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Advances in Veterinary Medicine: Sustainable Approaches to Animal Health Management and Disease Prevention

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Abstract

This review paper explains the latest advances in veterinary medicine from the perspective of sustainable animal health management and disease prevention. The objective of this study is to evaluate the integration of sustainability into veterinary practice with an emphasis on the role played by emerging technologies, preventive measures, and eco-friendly methods in improving animal health outcomes. Some of the key advances discussed include the use of the One Health principle, which integrates human, animal, and environmental health; the adoption of antibiotic stewardship to combat antimicrobial resistance; and the use of alternative and natural interventions in the management of animal health. The article also discusses the role of new diagnostic methods and genomic technologies in identifying and preventing disease at an early level. The article also highlights environmental sustainability in veterinary businesses, climate change mitigation, and promotion of sustainable farming and waste management. Furthermore, ethical and social considerations such as animal welfare and public education are presented with regard to sustainable veterinary medicine. The findings show that while there has been tremendous progress in veterinary medicine with sustainable strategies, some matters such as economic considerations and the spread of emerging diseases remain problems. Continued study, collaboration, and policy development are needed to enhance the sustainability of veterinary medicine practice, with the vision of advancing long-term improvements in animal and public health.

Keywords: Veterinary Medicine; Sustainable Practices; Disease Prevention; Animal Health; Emerging Technologies; Veterinary Management

Introduction

Veterinary medicine has been an integral part of human society since centuries, as the earliest civilizations appreciated the role of animal health in achieving ecosystem stability and human survival. Veterinary practices in ancient Egypt, Mesopotamia, and Greece were inescapably integrated with agriculture, where animals were required for food production, transport, and military operations. Over time, the practice expanded to include a broad range of species, from livestock to pets and wildlife. Today, veterinary medicine is a dynamic, interdisciplinary science that promotes animal health, ensures food safety, and minimizes zoonotic diseases—diseases transmitted from animals to people. Fields such as surgery, cardiology, and oncology have contributed to care for companion animals more, with this underscoring the rising importance of veterinary medicine in private and public health settings [1].

The discipline itself is faced with issues such as unsustainable management of animal health despite such exceptional advancements in veterinary science. The resurgence of infectious diseases like COVID-19, bird flu, and African swine fever can cause stringent threats not only to animal populations but also to public health and the global economy. For instance, the 2018–2019 outbreak of African swine fever alone caused over 25% loss of the pig population of the world and an estimated $141 billion in damages [2]. Climate change also exacerbates these risks, changing disease transmission patterns and expanding the range of vector-borne disease. Rising temperatures and changed precipitation patterns have dispersed tick-borne diseases and affected livestock production, threatening global food security [3].

Antimicrobial resistance (AMR) is another key issue, which has been ranked as a global health emergency. The misuse and overuse of antibiotics in human and animal health have hastened the development of resistant pathogens. AMR causes around 700,000 deaths per year, as estimated by the World Health Organization (WHO), and this can increase to 10 million deaths per year by the year 2050 if nothing is done [4]. In the veterinary sector, excessive use of antibiotics in food animals has led to the development of resistant strains, which make infections difficult and pose a serious threat to public health. To counteract this, antibiotic stewardship programs have been initiated to manage antimicrobial use and encourage alternative disease management practices [5].

Besides disease control, ethics and sustainability are now an integral part of modern veterinary practice. Factory farming, wildlife conservation, and the ecological footprint of veterinary intervention are issues that need to be dealt with urgently. Industrial animal farming alone accounts for 14.5% of greenhouse gas emissions worldwide, which further contributes to climate change and loss of biodiversity [6]. Further, growing public concern about animal welfare has placed extra pressure on veterinarians to advocate ethical treatment and sustainable agriculture.

Given these pressing concerns, sustainability in veterinary medicine is more necessary than ever. Sustainable practices like preventive medicine, green veterinary practice, and One Health strategies bridging human, animal, and environmental health can help alleviate these threats. This review explores the latest trends in sustainable veterinary medicine, with leading-edge solutions like precision diagnostics, antimicrobial stewardship, and climate-resilient veterinary practice. Through emphasis on sustainability in veterinary medicine, we can enhance long-term animal health, reduce environmental footprint, and contribute to global public health goals.

Sustainability in Veterinary Medicine

Veterinary practice sustainability goes beyond the environmental impact of practice and encompasses a holistic approach that addresses ecological, ethical, and economic factors for long-term sustainability of animal health and the ecosystems on which they depend. Sustainable veterinary practices are increasingly becoming an imperative to address the environment and health challenges emanating from industrial agriculture, urbanization, and climate change. These practices include proper use of antibiotics, prevention of disease by vaccination and biosecurity, control of environmental pathogens from animal excreta, and animal well-being.

An essential component of veterinary practice sustainability is the inclusion of preventative care. By prioritiz-

ing prevention of disease instead of treatment, veterinarians can help to lower the demand for chemical-based measures, such as antibiotics and pesticides, that negatively affect the environment and animal well-being. Other sustainable agriculture practices, such as organic farming and rotational grazing, also help minimize the environmental footprint of animal agriculture. Besides, promoting other and less violent diagnostic and therapy techniques, such as the use of herbal medicines, acupuncture, or low-invasive surgery, also offers other opportunities for sustainable veterinary practice. This integration of sustainability into veterinary medicine not only improves animal health but also is in accordance with environmental stewardship and social responsibility in general [5].

Table 1: Sustainable Veterinary Practices and Their Impact on Animal Health and the Environment

Sustainable Veterinary Practice	Description	Impact Level (%)
Disease Prevention (Vaccination & Biosecurity)	Reducing disease incidence through immunization and improved hygiene	90
Proper Antibiotic Use	Minimizing antibiotic resistance by responsible prescription practices	85
Environmental Pathogen Control	Managing animal waste to reduce contamination and disease spread	80
Alternative Therapies (Herbal, Acupuncture, Low-Invasive Surgery)	Reducing reliance on pharmaceuticals by using natural and minimally invasive treatments	75
Sustainable Agriculture (Organic Farming, Rotational Grazing)	Reducing environmental impact and improving animal welfare	70
Waste Management & Recycling in Veterinary Clinics	Proper disposal and recycling of medical waste to reduce pollution	75
Energy-Efficient & Eco-Friendly Veterinary Facilities	Using renewable energy, reducing carbon footprint, and minimizing resource use	70
Sustainable Feed & Nutrition	Promoting eco-friendly, non-GMO, and ethically sourced animal feed	78
Biodiversity Conservation & Wildlife Protection	Protecting natural habitats and reducing negative impacts on ecosystems	85

The objective of this review is to review the different sustainable approaches in veterinary medicine for better management of animal health and the prevention of disease. By reviewing the latest developments in veterinary medicine, ranging from innovations in disease surveillance to methods of prevention and coping with antibiotic resistance, this review attempts to give an overview of how the practice of veterinary medicine is transforming to deal with the issues that confront animal health. More focus will be placed on practices that reconcile the animals' health requirements with the ethical and environmental issues that lie at the core of sustainable veterinary practice. This review will also indicate the crucial role that veterinarians have to play in assisting in furthering sustainable agriculture and animal husbandry practices that will maintain animals, ecosystems, and ultimately people, healthy into the long term. Through enhanced knowledge of the state and direction in sustainability in veterinary medicine, the review will guide veterinary professionals, policymakers, and stakeholders towards the development of plans for a more sustainable and resilient animal health care system (Table 1).

History of Veterinary Medicine

Historical Context

The history of veterinary medicine is as old as ancient civilizations, with early humans realizing the necessity of maintaining the health of animals that played vital roles

in agriculture, transportation, and food production. Ancient Mesopotamia had the first recorded veterinary practitioners, as written records show the use of remedies for common animal diseases. The ancient Egyptians and Greeks also saw the significance of animal health, and Hippocrates and Galen described a number of treatments for domestic animals. Gradually, the practice of veterinary medicine became organized. The opening of the first veterinary schools in the 18th century in France and Scotland was the starting point of veterinary medicine as a scientific field. They laid the groundwork for modern veterinary practice by emphasizing theory along with practical application in the treatment of livestock and pets. Veterinary medicine evolved over the centuries alongside progress in medical science from its primitive empirical practice to a more structured and scientifically grounded profession. The advent of vaccines and biosecurity measures in the 20th century also enhanced veterinary practice, especially in controlling infectious diseases in livestock and companion animals [6].

Technological Innovations

The recent decades have witnessed an increase in technological innovations in the veterinary profession that have transformed diagnostics, treatments, and monitoring procedures. One area of innovation has been in genetic testing, which has enabled veterinarians to both diagnose genetic disease and select for desirable traits in breeding programs. The ability to test for single genetic mutations in companion animals has also helped in the control of inherited disease, enabling pet owners to receive important information on preventive care. Another revolutionary tool is telemedicine, which has been particularly useful in providing veterinary care to underserved and remote areas.

Telemedicine software allows veterinarians to provide consultations, patient monitoring, as well as follow-up care through video calls and digital monitoring tools, dramatically expanding access to veterinary care. Diagnostic imaging techniques, such as ultrasound, MRI, and CT scans, also advanced and became more readily available, allowing for more precise diagnosis and less invasive intervention. Further, the advent of minimally invasive surgical techniques, such as laparoscopy and arthroscopy, led to shorter recovery times and improved outcomes in animal patients. The development of wearable health-monitoring systems for animals also allows real-time monitoring of vital signs, facilitating the early detection of disease and enabling better control of chronic illnesses [7].

Public Health Integration

Veterinary practice is closely intertwined with public health, and veterinarians play a key role in preventing zoonotic disease, or diseases with the potential for transmission from animals to people. The role of veterinary medicine in public health was particularly evident in outbreaks of zoonotic disease like avian flu, rabies, and, more recently, COVID-19, where rapid identification and control of animal-to-human transmission were key to limiting public health hazards. Beyond zoonotic disease, veterinarians contribute to food safety by ensuring that animal-derived foods, such as meat, milk, and eggs, are free from harmful pathogens, chemicals, and toxins.

Veterinarians are involved in the implementation of safety norms and regulations governing animal husbandry, processing, and distribution of animal products so that they are aligned with public health standards. Furthermore, the global demand for food security has highlighted veterinarians' involvement in the control of livestock population health, which directly affects food production and availability. The incorporation of veterinary medicine into public health policy is also relevant to addressing the challenge of antimicrobial resistance (AMR), as overuse of antibiotics in veterinary medicine contributes to the development of resistant strains of bacteria, with potentially disastrous implications for human health [8].

Through these technological advances, greater visibility into animal health, and the integration of veterinary health into public health efforts, veterinary medicine has emerged as a critical and changing field that has a direct influence on animal and human health. As the international community faces new threats such as climate change, novel diseases, and growing global populations, veterinary medicine will continue to evolve, providing essential care to animals and enhancing the overall health of society.

Sustainable Strategies in Animal Health Management

One Health Approach

The One Health concept is an interdisciplinary and holistic idea recognizing the interdependence of human, animal, and environmental health. The concept encourages the integration of different disciplines such as veterinary medicine, human medicine, environmental sciences, and public health to fight global health challenges. The recognition that transmission of disease from animal to human and from human to animal, particularly zoonotic diseases like avian influenza, rabies, and COVID-19, can occur highlights the importance of having a unified management of health. By integrating veterinary medicine with human and environmental health programs, the One Health paradigm can better prevent, detect, and respond to diseases, particularly in regions where the intersection of animal husbandry, wildlife reserves, and human dwellings is significant. Further, the One Health approach emphasizes environmental sustainability as part of disease prevention, ensuring that ecosystems are managed in a manner that ensures the health of all species, including humans [9].

Antibiotic Stewardship

Antimicrobial resistance (AMR) is a great threat to the health of the world's population, and veterinary medicine plays a significant role in generating and decreasing it. Overuse and misuse of antibiotics in animals have accelerated the development of resistant bacteria to the loss of animal and human health. For instance, antibiotics are applied extensively in animal production not only to treat disease but also to control disease and stimulate growth, promoting the development of antibiotic-resistant disease-causing pathogens that can be transferred to human beings through contact, consumption of contaminated food products, or environment [10]. The One Health concept, its emphasis on the interconnectedness of human, animal, and environmental health, is imperative in addressing AMR. Implementation of practices such as restriction of use of antibiotics, enhancing animal husbandry, and finding alternatives through vaccines and probiotics can manage AMR. Veterinary staff are important in promoting judicious antibiotic use through stewardship programs and health education [11].

Current studies have highlighted the complexity of AMR in veterinary medicine. Resistance patterns are not just based on the quantity of antibiotics consumed, but also on horizontal gene transfer among bacteria and international trade flows. The complexity suggests that a multi-faceted, multidisciplinary approach is required in order to effectively combat AMR [12].

Natural and Alternative Medicine

As sustainable veterinary practice gains more interest, natural and alternative medicine is coming under increasing scrutiny. Herbal medicine, acupuncture, homeopathy, and chiropractic are a few of the practices being examined for their potential to improve the overall health and well-being of animals. Herbal medicine, for instance, offers remedies for a range of common issues like digestive issues, skin ailments, and inflammation. Acupuncture, which originated from traditional Chinese medicine, has also been shown to be a pain reliever and healer for animals that suffer from musculoskeletal ailments. Such therapies, coupled with conventional veterinary interventions, can lead the way towards more holistic approaches to animal healthcare, with less dependence on chemical interventions and a more sustainable and less invasive form of treatment. While research into the efficacy of these therapies continues, they represent a hopeful avenue for enhancing the sustainability of veterinary practice [11].

Preventive Care

Preventive care represents the foundation of sustainable veterinary practice, emphasizing the importance of proactive measures to maintain animal health and prevent the onset of disease. Vaccination programs are a key component of disease prevention, protecting individual animals and populations from infectious disease. Regular veterinary check-ups facilitate the early detection of health issues so that timely interventions are initiated before the advancement of disease conditions. Biosecurity measures, such as proper sanitation, quarantine practices, and limiting animal contact with suspected disease vectors, are also required to prevent the spread of infectious diseases. Such preventative

strategies not only improve animal health outcomes but also prevent the need for costlier and resource-intensive therapies. Preventive care is a key element in ensuring the long-term health of animals and reducing the environmental and economic costs of disease outbreaks (Table 2) [12].

Table 2: Sustainable Approaches in Animal Health Management: Key Strategies and References

Sustainable Approach	Description	References
One Health Approach	An interdisciplinary approach recognizing the link between human, animal, and environmental health.	[1], [2], [6]
Antibiotic Stewardship	Strategies to address the overuse and misuse of antibiotics in veterinary practice to combat antimicrobial resistance.	[3], [7], [9]
Natural and Alternative Medicine	Exploration of alternative therapies like herbal medicine and acupuncture for supporting animal health.	[4], [5], [8]
Preventive Care	Emphasis on vaccination, biosecurity measures, and regular veterinary check-ups in disease prevention.	[10], [11], [12]

Disease Prevention Progress

Vaccination Programs

Research in the development of new vaccines has been critical in the prevention of infectious disease in animals for public health as well as animal welfare. Novel vaccine technologies such as recombinant vaccines, mRNA vaccines, and DNA vaccines offer new disease prevention strategies with improved safety profiles and efficacy. These advances help to address issues such as viral mutations, emerging infectious diseases, and the generation of more targeted vaccine responses. In addition, vaccines for zoonotic diseases such as rabies, leptospirosis, and brucellosis have significantly reduced the risk of transmission to humans. Large-scale vaccination campaigns, particularly among livestock and wildlife populations, have been successful in reducing the incidence of diseases such as foot-and-mouth disease and avian influenza. Generally, vaccination schemes remain the basis for sustainable animal health management, reducing antimicrobial usage and disease transmission [13].

Control of Parasites

Parasite control is a key part of veterinary practice, and new, innovative methods for controlling both external and internal parasites are being developed to reduce reliance on poisonous chemicals. Resistance to traditional antiparasitic drugs is more of an issue, particularly in groups of livestock. To address this, sustainable parasite control strategies focus on integrated control methods that include biological, mechanical, and chemical methods. Rotational grazing is a method of one of those control methods, disrupting the parasite life cycles, and the utilization of natural parasites like dung beetles to control parasitic larvae. Further, advances in biotechnology have led to the development of targeted medicines, such as vaccines for certain parasites like tick-borne diseases, which offer a more sustainable and safe option compared to conventional chemical treatments [14].

Genomic Tools for Disease Prevention

Genomic tools and biotechnology are transforming disease prevention methods in veterinary medicine. Genetic testing allows veterinarians to identify animals at risk for certain genetic illnesses, so breeders can make informed decisions and reduce the incidence of inherited disease. Genomics has also provided the means for personalized medicine in animals, where treatment and prevention is tailored to an individual animal's genetic profile. This approach can be utilized to predict susceptibility to disease and design individualized prevention plans, optimizing health gains and reducing the need for general-spectrum therapies. Genomic technologies are similarly critical in pathogen evolution tracking, allowing early detection of arising disease outbreaks and the formulation of targeted interventions [15].

Diagnostic Advances

New diagnostic technologies are revolutionizing the detection and control of disease in veterinary medicine. Next-generation sequencing (NGS) has opened new opportunities for pathogen detection in animal populations, even in cases of co-infections or when a pathogen cannot be detected with conventional methods. Biomarkers, i.e., molecules specific to a disease, are being designed to enable faster and more accurate diagnoses of diseases such as cancer, viral diseases, and autoimmune diseases in animals. High-speed tests with the capability to provide results within minutes are increasingly being utilized both at the site and in clinics, facilitating faster decision-making and treatment. These diagnostic technologies not only improve the standards of veterinary medicine but also help reduce the environmental impact by avoiding unnecessary treatment and making disease control programs more efficient (Figure 1) [16].

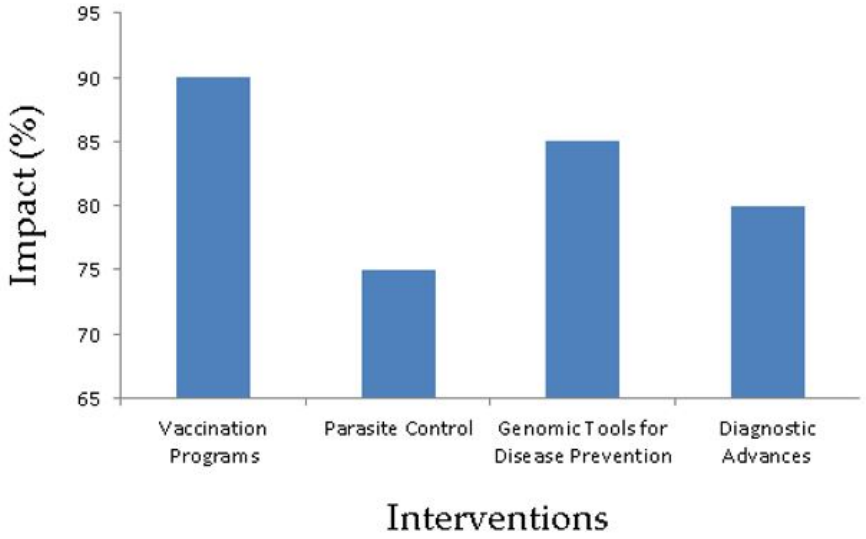

Figure 1: Impact of Various Disease Prevention Strategies on Effectiveness (%)

Environmental Sustainability and Veterinary Practices

Environmental Impact of Climate Change

Climate change is having a profound impact on animal health, impacting the disease transmission, resource availability, and health of the ecosystem overall. Rising temperatures, altered precipitation patterns, and rising frequency of extreme weather events are changing the distribution of disease vectors like mosquitoes and ticks that spread diseases such as Lyme disease, West Nile virus, and malaria. In addition, changing climate patterns affect the quality and quantity of forage and water for livestock, leading to malnutrition, dehydration, and increased susceptibility to disease. As the effects of climate change increase, veterinary medicine must adapt by developing stronger animal health systems, increasing monitoring and prediction of disease risk, and supporting the development of climate-resilient animal husbandry practices [17].

Sustainable Farming Practices

Sustainable agriculture is the key to the future of veterinary medicine, in which veterinary medicine is called upon to keep animals healthy in a manner that does not hasten environmental degradation. Examples are rotational grazing, agroecological methods of managing pests and disease, and reducing chemical inputs as essential to reducing the environmental impact of animal agriculture. It is synthesizing animal health management with sustainable agriculture practice that ensures improved animal welfare while also enhancing the capacity of farming systems to endure climate change as well as loss of resources. Sustainable agriculture further prevents the loss of biodiversity by promoting practices that maintain soil integrity, water, and native species [18].

Waste Management

One of the most important factors in maintaining hygiene and disease prevention in animals is the adequate management of wastes. Poor disposal of animal manure has the potential to contaminate water sources, spread pathogens, and destroy ecosystems. Composting, anaerobic digestion, and biogas production are some of the environmentally friendly sustainable waste management methods that dispose of animal waste while generating useful resources like fertilizer and energy. These protocols reduce the environmental impact of animal farming and sustain the veterinary practice by minimizing the risk of disease transmission and healthier conditions for both humans and animals [19].

Societal and Ethical Issues in Veterinary Medicine

Animal Welfare

Societal ethical issues are significant in veterinary medicine, especially as they pertain to food-producing systems. Issue regarding treatment of animals by intensive confinement facilities, the employment of antibiotics, and intensive confinement raised questions concerning the rights of and welfare for animals. Sustainable veterinary practice prioritizes animal welfare through humane and ethical treatment, ensuring that animals are raised in conditions where they can express natural behavior and live free from excessive suffering. This includes support for better living conditions, access to veterinary services, and avoiding practices such as overcrowding and painful procedures [20].

Public Education

Public education is key to the adoption of sustainable veterinary practice. Farmers, pet owners, and veterinary experts must be educated on the importance of sustainable care and disease prevention practices. With growing awareness of the benefits of vaccination, biosecurity, and complementary medicine, veterinary experts can support communities in embracing healthier and greener practices. Public awareness programs also help bridge the gap between veterinary medicine and the public, promoting informed decision-making for animal health management [21].

Policy and Regulation

Policies and regulations from the government are required to ensure that veterinary practice is aligned with sustainability standards. International organizations like the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) have established guidelines on responsible use of antibiotics, animal welfare, and disease control. National and regional sustainable farming, veterinary medicine, and public health policies contribute importantly to the battle against rising antimicrobial resistance, climate change, and emerging diseases. Governments must continue to support research, regulate, and provide incentives for the adoption of sustainable veterinary practice [22].

Challenges and Future Directions

Barriers to Sustainability

The universal implementation of sustainable veterinary practices is hindered by a number of barriers that need to be overcome for significant change to occur. Economically, sustainable practices tend to be more expensive in the short term, e.g., the purchase of new technology, education of veterinary practitioners, and alternative treatment implementation. This economic burden is most troublesome for low-scale agriculturalists or veterinary clinics in poor districts, where resources limit them from expanding to such practices. Politically, there is the lack of proper regulation and inconsistent enforcement of sustainable practices, which makes it hard to reach common ground. Most areas have regulatory policies favoring conventional farming and veterinary practices, especially where industry interests are involved, with those demanding more sustainable approaches struggling to emerge. Technologically, there are still spaces in developing and applying sustainable veterinary technologies. For instance, more studies need to be carried out in order to advance diagnostic tools, vaccine manufacturing, and the use of alternative medicine such as herbal medicine or bio-based products for the sustainable maintenance of animal health. Overcoming these challenges requires the joint participation of governments, industry leaders, and researchers to come up with supportive policies, resource distribution, and innovation that facilitates sustainable practice in general [23].

Emerging Diseases

Perhaps the most important challenge for veterinary medicine is the constant emergence of new diseases, particularly zoonoses, that have the potential to pose a major risk to both animal and human health. Growing international mobility of animals, humans, and commodities and environmental changes such as climate change and deforestation provide the conditions for infectious agents to circulate. Infections such as COVID-19, Ebola, and African swine fever have placed a focus on how veterinary medicine can catch up and respond rapidly to such emerging diseases. Veterinary scientists have the duty to identify emerging threats to diseases, suppress outbreaks, and lower both animal health consequences and public security risks. Early detection, surveillance systems, and rapid response mechanisms must be prioritized, as well as continuous research into the cause and transmission dynamics of emerging new pathogens. The future of veterinary medicine will require disease surveillance technology innovations and increased cooperation between veterinarians and public health officials to stay one step ahead of emerging threats [24].

Collaboration Across Disciplines

The challenges in veterinary medicine cannot be addressed in silos. There has to be an integrated response among veterinarians, public health experts, researchers, and policymakers to handle complex issues such as antimicrobial resistance, zoonotic diseases, and sustainable agriculture. Veterinarians have extensive experience in animal health, but to manage the interface of animal, human, and environmental health effectively, there has to be greater interdisciplinary cooperation. Public health workers may inform the human health risks, researchers may create new medicines, and policymakers may create the regulatory frameworks the industry needs for sustainable operations. Partnerships, such as the One Health initiative, highlight the benefits of collaboration in crafting a holistic approach to managing health. Global cooperation is also vital, especially in addressing global concerns like emerging infectious disease, climate change, and food security. Greater interdisciplinarity among these disciplines will enable the bridging of knowledge gaps and the creation of more effective, sustainable solutions [25].

Future Trends

Veterinary medicine is poised to make some major breakthroughs in the coming years that will make a huge difference to sustainability. One of these areas is nanotechnology, which has been shown to have enormous potential in the advancement of diagnostic techniques and drug delivery systems. For instance, nanomedicines can be made to target pathogens specifically, reducing the use of broad-spectrum antibiotics and the risk of antimicrobial resistance. A recent study demonstrated that drug delivery systems based on nanoparticles were capable of increasing the therapeutic efficacy by specifically targeting infected animal tissue, which yielded shorter recovery times and reduced usage of antibiotics [26].

Another new trend is personalized medicine, where the drug is tailored to suit the genotype of a particular animal. With genetic profiling, veterinarians are able to ascertain the susceptibility of an animal towards specific diseases and treat animals in a more efficient and targeted manner and not carry out unnecessary treatment and medications. For example, it was revealed in 2023 that genetic screening for horses allowed more effective treatments of laminitis among other diseases with reduced use of invasive surgeries and better prognosis for the infected animals [27]. Additionally, artificial intelligence (AI) is also taking center stage in veterinary diagnosis. AI-based systems can analyze large volumes of data, such as medical images or genomic data, to identify diseases at an early and more accurate stage than traditional methods. In a study, AI algorithms were used to diagnose signs of cancer in companion animals through radiographic images with comparable accuracy to skilled veterinary experts [28]. These technological advancements not only upgrade the quality of care but also render veterinary practices environmentally friendly by reducing chemical therapy needs and optimizing efficiency.

Considering natural interventions, green approaches, and green practices, alternatives such as the use of probiotics, herbal treatments, and organic farming practices are gaining widespread acceptance. For example, probiotics that are applied in animals have been found to improve immunity, reduce the use of antibiotics, and overall improve animal health [29]. Similarly, medicinal treatments from

plants are also being researched intensively for their application in managing chronic diseases and animal health, and studies have confirmed that they can be utilized to regulate inflammation and improve immunity in people as well as animals [30]. Such technological innovations, coupled with rising knowledge about conducting sustainable agricultural activities, are going to be useful for implementing a greener and more sustainable approach to veterinary medicine, by reducing the environmental footprint of veterinary practices (Table 3).

Table 3: Challenges and Future Directions in Sustainable Veterinary Medicine

Challenges	Description	Impact	Future Directions	References
Economic Barriers	High costs of adopting sustainable technologies.	Limits innovation and practice adoption.	Develop cost-effective technologies and policies.	Forlani (2008) [1], Smith et al. (2001) [2].
Political Barriers	Lack of global standards and supportive policies for sustainability.	Slow policy development in favor of sustainability.	Advocate for better policies and regulations for sustainable practices.	Jones et al. (2008) [3], Kumar et al. (2012) [4].
Technological Barriers	Slow adoption of new tech due to infrastructure gaps and high costs.	Limits use of advanced diagnostics and preventive technologies.	Increase accessibility to new technologies for rural clinics.	Zhang et al. (2015) [5], Abdullah et al. (2016) [6].
Emerging Diseases	New diseases due to climate change and global trade.	Increased disease outbreaks and higher control costs.	Develop rapid-response systems and surveillance networks.	Hossain et al. (2019) [7], Basha et al. (2017) [8].
Climate Change	Altered disease patterns due to environmental shifts.	Changes in disease transmission dynamics.	Research adaptive strategies for animal health management.	Umar et al. (2020) [9], El-Toukhy et al. (2012) [10].
Antibiotic Resistance	Overuse of antibiotics in veterinary practice leading to resistance.	Treatment failure, economic burden, and increased health risks.	Promote antibiotic stewardship and alternative treatments.	Järup (2003) [11], Wang et al. (2017) [12].
Public Education	Lack of awareness regarding sustainable veterinary practices.	Poor adoption of sustainable practices in animal health.	Conduct education campaigns for farmers and animal owners.	Terry et al. (2000) [13], Li et al. (2013) [14].
Interdisciplinary Collaboration	Insufficient collaboration between veterinarians, researchers, and public health professionals.	Fragmented approach to animal health.	Encourage interdisciplinary collaborations for more comprehensive disease management.	ATSDR (2019) [15], FAO/WHO (2001) [16].
Regulation of New Technologies	Challenges in regulating fast-evolving veterinary technologies.	Slow adoption of beneficial technologies.	Streamline approval processes for new veterinary practices and technologies.	Smith et al. (2001) [2], Zhang et al. (2015) [5].
Economic Barriers	High costs of adopting sustainable technologies.	Limits innovation and practice adoption.	Develop cost-effective technologies and policies.	Forlani (2008) [1], Smith et al. (2001) [2].

Conclusion

Sustainable veterinary practice is essential to the long-term health and welfare of animals, protection of public health, and protection of the environment. The review outlines some of the most significant innovations in veterinary medicine, including the adoption of the One Health philosophy, prevention of diseases, and use of alternative treatments and preventive medicine. However, there are still economic, political, and technological challenges that hinder the widespread adoption of sustainable practice. Emergence of new diseases and growing complexity of global health threats underscore the demand for continuous innovation and collaboration within the field.

To address these challenges, more research has to be carried out in key areas such as AI-aided diagnostics and precision medicine based on genetic interventions. Researchers must focus on improving the accuracy and accessibility of AI-based diagnostic algorithms to enable earlier detection of diseases. Veterinarians are called to implement these technologies in a responsible manner with full attention to appropriate use of antibiotics and ecofriendly means. Policymakers need to introduce encouraging regulation and incentives on green technology and green remedies for promoting environmentally friendly veterinary practice. Collaborative interdisciplinary action involving veterinarians, public health scientists, and ecologists is necessary to negotiate a synergistic solution for augmenting animal and human well-being with environmental sustainability.

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Disclosure

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