two or more purebred breeds. The majority of dairy cattle are purebred; however, crossbred dairy cattle have gained popularity recently [95]. Crossbreeding high-yielding exotic dairy breeds with African cattle genetic resources has been a common genetic improvement strategy in the tropics to increase dairy cattle performance [96]. For the most part, performance [97], reproduction, appropriate crossbreed levels, adaptive potential [98], and economic ramifications have been the focus of research on crossbreeding dairy cattle in the tropics thus far [99].

Abdulai and Huffman [100] reported that crossbreeding of native cattle with exotic dairy increased the genetic potential of cows for greater lactation yields, early maturity, younger age at first calving, and shorter dry intervals between lactations. Utilizing crossbreed in smallholder dairy farmers reported a threefold increase in milk production [101]. It is imperative that smallholder farmers understand crossbreeding, particularly how it works with auxiliary inputs like better housing, better management practices, and better diets for animal management. Osei-Amponsah et al. [7] reported that crossbreeding uses both additive and non-additive allele gene effects, leading to prolonged lactation intervals, shorter calving intervals, high milk yields, an older age at first calving, and possibly better producer profits.

Zebu cattle are the ancestors of tropical dairy cattle, which are ideally suited to the tropics due to their low nutritional requirements, tolerance of high temperatures and heat stress, partial resistance to illnesses, and pests like ticks [102]. Their genetic potential for great milk production is nonetheless underdeveloped, as evidenced by the fact that they rarely let down milk unless the calf specifically asks for it by sucking [103]. However, exotic breeds from temperate climates have better genetic potential for producing milk. This lays the groundwork for crossbreeding local tropical dairy cattle breeds to boost milk production. The adaptive capacity of Bos taurus cattle breeds from temperate regions and Bos indicus cattle breeds from tropical regions is combined through crossbreeding, which also enhances heterozygosity and genetic diversity [104].

3.6. Crossbreeding and genetic erosion and loss of animal genetic diversity in small scale animal agriculture

Crossbreeding offers multiple benefits, but there are also certain drawbacks and threats that need to be taken into account [105], which questions the conventional wisdom regarding it as a feasible alternative for the genetic enhancement of regional animal genetic resources in Africa. The possible loss of the purebred indigenous chicken genetic pool, the potential decrease or loss of certain indigenous chicken traits like the capacity for brooding, and defense and survival strategies like scavenging and aggression are a few of the problems. Additionally, crossbreeding often results in the transmission of the breeds' flaws, and any backcrossing to the parental breeds tends to lessen the original heterosis. Indiscriminate crossing is the highest-ranked cause of genetic erosion in Africa (**Figure 6**).

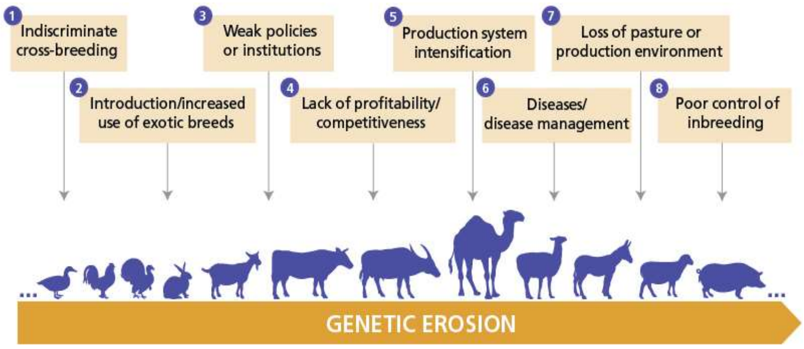

Figure 6. Top 8 reported threats to animal genetic resources [75].

Indiscriminate crossbreeding and breed replacement pose a threat to local livestock breeds and might result in the loss of ecologically significant features like disease tolerance; they must be avoided at all costs [106]. African animal genetic diversity is being lost, diluted, replaced, or eliminated through crossbreeding and small-scale animal agriculture. The adoption of highly structured crossbreeding schemes has been problematic in poorer nations since there is typically little to no control over mating. By randomly mating adapted and non-adapted breeds, the genetic integrity of indigenous breeds has been compromised, offsetting any early productivity advantages in first-generation crosses. Since the accounting of the loss of critical genes in local populations of animal resources has not received the attention it deserves, the amount of the loss will only become apparent when the damage is irreparable.

Initiatives for improving livestock, such as the creation of new breeding techniques, should be assessed in light of a variety of pertinent technological, socioeconomic, and environmental concerns [107]. Similarly to an "environmental impact statement" for infrastructure projects, breeding system development activities should be examined beforehand with a "genetic impact assessment", according to Hall and Bradley [108]. The African animal genetic portfolio has been diluted or eliminated as a result of unsystematic crossing or the widespread use of imported germplasm, which has resulted in genetic diversity loss [109].

It is now disputed whether domestic animal genetic resources can be successfully crossed with highly productive introduced genotypes in the long run because of the extent of domestic animal resource depletion [110]. The majority of domestic animal genetic resources, as far as is known, have been largely stable over millennia, require little maintenance, and are ideal for African rural economies sustaining animal agricultural systems.

3.7. Crossbreeding and its shortcomings in small scale animal agriculture

Africa is at risk of losing its vital regional animal genetic diversity, which might be disastrous given the impending climate change and variability. The genetic diversity among breeds is currently declining, leading to less variability. In the subsequent instance, indiscriminate breeding is likely to have contributed to the loss of some local animal genetic diversity. Several crossbreeding initiatives have been launched throughout Africa, but due to regulatory shortcomings and unsustainable practices, they have not been effective [111]. According to ZoBell and Chapman [112], crossbreeding schemes lacked proper organization and consideration for the environment in which the offspring would be employed. The purpose of crossbreeding has frequently been poorly defined, leading to poor breed selection or the selection of breeds that lack the necessary desired traits. Inadequate planning and study have frequently resulted in inappropriate breed combinations and inbreeding, which have had severe effects on crossbreeds with little to no usefulness.

The main obstacles to planned crossbreeding as a basis for livestock production by smallholder farmers included a lack of outset production data, an absence of well-organized institutional collaborative efforts, and little or no account of the needs, decisions, engagement, and traditional methods of smallholder farmers [82]. This is due to the ongoing, unsystematic, and rigorous use of local animal genetic resources in crossbreeding systems. Lack of proper planning on how to preserve viable crossbreeds as a breed for future usage also contributes to the non-sustainability of most crossbreeds [111].

The results of crossbreeding have been quite diverse and influenced by regional factors [113]. Crossbreds have occasionally performed poorly as a result of being unable to handle the extreme temperatures, lack of feed resources, and local diseases. The viability of crossbreeding programs has been questioned due to inadequate logistical support and a lack of additional socioeconomic support. Crossbreeding is not a one-size-fits-all solution for Africa as a whole because of the diverse agro-ecological nature and smallholder production systems, as well as the increased genetic diversity of domesticated animal genetic resources or breeds, which prevent any particular combination of specialized breeds from being successful for all of them. The current endeavor to conserve these species is threatened by crossbreeding practices, which have been linked to the genetic dilution of Africa's animal genetic resources [114]. To generate the crossbreds, populations of purebred animals must be maintained, which presents a challenge. Another is that when crossbreds mate with each other, the heterosis obtained from the crossing of various genetic lines during the development of the F1 generation is lost.

The differential environmental conditions, the production system, the culture of the people for whom the animals are kept, and the market to which the animals and animal products are sold have been the other major causes of the failure of crossbreeding schemes in Africa [111]. All of these factors contribute to a successful breeding program. It was more likely, though, that a lack of thoughtful preparation for maintaining sound crossbreeds as a breed for future use contributed to non-sustainability as well.

Both crossbreeding and the maintenance of a pure breed are essential. It is difficult to undertake crossbreeding without employing pure breeds. In terms of production, capacity to adapt to hard settings, and disease resistance, genetic diversity regulates a variety of valuable properties [115]. Wilson [83] said that because of poor characterization and failures to locate genotypes with the most desirable traits, indigenous animals are regularly used (though perhaps more commonly disregarded, particularly in Africa) in traditional breeding attempts.

3.8. Crossbreeding and genotype and environment interaction (GEI) in smallholder animal agriculture

The variation in the relative performance of a trait, indicated by two or more genotypes, when it is measured under two or more environments is known as the genotype-environment interaction (GEI). Both changes in the genotype categorization order and/or changes in the absolute and relative variances (genetic, environmental, and phenotypic) for various settings can be represented by these interactions [116]. The initial phases of crossbreeding programs in Africa were not backed by any empirical studies on the extent of GEI on crossbreeding in smallholder animal agriculture. This is despite the fact that GIE plays an important role in livestock populations and should be included in breeding programs in order to select the best animals for different environments [117]. When conducting these evaluations in various environmental settings, it is crucial to take potential genotype-environment interactions into account [118].

In order to increase production and animal welfare under various environmental and management situations, it is becoming increasingly important for livestock breeding programs to take genotype-by-environment interactions into account [119]. Most crossbreeding programs on the African continent have neglected to account for the effects of GEI, hence their failure. This is despite the fact the fact that GEI is well known to influence livestock production. It is common knowledge that an animal's ability to display any quantitative attribute depends on both its genetic potential and how it interacts with its environment. The foundation of the majority of crossbreeding initiatives in Africa is the idea that crossbred animals will outperform their indigenous counterparts but fall short of exotic improved breeds in terms of performance. Given this, it's possible that little thought was given to assessing the effects of genotype on environmental interaction due to a lack of actual data to back up this claim.

Burrow [120] investigated Bos taurus-based breeding techniques for beef and breeds capable of adapting to tropical climates in temperate and subtropical environments. Breed distinctions that exist in temperate regions are masked by environmental stressors in the subtropics. So that you may compare a breed's performance in diverse environments, it is best to classify breeds into breed types in tropical environments. Because there are environmental stressors in tropical breeding programs, there are more genetic variation sources. Investigating the genetic foundation of productive and adaptive traits is crucial for breeding programs in specific situations.

4. Future prospects for crossbreeding in small scale animal agriculture in Africa

The success of crossing local animal genetic resources and exotic breeds will depend on a paradigm shift in two aspects of breeding strategy. Firstly, crossbreeding should be part of community-based breeding programs that take into account the role of communities in deriving selection objectives. The previous approaches did not take into account the sociocultural, economic, and specific environmental implications associated with crossbreeding. Secondly, crossbreeding initiatives may depend on the development of novel breeding approaches such as genomics and other biotechnologies. Breeding plans that use both conventional and genomic data have been shown to provide positive outcomes in medium-scale breeds [121].

4.1. Crossbreeding as a component of a breeding program centered on community: Community based breeding program (CBBP)

CBBP has come to prominence as an effective strategy to facilitate sustainable livestock breeding in the smallholder livestock farming sector. Crossbreeding of local animal genetic resources and imported breeds is permitted under CBBP without exception in order to initiate and develop genetic improvement initiatives in smallholder farming systems [122,123]. By emulating policy orientations for sustainable livestock development and enhancing small scale livestock genetic improvement, small scale farmers must be placed at the center of livestock genetic improvement programs. Mueller et al. [124] claim that CBBP are more commonly connected to low-input communities where farmers are working together for improved genetic resource use. Small-scale, one- or two-tier structures are then employed to meet the breeding goals, which are frequently determined through a collaborative approach.

The CBBP may be put into practice as it takes steps to close the many knowledge gaps that prevent the management of livestock genetic advancements in the smallholder agricultural sector. Their implementation should be based on the development of institutional and policy frameworks that encourage cooperation and stakeholder involvement and enable the successful implementation of sustainable management methods at the proper scales [125]. Haile et al. [126] and Mueller et al. [127] have provided recommendations for CBBP based on their knowledge gained from starting new CBBP ventures. To be sure, there are issues that every new CBBP must deal with [128,129].

CBBP has emerged as a viable option to implement livestock breeding in smallholder systems [130–134]. Elsewhere, similar CBBPs for dairy goats (Mexico and Kenya), sheep (Ethiopia and Peru), Angora goats (Argentina), and local pigs (Vietnam) have shown that not only is the approach effective in genetic improvement, but it also builds local capacity and ownership and can be very sustainable given the right level of organisation and support among the participating farmers [133,135]. **Figure 7** shows the common cross-cutting agenda for CBBP collaborating partners and the CBBPs model, which can be adopted to accompany crossbreeding schemes in small scale animal agriculture.

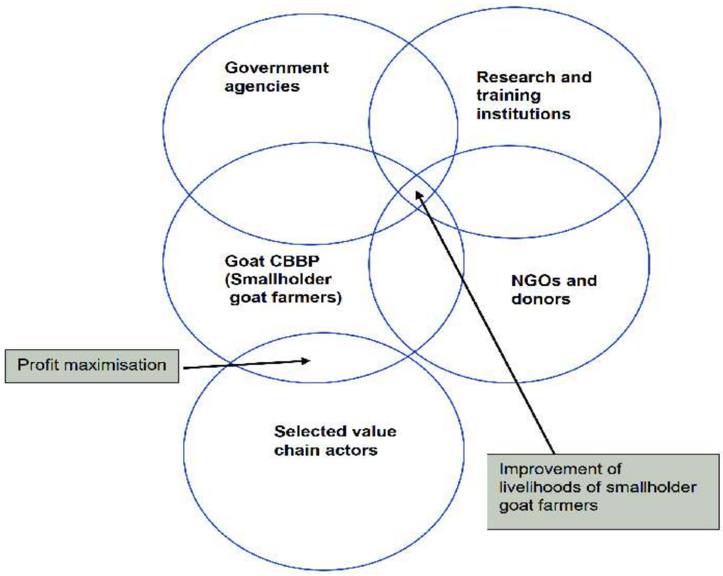

Figure 7. The common cross-cutting agenda for CBBP collaborating partners and the CBBPs model [123].

The subsequent implementation of prototype CBBPs was made possible by funding from governmental and commercial funding organizations, as noted by Haile et al. [136]. The pilot phase demonstrated that CBBPs are an effective and advantageous way to achieve genetic development and improve livelihood at the community level. Abate et al. [137] study of well-established CBBPs provided evidence supporting this claim, demonstrating that local farmers and communities are growing more interested in employing selected surplus males for CBBP breeding. It is now possible for farmers to have their preferred locally adapted improved breeds, a dependable system for multiplication and delivery, as well as feed and medical services, thanks to existing initiatives [138].

4.2. Extending the bounds of the genome's evaluation to include crossbreeding and selective breeding in Africa

Globally, genomics has culminated in noticeable genetic improvement in a wide range of animal species. Systematic genotyping continues to be carried out, and genetic analyses comprise an overwhelming number of economically noteworthy traits that have previously been reported by breeders. Culver and Labow [139] define genomics as an interdisciplinary discipline of biology that focuses on genome research. Over the last decade, livestock breeding has evolved toward genomic selection [95,140–142]. The genomic best linear unbiased prediction perspective has been regarded as the technique preferred for estimating breeding values in purebred breeding programs.

A genome is an organism's whole complement of DNA, including all of its genes. In contrast to traditional genetics, which focuses on individual genes and their functions in inheritance, genomics is concerned with the collective characterization and quantification of all of an organism's genes, their interrelationships, and their effect on the organism. Many landmark findings in animal genomics have profoundly changed many areas of animal breeding and production during the last few decades [143]. However, in the context of developing local resources and capability, the wise use of genomics has not yet been properly utilized in underdeveloped countries [144]. Advances in genomics and information technologies are excellent opportunities to achieve the necessary improvements. VanRaden et al. [95] demonstrated enhanced accuracy by integrating crossbred data to assist with training when predicting the performance of purebred and crossbred pigs using a support vector machine regression model. The computational task will be quite difficult because of the endless accumulation of genetic data.

The incorporation of dominance effects, breed-specific effects, imprinting effects, and the combined evaluation of purebred and crossbred performance data are only a few examples of how genomic models for crossbred animals add more complexity to purebred models [145]. Long-term breeding program design improvements may be made by better understanding the mechanisms of selection on a genomic level [146]. Genomic information may also be utilized for controlling production, evaluating and maintaining genetic diversity, and developing more effective crossbreeding strategies. Ibanez-Escriche and Simianer [147] cite genomic selection in dairy animals as an impressive narrative that has greatly advanced genetic progress in functional trait complexes such as those that affect health, animal welfare, and environmental impact, in addition to productivity.

In terms of genetic improvement strategies in particular, a significant portion of African livestock systems have not yet profited from livestock technological advances to the same degree as industrialized nations [148]. Using modern genomic technology to boost productivity and other production characteristics in indigenous animal genetic resources in Africa could be one way. Improvement can be achieved by using genomics as a tool to choose animals with better genetics to generate the next generation [149]. Ibanez-Escriche and Simianer [147] pointed out that the adoption of genomic selection in all other prominent farm animal species may proceed rapidly after; nevertheless, it is anticipated that the benefit will not be as great in those species as it is in the breeding of the dairy industry. In animals like pigs and chickens, this is mostly because of the low generations between births and the traditional breeding principles that have been used. Furthermore, the genotyping expenses for such species are unattractive when compared to the real value of a selection prospect.

Marshall et al. [18] reported that there are several instances of livestock genomics being used in African countries. The best breed type for the regional production systems of dairy cattle in Kenya, Senegal, and sheep in Ethiopia was determined with the use of genomic techniques. It is now under progress to cross-breed dairy cattle in East Africa using genomic selection and other genomics-related applications. Innovations in genomics and bioinformatics have made it possible to identify genomic variations and similarities across livestock breeds, which may be used to enhance genetic improvement strategies in Africa [150]. Some of these genetic signatures may help to explain the phenotypic distinctiveness of breeds [151,152].

They may also make it easier to prioritize breeding efforts and apply genomic technologies to maintain these critical features. An additional choice is the landscape genomics approach, in which the association between alleles and geographic locations and/or climatic variables is targeted and presumed to indicate the presence of indicators of adaptation, offering insight on the external factors acting on the genome [153]. The importance of using marker-assisted selection in the genomic animal genetic resources accessible in Africa [154], as well as its potential for addressing sustainable livestock production and climate change, cannot be overstated. Wray-Cahen et al. [155] assert that, while not an instantaneous panacea, genome editing offers a substantial chance to address the causes and effects of climate change, enhance human nutrition, and improve animal health, welfare, and production efficiency.

Despite the fact that advances in genomics and bioinformatics were created for breeds with high input and are thus more effectively used in that setting, However, their use in crossbreeding programs in small-scale animal agriculture is not excluded and may have a substantial positive impact if done appropriately. This is especially true when numerous innovations are used in close cooperation with the beneficiaries, who are smallholder farmers and breeders.

The sticking point in Africa is that a number of factors, including available research funds, socioeconomic restrictions, and extension services, impact the possible adoption of genomics by the livestock sector [156]. Aspects of biotechnology in the fields of animal genetics and breeding, such as the preservation of animal genetic resources, animal health, the physiology of growth, and animal nutrition, are now a reality and are making their way into the research and development plans of emerging nations. In addition, biotechnology is presenting hitherto unheard-of prospects for raising animal output in Africa.

4.3. Exploring the limits of phenomes in African selective breeding and crossbreeding programs

Houle et al. [157] describe phenomics as "the characterization of phenotypes through the acquisition of high-dimensional phenotypic data on an organism-wide scale." However, phenome relates to the interaction between the genes and the environment, so what occurs is also known as genotype-phenotype-environment (G-

P-E) interactions [158]. Reliable, autonomous, multipurpose, and high-throughput phenotypic technologies are becoming more significant instruments in breeding operations for accelerating genetic gain. With the fast advancement of high-throughput phenotyping tools, investigation into this discipline is about to enter an age currently known as 'phenomics'.

Molecular breeding techniques prioritize genotypic choices, although phenotypic data remains necessary [159–160]. However, in order to develop breeds or animal populations that are better adapted to current/future climate challenges, a new set of traits, such as morpho-physiological and physicochemical attributes and information relevant to the successful selection of genotypes or parents, must be incorporated. Such an approach leads us to an innovative way of thinking about phenomics. Phenomics is the semi-automatic collection of highly complex phenotypic data [161]. Pérez-Enciso et al. [162] noted that high levels of throughput phenomics in farm animal populations come from two directions: 1) novel characteristics that were formerly difficult to determine and measure can now be quantified; and 2) depending on prevalent production conditions, traditional characteristics are now visible almost continuously and non-invasively on a large number of animals as well.

Steibel [161] defines a phenotype as a collection of observable characteristics of the individual in question. In animals, the term "phenotype" can refer to either physiological traits (such as blood pressure and hormone levels) or external traits (such as coat color, liveweight, and milk output) [162]. It is generally agreed that the apparent phenotype is the consequence of the environment impacting the expression of an individual's genetic makeup [163]. The phrase "genome to phenome" refers to the relationship and causality between an animal's genetic composition (genome) and the sum of all phenotypes, or observable physical or physiological features or qualities (phenome) [143].

Jangra et al. [164] describe phenotyping as the procedure that involves determining the phenotype of preselected traits in specific individuals as well as collecting the relevant data. The phenotyping technique yields a phenotypic data set including animal identity variable(s) and as many phenotype variables as characteristics were assessed for each individual animal. Animal breeding is based on the well-known notion that there is phenotypic similarity between genetic makeups [165].

Overall, phenomics plays an important role in animal breeding [161] and more benefits can be accrued if it is integrated with other omics such as genomics, proteomics, and metabolomics to provide insights into the complex interactions between phenomes, the genome, and environmental factors, which will be beneficial for improving livestock management [166]. Zhao et al. [158] the era of high-throughput, automated, multipurpose, and trustworthy phenotypic technologies as becoming more and more significant tools for accelerating genetic gain in breeding operations.

As highly efficient characterization capabilities advance quickly, a new phase in this field of study known as "phenomics" is emerging. Multiple genome-mapping projects [157], environmental issues, and potential new methods for low-cost phenotyping [167] are rekindling interest in the collection of high-dimensional data on individual animals' phenotypes.

Despite the continent's considerable constraints in terms of animal breeding, the application of phenomics offers a promising alternative for improving indigenous animal genetic resources in Africa. A number of factors, including available research and development capacity, expertise and experience, socioeconomic constraints, and poor extension service delivery, may impact the possible application of phenomics by the animal breeding industry. The importance of adaptable breeds in difficult conditions must be addressed in the genetic improvement of livestock using phenomics innovations, improving reproductive and growth efficiency.

The development of the small scale animal agricultural sector, in particular, calls for the need for genetic research initiatives that will be aimed at bridging the gap between conventional animal breeding practices and eliciting technologies in genomics and phenomics. Farmers from smallholdings are able to benefit from better breeding stock as a result of any improvement through phenomics and genomics if socioeconomic concerns are addressed by national policy. The aforementioned significant group in terms of livestock production dynamics on the continent acts as a vital link in the spread of genetic resources from commercial farmers to smallholder farmers. In this sense, both genomics and phenomics might help to bridge the present barrier in the continental animal husbandry industry.

High dimensionality, according to Zhao et al. [158], should also aid breeders in optimizing where phenotypes are among the most important and what the probable barriers are. Whereas success in phenomics will largely depend on the rapidly evolving fields of sensor technology and machine learning, which might limit its application in Africa. This emphasizes the notion that prospective animal and crop breeders will need excellent practical and biological experiences, along with solid statistical and machine learning expertise. Africa has a duty to mobilise resources meant for training in this area if such technologies are to be adopted in a sustainable manner. Partnerships between the private and governmental sectors will be crucial in extending the phenome limits of selective breeding and crossbreeding initiatives in Africa.

Chakraborty et al. [168] observed that genetic gain has been sluggish, with long generation intervals in animal production. With the introduction of high-throughput omics approaches, along with the readily accessible multi-omics technologies and powerful analytic packages, various prospective tools and methodologies for estimating the animals' true genetic potential have been put in place. Now that it is possible to gather and access huge, intricate datasets containing an array of genomics, transcriptomics, proteomics, metabolomics, and phonemics data together with animal-level information (such as longevity, behavior, adaptation, etc.), fresh possibilities for learning more about the processes governing an animal's genuine performance are provided. For Africa, the adoption of omics technologies is hindered by their high cost and the need for specialists in a wide range of disciplines, including biology, bioinformatics, statistics, and computational biology [169].

The most significant advantage of phenomics, as well as the potential of genomics, to smallholder animal agriculture might lie in the characterization of local livestock populations, which may offer enormous promise in terms of gene introgression into exotic breeds. Using indigenous breeds' specific haplotypes, such as hypocretin receptors in trypanotolerance, the BOLA complex in tick resistance, and heat shock proteins in thermotolerance [170], could ultimately play a role in commercial livestock production. Nevertheless, precaution must be exercised in order to protect the limited genetic pool from indiscriminate crossbreeding, which has damaged the distinct traits of many indigenous breeds.

5. Implications

Africa has a diverse livestock and poultry sector, with a dual system of commercial and smallholder farmers. Crossbreeding has been used to improve performance in small-scale animal agriculture but faces challenges such as maximizing genetic potential and overcoming knowledge gaps. Smallholder farmers' inability to enhance their management skills has hindered crossbreeding's success. Factors such as low literacy rates, knowledge gaps, and a lack of understanding of improved livestock and poultry management practices also hinder crossbreeding's success. To increase milk, meat, and egg production for small-scale livestock, crossbreeding requires improved management practices. Smallholder farmers must understand how it interacts with complementary inputs like better feed, housing, and management practices.

Small-scale livestock and poultry farmers ought to take an active role in community-based animal breeding initiatives that promote crossbreeding for sustainability. Positive findings from early research on many animal species across Africa have made community-based livestock development projects seem like an attractive alternative for implementing livestock breeding programs in the smallholder livestock farming sector in Africa. In the process of addressing multiple knowledge gaps prohibiting the smallholder animal agriculture sector from managing livestock genetic developments, the CBBP may be implemented.

Crossbreeding in Africa is expected to be reinforced by genomic genetic prediction, but the outlook should take into account the socioeconomic background of small-scale agriculture as well as the environment underlying local livestock production. Research on animal breeding is about to enter a new era known as "phenomics" which can supplement genomic data for animal genetic improvement in Africa, thanks to the rapid growth of high-throughput phenotyping techniques. All things considered, phenomics has a bright future in animal breeding. It can further benefit livestock management by offering insights into the intricate relationships between phenomes, the genome, and environmental factors when combined with other omics like genomics, proteomics, and metabolomics.

Author contributions: Conceptualization, NA and EM (Enock Muteyo), writing—original draft preparation, NA, EM (Edmore Masama), and TM; proof reading, grammar checking and reference style, TM. All authors have read and agreed to the published version of the manuscript.

Funding: No funding was involved in preparation of this manuscript.

Conflict of interest: The authors declare no conflict of interest.

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