ADVANCING GENOMIC MEDICINE IN HUMAN, LIVESTOCK, AND POULTRY HEALTH: APPLICATIONS AND INNOVATIONS

G. Abbas[1£*], S. Jaffery[2£*], M. Arshad[1], M. A. Naveed[1], U. Farooq[3], M. Akram[4], A. H. Hashmi[5], S. Arif[1], R. Mahmood[6], M. F. Khalid[3], N. Arshad[1], A. Basharat[1], A. Muzaffar[1], U. Rasool[1], G. M. Gill[1], S. H Qamar[7], R. Mustafa[3], M. Auon[3], M. Jamshaid[1], N. Ikram[8], T. Mahmoosd[1],

[1]Riphah College of Veterinary Sciences, Riphah International University, Lahore,Pakistan
[2]Centre of Agricultural Biochemistry and Biotechnology (CABB), Faculty of Agriculture, University of Agriculture Faisalabad, Pakistan.
[3]University of Agriculture Faisalabad, Sub campus Toba Tek Singh, Pakistan.
[4]Govt. Shalimar Graduate College Lahore, Pakistan.
[5]University Institute of Food Science and Technology, University of Lahore, Pakistan.
[6]The University of Faisalabad, Faisalabad, Pakistan
[7]Global Technical Manager in Wuhan SunHY Biology, Chin
[8]Department of Zoology, Subcampus Toba Tek Singh, University of Agriculture Faisalabad, Pakistan.
£= these authors contributed equally
*Corresponding Authors Email: seemabjaffery03@gmail.com; ghulamabbas_hashmi@yahoo.com

ABSTRACT: Developments in genomics technologies and medicines have had revolutionized the process of diagnosis and treatment of diseases in humans, cattle, poultry and other animals. Advances in genome sequencing and other development like editing and annotation have made it possible not only to understand and treat the genetic diseases and disorders successfully but also help to apply genetic information as advanced data, cloud computing, analytic, infrastructure, and regulation leading to precision in medical profession and livestock farming. This have enabled medical professionals and scientists to have a deep awareness of the health and welfare features of different human and animals populations. The present review highlights the role of genomics medicines in improving the health and welfare of humans, poultry, and cattle by preventing genetic diseases through improving inherited characteristics (using technologies like CRISPR technology, genomics selection, and gene editing) and the developing advanced modified treatment programs according to genetics background of human and animals populations. The review also outlines the challenges and ethical concerns driving through these innovations and advancements.

Keywords: Genomic medicine, DNA sequencing, human, cattle, diseases, treatment, CRISPR.

(Received 16.12.2024 Accepted 01.03.2025)

INTRODUCTION

Over the past few decades advanced technologies are developing to understand and control the health of humans and animals due to which significant improvements have been made in genetics in contrast to the past (Abbas, 2007; Waheed *et al*., 2015; Cao *et al*. 2024). A study by Khan *et al*. (2023) reported that advanced sequencing and computer technology have made it possible to look at the genomes of different organisms to find genetic traits linked to many serious diseases. Wiggans and Carrillo (2022) revealed that genetic information is used to help doctors make decisions to treat patients. According to Jonathan *et al*. (2012), it has become an important tool for finding genetic diseases, suggesting better personal treatments, and exploring methods to prevent diseases in a better way. The effects of genomics technology (functional genomics, genome editing and DNA sequencing) not only can be seen in human health area but it also including animal farming i.e. raising of cattle and poultry (Wiggans *et al*., 2012; Kent, 2017; Guo *et al*., 2021).

Genomics medicine has changed the human medical and health intervention to disease diagnosing and treatment (Roth, 2019;Khoury, 2017). By knowing genetic mutations/variations that cause diseases, scientists can diagnose circumstances at an earliest stage, often before the onset of symptoms when the problem is more treatable. This detection of genetic disorders or diseases at their early stages is important in conditions like cystic fibrosis, hereditary cancers, and metabolic disorders, and neurological problems like Huntington's disease etc. (Aguiar *et al.,* 2017; Ali & Jacobsen, 2020; Pena *et al.*, 2020; Yilmaz *et al.,* 2020; Lomunova and Gershovich, 2023). Moreover, genomes sequencing of patients helps scientists/clinicians finding individuals who have more threat to specific diseases hence these patients can provide help by advising certain preventive measures and/or early treatments (Bagger *et al.,* 2024; Kingsmore and Saunders, 2011). Advising medicines as per individual's specific genomics profile is the most effective treatment strategy in current modern age. For example, pharmaco-genomics (the study of how genes influence a person's response to drugs) has led to safer and more effective medications, decreasing adverse drug reactions and improving treatment efficacy (Weinshilboum and Wang, 2017). This approach confirms that therapies are improved for the unique genetic makeup of each individual, making treatments more targeted and less trial-and-error-based.

Genomics medicine is also boosting the development of gene therapies, which seek to cure/treat genetic disorders by either replacing and/or correcting faulty genes in a person's cells (Sarkar *et al.,* 2020; Gonçalves and Paiva, 2017). Technologies such as CRISPRCas9 have speeded progress in gene editing, proposing a precise method of rectifying mutations at the DNA level (Singh *et al.,* 2021; Koslová *et al.,* 2020; Min *et al.,* 2019). Gene therapies have the potential to treat genetic disorders that yet have been known to be irreversible i.e. Duchenne muscular dystrophy (Salter & Stevens, 2017), certain types of inherited blindness and hemophilia (FDA, 2017; Johnston and McNally, 2021; Braga *et al.,* 2022; Deneault, 2024). Beyond human health, the use of genomics technologies in livestock and poultry holds the potential answer to a host of aggro-food security issues confronting agriculture. The use of genomics in animal breeding offers new avenues for enhancing the productivity and disease resistance attributes of farm animals. Genomics selection enables livestock breeders such as in cattle, pigs, and sheep to recognize animals much earlier as being more promising due to the existence of traits, which might be related to higher growth rates, milk yield, or even better feed conversion efficiency (Mueller and Van Eenennaam, 2022; Kramer and Meijboom,2022). Similarly, the application of genomics medicine has been aimed at developing genetic markers that have implications for disease resistance (Sharpe and Carter, 2006), hence providing breeding alternatives that are less prone to common diseases. For example, genomics testing in cattle can identify natural disease-resistance factors such as mastitis in dairy farms, while the more significant application in poultry has been to breed birds that are resistant to avian influenza among other infectious diseases (Stone *et al.,* 1985).

Besides achieving resistance to diseases, genomics is also helpful in developing efficient, sustainable, and environmentally healthy farming practices. This can be achieved by genomics selection for improved feed efficiency which results in a reduced input of resources used per unit of production. Genomics tools also help in monitoring animal welfare by identifying traits associated with resistance (against diseases and stress) and general health, ensuring that animals are raised in conditions that support their well-being.

Genomics technologies also play a crucial role in addressing the global challenges posed by infectious diseases through the integration of these technologies in livestock and poultry breeding programs. The threat from zoonotic diseases, which are the ones that can be transferred from animals to humans, continues to grow, so breeding animals with increased resistance to diseases is of great importance. Genomics medicine presents the tool for the discovery of genetic variations conferring resistance to diseases such as African swine fever, foot-and-mouth disease, and avian influenza. With this information, farmers and breeders can produce harder herds and flocks that will respond less and less to the need for pharmaceutical interventions like antibiotics, further helping in curbing this growing issue of antimicrobial resistance.

The review outlines the parallels as well as the unique challenges that might be involved with the application of genomics medicine in the health care of humans, animals, and birds. Though the technologies differ, the underlying principles remain common to both.

In each context, however, specific challenges arise. Human health raises questions about privacy, consent, and genetic discrimination as genomics data is integrated into healthcare systems (Oliver, 2017). In livestock and poultry, welfare concerns, environmental impacts, and ethical issues associated with genetic modification need careful consideration. Nevertheless, the benefits of genomics medicine whether in improving human health outcomes, enhancing agricultural productivity, or ensuring food security are undeniable. As genomics technologies continue to advance, the potential for improving both individual and societal health is vast.

The Role of Genomics Medicine in Human Health:

Genetic Diagnosis and Personalized Medicine: In human healthcare, the application of genomics medicine has fundamentally changed personalized medicine (Rahman and Barwell, 2024) and how genetic diseases are diagnosed and treated (National Human Genome Research Institute, 2024). The identification of genetic mutations responsible for diseases such as cystic fibrosis (Ali & Jacobsen, 2020), sickle cell anemia, and Huntington's disease has led to more accurate and earlier diagnoses (Yilmaz *et al.,* 2020; Lomunova and Gershovich, 2023; Pena *et al.,* 2020). Genomics sequencing, particularly whole-genome and exome sequencing, allows clinicians to identify mutations at an individual level, enabling more personalized treatment strategies (Carver *et al.,* 2021). Clinical genetics investigates the causes of disease within families, personalized medicine envisages promising responses to managing the diseases in individuals whereas the genomics approach forecasts the future risks using integrating wide-ranging datasets with therapeutic and health outcomes (Rahman and Barwell, 2024) also minimizes adverse reactions by tailoring treatments based on genetic profiles. This involves everything from understanding our biological history to mathematical algorithms that connect our DNA code to our postcode whilst also integrating whole genome sequencing, biochemistry, radiology, body mass index, phenotyping data, alcohol consumption, and even information about exercise and sleep (Rahman and Barwell, 2024). Possible uses of genomics interventions to treat human genetic recessive disorders are shown in Table 1. Genomic medicine has advanced the understanding of complex diseases (diabetes, cancer, heart diseases, etc.) that involve multiple environmental and lifestyle factors (Michalek *et al.,* 2024; Johansson *et al.,* 2023). The identification of genetic susceptibilities allows for targeted interventions, early screening, and preventive measures that can significantly reduce disease risk and improve quality of life (Smith *et al.,* 2023).

Pharmacogenomics: The study of how genes affect an individual’s response to drugs (Pharmacogenomics), has made significant developments in genomics medicine (Qahwaji *et al.,* 2024). Variations exist in genes encoding for drug-metabolizing enzymes (Zhou and Lauschke, 2022) receptors (Adams, 2008), and transporters (Sissung *et al.,* 2014) that can affect the safety and efficacy of medications (Tian *et al.,* 2022) i.e., patients with certain genetic variants might metabolize drugs more slowly (Roden *et al.,* 2011), resulting to high concentrations of the drug in the body leading to an increased threat of side effects. On the other hand, a person having varying genes to metabolize drugs too quickly may have reduced therapeutic effects. Therefore, by incorporating pharmacogenomic knowledge into clinical practice, doctors can prescribe the precise medication at the true dose for each patient, thus helping to minimize the harm and improve treatment outcomes.

Gene Therapy: Gene therapy involves altering the genetic material within a person’s cells to treat and/or prevent diseases (Kumar, 2007; Gonçalves and Paiva, 2017). It has emerged as one of the most exciting frontiers in genomics medicine, which holds the potential to treat genetic disorders that presently have no treatment, i.e., hemophilia, Duchenne muscular dystrophy (Espenhain *et al.,* 2019), and certain forms of blindness (Hasanzad *et al.,* 2021). Possible uses of genomics medicine tools and their application to treat human genetics recessive disorders are shown in Table 2. Gene therapy involves the addition of functional genes to exchange defective ones, the use of gene editing to correct mutations, and/or the quieting of problematic genes (Gupta and Shukla, 2017). The use of advanced technologies like CRISPR-Cas9 has enhanced the development of gene therapies, proposing more efficient and precise ways of rectifying genetic defects at the molecular level.

GENOMIC MEDICINE IN LIVESTOCK AND POULTRY HEALTH

Genomics Selection in Livestock: Genomics selection is a key application of genomics medicine in livestock production and genomics selection lets more accurate and efficient breeding of animals. By identifying genetic markers associated with desirable traits such as disease resistance, growth rate, and reproductive efficiency. This process reduces the time required for genetic improvement by enabling early selection of breeding stock based on their genetic potential rather than phenotypic characteristics alone. For example, genomics selection has been successfully used to enhance milk production in dairy cattle, improve meat quality in beef cattle, and increase egg production in poultry.

The use of genomics selection holds the potential to enhance animal health and welfare by recognizing genetic resistance to diseases, i.e., genetic markers associated with resistance to mastitis in dairy cattle, avian influenza in poultry, and porcine reproductive and respiratory syndrome in swine, have been identified through genomics researchers. Therefore, breeding animals with these genetic resistances can reduce the incidence of these diseases, improving animal health, and welfare and decreasing dependence on antibiotics and other medicines.

The phrase "genomics medicines" describes innovative treatments that use genomics information to prevent, treat, and/or control human genetic illnesses. Amongst the various interventions included in these medications are gene editing technologies (e.g., A. CRISPR-Cas9, TALENs), RNA-based treatments, whole-genome sequencing for diagnostics, and gene therapy with viral and non-viral vectors. Through the introduction of functional copies of genes, the correction of pathogenic mutations, or the silencing of defective genes, genomics medicine has demonstrated promise in treating recessive genetic disorders in humans. Patients suffering from disorders such as sickle cell anemia, cystic fibrosis, and Tay-Sachs disease are currently being treated using these strategies (Fletcher *et al*., 2017). The genomics tools that are utilized in the treatment of genetic diseases in livestock are listed in Table 3. Personalized medicine and the treatment of genetic disorders have made considerable strides forward, as seen by the fact that specific treatments, such as gene therapy for spinal muscular atrophy (SMA), have been granted regulatory approval. However, other treatments are still in the experimental or clinical trial stages (FDA, 2019).

Table 1: Examples of possible uses of genomics interventions to treat human genetics recessive disorders.

Genomic Tool/Medicine	Target Disorder	Purpose	Status	Reference
CRISPR-Cas9	Sickle Cell Anemia	Corrects mutation in the HBB gene	Clinical trials	(Park & Bao, 2021)
ZFN (Zinc Finger Nucleases)	Hemophilia B	Gene correction for FIX gene	Preclinical	(Suleiman *et al.*, 2021_
TALENs	Cystic Fibrosis	Repairs CFTR gene mutations	Early trials	(Owen *et al.*, 2013)
RNAi Therapies	Huntington's Disease	Silencing of mutant HTT gene	Approved	(Aguiar *et al.*, 2017; Carroll *et al.*, 2011)
Gene Therapy (AAV)	Spinal Muscular Atrophy (SMA)	Delivers functional SMN1 gene	Approved	(FDA, 2019)
Ex Vivo Gene Editing	Beta-Thalassemia	Edits HBB gene in hematopoietic stem cells	Clinical trials	(Rosanwo *et al.*, 2021)
Antisense Oligonuc leotides	Duchenne Muscular Dystrophy (DMD)	Exon skipping for DMD mutations	Approved	(Watanabe *et al.*, 2023)
Base Editing	Tay-Sachs Disease	Corrects point mutations in the HEXA gene	Preclinical	(Hung *et al.*, 2024)
Epigenome Editing	Fragile X Syndrome	Modulates FMR1 gene expression	Research stage	(Kimani *et al.*, 2018)
Prime Editing	Usher Syndrome	Precise DNA repair for USH2A gene	Preclinical	(Anzalone *et al.*, 2019)
Gene Silencing (siRNA)	Amyloidosis	Reduces TTR protein production	Approved	(Dave *et al.*, 2024)
CRISPR Activation (CRISPRa)	Alpha-1 Antitrypsin Deficiency	Enhances SERPINA1 gene expression	Research stage	(Yang *et al.*, 2024)
Genome-Wide Association Studies (GWAS)	Type 1 Diabetes	Identifies genetic risk factors for targeted interventions	Research stage	(Michalek *et al.*, 2024)
Viral Vector Based Therapy	Leber Congenital Amaurosis	Restores RPE65 gene function	Approved	(Varela *et al.*, 2022)
Genome Editing (HDR)	Phenylketonuria (PKU)	Repairs PAH gene mutations	Preclinical	(Richards *et al.*, 2020)
Somatic Cell Editing	Albinism	Targets tyrosinase gene mutations	Research stage	(Saha *et al.*, 2021)
CRISPR Epigenome Editing	Rett Syndrome	Reactivates MECP2 gene	Experimental	(Qian *et al.*, 2023)
Gene Drive Systems	Malaria	Alters mosquito genes to reduce disease transmission	Research stage	(Ye *et al.*, 2017)
Synthetic Biology	Phenylketonuria	Develops novel enzymatic pathways for Phe metabolism	Experimental	(Bry *et al.*,2018)
RNA-Based Vaccines	Cancer Immunotherapy	Induces immune response to target tumor antigens	Approved	(Pardi *et al.*, 2018)
Adaptive Cell Therapy	Leukemia	Uses CAR-T cells to target cancerous cells	Approved	(Lim & June, 2017)
Mitochondrial Replacement	Mitochondrial Disorders	Replace defective mitochondria with healthy ones	Clinical trials	(Almannai *et al.*, 2020)
CRISPR In Vivo Editing	Muscular Dystrophy	Directly repairs dystrophin gene in muscles	Preclinical	(Salter & Stevens, 2017)
Gene Augmentation Therapy	Retinitis Pigmentosa	Supplements of defective genes with functional copies	Clinical trials	(Jiang *et al.*, 2021)

Table 2:Examples of possible uses of genomic medicine tools and their application to treat human genetics recessive disorders.

Species	Recessive Disorder	Genomic Medicine Tool	Application	Notes	Reference
Human	Cystic Fibrosis	CRISPRCas9	Gene editing to correct CFTR mutations	Potential to cure CF by correcting gene mutations.	(Ali & Jacobsen, 2020)
	Sickle Cell Anemia	Gene Therapy (Lentiviral vectors)	Corrects the mutated hemoglobin gene	Proven effective in clinical trials for long term outcomes.	(Kanter & Falcon, 2021)
	Tay-Sachs Disease	RNA-based Therapies (e.g., ASO)	Modulating gene expression to compensate for HEXA deficiency	Focus on improving life expectancy and quality of life.	(Fletcher *et al.*, 2017)
	Phenylketonuria (PKU)	Enzyme Replacement Therapy (ERT)	Restoring phenylalanine hydroxylase activity	Dietary management and enzyme replacement to treat PKU	(Leeper *et al.*, 2015)
	Albinism	Gene Editing (CRISPRCas9)	Correcting mutations related to pigmentation	Research in progress for treating pigmentation	(Biffi, 2020)
	Beta-thalassemia	CRISPRCas9	Correcting mutations in the beta-globin gene	Trials show promise for normalizing hemoglobin levels.	(Forrester *et al.*, 2018)
	Duchenne Muscular Dystrophy	Exon Skipping (e.g., eteplirsen)	Skipping faulty exons to produce functional dystrophin	Approved by the FDA for certain patients.	(Espenhain *et al.*, 2019)
	Hurler Syndrome (MPS I)	Enzyme Replacement Therapy (ERT)	Restoring deficient enzyme activity	FDA-approved enzyme replacement for symptom management	(Ilyas *et al.*, 2016)
	Spinal Muscular Atrophy	SMN2 Gene Modulation (e.g., Spinraza)	Enhancing production of survival motor neuron protein	FDA-approved drug to slow disease progression.	(Al-Amin *et al.*, 2020)
	Sandhoff Disease	Gene Therapy, CRISPRCas9	Correcting defective HEXB gene	Ongoing clinical research, no standard treatment yet.	(Lyras & Lee, 2021)
	Mucopolysaccharidosis II	Enzyme Replacement Therapy (ERT)	Restoring enzyme function for better symptom control	FDA-approved treatment for managing symptoms.	(Cheng *et al.*, 2019)
	Canavan Disease	Gene Therapy, CRISPRCas9	Correcting the aspartoacylase gene	Research in early stages, gene therapy showing promise.	(Swarbreck *et al.*, 2020)
	Wilson's Disease	Genetic Counseling, Medications (e.g., chelating agents)	Copper metabolism correction	Diagnosis and treatment are crucial for preventing liver damage.	(Madu *et al.*, 2015)
	Retinitis Pigmentosa	Gene Therapy, CRISPRCas9	Gene modification to restore vision	Clinical trials advancing in gene therapy for the retina	(Roa-Linares *et al.*, 2016)
	Niemann-Pick Disease	Gene Therapy, Enzyme Replacement Therapy (ERT)	Gene correction or enzyme restoration	Clinical trials are ongoing for enzyme replacement.	(Burleigh *et al.*, 2018)
	X-linked Hypohidrotic Ectodermal Dysplasia	Gene Therapy (X-linked)	Restoring sweat gland function	Clinical trials focusing on gene transfer for skin function.	(Schneider *et al.*, 2023)

Retinoblastoma	CRISPR-Cas9, Targeted Therapy	Correcting mutations in the RB1 gene	Clinical trials exploring gene therapy for cancer treatment.	(StaninskaPięta *et al.*, 2020)
Homocystinuria	Gene Therapy, Enzyme Therapy	Correcting homocysteine metabolism issues	Clinical trials for metabolic restoration.	(Tovar *et al.*, 2018)
Alpha-1 Antitrypsin Deficiency	CRISPRCas9	Correcting mutations in the AAT gene	Early clinical trials targeting lung function restoration.	(Zhang *et al.*, 2015)

Table 3: Genomics tools used in livestock to manage genetic disorders.

Genomic Tool/Medicine	Livestock	Application	Purpose	Examples	References
CRISPR-Cas9 Gene Editing	Cattle	Correcting genetic mutations	Preventing hereditary diseases	Correcting Muscular Hypertrophy in cattle	Singh *et al.*, 2023; Ikeda *et al.*, 2017; Popova *et al.*, 2023;
Whole-genome sequencing (WGS)	Poultry	Identifying novel mutations	Detecting carriers and managing breeding programs	Reducing inbreeding related disorders	Tan *et al.*, 2012; Xiong *et al.*, 2023
Genomics Selection	Dairy Cattle	Selecting genetically superior animals	Improving health and disease resistance traits	Use to eliminate Bovine Leukocyte Adhesion Deficiency (BLAD)	Jonathan *et al.*, 2023; Wiggans and Carrillo, 2022; Kent, 2017
SNP Genotyping	Sheep & Goats	Marker assisted selection for genetic traits	Managing recessive mutations like Scrapie	Enhancing resistance to diseases	Cozzi *et al.*, 2024. Pogorevc *et al.*, 2024; Guo *et al.*, 2021
Gene Therapy	Swine	Correcting inherited disorders	Reducing susceptibility to Porcine Reproductive & Respiratory Syndrome (PRRS)	Gene therapy trials for immune enhancement	Watanabe *et al.*, 2017; Whitworth *et al.*, 2022; Matsunari,*et al.*, 2020

Disease Resistance and Vaccination: One of the most significant benefits of genomics medicine is that it can improve disease resistance in livestock, including cattle and poultry. Discovering genetic differences that influence susceptibility or resistance to viral diseases allows breeders to generate populations of animals that are naturally more resistant to diseases. This is of the intense importance to address the growing concern of antibiotic resistance (Kosur *et al*., 2014). For example, certain breeds of pigs are more resistant to porcine reproductive and respiratory syndrome (PRRS) but scientists by genetic modification technique have produced pigs breeds that are resistance to the fatal African swine virus (Yuan *et al*., 2022). Similarly, genomic research has led to the discovery of markers in chicken associated with resistance to avian influenza (Bakhshandeh *et al*., 2023; June Byun *et al*., 2017; Lyall *et al*., 2011) and such innovation help to conduct focused breeding programs in livestock and poultry (Chuang *et al*., 2024; Fulton, 2012). Breeding for disease resistance and development of next generation vaccines both have affected positively by genomics medicine.

Gene Editing in Livestock and Poultry: Applications of genomics medicines in agriculture sector are acquiring significant adoption due to the advanced gene editing technologies like CRISPR-Cas9 which has made it possible to alter animal DNA at required exact locations. This has made it possible for scientists to add or delete specific genes with high precision enabling to create genetically engineered livestock, poultry and other animals with desired characteristics i.e.higher growth potential or resistance against the diseases. Information in Table 4 describes the use of genome medications and devices to cure recessive genetic illnesses in animals.

Table 4: Genomics tools in livestock to manage recessive genetic disorders.

Species	Recessive Disorder	Genomic Tool	Application	Notes	References
Poultry	Dwarfism in chickens	SNP-based selection	Marker-assisted breeding	Increase growth rates while reducing disorder prevalence.	Perini *et al.,* 2023
Cattle	Congenital Muscular Dystonia	CRISPR-Cas9	Gene correction in embryos	Experimental; aims to correct defective	Min *et al.*,2019; Sergio *et al.*,2020;
Species	**Recessive Disorder**	**Genomic Tool**	**Application**	**Notes**	**References**
				gene sequences.	Popova *et al.*,2023; Gill *et al.*,2012
	Bovine Leukocyte Adhesion Deficiency (BLAD)	Genomic selection	Screening for carriers	Reduces incidence through selective breeding.	Patel *et al.*,2007: Meydan *et al*.,2010
	Deficiency of Uridine Monophosphate Synthase (DUMPS)	Whole-genome sequencing	Carrier identification	Prevents propagation of defective genes.	Rehman *et al.*,2021; Hayes *et al.*,2013; Perini *et al.*,2023;

Genomics medicines offer advanced therapies that have changed our understanding of the genome to treat, manage, or prevent genetic disorders. For livestock and poultry these "medicines" often come in the form of genomics tools and technologies rather than conventional drugs. With the sequencing of the chicken genome, genomics selection in poultry breeding has made tremendous steps forward (Hillier *et al.,* 2004**).** Millions of SNPs were identified to distinguish birds. This discovery allowed the development of SNP panels for rapid and cost-effective genotyping. Chip density has increased from 6,000 (Andreescu *et al.,* 2007)**,** to 600,000 SNPs (Kranis *et al.,* 2013)and expanded the number of geno-typed birds from hundreds to tens of thousands over time. Genomics selection increases the accuracy of breeding, reduces inbreeding, and allows selection for complex traits, although the high cost of geno-typing remains a challenge (Johnsson, 2023). This problem was solved by the invention of a technique known as imputation, which involves the inference of missing genotypes from high-density genotyped parents through the utilization of low-density SNP panels for the goal of selecting candidates at a cheaper cost (Wang *et al*., 2013). This method was developed in order to resolve this issue as it keeps accuracy whilst at the same time cutting cost, which finally results in an increased efficiency for the production of commercial chickens.

Genomic selection can improve genetic gain efficiently in poultry breeding experiment. A study conducted by Hy-Line International and Iowa State University demonstrated the power of genomics selection to improve the genetic gain in poultry (Wolc, 2015; Wolc *et al.,* 2011).For this a pure line of brown egg-laying hens was divided into two sublines, out of these one line was selected using traditional methods whereas the other line was selected earlier by genomics predictions. Results investigated that line which was selected through genomics predictions produced four generations in three years, whilst the line which was selected via traditional procedure produced only two generations. This revealed that selecting line using genomics predictions significantly reduced the generation interval. The line selected through genomics predictions outperformed in 12 of 16 traits than traditional selected line because of high accuracy in breeding values and fast generation turnover. Hy-Line International used these results as a springboard to extend genomics selection to other layer lines, with the 600,000 SNP chips and custom SNP sets. This method led to greater accuracy and became a standard in 2013. In the broiler, genomics selection was also integrated into breeding, allowing for imputation, thereby permitting cost-effective genotyping without sacrificing accuracy. Imputation methods achieved an accuracy of about 0.97 for immediate offspring, allowing the poultry industry to reduce costs while maintaining high precision in genomics breeding values. Scientists have edited the genes of poultry to make them resistant to avian influenza, reducing the need for vaccines and minimizing the risk of disease outbreaks. The potential applications of gene editing in livestock and poultry are vast, ranging from improving productivity to enhancing animal welfare.

The application of genomics medicine in poultry is still in its initial stages, particularly in the direct treatment of recessive disorders. Presently, there are few examples of using genomics medicine for treating recessive genetic disorders in poultry, and most current efforts yet focus on improving production performance and disease resistance. Some genomics interventions used for genetic improvements in poultry are shown in Table 5. However, innovations in genomics techniques like whole-genome sequencing, marker-assisted selection, and gene editing (CRISPR-Cas9) are paving the way to identify and correct harmful mutations that affect poultry productivity, health, and welfare.

Table 5: Illustrating some genomics interventions used for genetic improvements in poultry.

Genomic Tool/Medicine	Target Disorder	Purpose	Status	References
Gene Editing (CRISPR-Cas9)	Avian leukosis virus susceptibility	Alter specific genes to confer resistance	Experimental phase	Koslová *et al.*, 2020
Marker-Assisted Selection (MAS)	Growth, fertility, disease resistance traits	Identify genetic markers linked to favorable traits	Widely used in breeding programs	Sodhi *et al.*, 2013
Whole-Genome Sequencing (WGS)	Identification of recessive disease alleles	Detect mutations responsible for genetic disorders	Research phase	Wang *et al.*, 2023; Jeong *et al.*, 2023
RNA Interference (RNAi)	Viral diseases (e.g., Marek's disease)	Suppress viral gene expression	Research phase	Lambeth *et al.*, 2009
Genomic Tool/Medicine	**Target Disorder**	**Purpose**	**Status**	**References**
Genomics Selection	General genetic improvement	Enhance selection accuracy for resistance traits	Implemented in commercial breeding	Lee *et al.*, 2024

Ethical Considerations and Suggestions: Whilst the potential of genomics medicine in human, livestock, and poultry health is enormous, there are several challenges and ethical concerns that must be addressed (Ishii, 2017; De Graeff *et al.,* 2019). According to Andrews *et al*. (1994), the field of human health science is fraught with a number of significant obstacles. These challenges involve the demand for informed consent; favouritism based on genetic characteristics; and the requirement to protect specific personal information. It is necessary that genetic data should be used in a trusty and ethical way (Ishii, 2017) because of the increasing usage of genetic information in clinical practice (Stark *et al*., 2019). The reality that there are many strict protections in place to protect people's rights underlines the significance of this concern further.

In poultry and in the field of livestock, the ecological impact of gene editing and the safety of modified animals must be wisely considered for accidental concerns. Although gene editing has great potential to improve animal health, production, and welfare, its long-term effects on animal welfare and biodiversity are not fully understood yet.Therefore, careful and strict rules and regulations are necessary to ensure that genomics technologies are being used responsibly and sustainably in agriculture. Genomics medicine in livestock primarily focuses on genomics selection, gene-editing technologies like CRISPR-Cas9, and marker-assisted selection rather than established "medicines" as in human healthcare. Although gene therapy, CRISPR-Cas9, and RNA-based therapies have made strides in human genomics medicine, these treatments are still in different phases of development and clinical implementation.

Some of the problems in genomics selection in livestock, cattle, or poultry include its benefits be confined to large stack holders, for example, small stack holders may find it challenging to afford/access genomics technologies. Moreover, gene editing in livestock raises ethical concerns, especially regarding animal welfare. The absence of certain recognized rules or regulations may make it more challenging to employ genomics technology in agricultural settings.

Misuse of genomic medicine to promote scientific racism or racial discrimination in humans is one of its key ethical concerns as it can support racist ideologies like incorrectly linking certain genetic traits to disease susceptibility, behavior, and/or intelligence based on race disregarding the scientific confirmation, hence can cause increased health disparities, reinforcing harmful stereotypes which ultimately may results into genetic essentialism (where people are recognized based on their genes instead of their environmental factors or individual identity). Therefore, genomics research must focus on equity, respect for human diversity, and inclusion. Because of this, research is currently being conducted in order to enhance the accessibility, safety, and effectiveness of generic medications that are being produced.

Conclusion: Genomics medicines have changed livestock/poultry farming and human healthcare by using innovative methods to detect, prevent, and treat diseases through advanced genomic tools. This technology can enable personalized medicine, pharmaco-genomics, and gene therapy according to an individual's unique biologic makeup and background. It can transform how we treat people by focusing personalized healthcare and understanding of individual genetic variations, encouraging sympathy and diminishing one-size-fits-all approaches. Livestock and poultry genomics technologies, including gene editing, genomics selection, and disease-resistant breeding, are also progressing. These techniques improve animal health, happiness, and productivity. Genomics medicine has tremendous benefits, but it must overcome many issues before it can be applied across species. Although application and research in genomics medicine is under progress and prevailing, but it must be used morally to protect people, groups, and ecosystems. Genetic medicine can improve human, animal, and bird health in the future as well and could help solve some of our big health issues if it be handled appropriately, hence, can make farming more sustainable and productive to serve the increasing global human population.

REFERENCES

Abbas, G. 2007. Phylogenetic relationships among buffalo breeds of Pakistan using RAPD analysis. MSc (Hons) thesis submitted in the Department of Animal Breeding and Genetic, University of Agriculture, Faisalabad.

ANDREESCU, C., AVENDAÑO, S., BROWN, S.R. *et al*. (2007): Linkage disequilibrium in related breeding lines of chickens. Genetics 177:2161-2169.

Bagger, F.O., Borgwardt, L., Jespersen, A.S. *et al.* Whole genome sequencing in clinical practice. *BMC Med Genomics* **17**, 39 (2024). https://doi.org/10.1186/s12920-024-01795-w.

Bakhshandeh, S. Genome-edited chickens. *Nat Rev Bioeng* **1**, 793 (2023). https://doi.org/10.1038/s44222-023-00136-3.

Braga LAM, Conte Filho CG, Mota FB. Future of genetic therapies for rare genetic diseases: what to expect for the next 15 years? Ther Adv Rare Dis. 2022 Jun 10;3:26330040221100840. doi: 10.1177/26330040221100840.

Cao, D., Manzar Abbas, Fatima, Yunxia Li, Gaoping Zhao, Ghulam Abbas, & Xihe Li. (2024). BASE EDITING: A PROMISING TOOL FOR GENETIC MANIPULATION IN MAMMALIAN SOMATIC AND STEM CELL LINES. *Pakistan Journal of Science, 76*(04), 553–569. https://doi.org/10.57041/vol76iss04pp553-569

Carver T, Hartley S, Lee A, Cunningham AP, Archer S, Babb de Villiers C, Roberts J, Ruston R, Walter FM, Tischkowitz M, Easton DF, Antoniou AC. CanRisk Tool-A Web Interface for the Prediction of Breast and Ovarian Cancer Risk and the Likelihood of Carrying Genetic Pathogenic Variants. Cancer Epidemiol Biomarkers Prev. 2021 Mar;30(3):469-473. doi: 10.1158/1055-9965.EPI-20-1319.

Chuang, E.Y.S., Wellmann, R., Meijboom, F.L.B. *et al.* Simulation of dual-purpose chicken breeding programs implementing gene editing. *Genet Sel Evol* **56**, 7 (2024). https://doi.org/10.1186/s12711-023-00874-3

Cozzi P, Manunza A, Ramirez-Diaz J, Tsartsianidou V, Gkagkavouzis K, Peraza P, Johansson AM, Arranz JJ, Freire F, Kusza S, Biscarini F, Peters L, Tosser-Klopp G, Ciappesoni G, Triantafyllidis A, Rupp R, Servin B, Stella A. SMARTER-database: a tool to integrate SNP array datasets for sheep and goat breeds. GigaByte. 2024 Oct 21;2024:gigabyte139. doi: 10.46471/gigabyte.

Cuo, J., Jiang, R., Mao, A. *et al.* Genome-wide association study reveals 14 new SNPs and confirms two structural variants highly associated with the horned/polled phenotype in goats. *BMC Genomics* **22**, 769 (2021). https://doi.org/10.1186/s12864-021-08089-w.

Deneault, E. (2024). Recent Therapeutic Gene Editing Applications to Genetic Disorders. *Current Issues in Molecular Biology*, *46*(5), 4147-4185. https://doi.org/10.3390/cimb46050255.

Gill JL, James VM, Carta E, Harris D, Topf M, Scholes SF, Hateley G, Harvey RJ. 2012. Identification of congenital muscular dystonia 2 associated with an inherited GlyT2 defect in Belgian Blue cattle from the United Kingdom. Anim Genet. 43(3):267-70. doi: 10.1111/j.1365-2052.2011.02255.x.

Gonçalves GAR, Paiva RMA. Gene therapy: advances, challenges and perspectives. Einstein (Sao Paulo). 2017 Jul-Sep;15(3):369-375. doi: 10.1590/S1679-45082017RB4024.

Gupta SK, Shukla P. Gene editing for cell engineering: trends and application. Crit Rev Biotechnol. 2017 Aug;37(5):672–84. doi: 10.1080/07388551.2016.1214557.

Hayes, B.; Daetwyler, H.D.; Fries, R.; Guldbrandtsen, B.; Lund, M.S.; Boichard, D.; Chamberlain, A. 2013. The 1000 bull genomes project-Toward genomic selection from whole genome sequence data in dairy and beef cattle. In Proceedings of the International Plant & Animal Genome XXI, San Diego, CA, USA, 10–15.

Hillier, L.W. *et al*. (2004) Sequence and comparative analysis of the chicken genome provide unique perspectives on vertebrate evolution. *Nature*, 432(7018), pp. 695-716. doi: 10.1038/nature03154.

Ikeda, M., Matsuyama, S., Akagi, S. *et al.* Correction of a Disease Mutation using CRISPR/Cas9-assisted Genome Editing in Japanese Black Cattle. *Sci Rep* **7**, 17827 (2017). https://doi.org/10.1038/s41598-017-17968-w.

J. E. Fulton, Genomic selection for poultry breeding, *Animal Frontiers*, Volume 2, Issue 1, January 2012, Pages 30–36, https://doi.org/10.2527/af.2011-0028.

Jeong H, Kim K, Caetano-Anollés K, Kim H, Kim BK, Yi JK, Ha JJ, Cho S, Oh DY. (2016). Whole genome sequencing of Gyeongbuk Araucana, a newly developed blue-egg laying chicken breed, reveals its origin and genetic characteristics. Sci Rep. 24(6):26484. doi: 10.1038/srep26484.

Johansson Å, Andreassen OA, Brunak S, Franks PW, Hedman H, Loos RJF, Meder B, Melén E, Wheelock CE, Jacobsson B. Precision medicine in complex diseases-Molecular subgrouping for improved prediction and treatment stratification. J Intern Med. 2023 Oct;294(4):378-396. doi: 10.1111/joim.13640.

Johnston JR, McNally EM. Genetic correction strategies for Duchenne Muscular Dystrophy and their impact on the heart. Prog Pediatr Cardiol. 2021 Dec;63:101460. doi: 10.1016/j.ppedcard.2021.

Jonathan M. Schefers, Kent A. Weigel. 2012. Genomic selection in dairy cattle: Integration of DNA testing into breeding programs, *Animal Frontiers*, 2(1):4–29, https://doi.org/10.2527/af.2011-0032.

June Byun, S., Yuk, Ss., Jang, YJ. *et al.* Transgenic Chickens Expressing the 3D8 Single Chain Variable Fragment Protein Suppress Avian Influenza Transmission. *Sci Rep* **7**, 5938 (2017). https://doi.org/10.1038/s41598-017-05270-8.

Kent A. Weigel. (2017). Genomic selection of dairy cattle: A review of methods, strategies, and impact. Journal of Animal Breeding and Genomic, 1(1): 1-15.

Khan IM, Khan A, Liu H, Khan MZ. Editorial: Genetic markers identification for animal production and disease resistance. Front Genet. 2023 Jul 12;14:1243793. doi: 10.3389/fgene.2023.1243793.

Khoury MJ. No shortcuts on the long road to evidence-based genomic medicine. JAMA. 2017 Jul 4;318(1):27–8. doi: 10.1001/jama.2017.6315. doi: 10.1001/jama.2017.6315.

Kingsmore SF, Saunders CJ. Deep sequencing of patient genomes for disease diagnosis: when will it become routine? Sci Transl Med. 2011 Jun 15;3(87):87ps23. doi: 10.1126/scitranslmed.3002695.

Köser CU, Ellington MJ, Peacock SJ. Whole-genome sequencing to control antimicrobial resistance. Trends Genet. 2014 Sep;30(9):401-7. doi: 10.1016/j.tig.2014.07.003.

Koslová A, Trefil P, Mucksová J, Reinišová M, Plachý J, Kalina J, Kučerová D, Geryk J, Krchlíková V, Lejčková B, Hejnar J. (2020). Precise CRISPR/Cas9 editing of the NHE1 gene renders chickens resistant to the J subgroup of avian leukosis virus. Proc Natl Acad Sci U S A. 28;117(4):2108-2112. doi: 10.1073/pnas.1913827117.

Kramer, K., Meijboom, F.L.B. The Ethics of Innovations in Genomic Selection: On How to Broaden the Scope of Discussion. *J Agric Environ Ethics* **35**, 7 (2022). https://doi.org/10.1007/s10806-022-09883-6.

Kranis A, Gheyas AA, Boschiero C, Turner F, Yu L, Smith S, Talbot R, Pirani A, Brew F, Kaiser P, Hocking PM, Fife M, Salmon N, Fulton J, Strom TM, Haberer G, Weigend S, Preisinger R, Gholami M, Qanbari S, Simianer H, Watson KA, Woolliams JA, Burt DW. Development of a high density 600K SNP genotyping array for chicken. BMC Genomics. 2013 Jan 28;14:59. doi: 10.1186/1471-2164-14-59.

Lambeth LS, Zhao Y, Smith LP, Kgosana L, Nair V. Targeting Marek's disease virus by RNA interference delivered from a herpesvirus vaccine. Vaccine. 2009 Jan 7;27(2):298-306. doi: 10.1016/j.vaccine.2008.10.023.

Lee, J., D. H. Kim and K. Lee (2024). Myostatin gene role in regulating traits of poultry species for potential industrial applications. *Journal of Animal Science and Biotechnology*. 15:82, *2-9.*

Lomunova MA, Gershovich PM. Gene Therapy for Cystic Fibrosis: Recent Advances and Future Prospects. Acta Naturae. 2023 Apr-Jun;15(2):20-31. doi: 10.32607/actanaturae.11708.

Lyall, J., Irvine, R. M., Sherman, A., McKinley, T. J., Núñez, A., Purdie, A., Outtrim, L., Brown, I. H., Rolleston-Smith, G., Sang, H., & Tiley, L. (2011). Suppression of Avian Influenza Transmission in Genetically Modified Chickens. *Science*, *331*(6014), 223–226. http://www.jstor.org/stable/40986503

Matsunari, H., Honda, M., Watanabe, M. *et al.* Pigs with δ-sarcoglycan deficiency exhibit traits of genetic cardiomyopathy. *Lab Invest* **100**, 887–899 (2020). https://doi.org/10.1038/s41374-020-0406-7.

Meydan H, Yildiz MA, Agerholm JS. Screening for bovine leukocyte adhesion deficiency, deficiency of uridine monophosphate synthase, complex vertebral malformation, bovine citrullinaemia, and factor XI deficiency in Holstein cows reared in Turkey. Acta Vet Scand. 2010 Oct 7;52(1):56. doi: 10.1186/1751-0147-52-56.

Min YL, Bassel-Duby R, Olson EN. CRISPR Correction of Duchenne Muscular Dystrophy. Annu Rev Med. 2019 Jan 27;70:239-255. doi: 10.1146/annurev-med-081117-010451.

Mueller, M.L., Van Eenennaam, A.L. Synergistic power of genomic selection, assisted reproductive technologies, and gene editing to drive genetic improvement of cattle. *CABI Agric Biosci* **3**, 13 (2022). https://doi.org/10.1186/s43170-022-00080-z.

National Human Genome Research Institute. Genomic medicine. Accessed on https://www.genome.gov/genetics-glossary/Genomic-Medicine (cited March 2024.

Oliver JC. Bioinformatic training needs at a health sciences campus. PLOS ONE. 2017 Jun 14;12(6):e0179581. doi: 10.1371/journal.pone.0179581.

Patel RK, Singh KM, Soni KJ, Chauhan JB, Sambasiva Rao KR. 2007. Low incidence of bovine leukocyte adhesion deficiency (BLAD) carriers in Indian cattle and buffalo breeds. J Appl Genet. 48(2):153-5. doi: 10.1007/BF03194673.

Pena SA, Iyengar R, Eshraghi RS, Bencie N, Mittal J, Aljohani A, Mittal R, Eshraghi AA. Gene therapy for neurological disorders: challenges and recent advancements. J Drug Target. 2020 Feb;28(2):111-128. doi: 10.1080/1061186X.2019.1630415.

Perini F, Cendron F, Wu Z, Sevane N, Li Z, Huang C, Smith J, Lasagna E, Cassandro M, Penasa M. 2023. Genomics of Dwarfism in Italian Local Chicken Breeds. Genes (Basel). 14(3):633. doi: 10.3390/genes14030633.

Pogorevc N, Dotsev A, Upadhyay M, Sandoval-Castellanos E, Hannemann E, Simčič M, Antoniou A, Papachristou D, Koutsouli P, Rahmatalla S, Brockmann G, Sölkner J, Burger P, Lymberakis P, Poulakakis N, Bizelis I, Zinovieva N, Horvat S, Medugorac I. Whole-genome SNP genotyping unveils ancestral and recent introgression in wild and domestic goats. Mol Ecol. 2024 Jan;33(1):e17190. doi: 10.1111/mec.17190.

Popova J, Bets V, Kozhevnikova E. Perspectives in Genome-Editing Techniques for Livestock. *Animals*. 2023; 13(16):2580. https://doi.org/10.3390/ani13162580

Popova, J., Bets, V., & Kozhevnikova, E. (2023). Perspectives in Genome-Editing Techniques for Livestock. *Animals*, *13*(16), 2580. https://doi.org/10.3390/ani13162580.

Rahman I, Barwell J. Genomic medicine for the 21st century. Ann R Coll Surg Engl. 2024 Apr;106(4):295-299. doi: 10.1308/rcsann.2024.0030.

Rehman, S. u., Hassan, F. -u., Luo, X., Li, Z., & Liu, Q. (2021). Whole-Genome Sequencing and Characterization of Buffalo Genetic Resources: Recent Advances and Future Challenges. *Animals*, *11*(3), 904. https://doi.org/10.3390/ani11030904.

Rehman, S. u., Hassan, F. -u., Luo, X., Li, Z., & Liu, Q. (2021). Whole-Genome Sequencing and Characterization of Buffalo Genetic Resources: Recent Advances and Future Challenges. *Animals*, *11*(3), 904. https://doi.org/10.3390/ani11030904.

Roth SC. What is genomic medicine? J Med Libr Assoc. 2019 Jul;107(3):442-448. doi: 10.5195/jmla.2019.604.

Sarkar T, Sarkar S, Gangopadhyay DN. Gene Therapy and its Application in Dermatology. Indian J Dermatol. 2020 Sep-Oct;65(5):341-350. doi: 10.4103/ijd.IJD_323_20.

Sergio Navarro-Serna and Marcela Vilarino and Insung Park and Joaquin Gadea and Pablo Juan Ross. 2020. Livestock Gene Editing by One-step Embryo Manipulation. Journal of Equine Veterinary Science, 89: 103025.doi.org/10.1016/j.jevs.2020.103025.

Sharpe NF, Carter RF. Genetic testing: care, consent, and liability. Hoboken, NJ: Wiley-Liss; 2006. pp. 22–3.

Singh P, Ali SA. Impact of CRISPR-Cas9-Based Genome Engineering in Farm Animals. Vet Sci. 2021 Jun 30;8(7):122. doi: 10.3390/vetsci8070122.

Smith, M.C., O'Loughlin, J., Karageorgiou, V. *et al.* (2023). The genetics of falling susceptibility and identification of causal risk factors. *Sci Rep* **13**, 19493. https://doi.org/10.1038/s41598-023-44566-w.

Sodhi, S. S .,DK Jeong, N Sharma, JH Lee, JH Kim, SH Kim, SW Kim, SJ Oh. (2013). Marker assisted selection-applications and evaluation for commercial poultry breeding. Korean Journal of Poultry Science, 40 (2013), pp. 223-234.

Stone, Roger T. and Cundiff, Larry V., "Breeding Cattle for Genetic Resistance to Disease" (1985). Roman L. Hruska U.S. Meat Animal Research Center. 31. https:// digitalcommons.unl. edu/hruskareports/31.

Sudhakar A, Khade A, Nayee N, Chandrasekhar Reddy RV, Maurya B. Novel mutation in UMPS gene leads to false positive result of DUMPS (genetic disorder) in buffaloes: need for gene sequencing before confirming results of RFLP in new species. J Genet. 2021;100:55.

Tan, X., Zhang, J., Dong, J. *et al.* Whole-genome variants dataset of 209 local chickens from China. *Sci Data* **11**, 169 (2024). https://doi.org/10.1038/s41597-024-02995-w.

US Food & Drug Administration. FDA approves novel gene therapy to treat patients with a rare form of inherited vision loss [Internet] The Administration; Dec 19, 2017. Accessed on FDA approves novel gene therapy to treat patients with a rare form of inherited vision loss | FDA.

Waheed, M., S. Ali, M. S. Khan, S, Rehman, G. Abbas. 2015. Molecular genetic variations among some Punjab sheep breeds using RAPD analysis. Advances in Zoology and Botany, 3 (1): 1-5.

Wang J., Qiu-xia LEI and Ding-guo CAO and Yan ZHOU and Hai-xia HAN and Wei LIU and Da-peng LI and Fu-wei LI and Jie LIU (2023). Whole genome SNPs among 8 chicken breeds enable identification of genetic signatures that underlie breed features. Journal of Integrative Agriculture. 22(7): 2200-2212. doi.org/10.1016/j.jia.2022.11.007.

WANG, C., HABIER, D., PEIRIS, B.L. *et al*. (2013): Accuracy of genomic prediction using an evenly spaced, low-density single nucleotide polymorphism panel in broiler chickens. Poultry Science 92:1712-1723.

Watanabe S, Ishikawa K, Fish K, Oh JG, Motloch LJ, Kohlbrenner E, Lee P, Xie C, Lee A, Liang L, Kho C, Leonardson L, McIntyre M, Wilson S, Samulski RJ, Kranias EG, Weber T, Akar FG, Hajjar RJ. Protein Phosphatase Inhibitor-1 Gene Therapy in a Swine Model of Nonischemic Heart Failure. J Am Coll Cardiol. 2017 Oct 3;70(14):1744-1756. doi: 10.1016/j.jacc.2017.08.013.

Weinshilboum RM, Wang L. Pharmacogenomics: Precision Medicine and Drug Response. Mayo Clin Proc. 2017 Nov;92(11):1711-1722. doi: 10.1016/j.mayocp.2017.09.001.

Whitworth, K.M., Green, J.A., Redel, B.K. *et al.* Improvements in pig agriculture through gene editing. *CABI Agric Biosci* **3**, 41 (2022). https://doi.org/10.1186/s43170-022-00111-9.

Wiggans, G. R. and J. A. Carrillo. 2022. Genomic selection in United States dairy cattle, Front. Genet. 13:994466., https://doi.org/10.3389/fgene.2022.994466.

WOLC, A., STRICKER, C., ARANGO, J., *et al*. (2011): Breeding value prediction for production traits in layers using pedigree and marker based methods. Genetics Selection Evolution 43:5.

Xiong X, Liu J, Rao Y.2023. Whole Genome Resequencing Helps Study Important Traits in Chickens. Genes (Basel).30;14(6):1198. doi: 10.3390/genes14061198.

Yilmaz BS, Gurung S, Perocheau D, Counsell J, Baruteau J. Gene therapy for inherited metabolic diseases. J Mother Child. 2020 10;24(2):53-64. doi: 10.34763/jmotherandchild.

Yuan H, Yang L, Zhang Y, Xiao W, Wang Z, Tang X, Ouyang H, Pang D. Current Status of Genetically Modified Pigs That Are Resistant to Virus Infection. Viruses. 2022 Feb 17;14(2):417. doi: 10.3390/v14020417.