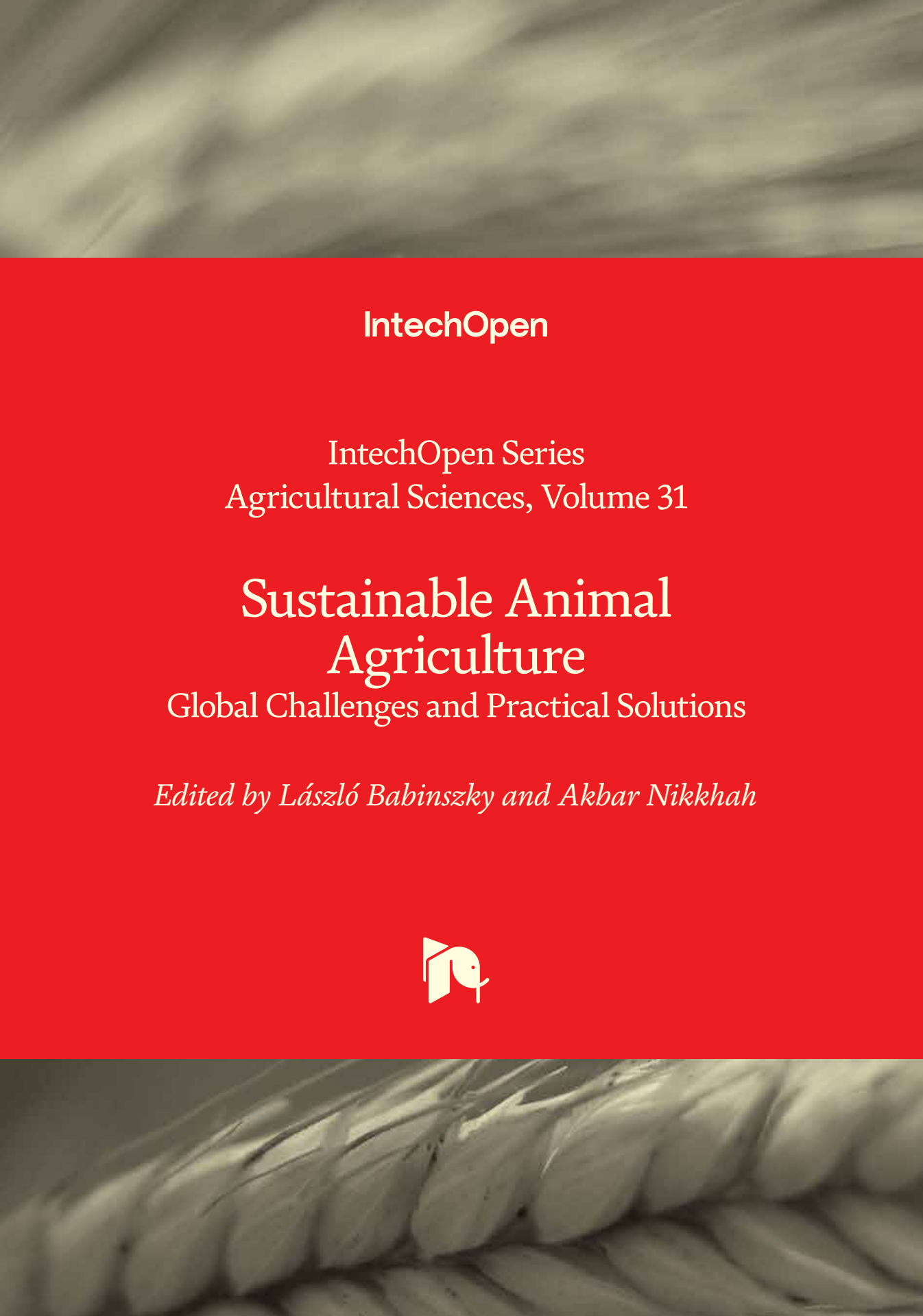




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Sustainable Animal Agriculture

Global Challenges and Practical Solutions

Edited by László Babinszky and Akbar Nikkhah



Sustainable Animal Agriculture - Global Challenges and Practical Solutions

*Edited by László Babinszky
and Akbar Nikkhah*

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Agricultural Sciences

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Aims and Scope of the Series

The importance of agriculture cannot be overstated. It helps sustain life, as it gives us the food we need to survive and provides opportunities for economic well-being. Agriculture helps people prosper around the world and combines the creativity, imagination, and skill involved in planting crops and raising animals with modern production methods and new technologies. This series includes two main topics: Agronomy and Horticulture, and Animal Farming. This series will help readers better understand the intricacies of production agriculture and provide the new knowledge that is required to be successful. The success of a farmer in modern agriculture requires knowledge of events happening locally as well as globally that impact input decisions and ultimately determine net profit.

Meet the Series Editor



W. James Grichar has been employed with Texas A&M AgriLife Research for over 45 years with an emphasis on research in agronomy, plant pathology, and weed science. He obtained his BS from Texas A&M in 1972 and his Masters of Plant Protection in 1975. He has published 195 journal articles, over 330 research reports and briefs, 11 book chapters, and over 300 abstracts of profession meetings. He also directs research in many crops including corn, grain sorghum, peanuts, and sesame. He has held various positions in different professional societies including the American Peanut Research and Education Society, Southern Weed Science Society, and Texas Plant Protection Conference in addition to being Associate Editor for Peanut Science and Weed Technology. Significant accomplishments have included spearheading efforts to determine the optimum planting time for soybean production along the upper Texas Gulf Coast. These efforts have shown growers that soybean yields can be improved by 10 to 20% by following a late March to early April plant date. He also has been instrumental in developing a herbicide program for peanut production in the south Texas growing region. Through the development and use of herbicides that are effective against major weed problems in the south Texas region, peanut yields have increased by 25 to 30%.

Meet the Volume Editors



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Prof. Akbar Nikkhah is a Highly Distinguished Professor and Scientist conducting multidisciplinary and interdisciplinary education and research, primarily in animal and dairy sciences, as well as nutrition. Dr. Nikkhah is also a poet composing poetry in different languages. Nikkhah's innovative science has been improving the quality of human life for all.

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Preface

Contrary to popular belief, sustainability is not a modern term. Historical records show that the idea of “sustainable development” emerged as early as 1713, when Hans Carl von Carlowitz, a Saxon tax accountant and mining administrator, published the first book on forestry (*Sylvicultura oeconomica*). In this book, the authors warn that wood is as essential as daily bread; therefore, forests must be used in a way that ensures tree growth remains in balance with the demand for timber. In his view, only this mindset allows for continuous forest use in the long term.

Since the 18th century, the definition of this term has undergone significant changes.

The current situation is well illustrated by the fact that there are now nearly 300 definitions of sustainability in the scientific literature, but there is still no universally accepted definition.

However, this term is playing an increasingly important role in global production. Compelling circumstances, such as environmental pollution, climate change, and various social problems, are prompting humanity to consider environmental protection, social responsibility, and economic viability in the long term, whether in industrial, agricultural, or other production contexts.

Agriculture, and within it, animal agriculture, plays a crucial role in sustainable production. As is well known, livestock farming has a significant ecological footprint, as it contributes considerably to greenhouse gas emissions and freshwater pollution. Furthermore, livestock farming drives increased land use, contributing to deforestation, particularly in regions where land is cleared for grazing or to grow crops for animal feed. Thus, the relationship between production and the environment is one of the key pillars of sustainability. The second pillar is society, which, through politics, regulations, legislation, and communication, can establish production systems that consider not only short-term interests but also those of future generations. The third pillar of sustainability is economic interest. This pillar suggests that if a form of production is not economically viable, it will be unsustainable in the long term and will have a negative impact on future generations.

In other words, profit-oriented production must be designed to be consistent with both current and future environmental and social expectations.

It is now also clear that sustainable animal agriculture is inconceivable without a healthy animal population and healthy compound feeds, as the production of safe and healthy animal-based foodstuffs for consumers is only possible with healthy animals and feeds that are both healthy and safe. This obvious fact highlights the importance of the relationship between animal and human health. Of course, the health status of the human population is also influenced by other important factors, such as the health of the environment or the society’s commitment to preserving human health. This brings us to the concept of One Health (OH).

The OH concept is also based on three pillars: environmental health, human health, and animal health (including both domestic and wild animals).

It is essential to recognize that the three main pillars of sustainability necessitate addressing numerous smaller challenges. Therefore, our book also explores topics that at first glance seem unrelated, but in fact all serve to promote the realization of sustainable livestock farming.

The same statement applies to the implementation of the OH concept.

The book aims to present the latest scientific findings in the field of sustainable animal agriculture (cattle, pigs, and poultry) and their practical application. A further aim is to present the role of the “One Health” concept in sustainable animal farming.

The authors of the book’s chapters are internationally recognized experts in their respective fields. Therefore, we hope that readers will find this information valuable and applicable to their everyday professional activities. If this is the case, then our efforts have not been in vain.

We recommend this book to researchers, university lecturers, PhD students, and all those involved in the practice of animal agriculture.

I want to thank the chapter authors for their excellent contributions. I am also grateful to the staff at IntechOpen for their technical assistance in publishing the book, especially Publishing Process Manager Ms. Karmen Daleta and Senior Commissioning Editor Ms. Lucija Tomicic-Dromgool.

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Chapter 1

Sustainable Swine Feeding: A Holistic Approach to Improve Productivity in Line with the One Health Concept

Veronika Halas, László Babinszky and Hedvig Fébel

Abstract

In the twenty-first century, animal agriculture worldwide faces challenges such as the growing demand for safe and healthy animal-derived foodstuffs (e.g., pork); furthermore, the rising environmental pollution from livestock production and global climate change. It is now clear that these problems can only be addressed with holistic solutions based on the principles of sustainability and the One Health concept. Therefore, the aim of this chapter is to present the key elements of sustainability and the One Health concepts and evaluate various feed additives used in the feed industry, as well as practical pig feeding strategies, based on the principles of sustainability and One Health. Based on the analysis of the data of more than 130 references, the following most important conclusions were drawn: (1) Promising alternatives to unsustainable growth promoters include postbiotics, parabiotics, and phytobiotics; however, it is important to emphasize that further validation on the farm is required. (2) To achieve sustainable pork production, it is necessary to implement special feeding solutions for sows and piglets that minimize the need for medication. (3) Sustainable feeding strategies are particularly important during the weaning phase. Methods are now available that support the optimal development and functioning of the gastrointestinal tract, thereby preventing gastrointestinal disorders such as postweaning diarrhea.

Keywords: swine nutrition, sustainability, One Health, feed additives, efficiency

1. Introduction

The global livestock sector faces several serious challenges in the twenty-first century. These include the growing world population, the increasing demand for high-quality, safe, and healthy animal-derived food, the reduction of arable land suitable for agricultural production, the rising environmental pollution from livestock production, global climate change, and the rapid depletion of the Earth's

freshwater resources [1]. According to various professional forecasts, the world's population will reach 10 billion by 2050, and food production will need to increase by 70% to meet the demand [2]. Statistical data show that pork is one of the most widely consumed meats globally, accounting for 34% of total meat consumption in 2022, alongside poultry (40%) and beef (22%) [3]. Global pork consumption grew by 77% between 1990 and 2022, reaching 113 million tons. Statistical data also forecast increasing global demand for pork, driven mainly by population and income growth in developing countries, excluding those influenced by Islamic and Jewish dietary restrictions. In turn, the growth of pork production may cause significant environmental problems.

Pig farming systems differ in their capacity to achieve key sustainability goals, including minimizing environmental impacts, mitigating climate change, reducing land use, enhancing economic viability, and improving animal welfare [4]. Achieving true sustainability is challenging, as these goals often conflict, requiring compromises to balance priorities. Thus, the question arises: can such a complex set of requirements be met to ensure that the global demand for pork is met in the right quantity, quality, and sustainable manner?

The growing global environmental challenges require pig farmers and scientists to improve production efficiency and reduce the environmental footprint of pork production. Sustainability is traditionally defined by three pillars: environmental protection, social responsibility, and economic viability [5]. However, societal perceptions and scientific claims can conflict, necessitating resolution for progress in pork production. Public acceptance of technologies is heavily influenced by scientific communication and media, including traditional outlets and social platforms.

Modern sustainable livestock farming is inseparable from animal welfare and healthy livestock, essential for animal well-being, food safety, and consumer health. This aligns with the One Health concept, which integrates the health and welfare of people, animals, and the environment [6]. These shared goals make sustainability and One Health (OH) complementary frameworks for producing safe, sustainable, and healthy pork.

This chapter aims to outline key elements of sustainable pig feeding to enhance productivity within the One Health framework. We critically evaluate different feed additives used by the feed industry and highlight practical feeding strategies aligned with sustainability and OH principles.

2. Sustainability

In the past three decades, it has become increasingly evident that global production and services cannot continue as they have been without causing severe, irreversible effects on our planet and, consequently, on humanity. As early as 1996, Vavra [7] warned that if the pace of resource exploitation continues, it will lead to the exhaustion of the Earth. This statement also applies to the agricultural sector. Most scientists agree that current livestock production systems are unsustainable, but the path toward a solution is imagined in various ways.

2.1 The concept and definitions of sustainability

The concept of sustainability, first articulated in the eighteenth century, has undergone significant changes over the centuries, yet science still owes it a precise

definition. The situation is well illustrated by the fact that there are nearly 300 definitions attempting to clarify what sustainability means, and further refinement of the concept is still needed [8].

A major milestone in defining sustainable development occurred in 1987, when the United Nations provided a relatively precise definition in the so-called Brundtland Report (World Commission on Environment and Development). The report was named after Gro Harlem Brundtland, a Norwegian physician and former prime minister, who chaired the commission in the mid-1980s. The final report was published in 1987 and was titled “Our Common Future.” According to the Brundtland Commission’s definition, sustainable development is “...development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [9]. The report is based on the premise that the only truly sustainable form of progress is one that simultaneously addresses the interrelated aspects of the economy, environment, and social well-being.

Although the definition of sustainable development has been modified in various ways and redefined according to different aspects since the Brundtland Commission’s report [10], it still forms the foundation of many definitions today.

2.2 Models of sustainability

The familiarity of sustainability as a concept is partly due to a simple and comprehensible model consisting of three dimensions: environmental (conservation), economic (growth), and social (equity) [10]. This model, known as the “three-pillar” (TP) or “triple bottom line” model (TBL) or the 3-overlapping-circles model, illustrates that sustainability lies at the intersection of these three factors. This approach encompasses environmental protection, social responsibility, and economic viability [5], but not necessarily organic agriculture.

Akkermans [11] summarized the content of the three pillars of sustainability in a very concise and clear manner:

- *Environment*: The environmental pillar of sustainable development includes regulations, laws, and other tools used to address environmental issues such as the management of land, freshwater, oceans, forests, air, natural resources, and wildlife. This pillar focuses on our planet and the human activities that impact the Earth. It aims to promote the recognition of our dependence on the diverse ecosystems of the planet and to take tangible steps to minimize human-caused negative effects.
- *Society*: The social pillar refers to initiatives, public policies, planning, and regulations that support social issues. It also includes how businesses engage with people—employees, customers, and the broader community.
- *Economy*: The economic pillar (or “profit”) encompasses the creation of economic value that also considers environmental and social costs. This pillar suggests that if something is not economically viable, it will be unsustainable in the long term and will have harmful effects on future generations.

Akkermans [11] emphasizes that the three pillars of sustainability are not separate, independent areas but form a unified system. He also stresses that to achieve sustainable development (whether local, national, or global), the social,

economic, and ecological elements must actively complement and strengthen each other. The conclusion drawn from this is that the more precisely we define the content of each pillar, the more accurately we can define the concept of sustainability.

2.3 Sustainability in agriculture and livestock production

Representing sustainability as a “triple bottom line” implies that true sustainability requires considering all three aspects. However, sustainable agriculture must take into account a fourth aspect, too. In livestock production, there are important ethical considerations regarding animal welfare [12]. There are several conflicting goals among the four sustainability aspects. For instance, economic efficiency increases when animals are kept in smaller spaces (i.e., higher animal density), which can lead to a deterioration in animal welfare. Similarly, promoting natural animal husbandry through deep litter bedding may increase ammonia emissions in the livestock sector.

Due to such reasons, further analysis of livestock systems is necessary, and the concept of sustainable livestock production needs to be refined [12].

2.4 The role of animal nutrition in sustainable livestock production

Heinzl [13] emphasizes that feeding plays a key role in achieving sustainable livestock production, with three main areas where the feed industry can contribute:

Optimal utilization of feed resources, including the optimization of feed conversion, maintaining feed quality, and the use of alternative ingredients. Optimizing the use of feed resources involves improving feed conversion, maintaining feed quality, and incorporating alternative ingredients not competing with human foods. Efficient nutrient utilization relies on gut health, supported by additives like enzymes and phytomolecules. Preventing nutrient loss due to poor storage or transport requires acidifiers, toxin binders, and antioxidants. Addressing stress with vitamins, trace elements, and plant-based additives further boosts feed efficiency.

Protecting the environment by reducing ammonia and methane emissions and reducing the energy demand of the feed industry: ammonia emissions can be reduced by improving protein digestion and amino acid utilization, aligning digestible amino acids with animal needs to minimize urinary nitrogen. While methane is a greater concern in ruminants, fiber-rich diets may still increase methane output in pigs.

Reducing the use of antibiotics to preserve their effectiveness for future generations: antibiotics have long been used to combat bacterial diseases, but their overuse increased antimicrobial resistance. Therefore, reducing growth promoter antibiotic use in animal husbandry is crucial for the sake of consumers. There are many options for this purpose, ranging from phytomolecules to egg immunoglobulins, beta-glucans/mannan-oligosaccharides (MOS), and various acidifiers (discussed in detail in Section 4.3.2).

As shown above, animal nutrition and feeding play a key role in sustainable livestock production, but animal health may be even more critical. Sick animals underperform, leading to economic losses, and their treatment can pose risks to consumer health and the environment. Therefore, it seems logical to integrate animal health into the sustainability concept with the help of the One Health approach.

3. The One Health concept

3.1 The history and current definitions of the One Health concept

Similar to sustainability, there is no unified, universally accepted definition of the One Health concept. Many define it simply as an approach that recognizes the interconnectedness of human health with animal health and our shared environment. According to Calistri et al. [14], “the One Health approach can be defined as a collaborative and multidisciplinary effort at local, national, and global levels to ensure optimal health status for humans, animals, and the environment.” The WHO [15] defines OH as an integrated, unifying approach that aims to balance and optimize the health of people, animals, and ecosystems in a sustainable way. The American health organization CDC (Centers for Disease Control) defines One Health as a collaborative, multisectoral, and transdisciplinary approach—working at the local, regional, national, and global levels—to achieve optimal health outcomes by recognizing the interconnections between people, animals, plants, and their shared environment [16]. Brown et al. [17] define this concept as “a unifying approach aimed at balancing and optimizing the health of people, animals, and ecosystems in a sustainable manner, recognizing the mutual dependencies and connections between humans, animals (both domestic and wild), plants, and the broader ecosystem.” The authors conclude in their review article that the literature primarily focuses on human and animal health, making the OH approach overly human-centric. Despite the concept’s suggestion of a shared “health care” across all fields, they suggest a more accurate OH concept could be achieved through a broader approach that includes greater integration of environmental and social sciences [17].

3.2 One Health models

In the literature, like the concept of sustainability, the OH concept is illustrated in various ways. OH models are similar to sustainability models in that experts often define the key components of these models differently.

The OH concept is built on three major scientific areas: environmental health, human health, and animal health (including both domestic and wild animals). One Health lies at the intersection of these three factors. Thus, OH represents a holistic approach to health, acknowledging the interdependence of human, animal, and (plant) health. One of the core principles of One Health is that diseases can be transmitted between animals and humans, and that environmental health plays a critical role in the health of both humans and animals [18].

From an animal husbandry perspective, One Health implies that the productivity and efficiency of this sector are determined by the interactions between animals, the environment, and workers. As already evident from the above, the foundation of sustainability lies in the environment (Earth), society (people), and the economy (profit generation dependent on production efficiency). It is also clear that the fundamental elements of the One Health concept are the health status of the environment, humans, and animals.

This raises the question of whether sustainability can be extended to the One Health concept; in other words, whether these two models can be combined. If so, would this integration result in a more precise and flexible model?

3.3 Expanding sustainability with the One Health concept

Sustainable livestock farming, and within it, sustainable feeding practices, cannot be fully realized without considering the health status of animals. Perry et al. [19] suggest that combining sustainability concepts with animal health perspectives enables a richer and more thorough analysis. The authors propose adding the animal-related pillar of One Health to the three traditional pillars of sustainability—economy, society, and environment—when dealing with livestock systems. They believe that improving livestock health can contribute to numerous environmental, economic, social, and health aspects of sustainability.

This raises the question of why livestock health is so important in sustainable livestock farming and how it impacts human population health. The issue needs to be examined from multiple angles. First, it is essential to understand how animal diseases affect the efficiency of production in specific sectors and how diseases alter the quality of animal products. Second, it is crucial to recognize the health risks that food products derived from diseased livestock might pose to consumers. Third, are there any feed additives that could negatively impact the quality of animal products and consumer health?

The case study analysis of Oxford Analytica [20] concluded that animal diseases reduce global production by 80 billion kilograms of meat and 179.5 billion kilograms of dairy annually, leading to a \$358.4 billion decrease in farmers' global yearly income. This sum represents not only a significant financial loss but also a severe drop in production. The same study also notes that in the pig sector, every one percent decrease in the global animal disease level results in an additional \$2.9 billion in revenue.

These figures indicate that sustainable livestock farming is unachievable without considering animal health, as diseases cause massive profit losses in the affected sector. Animal diseases not only affect the health of food animals but also pose risks to the health of people consuming animal-derived products.

In many cases, antibiotics are used to treat some animal diseases, which can pose serious health risks to consumers. While antibiotics can be useful when appropriately used for infection treatment or prevention, excessive use increases the number of resistant bacteria. It is proven that if an animal carries resistant bacteria, these bacteria can transfer to humans. Once resistant bacteria enter the human body, they can remain in the intestines and spread throughout the body or between individuals. Moreover, the extensive use of antibiotics in livestock feed can lead to so-called cross-resistance, making antibiotic treatments for human patients ineffective in many cases. Resistance has developed after the advent of every major class of antimicrobial drugs, varying in time from as short as 1 year (penicillin) to >10 years (vancomycin) (reviewed by Tadesse et al. [21]). According to the WHO's report, 700,000 deaths per year can be attributed to diseases that have become difficult to treat because of antibiotic resistance, and by 2050, that number could reach 10,000,000 [22].

The link between animal and human health is further complicated by the routine use of antibiotic growth promoters (AGPs) in livestock feed. The use of AGPs in animal diets has a long history, dating back to the mid-1940s when production benefits from antibiotics were first observed in broiler feed in the U.S. (see Section 4.1.1 for details).

These points highlight the close link between animal health and human population health. This suggests that applying sustainability and the One Health concept jointly in agriculture, especially in livestock farming and feeding practices, is essential. Therefore, we recommend expanding the "Sustainability Concept" with elements of "One Health" and applying this expanded model in feed practices, for example, in

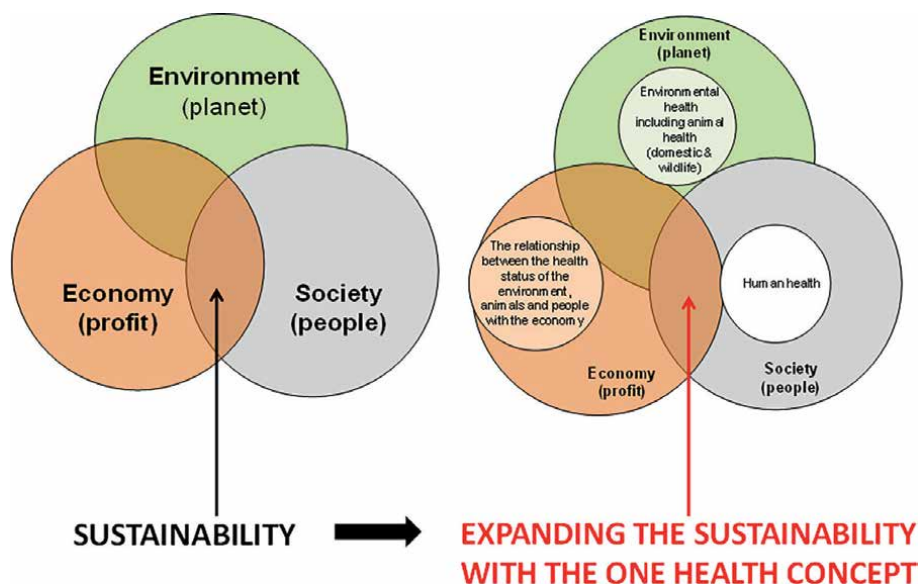


Figure 1.
 Expanding the concept of sustainability with the One Health concept.

evaluating compound feed and feed components. This expanded sustainability model is shown in **Figure 1**.

In the following section, some aspects of swine feeding, as well as the most important feed supplements, will be evaluated in the spirit of this approach.

4. Use of feed additives to improve sustainability with particular regard to the One Health concept

As highlighted above, livestock feeding in the twenty-first century requires a strong focus on sustainability, which includes feed security and safety, high biological efficiency, and a well-controlled pharmaceutical strategy supporting an integrated approach to maintaining both animal and human health.

According to the Total Nutrition Concept [23], dietary nutrients and nutraceuticals together determine the feeding value of a diet. Feed components yield the macro- and micronutrients; however, their bioavailability—digestibility or availability—can be modified by various feed additives. In this section, we introduce the zootechnical feed additives that are available on the market and used in pig nutrition that have relevance to sustainability. By definition, zootechnical additives are any additives used to favorably affect the performance of animals in good health or used to favorably affect the environment and include the following functional groups: (1) digestibility enhancers: substances that, when fed to animals, increase the digestibility of the diet through action on target feed materials; (2) gut flora stabilizers: microorganisms or other chemically defined substances that, when fed to animals, have a positive effect on the gut flora; (3) substances that favorably affect the environment; and (4) other zootechnical additives [24]. In the context of the One Health approach, we will discuss digestibility enhancers, which are mainly enzymes and acidifiers supplemented exogenously to compound feeds; gut flora stabilizers like probiotics, prebiotics,

symbiotics, postbiotics, and herb extracts (phytobiotics); as well as different growth enhancers, like subtherapeutic antibiotics, hormones, and specific trace elements.

4.1 Growth promoters

Growth promoters are feed additives containing specific substances or bioactive components used to enhance growth rate, improve feed efficiency, and ensure better overall health and productivity. These additives play a significant role in modern animal production, and particularly pig production systems, by optimizing performance while maintaining animal welfare and food safety standards. Although they are effective, there are a number of growth promoters whose use is not sustainable since they do not align with the One Health approach. Producers nowadays, particularly in Europe, increasingly seek natural, eco-friendly alternatives to synthetic additives to address environmental and consumer concerns.

4.1.1 Antibiotic growth promoters (AGPs)

As mentioned, historically, antibiotics were used at subtherapeutic levels to enhance growth and prevent disease in food-producing farm animals. The first evidence of the beneficial effects of AGP in animal performance was observed almost 80 years ago in poultry and pigs; however, at that time, the growth promotion was attributed to a so-called “animal protein factor” [25]. The mode of action of AGPs includes lower pathogen load via their inhibition of the normal intestinal microbiota, a higher rate of nutrient digestibility and absorption including amino acids, glucose, fatty acids, Ca, and trace elements, therefore better nutrient supply, energy, and nitrogen balance, as well as a reduction in the maintenance costs of the GI system (**Table 1**) [26].

Concerns about antibiotic use as growth promoters were formally raised as early as 1969 when biologist Michael (Lord) Swann presented a report to the British Parliament recommending a ban on subtherapeutic antibiotic use in animal feed. Following the Swann Report, the UK banned a number of antibiotics used as growth promoters, firstly penicillin and tetracycline.

However, new generations of antibiotics were continuously developed and routinely used in livestock farming. As the number of human deaths caused by AMR bacteria increased, regulations on antibiotic use in animal production became progressively stricter, particularly in Europe. By 2006, the European Union prohibited all antibiotic feed additives in daily routine [27].

It is important to note that these regulations apply only to EU member states and animal products exported to the EU. AGP use is regulated differently in other regions. In the U.S., restrictions on AGP use in feed have gradually increased. India only introduced limits on antibiotic residues in meat in 2011, while Brazil, Mexico, and several Latin American countries continue to use antibiotics both therapeutically and as growth promoters. The U.S. and Canada have also moved to limit the use of antibiotics in feed, and in January 2017, a new regulation was implemented requiring a veterinary prescription for therapeutic veterinary feed additives [28, 29].

Recently, a meta-analysis of Lekagul et al. [30] revealed that tetracycline was among the most commonly used antibiotics in pigs globally, with tetracycline resistance genes being some of the most prevalent antibiotic resistance genes found in the pig microbiome. Burow et al. [31] noted that contact with antibiotic-treated animals can facilitate the transfer of resistance to bacteria in untreated animals. Available data show that numerous wildlife species carry antimicrobial-resistant bacteria in a wide

Physiological	Nutritional	Metabolic
<i>Increase</i>		
	Energy retention	Liver protein synthesis
	Nitrogen retention	Gut alkaline phosphatase
	Vitamin absorption	
	Trace element absorption	
	Glucose absorption	
	Calcium absorption	
	Plasma nutrients	
<i>Decrease</i>		
Food transit time	Gut energy loss	Ammonia production
Gut wall diameter	Vitamin synthesis	Toxic amine production
Gut wall length		Aromatic phenols
Gut wall weight		Bile degradation products
Fecal moisture		Fatty acid oxidation
Mucosal cell turnover		Fecal fat excretion
		Gut microbial urease

Table 1.
Summary of reported physiological, nutritional, and metabolic effects of growth-promoting antibiotics (reviewed by Gaskins et al. [26]).

range of habitats, evidenced by the interface between human populations, domestic animals, and natural ecosystems [32]. In line with that, AMR bacteria have been identified even on various organic pig farms across Europe, albeit at lower levels compared to conventional farms [33]. It should be noted that AGPs significantly enhanced the growth performance of pigs and piglets by 15–20% when first introduced in the ‘50s. While AGPs continued to reduce postweaning diarrhea, their benefits have diminished over time due to improved farm hygiene, better management practices, and advancements in animal nutrition techniques. The ongoing challenge of antimicrobial resistance and its occurrence in the ecosystem underscores the need for stricter regulations and alternative strategies to ensure sustainable livestock production.

4.1.2 *Hormones, β -agonists, and Gonadotropin-Releasing Hormone (GnRH) analogues*

Hormones are natural endogenous drivers of physiological transactions. It is well-known that growth and reproduction are under the regulation of the endocrine system. In the ‘40s, there was active research on finding possible hormonal treatments as growth promoters. It included identifying effective hormones, specifically natural sex hormones, determining their proper dosages, and developing administration methods to improve feed efficiency and carcass quality [25]. Despite the positive experiences on use of estrogen and porcine somatotropin (pST), from ‘60s some European countries initiated to ban the use of hormones in farm animals due to the concerns over potential hormone residues. In the ‘80s, synthetic analogues, so-called β -adrenergic agonists, were tested, and their effectiveness in improving muscle mass and reducing carcass fat was confirmed in pigs [34, 35]; thus, they were introduced

in farm animals and practical pig feeding worldwide. The mode of action of both pST and β -adrenergic agonists is based on their nutrient repartitioning effect through reducing fat tissue growth by decreasing lipogenesis, glucose oxidation, and insulin-stimulated glucose metabolism, while also promoting muscle protein synthesis and slowing its breakdown. Unlike in many countries such as the USA, Canada, Japan, and Mexico, substances having a hormonal or thyrostatic action and beta-agonists for growth promotion of fattening pigs and cattle are also prohibited in the European Union (Directive 2003/74/EC). This ban applies to meat produced within the EU and to imports from other countries. The EU's concerns about hormone use in farm animals stem from potential health risks to humans, including carcinogenic, endocrine, and developmental effects. The EC panel report identified 17- β estradiol as a complete carcinogen, raising concerns about its safety in food production. Other hormones were noted to potentially cause immune, neurobiological, and genotoxic effects, further highlighting the risks of hormone residues in animal-derived food products [36]. Children, especially prepubertal ones, are identified as the most vulnerable group. The available data, however, does not allow for a quantitative risk estimate, and no safe threshold levels for these hormones have been defined.

Although the EU bans hormones in farm animal feeds, so-called immunocastration has been permitted since 2009. In the case of the most widely used method, animals are inoculated with the GnRH vaccine, which prompts the production of specific anti-GnRH antibodies in the body, thus inactivating endogenous GnRH. As a result, the secretion of luteinizing hormone and follicle-stimulating hormone decreases, leading to inhibited gonadal function and achieving the effects of castration. It is used to a great extent in some countries such as Brazil and Australia [37]; it seems still difficult to break through in Europe, where the estimated average percentage of immunocastrated pigs was 2.7 [38]. Advocacy groups, including the Federation of Veterinarians of Europe [39], have called for broader acceptance of immunocastration, citing its benefits for improved animal welfare, better growth rates and feed efficiency, and the absence of hormonal residues.

4.1.3 Trace elements used for growth promotion

It is well known that trace elements are essential for optimal growth. Certain trace elements, such as copper (Cu) and zinc (Zn), can have a growth-promoting effect, particularly in young animals, when provided in doses exceeding those required for maintenance and growth-related metabolic functions. While the excess amounts are not fully utilized in metabolic pathways and are eventually excreted, they still offer benefits beyond the standard nutritional requirements [40]. The pharmacological level of Cu and Zn helps animals better manage challenges such as suboptimal hygiene and stress conditions, particularly around weaning. Postweaning diarrhea (PWD) is a significant economic concern in pig farming, causing increased therapy costs, slower growth, and higher mortality. The main causative agent of PWD is enterotoxigenic *Escherichia coli*, which infects piglets orally [41]. These bacteria possess plasmids that may carry antimicrobial resistance genes and fimbrial adhesins, which are key for pathogenicity. The onset of diarrhea is caused by different toxins secreted by *E. coli*, which disrupt tight junctions, trigger excessive electrolyte and water secretion, and ultimately cause diarrhea. To handle PWD, multiple feed additives can be effectively used, such as subtherapeutic doses of antibiotics, colistin, Cu-sulfate, Zn-oxide, or other alternatives. Among them, medicated Zn-oxide was routinely but diversely utilized in European countries for more than 15 years after the ban of AGPs.

However, excessive use of Cu and Zn is not sustainable; it poses environmental risks due to mineral excretion. High concentrations of Cu and Zn in the manure, in case of improper handling, could destroy the soil ecosystem and reduce biodiversity. Furthermore, there is evidence that high-level dietary Cu and Zn are positively correlated with CFU of AMR bacteria strains [42] and may regulate the expression of genes that modify piglets' immune response [43]. Therefore, the EU limited the maximum dose of Cu and Zn in animal feeds and banned their use at levels higher than requirements for metabolic functions [37, 44]. Furthermore, Zn-oxide that was supplemented at a pharmacological level (up to 3000 ppm Zn) to reduce the severity of PWD cannot be used as an additive in piglet feeds from 2022. These regulatory changes necessitate the adoption of alternative strategies to maintain piglet health and growth performance, such as improved management practices, enhanced biosecurity measures, and the use of alternative feed additives that are discussed later in this chapter.

4.2 Digestibility enhancers: Enzymes and acidifiers

The feed industry widely incorporates enzymes as feed additives due to their ability to break chemical bonds that limit the bioavailability of certain nutrients, thereby enhancing growth and feed conversion in monogastric animals [45]. In the small intestine, proteases improve protein digestibility, phytase releases phosphorus from phytic acid, and carbohydrases such as xylanase and β -glucanase degrade arabinoxylans and β -glucans [46, 47]. These changes alter the nutrient content of digesta entering the large intestine, potentially shifting the host's microbiome composition. Carbohydrases, in particular, produce oligosaccharides from dietary fibers, which may exert prebiotic effects. Recognizing the potential of feed enzymes to modulate gut microbiota could lead to the development of enzyme solutions tailored to improve gut health and animal performance under specific production systems. When AGPs were banned in Europe, feed enzymes emerged as one of the most effective alternatives. Their growth-promoting effect—as single or multiple enzymes—is attributed to improved digestibility and the establishment of a healthier microbiome, which was consistently demonstrated both in research and in practical applications [45].

According to practical experiences, the other excellent group of alternatives for AGPs is the acidifiers. Both organic and inorganic acids have long been used as feed acidifiers and preservatives. Pigs prefer sour-tasting feed; the use of acidifiers—if not overdosed—often improves feed intake [46, 47]. The acidifiers commonly have bactericidal and/or bacteriostatic effects and also act by stabilizing the stomach pH and thus improving digestive capacity [48]. In piglets, particularly during the post-weaning period, gastric HCl production is often insufficient, resulting in suboptimal pH for pepsinogen activation. Acidifiers support the initial step in protein digestion, enhance gastric emptying, and stimulate digestive enzyme secretion. Additionally, the lower gastric pH optimizes dietary phytase activity, improving the bioavailability of minerals, particularly phosphorus (P) and calcium (Ca).

Until now, various acidifiers have been tested, and the benefits of them have also been confirmed in farm conditions as well (reviewed by Ferronato and Prandini [49]). Among inorganic acids, often called mineral acids, hydrochloric acid is repeatedly shown to improve average daily gain and feed efficiency. Short-chain fatty acids (SCFAs) are acids containing 2 to 5 carbon atoms, like acetic, propionic, butyric, and lactic acids, that are naturally produced in the intestine through microbial fermentation, but they can be used as feed additives too. They support intestinal health by

improving morphology, enhancing barrier function, and/or reducing inflammation. Medium-chain fatty acids (MCFAs) contain 6 to 12 carbon atoms; they integrate quickly into cell membranes, provide energy for young piglets, and exhibit strong antibacterial activity in the hindgut due to their high acidity. Additionally, organic acids like benzoic, sorbic, and lactic acid are used as preservatives for their antifungal properties.

The effectiveness of organic acids varies based on the characteristics of the target organism, particularly the complexity and structure of its outer cell wall or membrane. Gram-positive bacteria (e.g., *Clostridium perfringens*, *Enterococcus* spp., *Streptococcus* spp.) are primarily susceptible to MCFAs, while Gram-negative bacteria (e.g., *Escherichia coli*, *Campylobacter jejuni*, *Salmonella* spp.) are more sensitive to SCFAs (reviewed by Tugnoli et al. [50]). This difference arises from the lipophilic nature of MCFA, which gives them stronger antibacterial activity against Gram-positive bacteria, whereas the lipopolysaccharide layer in the Gram-negative cell wall provides resistance. Additionally, propionic and butyric acids are potent mold inhibitors, while acetic acid is widely used as an antifungal and can also reduce aflatoxin production.

Due to their antimicrobial and antifungal properties, organic acids improve the hygiene of feed and reduce both pathogenic and normal intestinal bacteria in the gastrointestinal tract. A lower number of microbes is lowering microbial competition for nutrients, minimizing subclinical infections, and reducing harmful bacterial byproducts. The antimicrobial effect of organic acids is based on their ability to penetrate bacterial cell walls, disrupting pathogens like *Salmonella*, *E. coli*, *Clostridia*, and *Listeria* [51]. However, as a key survival strategy, microorganisms could develop tolerance to acidic environments. This involves sensing environmental stress and triggering a programmed molecular response to produce stress-inducible proteins, which help prevent or repair damage [52]. Some proteins respond to a range of stresses, while others are specific to acid stress. Research links acid stress tolerance in enterobacteria to pathogenicity, with short-chain fatty acids potentially enhancing *Salmonella typhimurium* virulence by increasing acid tolerance [53]. In *Streptococcus mutans*, growth at acidic pH alters membrane fatty acid composition [54], suggesting these changes play a direct role in acid adaptation. Until now, there has been no indication that the use of acidifiers in practice would increase the biohazard, even if it is documented that microbiota would respond to acidifiers with specific genetic changes.

4.3 Specific feed additives supporting the host eubiosis

4.3.1 Pre- and probiotics, postbiotics, parabiotics

There are several terms related to biotics, each with distinct definitions that should be understood before discussing their roles in animal health. The term “biotic” originates from the Greek word *biotikos*, meaning “pertaining to life.” In the context of animal nutrition, biotics broadly refers to the ecosystem of microorganisms within the host. Unlike antibiotics, which act against the biota and reduce the number of microbes, other types of biotics aim to achieve eubiosis. They do so either by creating a favorable environment for beneficial microbes or by restricting the growth and activity of pathogenic microorganisms. In animal nutrition, probiotics are defined as viable microorganisms, which, after sufficient oral intake, lead to beneficial effects for the host animal because of an improvement of the intestinal microbial

balance [55]. Prebiotics are nondigestible feed ingredients that beneficially affect the host by selectively stimulating the growth and/or activity of one or a limited number of bacterial species already resident in the colon, and thus attempt to improve host health [56]. They significantly modulate the colonic microbiota by increasing specific bacterial populations, leading to compositional changes. The concept of synbiotics arises from combining the benefits of prebiotics and probiotics [56]. Nondigestible oligosaccharides, namely fructo-oligosaccharides, inulin, galacto-oligosaccharides, mannan-oligosaccharides, etc., are notable prebiotics that stimulate intestinal *Bifidobacteria*, making them predominant in feces after short-term intake. Beyond microbiota modulation, prebiotics influence lipid metabolism, likely through fermentation products (reviewed by Chung et al. [57]). Among nondigestible oligosaccharides, mannan-oligosaccharides (MOS) are unique, as they do not serve as a nutrient source for microbes but instead prevent pathogen colonization by adhering to mannan compounds [58]. As reviewed by Halas and Nochtka [59], MOS enhances the disease resistance in swine by promoting antigen presentation, thereby facilitating the shift from an innate to an adaptive immune response. Accordingly, dietary MOS supplementation shows potential growth-promoting effects in pigs raised in poor hygienic environments. However, this positive effect is not observed in healthy pig herds maintained under high hygienic standards, where a high growth rate is sustained even after weaning [59].

The history of probiotics has been a subject of debate within the scientific community, particularly among pig nutritionists. The selection and use of probiotic strains and nondigestible oligosaccharides have often been guided by empirical practices rather than evidence-based criteria. While the positive effects of pro- and prebiotics have been demonstrated under research conditions, their effectiveness as alternatives to AGPs has been inconsistently proven in farm conditions [60, 61]. Additionally, the insufficient characterization of commercial probiotic strains may explain the inconsistent results frequently observed in practical applications [62]. As a result, some sectors have regarded the probiotic concept as lacking robust scientific validation.

Although for a long time probiotics were believed to be safe, recently concerns about the use of live microbes have emerged, including their risk of translocating to the bloodstream, leading to bacteremia, especially in vulnerable individuals like children, immunocompromised, or critically ill patients [63]. Other issues involve the potential transfer of antibiotic-resistant genes, harmful metabolic activities, immune overstimulation, and disruption of normal microbiota colonization in neonates [64]. These challenges have prompted interest in alternatives like postbiotics, which are products of probiotic strains.

Postbiotics have been defined as “preparations of inanimate microorganisms and/or their components that confer a health benefit on the host,” which must include inactivated microbial cells or their components, with or without metabolites, that contribute to health benefits [65]. Postbiotics, also alternatively known as metabiotics, biogenics, or cell-free supernatants, are metabolic substances produced by secretions or released after cell lysis of beneficial microorganisms [66]. The effectiveness of postbiotics can be assessed in humans and livestock species, and their benefits are not restricted to the intestine [67]. Parabiotics—also named paraprobiotics, ghost probiotics, or inactivated probiotics—confer more direct benefits than probiotics by interacting directly with mucus layers and epithelial cells [66]. This is achieved through the release of bioactive components from lysates [68]. Parabiotics regulate the microbiota of the GIT by preventing the growth of harmful bacteria, such as hydrogen sulfide producers.

The beneficial substances of probiotics that are included in postbiotics and parabiotics are the antimicrobial agents like bacteriocins and short-chain fatty acids, vitamins (folate, vitamin B₁₂, and riboflavin), immunomodulatory peptides, biosurfactants, exopolysaccharides, and enzymes [69]. SCFAs, mostly lactic, formic, and butyric acids, produced by the probiotic bacteria, suppress pathogenic bacteria [70], improve gut health, and, in combination with enzymes like catalase and superoxide dismutase produced by the strain, reduce inflammation. Probiotic fermentation releases bioactive peptides with immunomodulatory effects, aiding lymphocyte proliferation, phagocytosis, and cytokine production, which bolster the immune system. Biosurfactants are amphiphilic compounds that disrupt pathogenic biofilms and prevent microbial adhesion, offering antimicrobial, anti-biofilm, and immunomodulatory benefits (**Figure 2**) [66]. Strain-specific exopolysaccharides may modulate immune responses by regulating cytokine levels and pathways and providing anti-inflammatory benefits. Probiotics produce enzymes like catalase and superoxide dismutase with anti-inflammatory actions. There is some evidence that mycotoxin binding capabilities are attributed to teichoic acid, lipoteichoic acid, and the S-layer, whether individually or in combination [71].

Although an increasing number of publications have recently become available on postbiotics and parabiotics, with their modes of action at least partially elucidated, access to on-farm results remains limited.

4.3.2 Phytobiotics and phytomolecules

Bioactive compounds as feed additives have been known for decades; they are often recommended in pig feeding, particularly in the most challenging

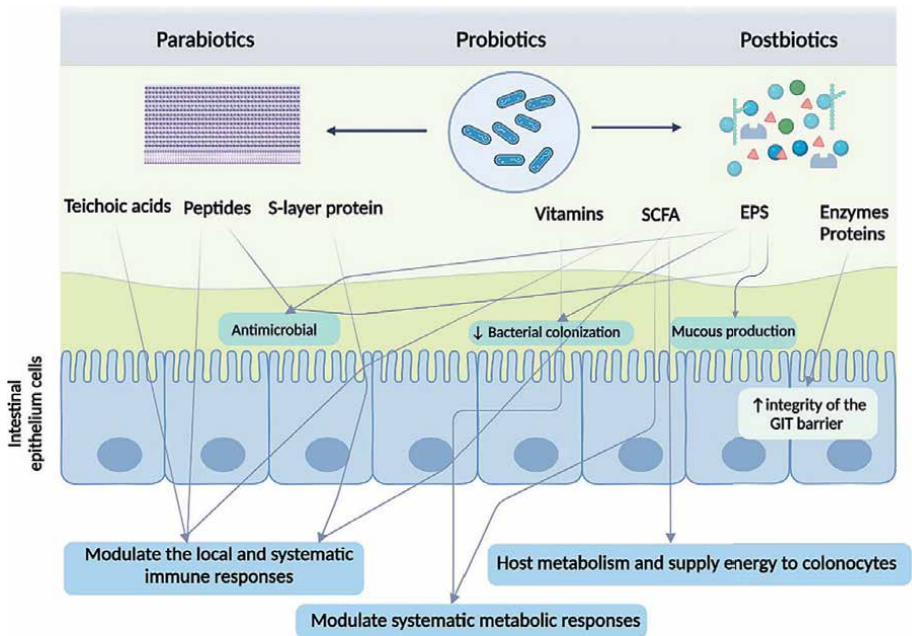


Figure 2.
Mechanism of action of postbiotics and parabiotics [66].

phases, like postweaning [72]. There is a wide variety of these compounds, such as glucosides, acids, polyphenols, polysaccharides, terpenoids, flavonoids, and alkaloids [73]. In addition, each may denote multiple compounds, e.g., plant-derived polyphenols can be tannins and their derivatives, curcumin, flavonoids, tea polyphenols, quercetagenin, thymol, carvacrol, etc. In this chapter, we cannot provide an overview of all phytobiotics; however, we summarize their mode of action as they are referred to as providing a natural and sustainable alternative to conventional prophylactic measures [74].

In an excellent broad review, Wang et al. [73] summarized the significance of phytogetic feed additives in animal feeding. Most of them exhibit antimicrobial, gut-modulating, and anti-inflammatory properties [75, 76], while some bioactive phytochemicals like essential oils are reported to enhance enzyme secretion and thus improve the digestibility of dry matter and crude protein (reviewed by Wenk [72]). Herbs and extracts can exert beneficial effects on the digestive tract by shifting the intestinal microbiome, as well as enhancing the regeneration of epithelial cells and thus improving the absorptive surface of the intestine. Herbal feed additives can increase the villus height-to-crypt depth ratio in the ileum, jejunum, and duodenum [77].

The effectiveness of phytobiotic feed additives varies based on factors such as the specific compounds used, their concentration of active compounds, and the overall diet composition. While some studies report positive outcomes (reviewed by [73, 77, 78]), others indicate inconsistent results [79, 80], highlighting the need for further research to optimize their application in pig nutrition. Overall, phytobiotics present a promising avenue for reducing reliance on antibiotics in pig production, but their implementation should be guided by comprehensive research to ensure consistent benefits and address any potential challenges.

In summary, feed additives reviewed in the previous section highlight a variety of options available on the market with proven benefits for the growth performance of piglets. However, the use of some additives raises sustainability concerns due to their potential environmental impact, such as hormones, growth-promoting antibiotics, and pharmacological levels of zinc and copper. Recent findings also suggest that antimicrobial resistance could develop in probiotics, further questioning their long-term viability. Alternatives such as postbiotics, parabiotics, and phytobiotics show promise in addressing these issues, but more on-farm evidence is needed to validate their efficacy. It is increasingly clear that relying solely on a single zootechnical additive is unlikely to fully address critical challenges. Instead, feeding strategies must be tailored to align with the principles of the One Health approach, integrating animal, human, and environmental health considerations.

5. Feeding strategies supporting health for sustainable pig production

In this chapter, we focus on two phases of pig production, such as sows and piglets, and exclude the fattening period. This exclusion is based on the fact that, although feeding strategies do influence growth performance and feed efficiency in growing and finishing pigs, they have a smaller impact on animal health. Once pigs are past the nursery phase, they are generally robust enough to handle environmental challenges. They can adjust their feed intake to meet nutrient requirements and maintain a relatively stable microbiome that protects them from mild bacterial infections commonly encountered in practice.

5.1 Impact of sow nutrition on the health of piglets

We intend to describe the feeding strategies involved in this topic in the spirit of the close relationship between sustainability and One Health (Section 3.3). For sows as well, good health is a key factor for the long-term sustainability of livestock.

5.1.1 Nutritional intervention during gestation

The link between sows' nutrient intake during gestation and fetal growth is of great importance in determining reproductive success, lifelong health, and neonatal productivity. Sows that lose too much weight during lactation will have less uniform piglet birth weights in their next litter [81].

The requirements of sows for energy, amino acids, vitamins, and minerals needed for maternal and fetal growth differ during gestation. The development rate of placentas and fetuses varies significantly [82]. Feeding a single diet to sows for the whole gestation period is therefore incorrect practice. Attention should be paid to the fact that biological changes during the gestation period occur in three distinct phases. During the first trimester (embryonic phase), the most important events are embryo elongation, migration, and placentation. Between day 30 and day 60 of gestation, tissue growth and vascularization of the placenta are accelerated. The explosive fetal growth occurs in the last trimester, when the weight of the fetuses increases by nearly 70%. The main development of mammary glands also occurs during this period. Considering the main principles of sustainability, it would be preferable to use a targeted nutrition strategy according to the different gestation periods. Some nutrients and nutraceuticals have specific roles in the different phases of gestation, which are described below.

Arginine supplementation during early gestation (<day 80) by promoting optimal intrauterine conditions may improve the weight of the placenta and the fetus [83]. Several factors may explain the beneficial effects of arginine. As a starting compound, arginine enhances the formation of NO (major regulator of uteroplacental blood flow, vasodilator, and angiogenic factor) as well as polyamines (regulators of protein synthesis). This results in higher placental delivery of nutrients and oxygen to the fetus during late gestation [84]. Another amino acid, glutamine, also plays an important role in fetal and postnatal survival and growth. Glutamine supplementation (1%) increased the birth weight and reduced variations in birth weight and preweaning mortality of live-born [85]. Sow diet enriched with methylated compounds, such as folic acid, betaine, or vitamin B12, has also been associated with increased fetal weight in late gestation [86]. These micronutrients provide beneficial effects for embryo and placental development and can increase litter size [87]. L-carnitine supplementation resulted in a larger placenta and heavier piglets at birth [88, 89]. The reason for the higher weight is that L-carnitine increased circulating concentrations of insulin-growth factor I (IGF-I) at mid-gestation in sows [90], which stimulates the proliferation and differentiation of muscle cells and regulates muscle growth and development. An adequate supply of Zn to sows is also important, as a deficiency in Zn during gestation can result in a general deficit in fetal growth [91]. Zn supplementation during the last third of sows' pregnancy had a positive effect on intestinal development and the immune function of the offspring [92].

5.1.2 Feeding strategies for the modulation of colostrum and milk production

Colostrum production and intake remain the major challenge in high-production breeds. Unlike milk yield, which responds to piglets' demand and litter size,

colostrum production is limited (approx. 2.5–5.0 kg in 24 h for 8–12 piglets) and highly variable among sows. This variability is influenced by sow nutrition and piglet intake. Larger litters often include more low-weight, low-vitality piglets with reduced colostrum consumption [93].

Different compounds (arginine, L-carnitine, tryptophan, valine, vitamin E, and phytogetic actives) can be used to increase colostrum and milk production [94]. To improve the milk production of sows, mammary gland growth and blood flow to the tissue must be increased. Correct dietary valine to lysine ratio (Val:Lys) for lactating sows in order to maximize litter weight gain and minimize tissue mobilization during lactation is important to take into account. Available experimental data on lactating sows confirmed the 0.90:1 Val:Lys ratio recommendation [95]. Soybean oil supplementation (3%) of the diet a week before farrowing, compared to the other fat sources (coconut and palm oil), increased fat content in colostrum and raised immunoglobulin concentration of piglets. Maternal dietary supplementation with conjugated linoleic acid (CLA) increased serum IgG levels in sows and piglets and enhanced IgG concentration in colostrum. CLA and linoleic acid, besides being important energy sources, are both fatty acids that have anti-inflammatory and immunomodulatory properties, thus improving the piglets' vitality. Sows fed an L-carnitine-supplemented diet produced more milk during lactation, even with negative energy and protein balance. L-carnitine may enhance the utilization of body fat in sows in negative energy balance [96]. Probiotic administration to sows during gestation and/or lactation has been shown to improve colostrum/milk quality and quantity and to modulate the piglet gut microbiome. Maternal probiotic supplementation had a positive effect on piglet growth and health [97]. Similar to probiotics, prebiotic administration (yeast hydrolysate, β -hydroxy- β -methylbutyrate) to sows during gestation and/or lactation has been shown to improve colostrum quality and quantity and to modulate piglet microbiome [98, 99].

5.1.3 Feeding strategies in order to modulate antioxidant status and immune response in sows

Fetal growth during late gestation and the synthesis of colostrum and milk during lactation contribute to the catabolic status of sows [100], leading to the production of reactive oxygen species (ROS) and the induction of oxidative stress [101]. Sows may experience increased oxidative stress and inflammation during gestation and early lactation [102].

Elevated levels of ROS in sows may significantly damage mammary epithelial cells and consequently affect milk yield performance [103]. Sows with lower litter performance at the initiation of the lactation period had lower serum antioxidant levels and higher thiobarbituric acid reactive substances (TBARS) [104]. This suggests that ROS in sows plays a relevant role in the growth of suckling piglets.

Vitamins, trace minerals, and biological antioxidants may play important roles in mitigating the effects of oxidative stress and scavenging the oxygen free radicals. Long-chain n-3 polyunsaturated fatty acids (PUFAs) decrease the production of inflammatory eicosanoids, cytokines, and reactive oxygen species and the expression of adhesion molecules. The addition of PUFA in the sow's gestation and/or lactation diets can increase the body weight of piglets [105] and reduce the postweaning inflammation process [106]. Vitamin E is a strong antioxidant agent that protects cell membranes from the lipid peroxidation chain reaction by acting in synergy with selenium. The addition of vitamin E and/or Se in the sow's diet during gestation and

lactation improved the number of piglets at birth, the weight of piglets at weaning, and enhanced milk fat content, humoral immune function (IgG and IgA), and the antioxidant activity in sows and piglets [107, 108]. Organic sources (Se yeast or selenomethionine) had a more pronounced effect compared to sodium selenite [109]. Plant extracts, which are rich sources of antioxidant phenolic and polyphenolic compounds, stimulate digestive secretion, the immune system, and intestinal microflora, and have anti-inflammatory activities and antioxidant effects [110].

5.1.4 Modulating microbiota in sows and its effect on piglets' health

Sows play a relevant role in the early process of microbiota establishment of their offspring. The sow is the first and main donor of fecal microbiota after birth, but the possibility of an entero-mammary route for microbial transfer should also be considered. The latter, in combination with the natural exposition of the piglets to the sow's feces, opens the possibility of gut microbiota modulation in pigs by supplementing sows with probiotics. *Enterococcus faecium* supplementation modified the fecal microbiota of sows, which led to different microbiota composition in their offspring [111]. Probiotic treatment in pregnant and lactating sows increased litter weight at delivery, reduced the occurrence of postweaning diarrhea, and improved microbiota balance [112]. These positive effects could be related to the increases in feed intake, which improved the sows' body condition score at the end of lactation.

5.2 Pre- and postweaning strategies to improve resistance and resilience of piglets

Mortality and morbidity of piglets in the pre- and postweaning period are still major problems in the pig industry, causing economic and ethical concerns for farmers and consumers [113]. This is the period with the highest incidence of animal health problems, leading to a particularly high rate of antibiotic use. Therefore, improving piglets' health is a key priority to achieve sustainable pig production with the help of the One Health approach.

The first few weeks of the piglets' lives (3–5 weeks, depending on the technology used on the farm) are crucial in order to make the weaning transition smooth and easy. The interventions used during the suckling, preweaning period will determine the success of weaning. Consequently, the main elements of feeding strategies are reviewed according to these two important periods of the piglet's life. This section discusses the suckling (preweaning) and postweaning periods separately.

5.2.1 Interventions during the suckling period to ease the transition at weaning for piglets

The main objectives of the preweaning interventions are to (1) promote improved gut structure and function (earlier maturation), (2) stimulate earlier intestinal enzyme production, (3) modulate gut microbiota, and (4) activate the immune system. Different methods can be used to achieve these goals, which are summarized in **Table 2**.

Instead of individually discussing the elements listed in the table, we would like to analyze the nutrition strategies according to the mode of action by which the different nutritional and feeding strategies modulate the maturation and functionality of the gut, immune system, and metabolism of young piglets, which are finally the bases of improving health and reducing the use of antibiotics (Section 3.3).

Oral supplementation	Creep feeding	Dietary intervention
Amino acids (glutamine)	Supplementary solid feed	Amino acids (glutamine)
Medium-chain fatty acids	Supplementary liquid feed	Fiber sources
Prebiotics (inulin, β -glucans)	Supplementary milk	Flavors
Fecal microbiota transplant		Prebiotics (oligofructose)
Nucleotides		Probiotics (yeast)
		Synbiotics
		Fat sources rich in medium-chain fatty acids

Table 2.
Prewaning nutritional strategies to improve the growth and health of piglets [104].

5.2.1.1 Gut structure and function

Gut maturity (cell-proliferation rate, intestinal integrity) at weaning might be modified by preweaning milk replacer supplementation. Milk supplement stimulated intestinal growth (26% increase in small intestinal weight and higher relative weight:length ratio) in suckling piglets fed milk replacer for 21 days [114]. These authors also observed an increase in crypt depth and a lower villus height: crypt depth ratio in the ileum of milk-supplemented piglets on day 21 (weaning). However, Hu et al. [115] did not observe any differences in villus height or crypt depth in the jejunum on day 28 (weaning) and day 35 (8 days postweaning) in suckling pigs supplemented with milk. The advantage of milk replacer supplementation on gut maturity is not consistent and is likely influenced by milk composition.

Glutamine or glutamate has many beneficial effects on pig growth, intestinal function, and structure. Glutamine supplementation enhanced intestinal integrity, cell survival, and villus height. The activation of mTOR cell signaling is responsible for these changes, with less decreased levels of tight junction-associated proteins [116]. Furthermore, dietary glutamate regulates expression of receptors (glutamate and taste) signaling in the porcine digestive tract to maintain gut motility and function [117]. It is important to note that the dose of glutamine is critical with regard to piglet growth. Excess glutamine can generate ammonia, which is not fully excreted by the kidneys and can therefore cause adverse effects. Glutamine is nowadays considered to be of particular importance for low-birth-weight piglets to improve intestinal health. A higher number of CD3+ intraepithelial lymphocytes was observed in piglets supplemented with glutamine, which indicates a more mature intestinal immune system [118].

5.2.1.2 Earlier intestinal enzyme production

Creep feeding (dry feed, liquid milk replacer, and/or liquid feed) is a possible strategy to increase preweaning feed intake. Dry forms of creep feed to suckling piglets can improve intestinal structure and help growth, resulting in heavier pigs at weaning. It may stimulate earlier enzyme secretion in the gut of piglets, which helps the digestion of non-milk ingredients found in diets after weaning. Creep feed supplementation should be started on days 7 to 10 of age to maximize intake. As the amount of feed intake is extremely variable, creep feed in liquid form can be a solution to encourage solid feed intake. Creep feeding is an option for piglets to

compensate for the reduction in milk production of sows during mid-lactation, which can occur mainly in large litters [119].

Supplemental milk supply to suckling pigs induces earlier gut maturation, which was indicated by altered enzyme production; lower lactase and higher sucrase activity on day 28 and higher maltase activity on day 35 were found in the jejunum of pigs [120]. Higher intestinal activity of sucrase and maltase is important for the digestion of vegetable-based components, and these pigs can digest more efficiently ingredients of the starter diet fed in the postweaning period.

Intestinal tract conversion can be accelerated by using exogenous enzymes. Supplementing suckling piglets twice a day for a week with porcine pancreatic enzymes increased villus height, reduced crypt depth, and increased adult-type enterocytes (cells have differentiated into those with an absorptive function) on day 16 after birth [120]. Suckling piglets fed a microbially derived enzyme-supplemented diet had decreased nitrogen excretion per kilogram of body weight gain. This indicates that enzyme supplementation could help in reducing the environmental impact of sustainable pig production [121].

5.2.1.3 Gut microbiota modulation

Newborn piglets are rapidly colonized after birth when exposed to maternal feces, maternal skin, and environmental microorganisms. Early postnatal colonization may be an important factor for gut health, both short- and long-term [122]. The progress in microbial colonization helps the development of gut barrier function and the maturation of the immune system [123].

The effect of preweaning liquid milk supplementation on intestinal microbiota composition is not consistent. Higher prevalence of beneficial bacteria was observed in the jejunum of piglets supplemented with milk from day 4 to 28 after birth [120]. However, the abundance of some beneficial bacteria (*Lactobacillus*) was reduced in pigs supplemented with milk from day 7 postpartum until day 21 (weaning) [124]. Differences in the composition of the supplementary milk fed may be behind the varying results.

Other strategies, such as fecal microbiota transplantation (FMT), have also gained interest in recent years [125]. Studies on the use of FMT in pigs have shown a positive effect on growth performance, gut health, and a decrease in postweaning diarrhea [126]. However, the risk of infection must be considered when using FMT, as the medium may contain viruses as well as pathogenic bacteria. This risk can be avoided by transplantation of bacteria-free filtrate of feces (fecal filtrate transplant, FFT). This method has a positive effect on intestinal maturation and microbiome in newborn piglets, which later determines intestinal function [127]. Filtration removes only the pathogenic microorganisms, leaving behind the bacteriophages that play an important role in the gut. Bacteria and bacteriophages interact with one another during early gut colonization, which results in changes in the composition of the microbiota. Due to their bacteriolytic properties, bacteriophages may be a potential preventive tool against intestinal bacterial infections and therefore provide the opportunity for an antibiotic-free pre- and postweaning period [128].

5.2.1.4 Immune system activation

Humoral and cellular functions develop after birth and are almost completed at 7 weeks of age. The intestinal microbiota plays a key role in the development, maturation, and regulation of the immune system.

The amino acid (AA) profile required to support the immune response (important acute-phase proteins) is drastically different from that for muscle protein synthesis. Neonates with Thr deficiency had impaired mucin production and gut function. Endogenous and bacterial Trp metabolites (e.g., serotonin, melatonin, skatole, indole, and tryptamine) play an important role in gut microbial composition and metabolism, immune response of the host, and host-microbiome interaction. Higher Trp intake resulted in a number of beneficial effects in the GIT of piglets (enhanced microbiome diversity, lower abundance of harmful bacteria, and increased levels of IL-8 and zonula occludens (ZO)-1 in intestinal mucosa).

Dietary supplementation of mannans derived from the yeast cell wall directly stimulated the immune system of nursery pigs. This beneficial effect is also transferred from the sow to the piglets through the milk. Intestinal production of T lymphocytes was positively influenced by feeding yeast-based feed additives, which can trigger a better systemic immune response in the host.

5.2.2 Weaning support: Intervention in the immediate postweaning period

In addition to a right feeding strategy for sows and newborns, the stressful period of weaning is the most sensitive phase in pig production. The most classic clinical symptom is the occurrence of postweaning diarrhea (PWD). However, piglets at postweaning often experience reduced feed intake and poor growth as well. Weaning is associated with high antibiotic use and, consequently, increased antimicrobial resistance. That is why the One Health concept has a crucial role to play at weaning time. Sustainability must be ensured so that the relationship between health (including environmental, human, and animal) and the economy is not jeopardized.

Alternative rearing strategies should be used in order to reduce stress-related problems. These methods support digestion and nutrient absorption; use high-quality, digestible ingredients with low anti-nutritional factors. A complex diet also integrates functional amino acids, carbohydrates, and additives to support the intestinal mucosa and gut microbiome.

5.2.2.1 Low-protein, amino acid-supplemented diet

There is a relationship between feeding high-protein (HP) diets and the prevalence of PWD in pigs. Protein levels above 20% will cause not only an extra feed cost but may also have a detrimental effect on the intestinal tract. More undigested protein in the large intestine enhances the growth of pathogenic bacteria. Higher proliferation of pathogenic bacteria can promote the production of potentially harmful metabolites (ammonia and amines). The recommendation is that low-protein (LP) diets should be fed that are supplemented with crystalline essential AA (particularly lysine, methionine, threonine, tryptophan, isoleucine, and valine) for meeting minimum digestible AA levels. Some conditionally essential amino acids (e.g., arginine, proline, and glutamine) also play critical roles in diets with reduced protein levels. As described earlier (Section 5.2.1.1), glutamine has a special function. Intestinal cells use glutamine as a source of energy; therefore, glutamine prevents atrophy and supports nutrient absorption, resulting in better growth postweaning [129].

High-digestibility (> 85%) ingredients for piglets need to be delivered. A large amount of animal by-products (fish meal, hydrolyzed mucosa, spray-dried blood plasma) and vegetable sources (extruded grains, potato protein, soy protein

concentrate) should be used at weaning. These components in the diet will significantly reduce the total quantity of undigested protein reaching the large intestine. This has two beneficial consequences: (1) less substrate for pathogenic bacteria proliferation; (2) lower nitrogen excretion to the environment.

5.2.2.2 Acid-binding capacity

The acid-binding capacity of the feed directly affects the capacity of the stomach to digest protein. As the postweaned piglet has limitations on producing and secreting acid, the less acidic environment of the stomach reduces proteolytic activation, which impairs digestion, leading to more undigested feed reaching the distal part of the gut. However, a low pH in the stomach serves as an important line of defense against foodborne pathogens. Feed ingredients vary in their acid-binding capacity. For example, most grains would be considered to have a low acid-binding capacity, while most vegetable protein sources have a medium acid-binding capacity [130]. According to Molist [131], postweaning feed should have an acid-binding capacity value lower than 250–300 meq/kg. The inclusion of organic acids, such as benzoic acid, plays an essential role in reducing acid-binding capacity. Lower pH in the gut exerts a favorable effect on reducing PWD in piglets.

5.2.2.3 Fiber type and level

Feeding soluble and rapidly fermentable fiber sources in the immediate postweaning period, especially if the weaning age is reduced, can have a negative effect due to the very limited feed intake capacity of piglets. The other fact is that fiber may act as an anti-nutritional factor, reducing nutrient digestibility and increasing endogenous mucin secretion, which further exacerbates the amount of undigested protein entering the distal parts of the intestine and reduces the availability of AA for growth. This is why the fiber content is usually kept low in a starter diet. After two weeks postweaning, when an improved adaptation of piglets to solid feed is expected, a gradual inclusion of soluble and fermentable fiber may be advantageous for enhancing fermentation of nutrients and improving absorption of short-chain fatty acids in the large intestine mucosa.

Dietary fibers are also known for regulating intestinal health. The selection of specific dietary fiber fractions may prevent (insoluble fiber) or stimulate (soluble fiber) the overgrowth of pathogenic bacteria. Thus, there is a need to identify dietary fiber fractions from raw materials to formulate diets. Dietary inclusion of carbohydrases (xylanase, β -glucanase), which increase the *in vivo* availability of short-chain oligosaccharides, has beneficial effects on gut health, thus preventing PWD. Combining dietary soluble fibers (inulin) and insoluble fibers (lignocellulose) in weaned piglet diets positively influenced nutrient digestibility, gut microbiota composition, intestinal barrier functions, and growth performance [132]. The presence of a high proportion of soluble fiber increases digesta viscosity and reduces the rate of nutrient absorption, promoting enterotoxigenic *E. coli* [133].

6. Conclusions

Based on the analysis of the literary data presented in this chapter, the following key conclusions can be drawn:

1. For the future of humanity, it is particularly important to meet the global demand for meat (e.g., pork) in an environmentally friendly manner, utilizing available resources rationally, while ensuring that the produced meat is healthy, safe, and of high quality. This goal can only be achieved if animal agriculture (e.g., meat production) is based on the principles of sustainability and the One Health concept.
2. Since sustainability and One Health share several common elements, the combined application of these two concepts—namely, the integration of sustainability with elements of the One Health approach—is recommended.
3. Feed additives contribute significantly to pig productivity, but certain types, such as hormones, growth-promoting antibiotics, and high levels of zinc and copper, raise sustainability concerns due to their environmental impact. Additionally, reports of antimicrobial resistance in probiotics may question their long-term practical use or at least need extended research to elucidate their risk.
4. The most critical phase in pigs is early life, as their microbiome is still developing. A wide range of feed additives is used in practice to stabilize gut microflora. To replace unsustainable growth promoters, various feed additives, including postbiotics, parabiotics, and phytobiotics, show promise but require further on-farm validation.
5. Specific nutritional solutions should be applied to sows and piglets in order to achieve more sustainable pig production without the need to rely on drugs. Feeding strategies are of particular importance at weaning time. Methods are available that support optimal development and function of the gastrointestinal tract, thus preventing intestinal disorders such as diarrhea in the postweaning period.
6. Correct implementation of feeding strategies offers the possibility to obtain healthier pigs without the need for antibiotics or at least with reduced use. This could be achieved by improving the animals' ability to cope with environmental challenges, including infection challenges, with minimal loss of function and production.
7. Adopting a holistic approach to feeding strategies, aligned with the One Health principles, is vital to addressing interconnected animal, human, and environmental health challenges.

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Tackling Antibiotic Resistance Threat through the One Health Approach: A Focus on Veterinary Medicine

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Abstract

Antibiotic resistance (ABR) represents a global public health threat, significantly impacting humans, animals, and the environment. This chapter explores the multifaceted causes and implications of ABR within the veterinary sector, namely in food-producing animals, emphasizing the urgent need for collaborative solutions through the One Health approach. It underscores the rising prevalence of resistant bacteria due to misuse and overuse of antibiotics in veterinary medicine and the commitment of nations to tackle this problem through regulations, policies, and action plans. Country- and region-specific conditions must be accounted for when developing and implementing interventions to tackle ABR. The interplay between ecological integrity, animal welfare, and food security is examined, showcasing how ABR hinders efforts to achieve sustainable development goals. Additionally, this chapter addresses educational initiatives targeting veterinarians and farmers as key actions to promote responsible antibiotic use and improve general animal management practices. This chapter also emphasizes the need for increased investment in research and technological innovations, such as antibiotic alternatives and improved surveillance systems, to effectively tackle ABR. Ultimately, a comprehensive strategy involving all stakeholders is essential to mitigate the repercussions of antibiotic resistance, ensuring not only the health of animals and humans, but also the sustainability of public health care worldwide. Key conclusions of this chapter are: (i) it is urgent to tackle ABR through the One Health approach to ensure a sustainable future; (ii) global collaboration and communication are paramount to effectively mitigate ABR emergence and spread; and (iii) investment in alternatives to antibiotics, educational interventions, surveillance and monitoring, and technologies should be prioritized.

Keywords: antibiotic resistance, medicines for veterinary use, antibiotics, animal welfare, food-producing animals, human-animal-environment interconnection

1. Introduction

Modern medicine was massively impacted by the introduction of antimicrobials – antibiotics, antivirals, antiparasitic, and antifungals – advancing the treatment of infectious diseases [1]. Despite this major achievement, the therapeutic effectiveness of these drugs is impaired by antimicrobial resistance (AMR), where microorganisms do not respond to antimicrobial treatments [2]. AMR is currently in the top ten global public health concerns of the World Health Organization (WHO) [3], and it leads to an increased risk of severe disease and long-term disability [2, 4]. A report from 2025 shows that resistance to commonly used antibiotics, including ampicillin, tetracyclines, and sulfonamide, still persists at concerning levels in key pathogens, in both humans and animals [5]. Moreover, AMR is a leading cause of death worldwide [6], and forecasts for the years between 2022 and 2050 show an alarming increase in AMR-caused (69.6%) and AMR-associated (67.0%) deaths [7].

Although the occurrence of AMR is a natural evolutionary phenomenon, its emergence and dissemination are accelerated by the inadequate use of antimicrobials in human and veterinary medicine, and agriculture practices, resulting in a high selective pressure of resistant pathogens [1, 2, 8, 9]. Considering the human-animal-environment interconnection, the effective management of AMR must, therefore, involve concerted and collective actions under the One Health approach [10, 11].

Around 60% of pathogens responsible for human infectious diseases originate from animals [12] and there is evidence that animal waste contributes to riverine abundance of antibiotic-resistant bacteria and genes [13]. In general, a rise in resistant pathogens has been documented in the past two decades in animals, food, and the environment. Consequently, ensuring animals' and ecosystems' health is essential to protect human health [12, 14]. In veterinary medicine, farmers and animal health professionals are becoming more aware of AMR and its consequences, being actively engaged in optimizing their practices to reduce the use of antimicrobials [15].

Since bacterial pathogens are, currently, the priority in terms of impact on AMR [16], in this chapter we will focus on antibiotic resistance (ABR), its causes and impacts, collaborative solutions under the One Health approach to ensure a sustainable development, and how veterinary stakeholders can help tackling this growing health crisis.

2. Antibiotic resistance: A global health threat

Originally, 'antibiotic' referred to an agent that microorganisms produced to eliminate competing bacteria within their surroundings [17]. Meanwhile, the definition was updated to include synthetic antibiotics, including sulfonamides and quinolones [18]. In 1910, salvarsan, from the synthetic group of arsphenamines, was the first drug used to treat syphilis. Since it was synthetic, salvarsan was not considered an antibiotic at the time. In 1924, bacterial resistance to salvarsan was reported [18, 19], even when its use was very limited, compared to modern antibiotics [18].

In the 1940s, penicillin replaced salvarsan due to higher availability, safety, and effectiveness [18]. The discovery of penicillin [20] was the ultimate catalyst of the antibiotic Era. The subsequent development of other antibiotics, including streptomycin, chloramphenicol, tetracyclines, erythromycin, vancomycin, and cephalosporins, provided remarkable advances in modern medicine and allowed the treatment of infections that would be fatal otherwise [21, 22]. Antibiotics have decreased

childhood mortality and prolonged life expectancy, being important in invasive surgeries and chemotherapy [23].

Despite the recognized and irreplaceable importance of antibiotics, resistant bacteria are increasing globally, causing an alarming number of untreatable infections [23]. ABR significantly impacts the health of ecosystems, animals, and humans, constituting a global health threat and contributing to increased mortality rates, clinical complications, and socioeconomical burden [2, 4, 24]. The limited number of effective antibiotics has narrowed over time, and those of a very young age, older adults, and the severely ill are more vulnerable to ABR, as well as people living in resource-constrained regions [14].

2.1 Antibiotic misuse and the emergence of resistant bacteria

Bacteria can be intrinsically resistant to drugs or acquire this resistance, with ecosystems acting as a reservoir of resistance genes that can be transferred into human-infecting pathogens [23, 25, 26]. Although ABR is a natural phenomenon, when microorganisms are exposed to antibiotics, the selective proliferation of bacteria inherently resistant or with acquired advantageous mutations is fostered [27, 28]. Hence, the widespread and indiscriminate use of antibiotics, not only in human and veterinary medicine, but also in horticulture, beekeeping, anti-fouling paints, and in laboratory testing, contributes to ABR emergence and spread [23, 29]. Although human antibiotic overuse and misuse are a major driver of ABR [30], in many countries, antibiotic use in animal farming may exceed that in human medicine [31–34].

Of note, despite clear proof for cross-transmission of resistant bacteria between livestock and humans and from farm to fork, the exact extent to which animal production contributes to the overall resistance burden remains unknown [29, 35]. Nevertheless, evidence suggests that restrictions on antibiotic use in food-producing animals are, in fact, associated with reduced resistance in these animals and humans directly contacting them [36, 37]. For instance, between 2014 and 2021, in countries where a reduction of animal consumption of third- and fourth-generation cephalosporins, quinolones, polymyxins, aminopenicillins, and tetracyclines was observed, a substantial reduction in resistance to these groups was reported in animals [38]. Also, colistin ban as a growth promoter led to decreased prevalence of resistance gene *mcr-1* across one-health setting [13].

2.2 Increasing population and global food demand as drivers for antibiotic consumption

From 2016 to 2023, worldwide antibiotic tons for human medicine rose by 20.9%, and it could reach an 11.5% increase by 2030 [39]. In food-producing animals, current trends point to an increase from around 99,502 tons in 2020 to 107,472 tons by 2030, an 8.0% increase [40]. Globally, it is estimated that 50–80% of total antimicrobials used per year are for production animals [41]. In 2020, China, Brazil, India, the United States, and Australia were the top five antimicrobial consumers [40], contributing to 58% of worldwide use [40]. This rise in antibiotic consumption may be justified by the growing population, increased demand for animal-derived products, as well as weak or non-existent regulation, particularly in low-income and middle-income countries (LMICs) [24, 42].

Global biomass of production animals surpasses that of human population [41] and according to OECD/FAO, by 2033, global meat production is projected to rise

12%, mostly in Asia, and growth in livestock population and in meat consumption are also anticipated to increase [43]. Dairy is expected to be the fastest-growing sector, led by India and Pakistan. Moreover, New Zealand and Australia are in the top ten exporters of food supplies, particularly livestock and dairy products [43].

Overall, global production and consumption of all animal-derived foods are expected to increase in the following years, especially in LMICs with rising population and income [44]. Nevertheless, consumers are shifting their preferences to healthier foods and are becoming more aware and concerned about animal welfare, increasing pressure to minimize antibiotic use in animal agriculture [43, 45, 46]. Also, the European Commission set a goal to, by 2030, reduce by 50% overall antimicrobials' sales for farm animals and aquaculture [45].

2.3 Antibiotic resistance compromises the progress toward sustainable development goals

Although economic development has greatly improved the well-being of many people around the globe, it often negatively impacts the environment and animal welfare, with the growing population exerting additional pressure in natural systems [47]. Ecosystem integrity is being threatened by large-scale deforestation, land usage and degradation, unsustainable agriculture practices, and others, being aggravated by unsustainable food production and consumption [47]. In the United Nations's resolution 'Transforming our world: the 2030 Agenda for Sustainable Development', from September 2015, 17 sustainable development goals (SDGs) were included (**Table 1**), focusing on environment and climate changes, societal issues, economics, education, and healthcare, including ABR [48]. Unfortunately, a 2024 report on SDGs progress reveals that only 17% of targets are progressing as expected, with an alarming 18% stagnation and 17% regression from the 2015 baseline [49].

In the context of sustainability, ABR poses a substantial barrier since it affects human and animal health, social well-being, economic progress, and the food chain [50–52]. Specifically, ABR may hinder SDG 1 (no poverty), SDG 2 (zero hunger), and SDG 3 (good health and well-being). As countries strengthen their economic capabilities and attempt to reach SDGs 1 and 2, the risk of antibiotic misuse grows, which, in turn, may drive ABR and limit progress toward SDG 3 that, without effective antibiotics, will be impossible to achieve [39]. SDG 2 could be achieved by increased productivity without resorting to massive use of antibiotics in animals through adequate husbandry, disease prevention measures, and suitable surveillance and regulation [53]. Since antibiotic residues and drug-resistant microorganisms are present in aquatic and land habitats [54], the prevalence of infectious diseases and ABR spread is increased, jeopardizing SDG 6 (clean water and sanitation), SDG 14 (life below water), and SDG 15 (life on land) [53, 55]. Moreover, SDG 8 (decent work and economic growth) may be compromised by ABR, creating a negative and irreversible impact on farmers' work [53], increasing healthcare expenditure, dropping productivity, and decreasing tax revenue and GDP [54, 56]. ABR may also undermine SDG 5 (gender equality) and SDG 10 (reduce inequalities) since socially and economically vulnerable people, namely women, children, migrants, and refugees, are at higher risk [53, 55, 57, 58]. Additionally, these individuals may live in regions where the existing healthcare infrastructures are deficient, and their access to effective antimicrobials may be limited [55, 58]. Noteworthy, although less deprived people may contribute more to ABR, the ones most likely to suffer the consequences are the ones of poorer communities, further exacerbating inequalities [59]. On the other hand,

SDG 1. <i>No poverty</i> : End poverty in all its forms everywhere
SDG 2. <i>Zero hunger</i> : End hunger, achieve food security and improved nutrition and promote sustainable agriculture
SDG 3. <i>Good health and well-being</i> : Ensure healthy lives and promote well-being for all at all ages
SDG 4. <i>Quality education</i> : Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG 5. <i>Gender equality</i> : Achieve gender equality and empower all women and girls
SDG 6. <i>Clean water and sanitation</i> : Ensure availability and sustainable management of water and sanitation for all
SDG 7. <i>Affordable and clean energy</i> : Ensure access to affordable, reliable, sustainable, and modern energy for all
SDG 8. <i>Decent work and economic growth</i> : Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
SDG 9. <i>Industry, innovation, and infrastructure</i> : Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
SDG 10. <i>Reduced inequalities</i> : Reduce inequality within and among countries
SDG 11. <i>Sustainable cities and communities</i> : Make cities and human settlements inclusive, safe, resilient, and sustainable
SDG 12. <i>Responsible consumption and production</i> : Ensure sustainable consumption and production patterns
SDG 13. <i>Climate action</i> : Take urgent action to combat climate change and its impacts
SDG 14. <i>Life below water</i> : Conserve and sustainable use the oceans, seas, and marine resources for sustainable development
SDG 15. <i>Life on land</i> : Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss
SDG 16. <i>Peace, justice, and strong institutions</i> : Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels.
SDG 17. <i>Partnerships for the goals</i> . Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development.

Table 1.
Sustainable development goals (SDGs) as established in the 2030 agenda for sustainable development [48].

in several LMICs, antibiotics are frequently used in illnesses that are directly attributable to lack of access to water, sanitation, and hygiene (WASH) infrastructures [42, 55] and to poor vaccination protocols [31, 55]. WASH is also directly connected to livestock health since animals may be exposed to hazards in contaminated water, which can cause botulism and salmonellosis and productivity loss [47]. Noteworthy, research is being conducted for sustainable management of animal wastewater by using aquatic plants (e.g., *Myriophyllum elatinoides*) to remove resistance genes in water and soil [60].

Within SDG 12 (responsible consumption and production), antibiotics may be considered as limited resources. Therefore, controlled access to and responsible use of antibiotics must be combined with research efforts on the development of new drugs and diagnostic tools (SDG 9: industry, innovation and infrastructure) [51]. Climate changes, considered in SDG 13 (climate action), also significantly affect ABR since rises in temperature lead to increased foodborne pathogens [28] and may favor the selection of resistant bacteria [61, 62]. Moreover, animals may be exposed to higher

stress levels due to increased temperatures, which could drive antimicrobial use in food-producing animals [63]. Finally, as ABR is not contained within borders, its successful long-term management is fully dependent on active and continuous collaboration between nations and stakeholders (SDG 17: partnership for the goals) [53].

3. Integrating human and animal health with environmental interface

The interface of human and animal interactions, and the environment, presents itself as a challenge for successfully mitigating ABR development and spread. The interconnection between these settings facilitates the transmission of resistant pathogens between ecosystems and populations [52]. Therefore, collaborative actions between nations and professionals with different expertise (epidemiologists, nurses, physicians, pharmacists, veterinarians, farmers, climate scientists, ecologists, wildlife experts, among others) are obligatory to achieve a common goal: ensure optimal health for people, animals, and the environment [12].

3.1 The One Health approach against antibiotic resistance

The One Health concept dates to the late nineteenth century. Around 1886, Pasteur reported the prevention of rabies in both dogs and humans *via* vaccination, a core element of the One Health approach [64]. The term itself was established during the first decade of the twenty-first century, evolving from Calvin Schwabe's coined term 'One Medicine', which recognized the interaction of humans and animals for nutrition and health [64, 65]. The One Health approach is a collective effort of different and complementary sectors to ensure the health of humans, animals, and ecosystems [10]. ABR is one of the problems addressed by this initiative, and it best represents the complex interconnection and interdependence of these three settings.

In May 2015, the international Tripartite – WHO, World Organization for Animal Health (WOAH), and the Food and Agriculture Organization of the United Nations (FAO) – introduced the Global Action Plan on AMR, with 194 countries committing to the development of National Action Plans (NAPs) [66]. To support coordinated actions and accelerate the progress of One Health initiatives in LMICs, particularly implementation of NAPs, the antimicrobial resistance multi-partner trust fund (MPTF) was created [67]. UN recently announced the Political Declaration of the High-level Meeting on Antimicrobial Resistance (General Assembly resolution 78/269), where a series of commitments to tackle AMR and to strengthen multisectoral progress at regional, national and global levels were outlined. These commitments included the development and implementation of NAPs, with funding directed especially to LMICs, and promotion of awareness through education and training [68].

In March 2022, the Tripartite partnership was further extended to a Quadripartite alliance, with United Nations Environment Programme (UNEP) [69]. This collaboration focuses on multifaceted and sustainable responses to global health threats and is advised by the One Health High-Level Expert Panel (OHHLEP) on how member states can effectively prevent and prepare for future health crises [70]. Soon after its formation, the Quadripartite launched the One Health joint plan of action (2022–2026) that is built around six interdependent action tracks (**Figure 1**) [47]. Also in 2022, the European UnEU reinforced its responsibility and commitment toward One Health's actions through the EU Global Health Strategy, outlining 20 guiding principles and recognizing the numerous unmet SDGs [71].

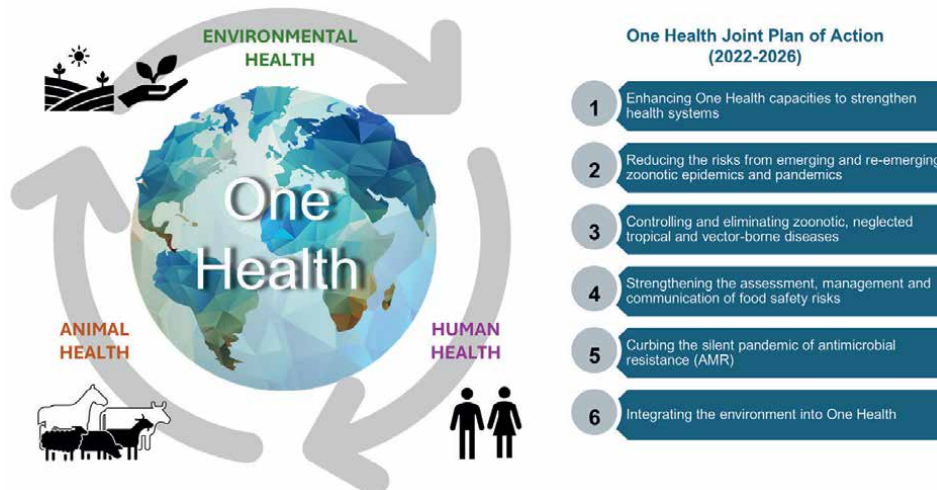


Figure 1.
One Health approach is a collaborative, multisectoral, and transdisciplinary vision that considers the interconnection and interdependence of human, animal, and environmental health. In the One Health joint plan of action (2022–2026), the Quadripartite established six interdependent action tracks for achieving sustainable health and food systems.

To integrate surveillance and monitoring data on antimicrobial use and AMR in humans, in the food chain, and in the environment, countries are encouraged to report these data using global databases, including the Global Antimicrobial Resistance Surveillance System (GLASS; WHO) [52], the Global Database for Antimicrobial Use in Animals (ANIMUSE; WOAHA), and the International FAO Antimicrobial Resistance Monitoring (InFARM) platform [72]. The gathered data can then be incorporated into Quadripartite' Global Integrated System for Surveillance of Antimicrobial Resistance and Antimicrobial Usage (GISSA) [72]. Furthermore, each country can report annually the efforts to evaluate progress on AMR management through the international tool Tracking AMR Country Self-Assessment Survey (TrACSS) [73, 74]. This enables them to keep track of their position within the global scenario and identify potential gaps to fulfill and areas to improve [74].

3.2 Antibiotic stewardship in agriculture

In the late 1940s, the use of antibiotics to increase animals' weight gain proved to be profitable in the United States [75]. In the mid-1950s, streptomycin was used for the treatment and prevention of plant bacterial infections, and tetracycline was applied as food preservative. These practices rapidly expanded to other world regions, and by the 1960s, antibiotics were widely used in global food production [75]. Around the same time, concerns on antibiotic use began slowly arising, in particular, penicillin residues in milk, leading the Food and Drug Administration (FDA) to introduce its first antibiotic monitoring program [76]. In 1969, the 'Swann Report' from the UK Joint Committee on the Use of Antibiotics in Animal Husbandry and Veterinary Medicine alerted to ABR emergence and urged the prohibition of medically important antimicrobials (MIAs) as growth promoters; however, concrete actions were not immediately implemented [29, 75, 77]. In the European Union (EU),

although MIAs are not banned from use in animals, they are under a very strict regulatory framework [78] and have been completely prohibited as production enhancers since 1 January 2006 [79].

Antibiotic classification lists have been established and updated over the years by several international entities as tools to promote antibiotic stewardship. Nevertheless, countries are encouraged to adopt their own MIAs lists that consider specific antibiotic use, regional health priorities, and epidemiological profiles [80]. In 2005, the WHO published its first list of MIAs, and the most updated version is from 2024 [81]. Here, antimicrobials are ranked according to their importance in human and veterinary medicine. Also, the WHO Expert Committee on Selection and Use of Essential Medicines has developed, in 2017, the AWaRe classification of antibiotics to identify priority antibiotics for monitoring and to provide recommendations for common infectious diseases [82, 83]. Antibiotics are divided into three groups based on their potential to induce and propagate resistance: Access (first- and second-line), Watch (broader spectrum), and Reserve (last resort) [82, 84]. The European Medicines Agency (EMA)'s Antimicrobial Advice Ad Hoc Expert Group (AMEG) has created four antibiotic categories to help veterinarians' prescription decision: A ('avoid'), B ('restrict'), C ('caution'), and D ('prudence'), last updated in 2020 [85]. In 2007, the WOAH established a list of antimicrobial agents of veterinary importance: veterinary critically important antimicrobial agents (VCIA), veterinary highly important antimicrobial agents (VHIA), and veterinary important antimicrobial agents (VIA) [86]. Last updated in 2024, this list addresses antimicrobials approved for food-producing animals, excluding those for human-only use [86].

Several international initiatives to tackle ABR are underway. The Farm to Fork Strategy is at the center of the European Green Deal and the Commission's SDGs. It aims to support sustainable food systems, recognizing the complex interconnection between healthy humans, society, and a healthy planet [45]. Among the addressed topics are animal welfare and AMR within the One Health perspective [45]. The Joint Programming Initiative on Antimicrobial Resistance (JPIAMR) has the European Commission and 29 countries as members, coordinating research funding and supporting collaboration under the One Health approach [87]. The independent network ReAct, created in 2005 and present in four continents, through its evidence-based knowledge repository (ReAct ToolBox), provides information to individuals, policy-makers, and organizations to take action against ABR [88].

4. Animal welfare and the use of antibiotics: One welfare

Animal welfare, which includes animal health, has been and continues to be influenced by modern animal agriculture practices. In countries with increasing population and food consumption rates, industrial animal production is favored over the 'free-range' mode since the former is economically more competitive [41]. Besides confining the animals in an unnatural environment, husbandry in high densities may increase animal disease occurrence and spread, and restrict movement and natural behaviors [41, 89]. Intensive animal production also replaces grazing and foraging with artificial and highly processed feeds, which may cause digestive disorders and negatively affect microbiota, increasing the risk of colonization by harmful bacteria [41].

Improving animal welfare and health is important to ensure that animal production is more productive and sustainable [41]. Good welfare is ensured when animals

are healthy, safe, comfortable, well-nourished, do not experience unpleasant states, and are able to express their natural behavior [90]. The European Food Safety Authority (EFSA), FAO, and WOAHP emphasize that animals' welfare is directly connected to food safety and foodborne diseases [91, 92]. This is addressed by the One Welfare approach, defined in 2018, that complements and partially overlaps the One Health vision, highlighting the interconnection between animal welfare, human well-being, and the environment [93].

Published by the WOAHP, the Terrestrial Animal Health Code is a guide for optimizing animal health and welfare worldwide [90]. Section 7 is dedicated to animal welfare, which is defined as *'the physical and mental state of an animal in relation to the conditions in which it lives and dies'* [90]. The Code's recommendations can help implement measures for the prevention, detection, monitoring, and control of pathogens in terrestrial animals, including mammals, reptiles, birds, and bees, with Section 6 containing standards applied to animal production systems, including biosecurity and ABR management [90]. Biosecurity in animal production systems involves a set of measures to prevent or minimize the risks of disease outbreaks [94, 95]. These include animal quarantine and control of animal movements, ensuring the hygiene of personnel, equipment, and vehicles, implementing appropriate vaccination protocols, and monitoring and reporting disease, and warranting water and feed quality [96]. Biosecurity is recognized as essential for animal welfare, food safety, sustainability, profitability, and, ultimately, public health [94, 95]. Farmers may be encouraged to invest in biosecurity through the shift in consumers' preferences, which are increasingly focused on local and high-quality products, even if associated with higher prices [46, 97].

It is recognized that better animal welfare enhances animal health and food quality and minimizes the need for drug use, namely antibiotics [45, 98]. Nevertheless, it is important to consider that adequate antibiotic use may often be necessary to ensure animal health and, thus, welfare [98]. As aforementioned, the industrial animal production is being pressured to meet the increasing food demand, while following adequate antibiotic use practices. Ensuring animal welfare and health may alleviate the overdependence on these drugs without diminishing productivity or increasing costs [99]. Again, implementing effective biosecurity measures and vaccination protocols can help prevent diseases in animals and, consequently, diminish the use of antibiotics [100]. International and country-specific guidelines include these interventions as critical steps for a successful antibiotic stewardship [50, 101].

In 2024, the European Partnership on Animal Health and Welfare was launched, aiming to support sustainable animal production, control infectious diseases, mitigate zoonotic risks, and promote the prudent use of antimicrobials to ensure optimal animal welfare and health. It follows the One Health and One Welfare approaches, being connected to the Farm-to-Fork strategy [45, 102].

5. Challenges and opportunities

In the fight against ABR, several opportunities can be explored to provide effective and long-lasting solutions, including the application of alternatives to antibiotics (**Figure 2**), increased awareness among stakeholders, and investment in technology and research. In turn, some challenges remain in the regulatory field, where, although countries are making efforts toward antibiotic stewardship, some gaps still need to be addressed.

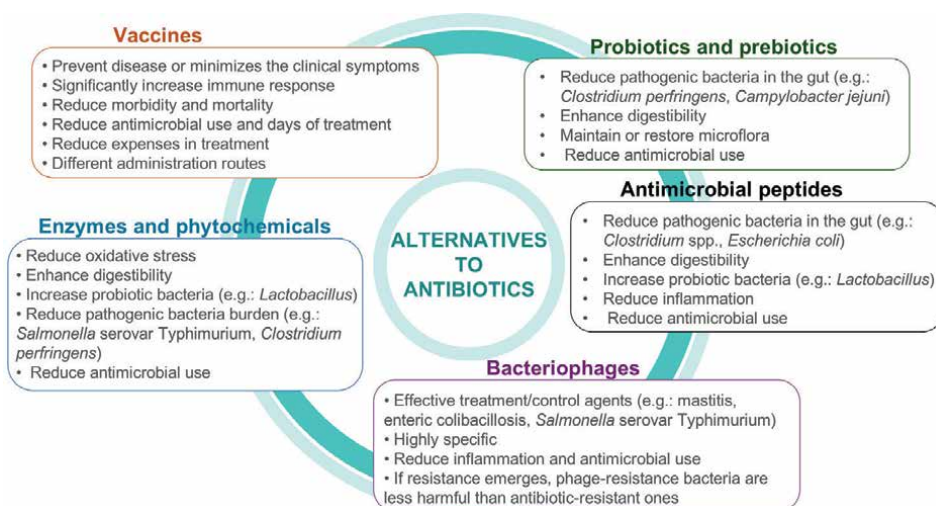


Figure 2.
Alternatives to antibiotics: positive impacts on livestock well-being and contribution to minimizing the use of antimicrobials in animals.

5.1 Alternatives to antibiotics in food-producing animals

5.1.1 Vaccines

Vaccination, as aforementioned, is the most cost-effective and efficacious alternative to the use of antibiotics, preventing diseases that were previously controlled with these drugs [103]. Current licensed bacterial vaccines are live-attenuated, inactivated (bacterins), toxoids (inactivated native toxins), and subunit vaccines (contain part of the target pathogen, e.g., polysaccharides).

Despite the benefits, robust and durable immunization against a broad range of pathogens is difficult and complex [103], and some vaccines have limited efficacy or induce severe side effects [104]. For example, as *Mycobacterium bovis* is resistant to most antibiotics, except fluoroquinolones, vaccination would be the most effective strategy. Nevertheless, currently available vaccines show moderate or very low efficacy (1–44%) [104]. Also, country-specific conditions may impede the successful vaccination of animals, as is the case with contagious bovine pleuropneumonia. *Mycoplasma mycoides* causes this disease and has been eradicated in most continents. However, in sub-Saharan Africa, it continues to inflict significant cattle losses due to economic limitations, conflicts, and climate hardships [104, 105]. Many of the challenges in vaccine development for food-producing animals could undoubtedly benefit from policy changes and better funding [106] since research interest in novel vaccine technologies, such as genetically modified live vaccines, is often hampered due to regulatory restrictions [106].

Vaccine administration method and regimen may also influence the success of disease prevention in animals. For example, user-friendly methods, namely through spray, drinking water or bait, may improve adherence, despite having limited effectiveness [106]. Also, parenteral route can be problematic to operator safety and can lead to reactions on the injection site [107]. Moreover, vaccination compliance may be hindered when multiple boost vaccinations are required or when cost-effectiveness is limited compared to antibiotics [106].

Within sustainability, vaccination prevents disease and, thus, reduces productivity losses and potentially reduces greenhouse gas emissions, contributing to SDGs 1–3 and 12–15 [107, 108]. Despite the undeniable benefits, in some cases vaccination does not fully prevent infection and may increase survival time of diseased animals, further potentiating disease transmission (e.g., *Mycoplasma hyopneumoniae*) [106, 109].

5.1.2 Probiotics and prebiotics

Molecules produced by different microorganisms are being investigated for improving animal nutrition and enhancing immunity [103]. Aiming to restore the microflora, enhance feed digestibility, and inhibit the growth of pathogenic bacteria, probiotics are added to the feed of food-producing animals [110]. Probiotics include yeast, fungi, and bacteria and some of the most commonly used ones are species of *Bacillus*, *Bifidobacterium*, *Lactobacillus*, *Lactococcus*, *Enterococcus*, *Pediococcus*, *Streptococcus*, *Saccharomyces*, *Aspergillus*, and *Candida* [110]. As probiotics are living microorganisms that affect the gastrointestinal system and that may interact with host animals at the genetic level, these are subject to regulation [111]. In the United States, microorganisms used as feed additives, termed direct-fed microbials, require approval by the Food and Drug Administration (FDA), unless considered as Generally Recognized as Safe (GRAS) for that use [103, 111, 112]. In the EU, probiotics for animal nutrition (zootechnical additives) must follow Regulations (EC) No. 1831/2003 and 429/2008, under the guidance of the European Food Safety Authority [111, 112]. The addition of prebiotics, non-digestible food ingredients to animals' feed may improve their health and productivity by stimulating the growth of beneficial gut microbiota, such as probiotics [112, 113]. Among the most common prebiotics employed in animal nutrition are inulin, fructo-oligosaccharides, galacto-oligosaccharides, cereal fiber, lacticol, and xylo-oligosaccharides [113]. When prebiotics are added together with probiotics, the designation is synbiotics [114].

5.1.3 Bacteriophages

Bacteriophages (phages) are viruses that infect bacteria to replicate and have been considered for the treatment of bacterial infections. A few bacteriophage products are on the market, with some having GRAS status. Besides being applied as therapy, phages can also be used for food biocontrol and for disinfection [115, 116]. Phages have been used as an additive in poultry feed or in drinking water [115, 116]. Suppositories containing *Lactobacillus* as probiotic and a cocktail of three *Escherichia coli* lytic bacteriophages were applied in young calves, exerting therapeutic and prophylactic effect on diarrhea [117]. Other bacteriophage research studies have also been conducted in pigs, sheep, horses, and poultry [116, 118]. As ABR crisis increases, bacteriophages might provide an alternative when antibiotics are either not available or ineffective. Despite their promise, phage isolation, propagation, purification, as well as stability are still challenging [115]. Furthermore, the high host specificity of bacteriophages may limit their application since the pathogenic bacteria must be identified prior to treatment to ensure an effective eradication of disease-causing bacteria [119].

5.1.4 Enzymes and phytochemicals

Animal gut health and productivity may be enhanced by feeding specific enzymes, including protease, phytase, and carbohydrase, that improve digestion and nutrient

absorption [120, 121]. In gastrointestinal diseases that require the use of antimicrobials, the enzymes can be beneficial and, in some cases, could be a suitable replacement [120]. Phytases commercialization is well established. However, the introduction of other feed enzymes may be difficult by low activity, high production cost, and lack of standardized production processes [122].

Phytochemicals or plant-derived bioactives are considered as GRAS and display a wide range of functions in animal production, namely improving nutrient conversion and gut health [123, 124]. These are included in animals' diet, boosting innate immunity, exerting antimicrobial activity, and augmenting animal growth performance [123, 125]. Examples of plant-derived bioactives with antimicrobial activity are phenolics/polyphenols, terpenoids/essential oils, alkaloids, and lectins/polypeptides [125, 126]. It has also been demonstrated that some natural extracts/compounds stimulate the growth of specific bacteria, functioning as prebiotics. This activity, together with antimicrobial capacity, modulates the host's intestinal microflora and controls pathogenic bacteria proliferation [123, 124]. Despite these promising data, the practical application of these phytochemicals in large-scale animal production systems should be pursued, as well as the establishment of an appropriate legal framework [123]. Also, the effectiveness of phytochemicals is often variable due to different plant sources, geographical site, growing conditions, concentration, as well as processing techniques and storage conditions. This variability is further exacerbated when heterogeneous mixtures of plant metabolites are used, such as essential oils [127–129]. The isolation and quantification of bioactives from plant extracts constitute additional challenges for their successful and consistent formulation as feed additives [130].

5.1.5 Antimicrobial peptides

Antimicrobial peptides, produced by most organisms against pathogenic infections, emerge as promising alternatives to antibiotics [131]. These peptides display broad-spectrum activity against bacteria, fungi, parasites, and viruses [132]. Antimicrobial peptides were reported to recover and maintain animals' gastrointestinal tract, stabilizing the epithelial barrier integrity, solving digestion problems, and promoting animal growth performance [133, 134]. Also, some of these peptides can reduce inflammation, modulate the immune response, and are associated with low levels of resistance [134, 135]. For instance, when added in feed, antimicrobial peptides may boost the number of beneficial *Lactobacillus* and *Bifidobacterium* (e.g., lactoferrin-derived peptide; [136]) and may reduce pathogenic bacteria (e.g., sublancin; [137]). In another study, β -defensin-1 application in piglets prevented respiratory infection by *Bordetella pertussis* [138].

Bacteriocins are a specific type of antimicrobial peptides that are produced mostly by Gram-positive bacteria, such as lactic acid bacteria. Evidence suggests that bacteriocins are a promising alternative to impair the proliferation of harmful bacteria and mitigate ABR [139]. Some limitations of antimicrobial peptides are weak stability and low industry yield [135].

5.2 Regulatory and policy challenges in large-scale livestock production

Global regulatory landscape on antibiotic use in food-producing animals is constantly evolving. In Europe, Regulation (EU) 2019/4 on Medicated Feed and Regulation (EU) 2019/6 on Veterinary Medicinal Products are currently in force, providing guidance on the prudent and responsible use of antibiotics in animals, namely

[140]. On 1 January 2006, the EU prohibited the use of all antibiotics for growth promotion [79], and, in February 2023, the EU adopted Regulation (EU) 2023/905, prohibiting imports from non-EU countries of animals and animal-derived products exposed to antimicrobials as growth promoters [141].

In the United States, under FDA Guidance for Industry (GFI) #213 and its Veterinary Feed Directive final rule, access to MIAs for administration in feed or drinking water are under veterinary oversight or prescription [142]. Also, GFI #209 focuses on the judicious use of MIAs in food-producing animals [143].

In South America, legislation in five large meat-producing countries (Argentina, Brazil, Chile, Colombia, and Uruguay) is moving toward international goals. Nevertheless, improvements are required, namely the ban of antibiotics as growth promoters, the establishment of minimum welfare and biosecurity standards, and the controlled access, use, and disposal of antibiotics [144].

In many Southeast Asia countries, appropriate control and monitoring of antimicrobial use are lacking, resulting in access to critically important antibiotics without prescription and their use as growth promoters [145, 146]. Furthermore, labeling livestock medicated feed is often misleading or imprecise since antimicrobials are not listed in the ingredients [147]. Despite this, several nations of this region have already developed more comprehensive legislation and policies to reduce the inadequate use of antibiotics in animal production [146].

In Africa, weak antimicrobial regulations in both human and veterinary medicine, uncontrolled access to veterinary drugs, deficient surveillance systems, and lack of updated guidelines impair successful antibiotic stewardship. However, these limitations are being addressed in NAPs that are being developed by some countries [148]. Moreover, the Africa Centres for Disease Control and Prevention, officially launched in January 2017, has established a One Health Programme and is working with several national and international institutions to monitor ABR, minimize the emergence of new resistant strains, and reduce ABR-associated consequences [149].

Overall, countries around the globe are identifying gaps and working to promote the adequate use of antibiotics in animals and to tackle ABR, either through regulatory frameworks, guiding documents, or both [75]. It is necessary to account for key disparities found between countries/regions in terms of culture, internal policies, attitudes, and perceptions about ABR, and financial resources. The effective implementation of antibiotic stewardship programs is, therefore, a process that needs to be continued and tailored for each case.

5.3 Education and awareness among veterinarians and farmers

An important part of successfully achieving the responsible use of antibiotics in animals is increasing awareness about ABR through education of farmers and veterinary personnel [35, 150, 151]. Farmers' knowledge regarding the negative impacts of ABR is driving the reduction of antibiotic use [152], and access to adequate training and education can foster good health management practices and biosecurity [150, 152]. For instance, farmers aware of animal welfare importance ensured good production practice, increasing productivity and sales and, at the same time, reducing mortality [95, 153]. Also, as aforementioned, awareness and expectations of consumers for adequate on-farm practices are influencing decision-making on measures that ensure animal welfare.

In the case of LMICs, smallholder farmers are predominant and barriers, such as inadequate infrastructure, weak disease surveillance, lack of financial resources, and

poor collaboration among stakeholders, further compromise animal welfare [154, 155]. Considering these difficulties, the International Centre for Antimicrobial Resistance Solutions (ICARS), initiated by the Danish government and officially established in November 2021, helps translating LMICs NAPs into concrete actions through funding campaigns and relevant training, engagement, and awareness-raising initiatives [156].

Veterinarians, together with farmers, are at the forefront of animal welfare and health. Thus, a strong communication between them can facilitate prudent antibiotic use and good farm practices, with veterinary professionals acting as trusted sources of information and advisers [157]. In this context, and to ensure that veterinarians are updated, comprehensive and ongoing training programs should be promoted, enabling these professionals to work independently and make informed decisions regarding antibiotic prescription and use [158]. Veterinarians recognize their key role as antimicrobial stewards [159]; however, in some regions, the interaction between farmer and veterinarian is very sporadic or even inexistent, which, together with their lack of knowledge, further promotes the misuse of antibiotics in animals [160].

5.4 Future research and technological innovations

Among the obstacles for effective ABR management are the lack of investment on clinical and preclinical development of novel antibacterial agents and, in many situations, the limited access to and availability of approved antibiotics [161]. Antibiotics that are currently approved or under investigation poorly address WHO-defined innovation criteria: (i) new chemical class; (ii) new target; (iii) new mechanism of action; and (iv) absence of cross-resistance [161, 162]. Of concern is that more than 80% of recent antibiotic approvals are derivatives of known classes to which resistance is already observed [161]. These facts further instigate the reduction of antibiotic use in animals. While existing alternatives improve animal health and minimize or may prevent the need for antibiotics, more effective options are required to fully replace antibiotics in disease management, and their success in reducing ABR should be closely monitored [163].

The STAR-IDAZ International Research Consortium [164], with 36 partner institutions from all over the world, focuses on animal health research, having One Health as pillar. Within ABR, the priority is the development of alternatives to antibiotics, namely research on sustainable and tailored bacteriophage cocktails, immunomodulators, and probiotics [165]. A key resource used by STAR-IDAZ is DISCONTTOOLS (DISease CONtrol TOOLS: diagnostics, vaccines, and pharmaceuticals), which provides updated data on more than 50 animal infectious diseases and identifies and prioritizes research needs [166].

Canada's International Development Research Centre (IDRC) [167], established in 1970, supports several innovative veterinary projects in developing countries. Research efforts are focused on reducing antibiotic use in animal through alternatives, including bacteriophages, antimicrobial peptides, nanosystems and nanoparticles, vaccines, and mechanical thermoregulation in aquaculture, among others [167]. The Global AMR R&D Hub, launched in May 2018 and following a One Health approach, facilitates international multisector collaboration in research and development against AMR, working with other international organizations, including STAR-IDAZ and ICARS [168].

Noteworthy, modeling studies on curtailing antibiotic consumption in animals showed that, in isolation, this may not be sufficient to reduce ABR in humans [169, 170]. For an effective impact on ABR, interventions to reduce the rate of animal-human transmission of resistance are also required [169, 170] since, when resistance has a very high transfer rate, limiting antibiotic use may not be a viable strategy to

mitigate ABR [13]. Investment in vaccination should be reinforced and focused on better understanding the virulence mechanisms and host-pathogen interactions, and the development of new oral-vectored vaccines using *Bacillus* spores or live recombinant vectors, combination vaccines [106, 171], mRNA-based vaccines, and nano/microparticles delivery technologies (e.g., lipid nanoparticles, microspheres, and polymeric implants) [107, 172]. New technologies for animal self-vaccination are being explored, namely a sprayer device containing a *Salmonella* vaccine that was successfully tested in pigs. This strategy, besides allowing self-oral administration, provided environmental enrichment for improved animal welfare [173].

Furthermore, technological advances and AI have been combined for application in precision livestock farming to enhance productivity and minimize disease onset [174–176]. Real-time monitoring of each animal behaviors and physical parameters allows a more precise and earlier detection of any signs of distress or disease, enabling a better management of well-being and health [174–176]. AI-based closed-circuit television live surveillance system has also been successfully employed on LMICs farms. The major advantages of this technology were increased profitability, reduced medical expenses and antimicrobial use, and long-term decrease in mortality rates [177].

6. Conclusions

Based on the literature cited in this chapter, the following key conclusions can be drawn:

- ABR is a public health threat with a global impact.
- To effectively tackle ABR and ensure future sustainability, a One Health approach is fundamental.
- Collaboration and communication among stakeholders worldwide must be solidified.
- Stakeholders within the veterinary sector should prioritize measures to reduce disease burden, research and development of alternatives to antibiotics, and improved surveillance and monitoring programs.
- The use of antimicrobials for growth promotion purposes should be phased out.
- Educational interventions in ABR and prudent use of antibiotics in food-producing animals should be promoted among farmers, communities, and veterinary professionals.

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Conflict of interest

The authors declare no conflict of interest.

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Advanced Strategies in Gut Microbiota Modulation for Enhancing Livestock Health

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Abstract

The modulation of gut microbiota presents a promising avenue for improving livestock health, productivity, and sustainability. Traditional strategies such as probiotics, prebiotics, and synbiotics have demonstrated effectiveness in enhancing gut health and immune function while reducing the reliance on antibiotics. Recent advances have introduced innovative approaches, including postbiotics, fecal microbiota transplantation (FMT), and precision biotics, to emerging strategies such as synthetic biology applications and bacteriophage therapy, offering targeted interventions with the potential for high specificity and efficacy. However, successful integration into agricultural systems requires navigating complex regulatory frameworks and addressing safety, scalability, and economic feasibility concerns. This chapter aims to critically assess traditional, advanced, and emerging microbiota modulation strategies, evaluating their mechanisms, applications, and limitations while highlighting their transformative potential in achieving sustainable livestock production and addressing global public health challenges. The chapter offers practical guidance for veterinarians, researchers, policymakers, and producers seeking to integrate microbiota-based strategies into modern livestock operations.

Keywords: gut microbiota, livestock health, sustainability, antimicrobial resistance, antibiotic alternatives

1. Introduction

The global livestock sector is at a pivotal crossroads, driven by increasing protein demand, changing consumer preferences, and technological advancements. Consumer preferences are shifting toward sustainable and ethical products, with animal welfare and environmental impact becoming key purchasing factors. Rising demand for sustainable offerings is evident, as two-thirds of global consumers are willing to pay more for products meeting these criteria [1]. The livestock industry faces unprecedented challenges to reduce antimicrobial use to combat antimicrobial resistance (AMR). The growing concern over the emergence and spread of antimicrobial resistance from the unrestricted antimicrobial use in livestock feed has catalyzed

a paradigm shift toward alternative strategies for promoting animal health and productivity [2–4]. Modulating the gut microbiota has emerged as a promising approach that aligns with sustainable agriculture principles and the One Health concept [2, 5].

Recent advances in molecular techniques and bioinformatics have revolutionized our understanding of the gut microbiome's crucial role in livestock health [6, 7]. The gut microbiota influences numerous physiological processes, including nutrient absorption, immune system development, and protection against pathogens [7]. A healthy, diverse microbiome has been associated with better feed efficiency, stronger immune function, and enhanced disease resistance [8]. This has led to heightened interest in strategies to manipulate gut microbiota for improved livestock outcomes.

Microbiota modulation strategies encompass a wide array of approaches, from traditional methods such as probiotics, prebiotics, and synbiotics to more recent innovations that involve advanced, targeted interventions [9]. Each intervention requires a thorough understanding of the intricate relationships between host animals, microbes, and environmental conditions [10]. Moreover, these approaches must be adapted to the specific needs of diverse livestock species, production stages, and management systems, underscoring the complexity of practical implementation [11].

This chapter aims to critically assess traditional, advanced, and emerging microbiota modulation strategies by evaluating their mechanisms, applications, and implementation challenges. It highlights their transformative potential for sustainable livestock production and global public health, addressing regulatory requirements and economic considerations within the broader One Health and sustainability frameworks. The chapter offers practical guidance for veterinarians, researchers, policymakers, and producers seeking to integrate microbiota-based strategies into modern livestock operations.

2. Gut microbiota in livestock

The gastrointestinal tract harbors a complex community of microorganisms, comprising bacteria, archaea, fungi, and viruses, collectively known as the gut microbiota [12]. Research shows that more than 98% of isolated genetic sequences in the gut are bacterial, which has made bacteria the primary focus of microbiota research [6, 13]. This microbial population outnumbers host cells, with microbial genes exceeding the host genome. Ruminants, such as cattle, goats, and sheep, demonstrate unique microbial compositions adapted to their complex digestive system, whereas monogastric animals like pigs and poultry show different patterns of microbial colonization, reflecting their distinct digestive physiologies [14]. Microbial distribution varies throughout the digestive tract, with their composition responding to different factors as host age, genetics, diet, and environment.

2.1 Implication of gut microbiota in sustainable livestock

After birth, beneficial microbes colonize the animal's gut, establishing the foundation for healthy microbiota development [15]. A well-balanced gut microbiota serves multiple important functions that directly impact sustainable livestock production through improved feed efficiency, reduced antimicrobial use, and environmental stewardship. The gut microbiota enhances nutrient absorption, and energy metabolism, reducing feed wastage and promoting optimal growth. Beneficial bacteria, viruses, and fungi protect against pathogens by outcompeting harmful microbes and strengthening gut barrier function [14]. They promote healthy cell growth and strengthen cellular junctions,

preventing ‘leaky gut’ syndrome and associated inflammation and disease [16]. In ruminants, specialized microbial consortia break down fibrous plant materials into short-chain fatty acids (SCFAs), while in pigs and poultry, gut microbes enhance digestion in simpler gastrointestinal tracts [17]. A healthy microbiota reduces dependence on antibiotics by strengthening immune responses and preventing pathogen overgrowth [18]. This supports the One Health framework by addressing antimicrobial resistance (AMR) concerns. Additionally, optimal gut microbiota can reduce greenhouse gas emissions and nitrogen excretion through improved microbial fermentation pathways [19].

Host genetics significantly influences intestinal microbiota composition, as demonstrated by breed-specific and sexual differences (**Table 1**) [15, 20–30]. Environmental factors and management practices also play a crucial role in modulating gut communities and microbial diversity (**Table 2**) [20, 21]. Additionally, the extensive use of antimicrobials, both for growth promotion and therapeutic purposes, disrupts gut microbiota diversity, creating conditions that favor the proliferation of antimicrobial-resistant bacteria.

2.2 Problem associated with imbalance of gut microbiota

Disruption of the gut microbiota balance, a condition termed as dysbiosis, leads to various health and production challenges across livestock species. In ruminants,

Species	Category	Subcategory	Microbiota diversity
Cattle	Breed	Charolais, Xinjiang Brown	Lower
		Composite Hybrids, Angus	Higher
	Sex	Bull	Lower
		Cow	Higher
Sheep	Breed	Large-tailed Han	Higher
		Small-tailed Han	Lower
	Sex	Ram	Variable
		Ewe	Variable
Goat	Breed	Hainan Black	Higher
		Saanen White	Lower
	Sex	Billy	Variable
		Nanny	Variable
Pig	Breed	Duroc, Large White	Lower
		Landrace	Highest
	Sex	Boar	Variable
		Gilt	Variable
Poultry	Breed	Indigenous	High
		Commercial broiler	Lower
	Sex	Cock	Lower
		Hen	Higher

Table 1.
Host genetic factors affecting gut microbiota composition.

Factor	Impact on microbiota	Key considerations
Housing Conditions	Significant	Ventilation, stocking density, hygiene
Diet	Major	Feed composition, feeding frequency, supplements
Pathogen Exposure	Variable	Disease status, vaccination, biosecurity

Table 2.
Environmental factors affecting gut microbiota composition.

rapid fermentation of concentrated feeds results in ruminal acidosis, lowering feed efficiency and nutrient absorption [31]. Microbial disruptions may also increase methane production, affecting energy utilization and the environment [32]. Weaning-associated dysbiosis compromises intestinal barrier function, reduces villus height, and shortens the small intestine [33]. Microbial disturbances frequently cause necrotic enteritis and reduce nutrient absorption in poultry production [34]. The compromised intestinal environment creates favorable conditions for foodborne pathogen colonization [35]. Both therapeutic and subtherapeutic antimicrobial use severely reduces beneficial bacterial populations, selecting for antimicrobial-resistant strains and impairing normal gut metabolism. Such disruptions can have lasting effects on animal health and performance.

3. Gut microbiota modulation strategies in livestock

Current studies on gut microbiota modulation have extensively explored traditional strategies, such as probiotics, prebiotics, and synbiotics (**Figure 1**), which have demonstrated significant potential in promoting gut health, enhancing immunity, and improving animal productivity. However, recent advancements in microbiome research and high-throughput technologies have driven the development of innovative, targeted approaches. These advanced strategies, including fecal microbiota transplantation (FMT), postbiotics, and precision biotics (**Figure 1**), aim to refine microbiota functionality and address specific challenges in animal health and production. The following sections examine both ongoing traditional and emerging advanced strategies, highlighting their mechanisms, applications, limitations, and future potential in promoting sustainable practices.

3.1 Prebiotics

Prebiotics, defined as non-digestible food components that selectively stimulate the growth and activity of beneficial gut microorganisms, have been shown to improve health by restoring microbiota communities [36]. These components, typically insoluble fibers isolated from plants, legumes, grains, and fruits, act as fermentation substrates for probiotics or native beneficial microbiota, resulting in the production of SCFAs like acetate, propionate, and butyrate [37]. These SCFAs lower intestinal pH, create favorable growth conditions for beneficial microbes, and suppress pathogenic species such as *Salmonella*, *Escherichia coli*, and *Campylobacter* [38, 39]. Additional pathogen inhibition occurs through the coating of the host gut wall surface, blocking pathogen colonization and downregulating the expression of virulence genes [39]. To be considered beneficial, prebiotics must evoke a net health benefit by selectively impacting microorganisms and producing metabolites linked to specific health benefits [40].

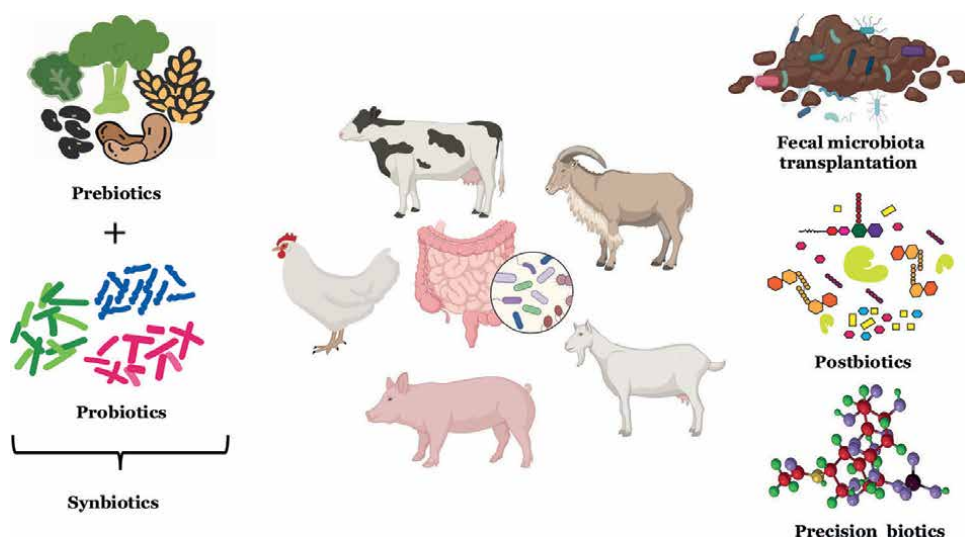


Figure 1.
 Different gut microbiota modulation strategies in livestock production.

Prebiotics have been widely studied and used in livestock production, where differences in animal species' anatomy, physiology, and dietary requirements must be considered when evaluating their impact [40]. Common prebiotics in livestock nutrition include fructo-oligosaccharides (FOS), galacto-oligosaccharides (GOS), inulin, isomalto-oligosaccharides (IMO), xylo-oligosaccharides (XOS), mannan-oligosaccharides (MOS), lacticol, lactulose, and cereal fiber [41, 42]. Novel prebiotics, which differ from traditional non-digestible carbohydrates, include compounds such as proteins, hydrolysates, peptides, amino acids, and nucleotides, have also been selectively utilized by host microbes to provide health benefits [43–45].

These prebiotics have demonstrated microbiota-modulating abilities when included in livestock diets. For instance, Sayed et al. [46] showed that MOS and beta-D-glucan improved the gut microbiome of broiler chickens under heat stress by increasing beneficial bacteria, reducing pathogens, enhancing immune function, and promoting growth. Additionally, cellooligosaccharides (CE) promoted the growth of butyrate-producing bacteria in the calf intestine, improving epithelial structure [47]. Fructooligosaccharides (FOS), resistant to enzymatic degradation, serve as substrates for specific intestinal microorganisms, promoting gut health by enhancing populations of *Bifidobacteria* and *Lactobacillus* in the cecum of poultry birds [48, 49]. Further, MOS supplementation increased intestinal villi length and enhanced nutrient absorption in lambs [50, 51], and lambs fed MOS and beta-glucan exhibited improved feed intake, weight gain, and nutrient digestibility [52, 53]. Supplementing nucleotide blends to 3-day-old weaned pigs altered the colonic microbiota, reducing the Firmicutes-to-Bacteroidetes ratio and increasing beneficial bacteria such as *Faecalibacterium*, *Blautia*, and *Prevotella*, while also enhancing SCFA production [54]. Similarly, Zheng et al. [55] documented that supplementing pig diets with Red-osier dogwood (ROD) polyphenol extract conferred health benefits by modifying the gut microbiota, notably through a significant increase in *Lactobacillus* populations. However, some inconsistencies in performance outcomes across studies highlight the need for further research to optimize prebiotic applications for livestock species, considering factors like formulation and species-specific responses [50].

3.2 Probiotics

Probiotics are live microorganisms that are generally recognized as safe and confer health benefits to the host when administered in adequate amounts [56]. In livestock, commonly used probiotic species include bacterial genera such as *Lactobacillus*, *Streptococcus*, *Enterococcus*, *Lactococcus*, and *Bifidobacterium*, as well as non-bacterial species like *Saccharomyces* (*S. cerevisiae* and *S. boulardii*), *Candida pintolopesii*, and *Aspergillus oryzae* [56]. These probiotics are typically administered orally, although other routes are also employed [57].

While probiotics are considered an alternative to antibiotic growth promoters, their mechanisms of action are distinct. Probiotics generally promote gut health through mechanisms like competitive exclusion, as seen with *Bifidobacterium bifidum* and *Lactobacillus rhamnosus*, which help maintain a healthy gut environment by outcompeting harmful bacteria for nutrients and adhesion sites [58]. Other mechanisms include bacterial antagonism (e.g., *Bacillus coagulans* secreting antimicrobial substances to inhibit harmful bacteria), immune system stimulation (e.g., *Lactobacillus acidophilus* enhancing the immune response and digestion by producing enzymes that help break down lactose) [59] and have been shown to improve nutrient utilization and absorption, resulting in enhanced feed efficiency and growth performance in animals [60]. Probiotics also influence luminal pH and enhance intestinal barrier function [61].

Probiotics are available in various formulations, and their efficacy can vary based on whether they are mono- or multi-strains. Their effects are species-specific and may also depend on the physiological and immunological condition of the host [62, 63]. In ruminants (e.g., cows, sheep, goats), probiotic strains like *Saccharomyces cerevisiae*, *Lactobacillus*, *Enterococcus faecalis*, *Bacillus subtilis*, and *Bifidobacterium bifidum* have been shown to positively influence milk production, milk allergy reactions, intestinal maturation, and reduce ruminal acidosis. These probiotics also positively affect rumen microbial ecology, nutrient breakdown, and weight gain, thereby improving the overall well-being and productivity of ruminant animals [64–66]. In non-ruminants, probiotics also support nutrient digestibility, gut health, and performance. For poultry, strains such as *Lactobacillus*, *Bifidobacterium*, and *Enterococcus* have been shown to improve feed efficiency, egg production, egg size, egg quality, and nutrient utilization [66]. In pigs, *Enterococcus faecium* is commonly used as a probiotic due to its ability to adhere to the gut mucosa, effectively colonizing the intestinal tract and improving daily weight gain and nutrient conversion [67]. Several studies have also indicated that multi-strain probiotics can enhance growth performance, feed efficiency, and nutrient digestibility in various livestock [56, 68, 69]. Despite the proven benefits of probiotics, there is still a need to optimize their formulations, dosages, and industrial application methods to maximize effectiveness, ensure safety for both animals and consumers and achieve sustainability.

3.3 Synbiotics

Synbiotics are a combination of prebiotics and probiotics that may provide synergistic health benefits to the host, often outperforming either component alone by improving the survival and colonization of beneficial microorganisms in the GIT [70]. They are increasingly explored as a targeted approach to modulating the gut microbiota and promoting host health [8].

The mechanisms of action for synbiotics are complex due to their multi-component nature [71]. Two primary approaches may be involved: complementarity and

synergism. In the complementary mechanism, prebiotics and probiotics function independently, providing additive benefits by targeting the host microbiota as antioxidants or through other health-promoting pathways [72]. In the synergistic mechanism, prebiotics are selectively utilized by co-administered probiotics, enhancing the probiotics' performance and generating enhanced health outcomes compared to the individual components [71]. These mechanisms enable synbiotics to achieve one or more health benefits through their carefully designed multi-component interaction [71].

Several synbiotic formulas are available on the market for livestock production. Examples include Biomin® IMBO (ME BIOMIN GmbH), which contains *Enterococcus faecium* and FOS for use in poultry, pigs, and calves; PoultryStar® (ME BIOMIN GmbH), comprising *Bifidobacterium animalis*, *Enterococcus faecium*, and several *Lactobacillus* species (e.g., *L. reuteri*, *L. salivarius*, *Pediococcus acidilactici*) combined with inulin for poultry; and Synbiotic Poultry (Vetafarm), which features a diverse blend of *Lactobacillus* species (e.g., *L. acidophilus*, *L. casei*, *L. salivarius*, *L. plantarum*, *L. rhamnosus*, *L. brevis*), *Bifidobacterium* species (*B. bifidum*, *B. lactis*), and *Streptococcus thermophilus*, paired with inulin for poultry applications [73].

The individualized composition of the microbiome plays a significant role in the effectiveness of gut manipulation strategies. Host-specific factors shape microbial colonization by favoring microbes adapted to the host's unique conditions [64, 74]. Research has shown promising results for synbiotics. For example, Song et al. [75] found that a synbiotic formulation of microencapsulated *Lactobacillus plantarum* (MLP) and FOS improved growth, immune and antioxidant parameters, and calcium and phosphorus digestibility, suggesting it could serve as a substitute for antibiotics in broiler feeding. Other studies have demonstrated the effectiveness of synbiotics as alternatives to in-feed antibiotics [76, 77]. However, some studies have reported no effects of synbiotic supplementation on broiler growth [78, 79], which may be due to variations in the composition and dosage of the synbiotics used [76].

3.4 Fecal microbiota transplant

Fecal microbiota transplant (FMT) involves administering stool from a healthy donor into a recipient's intestinal tract to alter the microbial composition and achieve therapeutic benefits [80]. In livestock, FMT has been explored as a tool for improving disease conditions, enhancing feed efficiency, and promoting weight gain in food-producing animals.

The individualized composition of the microbiota plays a significant role in the effectiveness of gut manipulation strategies. Host-specific factors shape microbial colonization by favoring microbes adapted to the host's unique conditions [74]. Studies have demonstrated the therapeutic potential of FMT in various contexts. Niederwerder et al. [81] demonstrated that administering FMT containing a diverse microbiome to weaned pigs prior to co-infection with porcine reproductive and respiratory syndrome virus (PRRSV) and porcine circovirus type 2 (PCV2) significantly reduced morbidity, mortality, pathology, and virus replication compared to controls. Hu et al. [82] showed that FMT from adult Jinhua pigs improved intestinal health, enhanced immunity, and promoted weight gain while reducing diarrhea in neonatal crossbred piglets. Siegerstetter et al. [83] demonstrated that FMT from highly feed-efficient donors administered to young chickens increased total feed intake and overall weight gain in females, highlighting its potential to enhance growth performance. In addition, the use of FMT in beef calves has also been reported to ameliorate diarrhea and possibly improve growth performance [84].

However, while FMT is a promising technique, it is currently not yet a viable option in large-scale livestock operations due to several challenges. Safety considerations are critical, requiring rigorous screening protocols to exclude pathogens and transmissible traits. Practical barriers include the lack of standardized protocols for material preparation, storage methods, and administration procedures regarding volume, frequency, and duration [81]. The current reliance on antibiotics prior to FMT raises additional concerns about promoting antibiotic resistance, potentially undermining the approach's broader applicability. Economic feasibility, regulatory frameworks, and quality control standards also need development. Future research should focus on evaluating FMT outcomes without antimicrobial conditioning and establishing standardized protocols suitable for large-scale implementation [81].

3.5 Postbiotics

Postbiotics have emerged as a promising alternative in animal health and production, offering significant benefits without requiring live microorganisms. The International Scientific Association of Probiotics and Prebiotics defines postbiotics as a “preparation of inanimate microorganisms and/or their components that confer a health benefit on the host” [85]. Derived from microbial secretions or released during cell lysis, postbiotics include diverse components such as exopolysaccharides (EPS), short-chain fatty acids (SCFAs), enzymes, cell-free supernatants (CFSs), bacterial lysates, and other metabolites produced by the gut microbiota [86]. These can be administered through oral routes, topical applications, gavage, or intra-mammary infusion, making them versatile for various applications in livestock systems [86].

Although postbiotics are non-living, they share mechanisms of action with probiotics. Their bioactive compounds interact with host systems, conferring health benefits such as improved gut health, immune regulation, and pathogen inhibition [60, 86]. For example, exopolysaccharides (EPS) reduce pathogen adhesion and strengthen epithelial barriers in a structure-dependent manner [36]. EPS are metabolized by beneficial microbes such as *Bifidobacterium spp.*, resulting in the production of SCFAs like butyrate, acetate, and propionate, which regulate immunity and enhance gut barrier function [87]. Postbiotics also lower gut pH, fostering the growth of beneficial microbiota while inhibiting harmful microbes [88]. Additionally, they compete with pathogens for adhesion sites and disrupt quorum sensing, further enhancing gut health and reducing disease risks [89, 90].

The benefits of postbiotics have been demonstrated across various animal species. This stability ensures the retention of their functional properties, making them particularly suitable for livestock. In poultry, postbiotics derived from *Bacillus subtilis* have been shown to improve growth, reduce mortality, and enhance immunity in broiler chicks [91]. Similarly, *Lactobacillus plantarum* postbiotics increased the abundance of beneficial bacteria and reduced *E. coli* and *Salmonella* counts in heat-stressed broilers [92]. In lambs, postbiotics from *L. plantarum* improved gastrointestinal histology, barrier function, and immune markers [93]. For pigs, *Lactobacillus fermentate* postbiotics enhanced gut microbiota diversity and improved growth in *E. coli*-challenged animals [94].

Postbiotics also offer industrial advantages, including heat resistance, stable chemical structures, and extended shelf life, which enhance their safety and feasibility for large-scale application [95, 96]. However, while postbiotics present lower risks than live probiotics, potential concerns remain. For instance, toxic metabolites or substrates released from dead bacteria need further investigation to ensure safety [90].

Despite these challenges, postbiotics hold considerable promise for improving animal health and productivity, though additional research is required to optimize their use and address species-specific effects [60].

3.6 Precision biotics

Advances in high-throughput sequencing technologies have revolutionized gut microbiome research, allowing for detailed and accurate analysis of its composition and function [97]. This progress has led to the emergence of precision biotics (PBs), which are designed to specifically modulate gastrointestinal tract (GIT) microbiome pathways, resulting in enhanced growth performance in livestock, particularly poultry [98]. Precision biotics are complex glycans with specific glycosidic linkages [99] and varying chain sizes that influence microbiome metabolic functions beyond merely altering microbial taxonomic composition, ultimately promoting increased beneficial outputs [100].

The conserved nature of microbial pathways across bacterial species provides an advantage for PBs, as the taxonomic composition of gut microbiota often varies significantly among chickens from different farms due to environmental factors [37]. By targeting these metabolic pathways and their resultant metabolites, PBs can enhance energy efficiency and reduce intestinal ammonia production, benefiting both animal health and the environment [99, 101]. These properties are particularly relevant in the context of increasing focus on sustainability. Moreover, the modulation of microbiome pathways improves host resilience against enteric challenges, making PBs valuable for broiler chickens raised in commercial conditions [102].

Some studies have highlighted the effectiveness of PBs in poultry production. Bortoluzzi et al. [103] demonstrated that a precision biotic significantly improved broiler growth performance by inducing functional changes in the cecal microbiome, including enrichment of carbon and nitrogen metabolism pathways. These changes were associated with an increased carbon metabolism index, potentially leading to higher production of endogenous short-chain fatty acids (SCFAs). Earlier work by Bortoluzzi et al. [98] reported similar benefits, including enhanced nitrogen metabolism and improved welfare. Blokker et al. [101] showed improved intestinal integrity, growth performance, and nutrient transporter gene expression in broilers under enteric stress, demonstrating effects comparable to those of growth promoters. Similarly, Yan et al. [102] reported increased body weight, better feed conversion ratios, and reduced *E. coli* and *Salmonella* counts through microbiome shifts favoring beneficial pathways.

Though these studies have confirmed that the PB can precisely shift microbiome functions and significantly increase the productivity and health of broiler flocks, many other aspects still need to be evaluated. Factors such as diet composition, and interactions with other additives like feed enzymes and probiotics need to be evaluated to fully understand the mechanisms underlying PB effectiveness [102]. As research continues, precision biotics hold significant potential for enhancing poultry production and health while addressing sustainability challenges.

4. Other potential gut microbiota modulation strategies

While existing interventions have demonstrated their effectiveness in modulating the gut microbiota, there are other techniques that could further enhance livestock

health and performance. Synthetic biology and phage therapy are two promising ways to control harmful bacteria, offering an alternative to both antibiotics and traditional methods of managing gut bacteria.

4.1 Synthetic biology

Synthetic biology focuses on the design and engineering of living organisms to achieve innovative functions and characteristics [104, 105]. Synthetic biology approaches aim to enhance livestock production with superior traits by modifying genomes [106]. Some of the gene editing technologies that have been used in livestock are zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and CRISPR-Cas9.

ZFNs were the first engineered endonucleases, shown to effectively suppress specific genes in experimental animals [107]. They were applied in cattle to boost milk production by mutating the beta-lactoglobulin (BLG) gene, resulting in milk produced about 30 times faster than in conventional cows, as well as to developing *Staphylococcus aureus*-resistant cattle, and pigs with increased muscle mass by disrupting the myostatin (MSTN) gene [106, 108, 109]. TALENs is a second-generation gene editing tool which is a more flexible design compared to ZFNs. This method was successfully used to produce hornless cattle, produce pigs resistant to African swine fever, and generate muscle-modified livestock [106, 110]. CRISPR is the most current or third-generation gene editing tool that uses a guide RNA (gRNA) to bind to a target DNA sequence and recruit the Cas9 endonuclease to induce double-strand breaks [111]. The application of this method was used in pig to improve productivity, reproductive traits, and resistance to diseases. For instance, porcine reproductive and respiratory syndrome (PRRS) virus-resistant pigs were produced using this method by targeting potential viral receptors [112].

4.2 Bacteriophage therapy

Bacteriophage therapy is an emerging alternative to antibiotics in treating bacterial infections. Bacteriophages or phages are viruses that selectively infect and destroy bacteria [113]. This method can be applied as biocontrol agents for key foodborne pathogens- for example, preventing mastitis caused by *Staphylococcus aureus* in cattle, salmonellosis by *Salmonella enteritidis* in swine and campylobacteriosis or salmonellosis by *Campylobacter jejuni* and *Salmonella Gallinarum* in poultry [114–117]. The integration of advanced technologies like CRISPR/Cas9 systems to enhance phage efficacy and overcome bacterial resistance is a promising approach in the development of phage therapy [118]. CRISPR-enhanced phages can rapidly eliminate bacterial populations, thereby decreasing the likelihood of resistance. This combination therapy could lead not only to improved animal health but also contribute significantly to food safety and public health by reducing the prevalence of antibiotic-resistant pathogens in the agricultural sector [119].

5. Regulatory considerations for gut microbiota modulation strategies

The development and application of gut microbiota modulation strategies in livestock require navigating complex regulatory frameworks. These frameworks aim to ensure the safety, efficacy, and ethical considerations of microbial-based

products while balancing the need for innovation and sustainability in agriculture [40]. Regulatory authorities such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) oversee approval processes, focusing on risk assessments, environmental impacts, and consumer safety. Products like prebiotics, probiotics, and synbiotics, which have a longer history of use, are generally better understood and face fewer regulatory hurdles. Many, when approved, have Generally Regarded As Safe (GRAS) status or Qualified Presumption of Safety (QPS) based on regional regulatory requirements [40, 73, 120]. Nevertheless, even traditional strategies must undergo rigorous safety evaluations, particularly when introducing novel formulations for animal feed [8, 40, 120].

For newer strategies, the lack of standardized guidelines for evaluating their safety and functionality poses challenges. For instance, postbiotics lack comparable oversight, leading to risks of inconsistent quality and misleading claims that could erode industry credibility [86, 88]. Similarly, synthetic biology, and the use of bacteriophages, with their potential for horizontal gene transfer and environmental persistence, demand comprehensive assessments to fully mitigate unintended consequences. Establishing robust guidelines for these innovative interventions is critical to mitigate risks and ensure their responsible use.

As microbiota-targeting strategies expand, international harmonization of regulations is essential to facilitate their adoption and integration across global livestock industries. In addition, criteria such as costs, management friendliness, and readily available sources for large feed volume use have to be included in the overall vetting process. The selection of microbial strains that are easily accessible and financially feasible for large-scale production is vital [121].

6. Conclusions

Based on the literature cited in this chapter, the following key conclusions can be drawn:

- Traditional strategies for gut microbiota modulation, including probiotics, prebiotics, and synbiotics, have demonstrated effectiveness in enhancing gut health, boosting immunity, and improving productivity in livestock while reducing reliance on antibiotics.
- Advanced approaches, such as fecal microbiota transplantation (FMT), postbiotics, and precision biotics, offer targeted interventions that refine gut microbiota functionality, addressing specific health challenges and optimizing livestock performance.
- Emerging technologies, including synthetic biology and bacteriophage therapy, provide precise tools for manipulating gut ecosystems, offering specific pathogen control without disrupting beneficial microbial communities.
- The integration of microbiota modulation strategies in livestock systems contributes significantly to One Health objectives, including improved animal welfare, reduced antimicrobial resistance, enhanced feed efficiency, and environmental sustainability.

- Despite their promise, these strategies face challenges related to mechanistic understanding, species-specific responses, scalability, cost-effectiveness, and long-term impacts, which require further investigation and development.
- Collaboration between researchers, industry stakeholders, and regulatory bodies, combined with practical training for farmers and veterinarians, is essential to optimize microbiota-based interventions and ensure safe and effective application in commercial livestock systems.
- The continued advancement and application of these strategies are vital for achieving sustainable livestock production, supporting food security, and promoting environmental stewardship.

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Synergistic Effects of Molecular Structure and Nutritional Properties in Enzymatically and Thermally Treated Oat Tissues Revealed Using Synchrotron and Global Molecular Spectroscopic Techniques

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Abstract

This article aims to review how to use cutting-edge synchrotron-based and global-based molecular spectroscopic techniques to reveal synergistic impact and interactive association between molecular structure and nutrient properties and supply in enzymatic and thermally treated oat endosperm tissue and whole oat grain. The review includes (1) advanced molecular spectroscopic technique sourced by synchrotron radiation and its application; (2) advanced technique global-sourced molecular spectroscopy and its application; and (3) research progress on cereal oat grain. The emphasis of this review is on the principle, theory, and current applications of molecular spectroscopy. The information described in this article gives better insight into the utilization of cutting-edge molecular spectroscopy to reveal molecular structure features that are associated with nutrition values. Future oat research directions are also provided, including advancing oat molecular structure and nutrition interaction knowledge by increasing and enhancing the basic understanding of the nutritional relevance of biopolymers' intrinsic structure and chemistry on both cellular and molecular bases.

Keywords: molecular spectroscopy and application, structure and nutrition interaction, cereal oat grain, inherent structure, endosperm tissue, processing and treatments

1. Introduction

Nutrient metabolism, utilization, and availability in animals are dependent on not only the feed's chemical profiles such as protein and carbohydrates but also the feed's internal structure. We often use traditional “wet” chemistry methods to study the chemical and nutrient profile of feeds. These “wet” chemistry methods involve using harsh chemicals, grinding samples, and digestion, making it impossible to explore inherent structure within intact feed tissues [1]. Because of the harsh chemicals, grinding and digestion during lab processes destroy the feed's internal molecular structure making it impossible to link the original feed's inherent structure to nutrient metabolism, utilization, and availability in animals. Therefore, traditional “wet” chemistry analytical methods are not sufficient for accurately assessing feed quality, limiting our advances in feed science and animal nutrition for sustainable animal agriculture.

A novel, cutting-edge molecular spectroscopy technique with synchrotron radiation has been developed to explore biological samples within intact tissue at cellular and molecular levels. This technique can simultaneously provide four kinds of information, including tissue chemistry, tissue structure, tissue nutrition, and tissue environment. Therefore, using this data, it is possible to link tissue structure information to nutrient absorption and utilization in animals.

This article aims to review how to use cutting-edge synchrotron-based and global-based molecular spectroscopic techniques to reveal synergistic impact and interactive associations between molecular structure and nutrient properties and supply in enzymatic and thermal treated oat endosperm tissue and whole oat grain. The review includes (1) advanced molecular spectroscopic techniques sourced by synchrotron radiation and its application; (2) advanced techniques, global-sourced molecular spectroscopy, and its application; (3) research progress on cereal oat grain. This review focuses on the principles and theory of advanced molecular spectroscopy and its current applications. Future research direction is also provided.

2. Advanced molecular spectroscopic techniques sourced by synchrotron radiation

2.1 What is a synchrotron and what are the major components of a synchrotron

A synchrotron is a source of bright light that researchers can use to gather the structural information of materials at a molecular level. A synchrotron facility usually comprises six major components: an electron gun, linear accelerator (also named LINAC), booster ring, storage ring, beamlines, and end experimental stations [2]. Thermionic emissions from the electron gun generate electrons, which are then accelerated by the linear accelerator and injected into the booster ring. Electrons get a boost of energy until they reach a target energy level and then are transferred to the circular storage ring. Different synchrotron facilities have different targeted energy levels. When traveling in the storage rings, electrons emit an extremely brilliant light, including the visible, ultraviolet, and X-ray regions of the light spectrum; the light is then redirected into the beamlines [3, 4]. The beam is non-divergent, intense, and extremely fine [1, 5, 6]. Scientists could select specific wavelengths of synchrotron light to explore samples through beamlines and observe the interaction between the light and matter of samples at the end experimental stations.

2.2 Principle and theory of synchrotron radiation-based Fourier transform infrared microspectroscopy (SR-FTIRM)

There are four kinds of energies in a molecule consisting of translational, rotational, vibrational, and electronic energies. Generally, molecules vibrate separately at their own equilibrium position since each functional group vibrates individually but weakly interrelates as entities [7]. However, electromagnetic spectrums such as infrared radiation (IR) could result in changes in the equilibrium status and energy transitions in a molecule between rotational and vibrational energy [8]. These transitions lead to a net alteration in the dipole moment and the IR absorption by the sample's molecules. The absorbed and transmitted IR bring a unique spectrum. This spectrum represents a molecular fingerprint for samples, which is helpful to identify different functional groups [6, 9–12].

Synchrotron radiation-based Fourier transform infrared microspectroscopy (SR-FTIRM) combines a synchrotron light source (**Figure 1**), Fourier transform infrared (FTIR) spectroscopy, and microscopy together. Benefiting from synchrotron light brightness, which is usually ca. 100–1000 times brighter than a conventional global source and has a small effective source size, SR-FTIRM could explore the molecular chemistry within microstructures of biological samples with high signal: noise ratio at ultra-spatial resolutions as fine as 3–10 μm [6, 9–13]. For instance, the normal size of a plant cell is about 5–30 μm . A spectrum comparison of signal: noise ratio between global and synchrotron FTIR microspectroscopy at a $5 \times 5 \mu\text{m}$ area was reported by Miller [5] and Miller et al. [14].

Thus, structural information of samples like quantity, composition, and distribution of chemical components and functional groups can be revealed through SR-FTIRM combining chemical and spatial information [10–12]. Without homogenizing the sample like traditional wet analytical methods, SR-FTIRM can be applied to understand and analyze plants, seeds, feeds, and food tissues at a molecular level.

2.3 Current application - synchrotron radiation-based infrared microspectroscopy

As of now, SR-FTIRM has been advanced as a rapid, direct, non-destructive, and non-invasive bioanalytical technique [6, 9, 15–19]. One application of SR-FTIRM

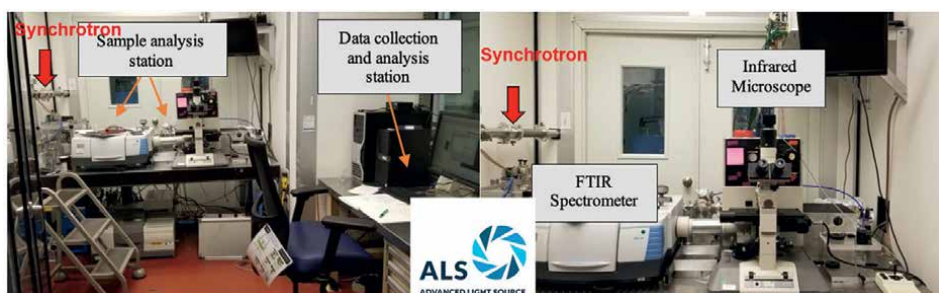


Figure 1. Synchrotron radiation-based FTIR microspectroscopy at Advanced Light Source (ALS, Lawrence Berkeley National Laboratory, U.S. Department of Energy) as one of the examples that our SRP Chair (PY.) team use for feed/food molecular structure and molecular nutrition research programs (Beamline 1.4 Infrared Microspectroscopy; Sourced from Hans Bechtel and Lisa Miller).

that does not damage the intrinsic structure of the sample is to chemically image the microstructures of feed tissues within cellular dimensions. This technique is valuable when intact plant components need to be studied. For instance, starch granules in a seed's endosperm are crucial in cereal research [20]. Moreover, SR-FTIRM images can provide tissues' locations in a chemical sense and clearly display the chemical and functional group distributions. Yu et al. [10–12] studied the spatial structures of Harrington barley tissue and concluded that the protein structures in the pericarp and endosperm regions were totally different.

Another application of SR-FTIRM is to discover the ultrastructural chemical makeup and density of samples. The SR-FTIRM technique measures the absorbed peak heights and areas of various chemical bonds and functional groups, which indicate the chemical makeup of tissues [21]. Research on yellow-, brown-seeded rape seeds at an ultra-spatial resolution illustrated the broad bands of the functional groups from total CHO at ca. 1180–900 per cm and amide I at ca. 1650 per cm [22–24]. These results can be used to predict the nutritional value and quality of various plant samples to select the most appropriate feeds [25].

A third application of SR-FTIRM includes detecting the chemical differences in the ultrastructural matrix of samples related to rumen degradation characteristics. The tissue's starch and protein content and ratio are related to rumen degradation and affect animal performance and health. The study aimed to find the specific associations between the starch-protein matrix and nutrient degradation. The results of the study on Valier barley showed that the slow rate of rumen nutrient degradation *in situ* may be associated with low starch: protein ratio in the grain's micro-endosperm [10–12]. In addition, Theodoridou et al. [26] found that the percentage of β -sheet for yellow canola seeds was relatively lower ($P < 0.05$), in contrast with the black-type canola seed.

The fourth application of SR-FTIRM is to disclose the chemical features of feed protein secondary structures and their relation to protein values. α -helix and β -sheet are important protein secondary structures, and their content and ratio greatly influence protein rumen digestion. For example, barley, wheat, and oats have a low percentage of β -sheet but a higher percentage of α -helix [16, 19]. However, this contrasts with the results of feather protein, which has a low digestibility in animals.

The use of SR-FTIRM analysis allows the evaluation of intrinsic structures in separate parts of plant tissues that can be chemically identified and analyzed regarding feed quality and nutrient utilization, providing an improved understanding of feed and nutrition research.

3. Advanced spectroscopic techniques, global-sourced molecular spectroscopy

3.1 Principle and theory of FTIR, ATR-FTIR and DRIFT

The primary principle of IR spectroscopy is to obtain information on absorbed and transmitted IR that is transferred to a unique spectrum, which acts as a molecular fingerprint for samples to identify different functional groups at a specific wavelength range. The FTIR spectroscopy consists of a global light source and an interferometer which generates an interference pattern, and then a characteristic absorption spectrum is recovered through a mathematical technique named Fourier transformation [9, 27, 28]. Shifts in the frequency of absorption

bands and changes in relative band intensities could indicate changes in the chemical structure or changes in the environment around the sample [29, 30]. In order to obtain the relative scale of absorption intensity, a background spectrum must be measured, usually by choosing no sample in the beam. However, the drawback of FTIR is that the sample needs to be ground, which limits the flexibility for the analysis of solids [9].

Attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy is a sampling technique combined with IR spectroscopy, which can be used to illustrate the molecular components of various solid or liquid samples. The IR interacts with the sample through evanescent light waves, penetrating the sample near the surface ($\sim 1 \mu\text{m}$). The evanescent light waves are attenuated due to the resonances of molecular vibrations located in the interface between the sample and a crystal of high refraction index (ZnSe, Cs, Si or diamond) [27, 31]. The ATR-FTIR spectra provide information on functional groups near the surface ($\sim 1 \mu\text{m}$) of an internal reflection element (IRE). A key advantage to ATR-FTIR relative to other FTIR collection methods and analytic techniques, in general, is the ability to collect accurate spectra of samples in the presence of water.

Diffuse reflectance Fourier transformed infrared (DRIFT) spectroscopy is an IR spectroscopy sampling technique for powder samples, relying on particle scattering and refraction. Several particles' characteristics, such as shape, refractive index, reflectivity, compactness, and absorption are analyzed. In order to decrease Mie scattering, the size of particles should be less than the wavelength of the global light at the same time.

3.2 Current applications of FTIR, ATR-FTIR and DRIFT

The FTIR method helps to identify unknown materials, determine the quality or consistency of a sample, and determine the number of components in a mixture, due to the ability to detect subtle changes in chemical structure. Research showed that unique structures of the cell wall complex could be detected by FTIR owing to sensitivity to the secondary structure of a protein [32]. The FTIR technique has also been used to investigate changes in the chemical composition of a sample. For instance, a study was conducted to monitor the changes in cell walls at different growing stages of cotton fiber, and to determine the differences in cellulose through multiple vibration changes in the spectrum [33]. Also, the quality of barley silage was briefly evaluated by FTIR spectroscopy regarding digestible fiber [34, 35]. Other research examples include time-resolved FTIR imaging of protein aggregation within living cells [36] and tablets [37].

The ATR-FTIR method is used to obtain molecular chemistry images. The penetrating depth using ATR-FTIR demonstrates that a thin layer of sample adjacent to the surface of an ATR element can be measured, which means that ATR imaging can be formed [27, 31]. For example, ATR-FTIR imaging has been applied to study the effect of surface properties on the crystallization and adsorption of proteins from a solution [38, 39]. ATR-FTIR spectroscopy has been used as a non-invasive and non-destructive method with high reproducibility. Hence, it has been utilized to quickly characterize the molecular structures of several feeds [40]. The data could also be used to predict nutrient profiles and degradation in samples like transgenic alfalfa [41] or oat and barley grains [42]. In addition, Kuimova et al. [43] also showed an example of in situ measurements using macro and micro ATR-FTIR imaging to study chemical changes in live cells.

The DRIFT can be used to obtain the molecular structure of power samples. Research has shown a significant difference in the α -helix to β -sheet ratios of three autoclaved Vimy flaxseeds using DRIFT analysis [44]. Olale et al. [45] used the DRIFT technique to potentially predict the fructose and glucose contents of mango. Besides, DRIFTS provided discrimination between roasted coffee and adulterated samples [46]. Also, DRIFT can be used to study the surface chemistry of powders, especially for heterogeneous catalysis, polymers such as foams and fiber, and materials with dull surfaces like fabrics without prior preparation.

4. Research progress on cereal oat grain

4.1 Oat grain for feed and food

The genus *Avena* has about 70 species that are mostly commercially grown [47]. The most prevalently cultivated species is *Avena sativa* L., also known as white oat [48], in developing countries. Oat cereals, which prefer cold and moist climates [49], are mostly cultivated in American and European countries. In 2018, the global production of oats was 23 million tons. Russia led the yield with 20% of the total, and Canada with 15% (about 3.4 million tons), according to the Food and Agriculture Organization of the United Nations (FAOSTAT) [50] (shown in **Figure 2**).

Cereals supply most energy in the form of carbohydrates, mainly from starch stored in the endosperm. Oat grains comprise bran, endosperm, and germ and are a good source of protein, unsaturated fatty acids (FA), phenolic compounds, dietary fiber, and starch. Oat hulls represent 28–32% of oat grains and consist of 83% of a cell wall rich in structural carbohydrates and lignin. This cell wall composition decreases the metabolizable energy and nutritional value of the grain [51]. About 75% of oat grains are mainly fed to horses and ruminants [52, 53], and the rest is used for food products and the pharmaceutical industry [54].

As a feed resource, oat grains have limited energy use in pig and poultry diets due to the high fiber. Therefore, the outer hull is usually separated from the inner oat groats before feeding animals. Research has shown that dehulled oats contained more crude protein, crude fat, and polyunsaturated FA, resulting in changes in *in vitro* digestibility [55]. Naked oats are considered to have a higher nutritional value because

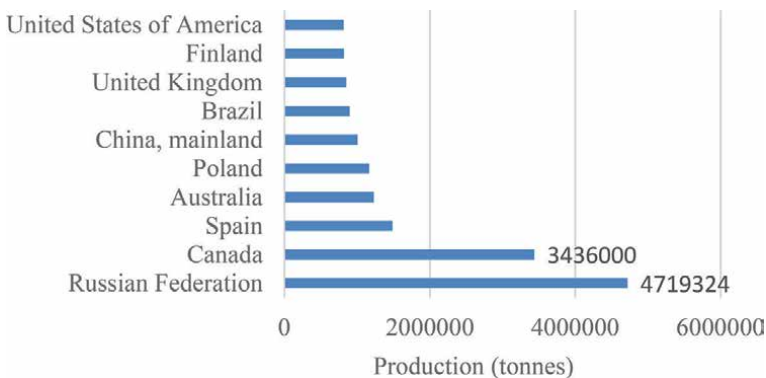


Figure 2. Production of oat: top 10 producers (in 2018) (Sourced from Food and Agriculture Organization of the United Nations (FAOSTAT), [50]).

besides mechanically reducing the content of the hulls, the glumes are genetically removed as well. Biel et al. [56] showed that dehulled and naked oats had a significant decrease in dietary fiber content and a significant increase in nutrient content compared to hulled oats. Besides, studies have evaluated the effects of replacing barley and wheat with oat grains [57]. For ruminant systems, not only do the nutrient contents matter, but the rate of nutrient degradation also plays a vital role. The low digestibility of oat hulls promotes delayed intestinal nutrient absorption, which is important for an optimal protein degradation balance.

As a food resource, oat grains (high fat) are a good source of lipids, proteins (with β -gluten protein and low prolamins content), and dietary fiber, especially β -glucan which supports cardiovascular health and helps against blood cholesterol, glucose, and coeliac disease [58, 59]. Due to these health benefits to humans, oats have been widely traded and consumed as oatmeal, oat flour, and flakes in most developed countries [47, 53, 60]. In addition, oats have been utilized in clinical areas to reduce gluten allergies [61].

Recently, the Crop Development Center (CDC) in Saskatoon, Canada, has technologically advanced oat varieties into two types of cool-climate adapted oat grains through its CDC oat breeding program. The feed-type oat, CDC Nasser, contains a high fat content and low-lignin hull, while the CDC Arborg, a milling type, has a high yield and high β -glucan content. The Cereal Research Center, based in Winnipeg, Canada, also developed a milling type of oat named Summit. Moreover, CDC Haymaker, a forage-type oat, has been mainly grown for silage. More trials are necessary to clarify the nutritional valuation and make the most of improved oat varieties. Recently summarized cereal grain characteristics affecting digestive behavior and nutrient utilization on a quantitative basis: comparison among oats, hulled barley, and hullless barley grains have been reported by our team [62].

4.2 Feed processing technology for oat grain research

For the animal industry, dehulling, rough grinding, extrusion, dry rolling, steam rolling, steam flaking, and micronizing could increase the feeding value for cattle [63]. Milled oats have a good quality appearance and taste. Heat treatment is a common method in grain processing, which in oats aims to inactivate enzymes that hydrolyze lipids during storage [64]. Thermal processing also affects the grain's structure, physicochemical properties, and nutrition [65]. For instance, autoclaving could sterilize feeds, deactivate anti-nutritional factors, and alter nutrient availability.

Mechanical processing, temperature, pressure, and moisture break the covalent bonds and disrupt the physical structures of macromolecules [66–69]. Hence, combining a heating process with moisture and pressure can change the chemical profile of oat grains, including starch and amide I to amide II ratio [70, 71]. Research shows that moisture heating allows better heat penetration into inner tissues than dry heating [70]. Mostafizar et al. [72] compared the molecular changes of oat grains treated with dry roasting and microwave irradiation using ATR-FTIR microspectroscopy. The results showed a lower rumen degradability of protein and starch, a lower amide I to starch ratio, and a higher α -helix to β -sheet ratio for oat grains processed by microwave irradiation compared to dry roasting. Tosta et al. [57] found that rolled oats produced a higher milk yield and milk fat percentage than pelleted and steam-flaked oats. Also, the protein fraction PB1 and bypass CP of steam-flaked oats were increased, while the fraction PA2 and EDCP in the rumen were decreased when compared with rolled oats [42].

Different heating processes, including selected instruments, time, temperature, and moisture diversely influence the oats' nutritional qualities. It is promising to find optimal thermal processing for oat grains to understand better the relationship between induced structural changes and nutritive values in ruminant research.

4.3 Innovative fibrolytic enzymes for improvement of nutrient utilization of oat grains

Ferulic acid (FA; 4-hydroxy-3-methoxycinnamic acid) and *p*-Coumaric acid found in the complex cell walls of oat hulls are considered a hindrance for oat hull biodegradation by rumen microorganisms due to their function of cross-linking between lignin and polysaccharides or between polysaccharides. Breaking the ester-linkage by fibrolytic enzymes improves the feed fiber. Studies have illustrated that esterase enzymes play a significant role in cell wall degradation in the rumen [73, 74].

A study on oat hulls treated with *Aspergillus* ferulic acid esterase (FAE) illustrated that with *Trichoderma* xylanase, more FA was released compared to without *Trichoderma* xylanase [75, 76]. In the release of reducing sugars experiment, the results show that oat grains, pretreated with FAE and xylanase, had the highest concentration of reducing sugars when adding cellulase [10–12]. Similarly, multienzyme pretreatments on oat hulls could improve ruminal digestion compared with alfalfa and wheat straw [23, 24]. However, on the release of *p*-Coumaric acid by FAE, there was no significant difference in whether *Trichoderma* xylanase existed [6, 17–19, 75, 76].

An innovative fibrolytic enzyme mixed with xylanase and cellulase that is derived from *Trichoderma reesei* (FETR) has been tested in barley and faba bean silages [77, 78] but not yet in whole oat grains.

5. Conclusion and future research

5.1 Conclusion

- Up to now, only limited studies have been conducted on the newly or recently developed milling- and feeding-type oats to determine biodegradation kinetics and nutrient availability.
- No systematic research has been conducted to determine the magnitude of the difference in chemical and nutrient profiles using newly updated and developed analytical methods.
- No systematic research has been conducted using advanced synchrotron radiation-based analytical techniques to reveal the intrinsic structure of oats at cellular and molecular levels.
- Studies using global-sourced vibrational spectroscopy to analyze the interactive associations between nutrient supply and intrinsic structure makeup are limited. Also, limited experiments have been performed on the effect of different thermal processing on oat grains.
- No systematic study shows the interactive association between processing methods, fibrolytic enzymes, and thermal processes.

- No systematic study on integrating nutritional genomics technologies including metabolomics and proteomics with advanced molecular spectroscopy technologies.
- It is of great interest and great importance to detect the synergistic effect between thermal processing and enzymic treatment in oat tissues and whole oat grain on induced changes in molecular structure, nutrient properties, feed milk value, and absorbable nutrient supply in ruminants and their interactive associations.

5.2 Future research

- Future research is needed: (1) To advance our current knowledge by increasing and enhancing the basic understanding of the true nutrient supply to dairy cattle and beef cattle through feed additives and thermal processing; (2) To integrate nutritional genomics technologies, including metabolomics, proteomics with advanced molecular spectroscopy technologies; (3) To advance our feed molecular structure and nutrition interaction knowledge by increasing and enhancing basic knowledge of the nutritional relevance of biopolymers intrinsic structure and chemistry on a molecular basis; (4) To increase economic returns to oat producers and related industries through efficient utilization of new feed-type or milling type oat grains.
- In details, future research should focus on (1) using advanced synchrotron techniques (e.g., SR-FTIRM) to reveal molecular structure spectral features of new oat endosperm tissues at molecular and cellular levels: Studying synergistic effects between enzymatic treatments and thermal processing; (2) using advanced global-sourced spectroscopic techniques (e.g., ATR-FTIR or DRIFT) to study molecular structure spectral features of whole oat grains or other cereal grains: detecting synergistic impact between enzymatic treatment and thermal processing; (3) using a systematic approach to detect the synergistic impact between enzymatic treatment and thermal processing on chemical and nutrient properties of whole oat grains in ruminant systems; (4) revealing enzymatic treatment and thermal processing induced changes in microbial protein synthesis and true nutrient supply of whole oat grains; (5) revealing interactive associations between induced molecular structure changes and nutrient properties and true nutrient supply in ruminant systems; (6) developing absorbable nutrient supply prediction equations based on processing induced molecular structure changes; (7) studying nutritional genomics including metabolomics and proteomics with advanced molecular spectroscopy technologies.

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Recent Research and Development in Feed Chemistry, Feed Processing, Nutrition Modeling and Evaluation, Molecular Structure and Nutrition Interaction for Dairy Cattle

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Abstract

The research landscape in the field of animal nutrition, particularly dairy cow nutrition, encompasses various interrelated aspects, each of which plays a crucial role in optimizing feed quality, diet formulation, and ultimately, milk production. Developments in dairy nutrition models and methods for evaluating feed quality are crucial in expanding our knowledge of the nutrition of dairy cows. In this article, we examine the requirement of blending and pelleting feed ingredients, along with how these procedures may enhance feed efficiency and dairy cow nutrition in general. We discuss several models, including the DVE/OEB system, energy systems, and the Cornell Net Carbohydrate and Protein System (CNCPS), emphasizing how these models have been developed over time and helped create more precise dietary formulations. We also look at the advancements in treatments and technology for feed processing, highlighting their significance for optimizing nutrient utilization. In addition, we investigate the importance of feed inherent structure at a molecular level and feed chemistry to comprehend the interactions between nutrients and also between molecular structure and nutrient utilization and availability in dairy cows. Finally, we thoroughly discuss the relationship between nutrient availability and utilization and processing-induced feed molecular structure changes. The information described in this article gives better insight into feed science and nutrition research progress and updates, and helps to develop sustainable livestock farming.

Keywords: feed molecular structure, feed chemistry, feed quality, nutrient modeling, molecular spectroscopy, animal performance, dairy cows

1. Introduction

Research in feed science is instrumental in optimizing animal nutrition, enabling the formulation of precise, well-balanced diets for livestock, and, consequently, maximizing growth, reproductive performance, and overall health. The basis of animal agriculture is firmly supported by the science of animal nutrition, with feed science playing a pivotal role. This discipline is indispensable for several reasons, given its significant impact on food production, animal health, environmental sustainability, and human nutrition. Food's bioactive function is intrinsically linked to its constituent components. Moreover, comprehending the internal structural makeup of different chemical functional groups and feed nutrients is mostly essential for understanding the nutritional values and digestive behaviors of feeds in ruminants, as feed nutrients' intrinsic structure closely correlates with total absorption [1]. Furthermore, the metabolic utilization and nutrient availability within animal nutrition are directly affected by the molecular structure of the feed consumed by the animal. The internal structural changes in feed that occur during mechanical, chemical, and/or thermal processing have a direct impact on animal nutrition and performance [2]. Additionally, the chemical composition and structural characteristics of feed nutrients play a vital role in determining the nutritional value of feed components and their effectiveness in supporting livestock health and performance. Understanding the chemical composition of feeds enables us to comprehend the diverse bioactive effects of different feed types. For maximizing nutrition, minimizing environmental effect, maintaining food safety, and improving animal health and welfare, it is essential to research the molecular structure of animal feed. This research promotes effective and sustainable animal agriculture and advances food security worldwide.

Blends are a combination of single feeds that can be given to animals through trough feeding systems or as a component of a diet in a mixer wagon. Blends have seen a surge in popularity in recent years as farmers look to improve their time efficiency and cash flow [3]. The only goal of mixing is to evenly distribute the ingredients throughout the mixer before delivering the uniform mixture to the intended consumer. This mixture may contain as few as two ingredients (for example, whole oats mixed with 1% molasses for horses) or as many as thirty (for example, cereals, plant proteins, animal proteins, vitamins, minerals, feed additives, enzymes, and various liquids for weanling pigs). Ingredient qualities, equipment properties, and management all have an impact on this purpose [4]. Feed mixing ensures that an animal gets all the specified nutrient allotment each day with the aim of supplying a cost-effective, palatable, and nutritionally sufficient feed to encourage ideal body development, health, and production [5, 6]. Great efforts are taken to make a uniform blend of feed for the diet, reduce the harmful effects of components' trypsin inhibitors, lectins, and glucosinolates (which are antinutritional agents), improve feed safety (decrease in microorganisms), improve feed efficiency (increase nutrient digestibility/absorption), increase feed consumption to reduce spoiling, and strike a balance between animal health (fineness of grind) and feed efficiency. A high-quality feed mixture assures that cattle will thrive and be able to meet the growing demand for food [7].

Farmers feed their livestock one or two feed ingredients, which do not meet the nutritional requirements of the animal. As a result, dairy cows either fail to produce milk to the full extent of their genetic capacity, or milk production is not cost-efficient. American researchers discovered in the 1980s that cows ate pelleted feed more quickly than coarse mix, crumbles, and meal feed forms. A cattle feed pellet-making machine uses a variety of raw materials, including cereals, oilseeds, and legume plants forage,

dried feed by-products, additives like vitamins, minerals, chemical preservatives, and other necessary micro-ingredients, to create cattle feed pellets, a type of compound feed. The pellets are formulated to meet the nutritional requirements according to the breed, age, sex, and stage of production of the ruminant. As a result, different cattle feed pellets with different nutrition and components are suited for bulls, cows, heifers, and buffalo [8]. Pellets are manufactured when a feed ingredient or a feed ingredient mixture is pressed through a cylindrical die with a length up to four times its diameter. The final pellet quality can be determined by several steps in the pelleting process, though the fundamental steps are the same for every mill operator. These include the following: weighing, grinding, mixing, conditioning, pelleting, and cooling [9–11]. Pellet quality also depends on the primary ingredients used and the proportion. Pelleting prevents component segregation such that animals cannot choose some feed ingredients and reject others. It also contributes to decreasing feed waste, preventing insect and mold infestations, maintaining vitamin A's effectiveness, guaranteeing fewer storage losses, and stopping the breakdown of minerals once the feed has been mixed. It also improves digestibility and palatability; pellets are simple to manage and reduce the chance that meals will be contaminated with undesired elements. If *Salmonella* or *E. coli* bacteria are found in the feed, they will most likely be eliminated due to high temperatures [12]. Pellets are typically nutrient-dense; therefore, the animals often perform well [11]. Additionally, feedstuff pelleting techniques may lessen the impact of antinutritional factors that are frequently disregarded, but they may also be advantageous for better handling, storage, and logistical techniques. To give rumen microorganisms a higher surface activity, a mild pelleting process at 75–85°C modifies the synthesis of proteins. Pelleting enhances the breakdown of neutral detergent fiber (NDF) and enhances the digestion of ruminal starch in feeds containing low levels of fermentable starch, such as maize. Additionally, the overall dry matter degradability increases. It is significant to note that balanced forage NDF (fNDF) should always be prioritized even though pelleting does not significantly change ruminal pH due to the sluggish nutrient release of pellets [9]. Feed pellets can more easily and more quickly be consumed by cattle than crumbles, meals, and coarse fix [13].

It should come as no surprise that feed represents the largest expense for dairy farms. A typical dairy operation spends 65% or more of its budget on feed. So, monitoring a significant portion of a farm's overall profit margin by monitoring the feed cost is a straightforward and successful strategy [14]. The livestock sector of western Canada and the malting sectors nationwide rely heavily on barley as a crop. Over 40% of the barley acres in Canada are planted in Saskatchewan. According to the Government of Saskatchewan [15], barley prices increased from \$147 in October 2019 to \$265 per ton in October 2023. Canola accounts for over 30 percent of the acres planted in Saskatchewan. Canola prices increased from \$417 per ton in October 2019 to \$662 per ton in October 2023. Corn prices increased from \$143 per ton in October 2019 to \$180 per ton in October 2023. Nearly one-third of Saskatchewan's cropland is used for growing wheat. Wheat prices increased from \$220 per ton in October 2019 to \$323 per ton in October 2023. Moreover, soybean prices have increased from \$328 per ton in October 2019 to \$464 per ton in October 2023. Saskatchewan grows more than 40% of the oats in Canada. Oats are mostly imported from Canada, which accounts for most of the global oat trade. Oats increased the price from \$187 per ton in October 2019 to \$289 per ton in October 2023.

Improving feed efficiency is a crucial strategy in animal production, not only to enhance competitiveness but also to promote environmental sustainability. The development of alternative feeds, particularly those based on local resources, is anticipated

to foster feed self-sufficiency in livestock production [16]. Livestock farmers continuously seek ways to provide cost-effective, safe, and efficient nutrition to their animals. While traditional sources like hay, pasture, forages, and grains form the bulk of livestock diets, there is a growing interest in integrating alternative feeds that can complement and enhance cattle nutrition. Efficient sourcing of non-traditional feeds can lead to increased profitability. For many farmers, the search for substitute feeds becomes essential when high-quality hay supply dwindles due to factors like shrinking production acreage and unpredictable weather conditions such as late spring frosts, heavy rainfall, or drought [17]. The nutrient composition of these alternative diets can vary significantly, requiring careful evaluation of their feed value. To formulate a well-balanced, cost-effective diet for livestock, producers must consider the energy, protein, and essential mineral content of these alternative feeds [18].

The main objective behind this comprehensive review is to elucidate the motivations behind conducting research in feed science, feed chemistry, feed processing, and feed molecular structure, and to understand the importance of doing research in these areas. The secondary objective is to investigate the importance of feed processing for dairy cows, advancements in feed processing, and its effects on molecular structures of feeds, rumen parameters, and production performance of cows. Examining variables such as degraded protein balance, truly absorbed rumen undegraded protein, rumen bypass fat, the ratio of forage to concentrate, the volatile fatty acids (VFA) and C2:C3 acid ratio, net energy supply, total metabolizable protein, etc. Furthermore, to review the progress and developmental changes made in feed quality evaluation techniques and dairy nutrition models. Moreover, to know the importance of different spectroscopy techniques and advancements in spectroscopy and its implementation to advances in feed science and ruminant nutrition research. Finally, this article demonstrates how novel feed and nutrition research can help develop sustainable livestock farming.

2. Progress in feed quality evaluation techniques and dairy nutrition models

2.1 Progress in the Cornell net carbohydrate and protein system

A mathematical model known as the Cornell Net Carbohydrate and Protein System (CNCPS) is used to assess the nutritional needs and requirements of cattle in various production scenarios. It is based on animal, environmental, and feed composition data. Different physiological phases (lactation, pregnancy, and growth), body reserves, and environmental factors are all considered when estimating an animal's needs [19]. Since its initial release in 1991, the Cornell Net Carbohydrate and Protein System has undergone constant modification [20]. The CNCPS predicts the amount of ruminal fermentation, microbial protein production, post-ruminal absorption, and the animal's overall supply of metabolizable energy and protein using feed carbohydrate and protein degradation and transit rates. Farms raising dairy and beef cattle have found success in evaluating and creating rations using the CNCPS [19]. The CNCPS Model v7 is the latest and most revised model. It has updated the gastrointestinal model's overall dynamic structure, including feed, and the premise for determining microbial digestion is nitrogen and AA. This model has included protozoa metabolism in the microbial sub-model [21]. The main impacts of ruminal protozoa are fiber degradation and pH stabilization. Protozoa constitute approximately 10% of the rumen microbial biomass

in high-producing dairy cows [22]. The CNCPS v7 has a mechanistic sub-model for nitrogen recycling estimation, as well as endogenous nitrogen transactions along the gastrointestinal tracts. Post-rumen models have been expanded, aiming to include a separate small and mechanistic large intestinal model. Updated post-absorptive efficiency of EAA for beneficial use is also included in the model [21].

2.2 Model and progress in the energy system

Over the past 200 years, several feed evaluation systems have been created for energy prediction and assessment. The most common was the Hay system, developed in 1809, and the first attempt to introduce replacement values. Followed by the Total Digestible Nutrients (TDN) system. The TDN system was the most widely used in America, Asia, and some parts of Africa. The Scandinavian feed unit (SFU) was another energy system developed in Denmark circa 1880, where a feed unit was defined as 1 kilogram of concentrates. Nearly a century ago, in Germany, Kellner and Fingerling invented the Kellner system, mostly used for fattening cattle. Sir Kenneth Blaxter created the British system (ME) in the 1960s [23, 24] and revised it by MAFF [25].

Metabolizable energy is used to express the energy values of feeds. Because the ME is utilized to estimate energy requirements, this system is regarded as a net energy system. American feed evaluation systems, except for TDN, can be split into two main categories: the California Net Energy System (NEM, NEg) as described by Lofgreen and Garrett [26] and the Beltsville net energy system for lactation (NEL) as described by NRC [27]. The Dutch net energy lactation system (NEL) is described by Van Es [28, 29]. Van Es suggested a technique for quantifying the energy value of feeds for milk production, based on nearly all of the data from energy balancing trials with dairy cows [30]. A ME requirement for maintenance (MEM) of 488 kJ/d/kg metabolic body weight (BW^{0.75}) was established by Van Es in 1975. Studies conducted in the UK and the USA in 2015 found that the MEM was higher, at about 700 kJ/d/kg BW^{0.75}. The efficiency with which ME is used to produce milk increases in tandem with the rise in MEM (kJ). For many years, estimates of the energy requirements of grazing animals, as well as the energy value of grazed forage diets and supplemental needs, have been produced successfully using the California Net Energy System (CNES) [31]. Like all existing energy systems, the NEL system has two major issues. Firstly, cows do not need energy per se; instead, they need ATP and the substrates that contribute to ATP synthesis. The energy systems were then based on the calorimetry quantification, as it is not practical/viable to measure ATP. The second issue lies in the fact that diets contain NEL, but feeds do not. However, NEL concentrations are designated in feeds so that diets can be designed by using linear programming [32]. One more problem is that applying this or any energy accounting system in the field is acquiring accurate estimates of forage intake [31].

2.3 Rumen N to energy synchronization and hourly effective degradation ratio

The word “synchrony,” which has Greek origins for “together” and “time,” refers to events that happen simultaneously in general [33]. When it comes to ruminant nutrition, “synchrony” refers to providing energy (ruminal fermentable carbohydrates) and rumen degradable protein (RDP) at the same time so that ruminal microorganisms can use both to grow. It has been suggested that ruminal MPS can be increased, animal performance and N utilization efficiency can be enhanced, and urine N

excretion can be reduced by synchronizing the ruminal breakdown rates of protein and carbohydrates [34]. Theoretically, rumen microorganisms should be able to use nutrients more effectively when energy and nitrogen supplies are synchronized. This should maximize the microbial protein synthesis and production of VFAs, which in turn increases the amount of AA that reaches the small intestine. Maximizing the synthesis of microbial protein could improve animal performance and mitigate nitrogen losses to the environment [35, 36]. According to Sinclair et al. [37], microbial protein synthesis was 11–20% greater and microbial N production was more efficient when cows were fed with a synchronous diet. Synchronizing the degradation rate affects the digestibility of dry matter [38], organic matter, and neutral detergent fiber [39] and can increase microbial nitrogen synthesis (MNP) [38]. The N to E synchronization and hourly effective degradation ratio can be used to compare different feeds to know about high-quality feed with respect to protein and energy [40].

2.4 New concept of feed evaluation methods: Feed milk value

Feed milk value (FMV) is a new feed evaluation method through which we can predict feed value and the amount of nutrients supplied to dairy cows for milk production. According to Theodoridou and Yu [41], the FMV can be determined by different evaluation models for nutrient supply for dairy cattle, e.g., NRC, DVE/OEB, and PDI. Feed milk value can be used to estimate the efficiency of specific feed, and comparison can be made between the feeds. Guevara-Oquendo et al. [40] estimated the FMV based on the NRC model and the DVE-OEB system. The findings in this study were in agreement with NRC [42], in which the protein content in milk was 33 g protein/kg of milk, and the efficiency of using metabolizable protein for lactation was assumed to be 0.67 [42].

2.5 Model and progress in the DVE/OEB system (v1994 system vs. v2010 system)

The Digestible Crude Protein (DCP) system was superseded in the Netherlands in 1991 by the DVE/OEB system, a new system for evaluating proteins. The primary goal of the system's development was to reduce unnecessary nitrogen losses by feeding dairy cows according to a more precise need. Accurately forecasting the synthesis of milk protein was the second goal [43]. Based on new research findings, the DVE/OEB v1994 system has recently been updated to the DVE/OEB v2010 system [44, 45].

2.6 Progress in the NRC dairy nutrition requirement model (v2001 vs. v2021)

To create more profitable diets and reduce the environmental impact of nitrogen loss, it is crucial to accurately estimate the amount of protein needed for maintaining and supporting lactation in dairy cows [46]. For decades, NRC has been providing fundamental dietary recommendations for dairy cows. They published eight sets of these guidelines over 75 years, with the most recent in 2001. However, a new model was introduced in 2021, which is now referred to as [47], with NASEM representing the National Academies of Sciences, Engineering, and Medicine [47].

The 2001 NRC primarily considered animal parameters like body weight, days in milk, and milk production when estimating dry matter intake (DMI). It worked well when production measures were known, but not as effectively when designing diets without considering actual production. The updated [47] provides two equations: one based on animal factors alone and another considering both animal factors and feed

composition. With today's high-producing cows, these revised equations are expected to be more accurate, accounting for how feed affects DMI and performance [48].

The [47] includes critical recommendations for trace minerals, specifically, trace mineral requirements (Req) and adequate trace mineral intake (AI). These guidelines cover nine essential trace minerals for dairy cattle: chromium (Cr), iodine (I), cobalt (Co), molybdenum (Mo), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and selenium (Se). Notably, the Cu, Mn, and Zn recommendations significantly differ from the 2001 NRC Guidelines. The Fe and Se recommendations remain unchanged, while minor changes are observed for Cr, I, and Co [47].

The section on proteins and amino acids has seen substantial changes from the 2001 NRC guidelines. This is largely due to improved estimates of protein digestibility that include RUP, supported by a larger ingredient database. The new metabolizable protein (MP) measurements exclude endogenous protein, which does not affect MP levels. A novel response model has been introduced, featuring more amino acids beyond lysine and methionine. Rather than a fixed percentage, the efficiency of metabolizable amino acid to MP conversion now varies based on the total essential amino acids available [47].

Regarding the energy discount equation for Net Energy for Lactation (NEL), [47] features improvements and rectifies past errors. It includes residual organic matter (ROM) and starch in the NFC fraction to better assess energy supplied by various starch sources. The digestibility coefficient for fatty acids (FA) has also been modified, resulting in a different calculation for digestible FA compared to the 2001 NRC guidelines [47, 48].

2.7 Techniques for in vivo animal production trials

In vivo animal production trials are mostly used to measure digestibility. Common methods are nylon bag techniques, marker techniques, difference techniques, and conventional digestion trial techniques [49]. An indirect approach to quantifying digestive parameters is made possible via markers. Markers are used to make it easier to quantify digesta fill and transit rate as well as the link between diet digestibility and consumption [50]. One feature of this approach is that the indicator substance and nutrients in the feed and excrement are used to compute the digestibility [49]. One of two methods is typically used to provide them: either as a pulse (or bolus) dosage or as a steady amount in the diet. Markers are non-absorbable by the animal, closely linked to the digesta fractions, and do not impede the gastrointestinal tract's normal operation. Digesta markers can be broadly classified into two groups: internal markers and external markers. Internal markers are substances naturally found in feeds, such as lignin, silica, and acid-insoluble ash. Unreactive preparations known as "external markers" can be given or added to the feed. Feed particles have been dyed or stained, and insoluble metal oxides or rare-earth elements have been utilized to study digestibility and digesta flow [50]. In vivo acid detergent fiber (IVADF), in vivo neutral detergent fiber (IVNDF), and acid detergent lignin (ADL) solution were used as markers for estimating digestibility and fecal output in lambs given four different feeds [51]. Double markers and triple markers in vivo digestibility methods are used mostly to measure duodenal organic matter flow [52] and ruminal digestion of organic matter and neutral detergent fiber [53], respectively. Intravenous infusion of double-marker urea has also been widely used to determine endogenous nitrogen recycling [35, 54]. Acid-insoluble ash (AIA) is also used as an internal marker for measuring the apparent digestibility of concentrate diets [55].

3. Progress in feed processing technology and technical treatments

3.1 Feed processing purpose

Feed processing typically entails modifying the physical and occasionally chemical properties of feed ingredients to maximize animal consumption and improve diet mixing and stability. Processing aids enhance digestibility [56] and bioavailability of feed, as finely ground feed particles are more easily absorbed than whole or coarse feed ingredients. Moreover, steaming contributes to partially breaking down proteins, increasing hydration, and promoting starch gelatinization [57]. Particle size and feed processing are key factors in optimizing the nutritional advantages of feed for livestock. Current food technologies aim to increase nutritional intake and improve feed efficiency. Feed is processed for several purposes, including enhancing palatability, changing the size of the particles, making the feed more digestible, modifying the rate, site, and degree of digestion, and making storage or preservation easier [58]. These changes in the feed aim to increase animal yields and achieve optimal nutrient utilization. Rahmadani et al. [59] observed that chemical processing works well to slow down the breakdown of starch in ruminant feed and may even improve starch utilization by ruminants.

3.2 Common feed processing methods

Feed processing methods for ruminants involve several techniques to enhance the nutritional quality, digestibility, and palatability of feeds. Roughages are physically processed with dry and wet processing methods. Dry processing methods include baling, chopping, grinding, pelleting, and cubing, while wet processing of roughages includes soaking and chaffing. Similarly, alkali, urea, and lime treatments are classified as chemical methods. Some biological methods are also applied in roughages [60]. According to Havekes et al. [61], feeding shorter chopped wheat straw to dry cows on a high-straw diet enhanced intake and decreased sorting, producing healthier metabolism and a more stable rumen environment during early lactation. Beauchemin et al. [62] found a reduction in intake and milk production when cows were fed only cubed hay or silage in comparison to long hay or coarsely chopped silage.

Dry processing of grains includes grinding, cracking or dry rolling, crimping, crumbling, popping or puffing, micronizing, roasting, and dehulling. Wet processing methods of grains include soaking, reconstitution, steam rolling, steam flaking, extrusion, exploding, pelleting, and gelatinization [60]. In the study by Risyahadi et al. [63], milk output, milk lactose concentration, dry matter content, and protein digestibility were all significantly increased by extruded feed, but milk fat and protein concentration remained unaltered. The choice of feed processing method is based on the type of feed ingredients available, nutritional requirements of the ruminant group, and production goals. Proper feed processing can improve nutrient utilization, reduce waste, and ultimately contribute to the overall health and performance of ruminants.

3.3 Fermentation treatments

Fermentation has been a time-tested method for preserving and processing foods, dating back thousands of years [64, 65]. It has gained attention for its role in modifying the nutritional value of livestock feed and the production of livestock products [66].

The livestock feed industry heavily relies on fermented feeds and feed products, with a historical tradition of feeding fermentation by-products from brewing and distilling industries, particularly ruminants, as protein and energy supplements [67]. Fermented feeds contain beneficial bacteria that could alter the ruminal and/or intestinal environment of cows, enhancing disease resistance. Moreover, these feeds exhibit increased shelf life and reduced spoilage, which helps to reduce costs [68]. One potential technique to enhance the quality and long-term storage of Total Mixed Rations (TMR) is fermentation [69].

In the realm of livestock feed processing, solid-state fermentation is widely employed. Solid-state fermented feed refers to the process of modifying the nutritional qualities, digestibility, palatability, and safety of feed by harnessing naturally occurring or artificially added microorganisms under controlled conditions, typically in feeds with moisture content below 70% [70]. The invention describes a fermented feed for dairy cows made from distillers' grains and wheat straw as raw materials. It is made by microbial fermentation, has a high protein content, strong palatability, and is rich in probiotics like *Bacillus subtilis* and *Saccharomyces cerevisiae* [71]. The structural characteristics of plant residues, particularly lignocellulosic components, provide a stable foundation and substrate for microbial fermentation. This process produces value-added products through solid-state fermentation [72]. The addition of solid-state fermentation biomass has a profound impact on the nutritional composition of feed, animal performance, hemo-biochemical state, gut morphology, gut microbiota, carcass characteristics, rumen fermentation, and a reduction in enteric methane emissions from animals [72]. Additionally, solid-state fermentation is instrumental in the production of feed for ruminants, including the cultivation of mushrooms, offering further versatility and sustainability in the livestock feed industry [73].

3.4 Enzyme treatments

Enzyme treatments are commonly used in feed processing, particularly in the formulation of livestock feeds. The process of applying enzymes to feed can take many different forms. It can be applied to forage during harvest, ensiling, or feeding [74]. The biotechnology sector initially developed beta-glucanases and arabinoxylans as enzymes. These enzymes were used to break down the fibrous parts of the grain, called non-starch polysaccharides. Recently, fodder cell wall digestibility has significantly improved with the use of exogenous enzyme technologies. The two most widely used enzyme complexes belong to the hemicellulose and cellulase families. These enzymes are typically recognized as multicomponent enzymes that, when added to feed, may help preserve feed, particularly silage. Utilizing a combination of fibrolytic enzymes in high-grain diets primarily composed of barley grain can enhance the digestion and utilization of fiber [75]. Fibrolytic enzyme treatments can also increase hull degradation [76], as well as dry matter digestibility and neutral detergent fiber degradability [77], which can lead to higher milk yield if doses are critically calculated [78]. Although fibrolytic enzymes are not beneficial for maize diets, they can be utilized to increase the digestibility of barley-based diets [62].

3.5 Blending

A well-balanced and nutritionally complete diet for ruminant animals such as cattle, sheep, and goats. Blending is a crucial step in formulating a Total Mixed Ration (TMR) or other types of ruminant diets. For growing cattle, blended pelleted

products can be a good source of additional energy and protein [79]. Blending could reduce feed wastage, optimize feed utilization, provide uniformity, increase the value of low-quality feed when blended with high-quality feed, and reduce picky behavior in animals [80]. Blending liginosulfonate with carinata seeds and carinata co-products can reduce the ruminal degradation of CP [81].

3.6 Pelletting

Pelleted feeds are a crucial aspect of modern animal nutrition, serving as agglomerated feed products formed by compacting and shaping individual ingredients or mixtures. This process is achieved by subjecting the materials to pressure, moisture, and heat, which results in the formation of larger, more manageable feed particles. Pelletting transforms small, often dusty, and challenging-to-handle feed items into larger and more appealing feed. The advantages of pelleted feeds include improved handling, enhanced feed intake, and superior feeding outcomes for livestock (CPM.net).

Research has shown that the pelletting process can lead to significant improvements in the nutritional composition and digestibility of feeds. When legumes are processed into pellets, notable reductions are observed in the fiber fraction, antinutritional components, and gas production, which makes the feed more nutritionally and palatably desirable [82]. Additionally, pelletting has been found to decrease the fast-degradable fraction of dry matter and starch in wheat samples, influencing their overall degradability [83].

In the context of feedlot fattening, pelletting plays a pivotal role in impacting the overall performance of animals. It can lead to increased feed intake, which in turn enhances growth performance [84, 85]. However, it is worth noting that for small ruminants, while pelleted feed can enhance production performance, it may also lead to decreased nutrient digestibility [86]. The conditioning temperature during the pelletting process is another critical factor influencing feed conversion ratio and volatile fatty acids (VFA) production [87].

In the dairy industry, pelletting of feed has direct effects on milk production, milk fats, milk proteins, and cows' behavior. Research indicates that pelleted feed can result in increased dry matter consumption and greater milk production, especially when an all-hay ration is pelleted. Interestingly, variations in milk output tend to disappear when pellets are combined with concentrates or fed alongside pelleted fodder. Moreover, pelletting has been shown to reduce the time required for prehension and mastication of feed, accelerating the fermentation processes in the rumen [88–90].

3.7 Impact of thermal feed processing on key nutrients of protein and starch

In the ruminant nutrition sector, thermal feed processing uses heat to alter and enhance the nutritional value, safety, and digestibility of feed components and completed rations for livestock, including cattle, sheep, and goats. The principle is that the grain is steam-cooked to a temperature of 70–100°C, depending on the treated grain. It then passes between two rollers and crashes. The temperature, humidity, pressure, and compression time are combined to generate a new product. These processed grains and legumes have considerably different characteristics from conventional feed ingredients [91]. During the process, amino groups bind with carbonyl groups of reducing sugars such as those found in lactose and glucose in an event called the Maillard reaction. Room temperature can trigger the Maillard reaction, although it intensifies with increasing temperature, duration, moisture (highest at 40–70%), and

alkalinity (linear between pH 3 and 8) [92, 93]. In the early stage of the Maillard reaction, lysine is bound to sugars by a heat process, but it is still detectable in chemical assays. However, chemically analyzed lysine is reduced due to the formation of melanoidins in the late stage of the Maillard reaction. It is during this stage that coloration changes occur. Widespread evidence has shown that feed components like field peas, soybean meal, canola meal, peanut meal, and sunflower meal negatively impact lysine bioavailability due to the Maillard process [92, 93]. The Maillard reaction also reduces starch digestibility [94]. The creation of cross-linkages, which slows down the pace of protein digestion by either obstructing the sites where enzymes attack or inhibiting enzyme penetration, results in the loss of amino acid availability.

Gelatinization is another process that occurs when using thermal techniques on feeds. Starch gelatinization is an order-disorder phase transition that involves amylose leaching, hydration and swelling, heat absorption, and the diffusion of water into starch granules (Benison [95]). Heat and water during gelatinization cause the starch granules to expand. Consequently, the water is absorbed gradually and irreversibly. Gelatinization impacts starch digestibility [96]. The amount of gelatinization during feed processing is limited by the low water content; however, the starch's characteristics will influence the temperature and degree of gelatinization, which could impact digestion [96]. Compared to corn or sorghum, barley grain may have less of an advantage from starch gelatinization in animal performance because barley starch is more easily broken down in the rumen after being exposed to microorganisms [76].

4. Progress in feed chemistry and molecular structure and nutrition interaction research

4.1 Why do feed chemistry and molecular structure associated with nutrient utilization study?

Feed chemistry studies are crucial for optimizing animal nutrition, ensuring feed safety, complying with regulations, and advancing research and innovation in the field of animal nutrition and agriculture. The structure and chemical makeup of feed proteins have an impact on protein nutritional value as well as how well cattle are able to utilize them [1]. Protein absorption in the small intestine and protein accessibility to internal digestive enzymes in the animal gastrointestinal tract are significantly influenced by the conformation or structural makeup of the feed [97]. Studying the molecular structure of feed is important to find nutrient availability and nutrient interactions [2, 98], rumen degradability of feeds and their constituents digestibility [99], and detection of processing-induced changes [100]. Studies of nutrient interaction are crucial for optimal health and well-being, good microbial activity, favorable ratios of VFAs, and good productivity in dairy cows [101].

4.2 Molecular spectroscopic techniques for feed chemistry and inherent structure study

Wet chemistry analysis is only able to provide the chemical makeup of feeds, irrespective of their nutritional value and digestive characteristics in ruminants. Since the intrinsic structure of feed nutrients is more closely linked to their overall absorption, studying the internal structural makeup of functional groups and feed nutrients is

frequently essential for comprehending the digestive behaviors and nutritional values of feeds in ruminants. Near-infrared reflectance spectroscopy, Raman spectroscopy, fluorescence-transformed infrared spectroscopy (FTIR), diffuse reflectance infrared Fourier transform spectroscopy (DRIFT), and attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectroscopy ATR-FTIR, NMR spectroscopy, circular dichroism (CD) spectroscopy, and synchrotron FTIRM are some major spectroscopic techniques used for feed chemistry and inherent structure studies [1, 102, 103]. ATR-FTIR is also used to determine mineral chelation in proteinates used as animal feed additives [104]. Moreover, CD spectroscopy is used to determine protein-protein interactions [105] and structural changes after thermal processing [106].

4.2.1 Grading near-infrared spectroscopic technique

Grading near-infrared spectroscopy (NIRS) is an analytical method that examines samples for compositional or distinctive features by employing near-infrared radiation. It is easy to use, has little sample preparation, no hazardous chemical waste, fast analysis, and gives simultaneous results for multiple parameters [107].

Principally, NIRS makes use of the electromagnetic spectrum's region that is closest to visible light, between 780 and 2500 nanometers (nm). The wavelengths in this region are longer than those in visible or ultraviolet spectroscopy because they are characterized by low-energy photons [108]. Due to the special relationship that near-infrared radiation has with matter, near-infrared sensing operates differently in that infrared radiation affects whole molecules instead of just the electrons within atoms of a chemical element. More precisely, it modifies the vibrational motion of the molecules. A molecule absorbs electromagnetic photons when it is exposed to near-infrared light, which initiates the vibrational transition process, causing the molecule to stretch, contract, bend, and rock back and forth. This technique is why NIR spectroscopy is often called vibrational absorption spectroscopy. The idea behind NIRS is to identify the vibrational mode that a molecule enters when exposed to infrared radiation and the frequency of radiation that is required to excite the molecule into a higher vibrational state [109, 110]. In the NIR range, several chemical compounds each absorb and scatter light in a unique way. Certain chemical bonds, functional groups, and molecular configurations within the sample all have an impact on this interaction. It is feasible to detect and quantify different chemical contents in a sample by examining the absorption and scattering patterns of NIR light [108].

4.2.2 Fourier transform infrared spectroscopy (FTIR), microspectroscopy (FTIRM), and synchrotron FTIRM

In Fourier-transform infrared spectroscopy, or FTIR, the vibration of molecules is the subject. A molecule can be identified by combining all its functional groups, each with a distinct vibrational energy. Particle analysis, multilayer film characterization, and sample identification are thereby made possible by FTIR microscopy [111, 112]. The range of infrared wavelengths that a material absorbs is measured by FTIR analysis. To do this, infrared radiation (IR) is applied to material samples. The sample's molecular makeup and structure are ascertained by measuring its capacity to absorb infrared light energy at different wavelengths. An optical signal containing all of the infrared frequencies is produced by a straightforward instrument known as an interferometer, which is used to identify samples. The signal is then deciphered using the Fourier transformation, a mathematical method. A mapping of the spectral

information is then produced by this computer-generated method. The FTIR spectrum, which is the resultant graph, is subsequently identified by cross-referencing it with reference libraries [113].

The creation of imaging systems and microscopes is one of the most recent significant developments in FTIR instrumentation, responsible for being named Fourier transformed infrared microspectroscopy [114]. The FTIRM integrates an FTIR device with a microscope to provide even more details about the chemical fingerprints of the organic and inorganic substances found in trace amounts of evidence. In FTIR or FTIRM, the mathematical procedure known as the Fourier transform (FT) is used to change an amplitude-time spectrum into an amplitude-frequency spectrum and vice versa. Since retardation and time in FTIR spectrometry are exactly proportional, FT is frequently employed to obtain the amplitude-wavenumber spectrum from the amplitude-retardation spectrum and vice versa [115].

Fourier transform infrared microspectroscopy (SR-FTIR), which uses synchrotron radiation (**Figure 1**), has been created as a quick, straightforward, non-destructive, and bioanalytical method. By utilizing synchrotron light brightness and a small effective source size, this method may investigate the molecular chemistry in biological tissue microstructures at ultra-spatial resolutions inside cellular dimensions without damaging innate structures [116]. With synchrotron, localization of pure protein is achievable, which is not possible through conventional methods [117]. The SR-FTIR microspectroscopy is superior to other techniques in that it offers a greater spectral quality (signal/noise ratio) and a wider spectrum (down to THz) at the maximum

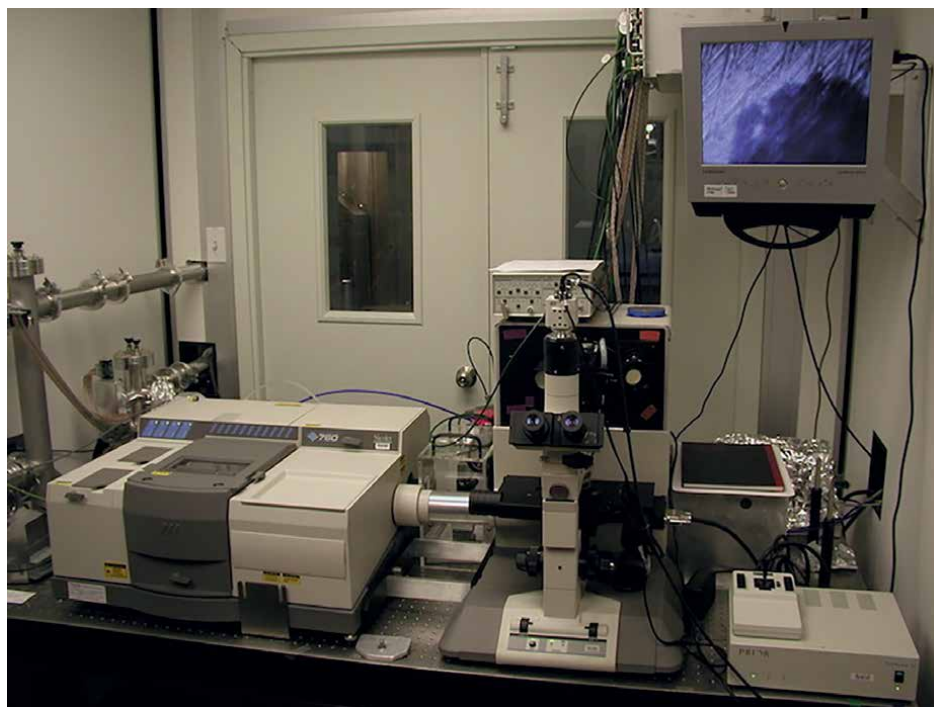


Figure 1.
Synchrotron-radiation-based FTIR microspectroscopy at Advanced Light Source (ALS, U.S. Dept. of Energy) as one of the examples that our SRP Chair (P.Y.) team uses for feed/food molecular structure and molecular nutrition research programs (Beamline 1.4 Infrared Microspectroscopy; sourced and supported by Hans Bechtel and Lisa Miller).

spatial resolution (diffraction restricted) [118]. Synchrotron FTIRM helps identify protein structures and chemical differences in the ultrastructural matrix of endosperm tissue between feeds after processing. The distribution and intensities of the biological elements in the feed tissue's microstructure within the cellular dimension may then be imaged [119].

4.2.3 The ATR-FTIR spectroscopic technique

In Fourier transform infrared (FTIR) spectroscopy, one of the most often used sampling methods is attenuated total reflectance, or ATR, along with transmission. Total internal reflection (ATR) relies on the interaction between the sample and infrared (IR) light only at the point of reflection. The sample and the ATR crystal are in contact during ATR-FTIR spectroscopy. The sample on the surface in touch with the ATR crystal is impacted by infrared radiation as it passes through the crystal [120–122]. When an infrared beam comes into contact with a sample, an attenuated total reflection accessory measures the changes that take place in the beam [121–123]. Total internal reflection happens because the two materials show different refractive indices [120–122].

4.3 Molecular spectral analyses: Univariate and multivariate

In the field of spectroscopic analysis, researchers employ a range of data analysis techniques to decipher the complex molecular structures of various substances. Two notable methods utilized for this purpose are Principal Components Analysis (PCA) and Hierarchical Cluster Analysis (HCA). Abeysekara et al. [124] emphasize that these techniques are instrumental in identifying spectral differences between multiple functional groupings, even in cases where the precise spectral assignments remain unknown. Through PCA and HCA, researchers can statistically and qualitatively distinguish one group from another, providing valuable insights into the composition and characteristics of the materials under investigation [124]. While PCA and HCA are powerful multivariate approaches for spectral analysis, it is essential to consider the broader spectrum of data analysis techniques available. Univariate analysis focuses on single variables, offering a foundational understanding of data through data collection, summarization, and pattern recognition. It is particularly useful for comprehending the distribution of a single variable [125]. However, multivariate analysis becomes indispensable when dealing with complex data involving multiple variables. As described by the University of West Georgia [126], these techniques encompass both descriptive and inferential methods, such as multiple regression and structural equation modeling, which can reveal intricate relationships between variables and predict outcomes. Multivariate exploratory approaches, as detailed by Abeysekara et al. [124], play a vital role in comparing spectra by considering underlying structural differences, irrespective of the precise spectral band assignments. These techniques, including PCA and HCA, allow researchers to perform comprehensive comparisons using extensive spectral data, ultimately classifying spectra based on their similarities and differences [119, 126]. Fundamentally, multivariate analysis empowers spectroscopists to explore and interpret intricate data patterns, contributing significantly to understanding molecular structures and their distinctions [119, 124]. Thus, multivariate molecular analysis has been applied as a useful tool to discriminate and classify inherent protein and carbohydrate molecular structure in single feed offered to ruminants [127].

5. Conclusion and summary

- The recent research progress in feed science, feed cost, processing and blending, feed chemistry, nutrient modeling, feeding efficiency, and cutting-edge techniques and feed evaluation methods has been thoroughly evaluated. All these key factors play important roles in optimizing nutrient supply and influencing sustainable animal production performance.
- Advanced technology with a synchrotron source enables the detection of the feed's inherent structure at a molecular basis. Processing-induced feed molecular structure is highly associated with nutrient availability and utilization.
- The information described in this article gives better insight into feed science and nutrition research progress and updates, and helps to develop sustainable livestock farming.

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Applications of Green Agricultural Technologies (GAT) and Sustainable Analytical Methods (SAM) in Precision Animal Agriculture and Product Quality Testing

Haruna Gado Yakubu, George Bazar and Tamas Toth

Abstract

Modern agricultural development is primarily based on applying environmentally friendly and efficient technologies to deliver farm productivity. This chapter examines the advancements made in green agricultural technologies (GAT) and sustainable analytical methods (SAM) for precision animal production systems. The application of Unmanned aerial vehicles (UAV) enables real-time monitoring of pasture fields, animal behaviour and health. The application of NIR in the dairy industry has revolutionised feed and milk quality analyses, by providing real-time, accurate and precise nutritive and quality feedback. Smart feeding and milking have ensured efficient feeding and milking of a large number of animals within short periods. These technologies have significantly improved the efficiency of livestock production systems, enhanced ecosystem integrity, reduced drudgery, improved animal welfare and physiological conditions, and increased farmer income. Notwithstanding, the complexities involved in the application of some of the technologies and the high cost of almost all of them are hindering their adoption in low-income countries. Stakeholders and policymakers must collaborate effectively to make these technologies affordable in low-income countries, thereby enhancing precision livestock agriculture worldwide. On the other hand, where GAT and SAM are available, many expect a self-evident agricultural revolution simply to be an investment. Professionals, however, must understand that all new technologies and methods also require knowledge and experience in application, not only in development. Currently, most of the portable technologies are operational in offline mode, while others require network connectivity (online) for efficient operation. Manufacturers and users must consistently review the performance of these technologies for the effective design and development of future generations of the devices.

Keywords: precision agriculture, green technology, digital sensors, rapid analyses, smart farming

1. Introduction

The role of green agricultural technologies (GAT) and sustainable analytical methods (SAM) cannot be overemphasised in current agricultural development conversations, more so when current agricultural activities are climate and data-driven (smart agriculture) [1]. The global human population is estimated to be 9.8 billion by 2050 [2], coupled with a predicted worsening global climate [3]. Urgent steps and actions must be taken to sustain the production of animals to meet growing demands for animal protein [4]. However, the steps and actions must be designed and aimed at reducing the ecological footprint associated with current animal production systems [5]. The acquisition and utilisation of agronomic data to make informed or efficient decisions to boost or sustain animal production in the current smart agriculture era has sparked intensive development and advancement of some effective tools of green agricultural technologies (GAT) [6].

The application of GAT tools such as remote or digital sensing, robotics and big data technologies in animal farming has reduced the variable cost of production, increased efficiencies, improved animal welfare, and increased productivity per land area [7].

Related technologies referred to as sustainable analytical methods (SAM) have also been developed to reduce the labour intensiveness of conventional analytical methods, the environmental hazards associated with reagents, the time and cost of analyses, and improve the accuracy and precision of test results of animal feed and products, such as meat, milk and eggs. SAM tools such as near-infrared (NIR) spectroscopy, hyperspectral imaging, and machine olfaction or volatiles-sensitive sensor technology have revolutionised the science of feed and animal product quality testing.

The effective combination of GAT and SAM techniques in animal production systems to improve production, enhance management and welfare, and increase farmer profitability while minimising destruction to the ecosystem encompasses the concept known as precision animal farming or agriculture [8].

The aim of this chapter, therefore, is to present to readers the current advances made with GAT and SAM to advance precision animal production systems.

2. The concept of GAT and SAM in modern agriculture

2.1 Green agricultural technologies (GAT)

As a term or concept, GAT, also known as clean technologies, can be defined as technological tools in modern agriculture that work to reduce the negative impacts of farming activities on the environment [9]. GAT has become an important sustainable strategy for solving the global climate challenges confronting agriculture [10]. The application of GAT tools in the implementation of sustainable agricultural development strategies has led to the utilisation of animal resource efficiency and reduced environmental or ecological degradation [11]. At the global policy level, GAT falls within three main United Nations Sustainable Development Goals (UNSDGs), that is, *goal 2*: end hunger, achieve food security and improved nutrition and promote

sustainable agriculture; *goal 13*: take urgent action to combat climate change and its impacts; and *goal 15*: protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss [12].

GAT tools used in precision animal farming include remote sensing (RS) [13], drone technology (DT) or digital imaging (DI) [14], which are mostly used to remotely gather agronomic information on pasture lands, animal growth data, robotics [15] for smart feeding, milking and care for animals, and digital sensor technologies (DST) [16] for control feeding.

2.2 Sustainable analytical methods (SAM)

The advocacy for more environmentally friendly analytical methods birthed SAM, which are rapid or correlative analytical methods that employ digital sensor technology and machine learning techniques to evaluate animal farm inputs and products that would have ordinarily been done with conventional methods [17]. They are sometimes referred to as green analytical methods (GAM) because their application mostly avoids environmental destruction [18]. SAM techniques, mostly, do not use reagents, are non-destructive or non-invasive, provide real-time data or results, are sensitive, precise, and accurate, and are generally relatively cost-effective in the long run when compared with conventional or wet chemistry methods [19]. Some of the most effective SAM technologies, mostly used in precision animal agriculture, include (i) near-infrared (NIR) spectroscopy, which has been largely accepted worldwide as an effective feed analytical method that provides real-time nutritive data on farm inputs like animal feed, and products such as meat and milk [19], (ii) [19] hyperspectral imaging which employs spectroscopy and digital imaging to provide valuable quality information on animal products [20] and (iii) machine olfaction or volatiles-sensitive sensor technology, which is effectively complementing human sensory tests aimed at evaluating animal products' smell or aroma [21].

SAM technologies can be recognised as tools that record the digital chemical fingerprint of substances. In some exploratory approaches, the chemical fingerprints are used only, and differences of samples or sample sets are described based on the variations found in the NIR, hyperspectral, or digital smell data, solely. However, in most applications, multivariate data recorded with SAM technologies are translated to predict quantitative or qualitative properties. **Figure 1** shows the general theory of development and application of SAM technologies.

At the development stage, combined input data is required: (i) multiple samples must be measured with both the SAM fingerprinting technology and (ii) reference data originating from, for example, laboratory measurements or sensory panel tests must be collected for each sample. The reference data may include continuous or discrete variables. Continuous variables can describe the chemical composition and physical or sensory attributes, while discrete variables can define the group identity within the sample set. There might be a direct or indirect relation between the continuous and discrete variables of a sample set; however, the definition of the data type is crucial: continuous variables are used for quantitative calibrations, and discrete variables are used for qualitative classifications. After recording the chemical fingerprints and the reference data of a bunch of samples, correlative approaches can take place when the pairs of fingerprints and reference data of each sample are compared, employing various mathematical-statistical modelling techniques. The paired data of many samples is collected into a large database. Development steps include data

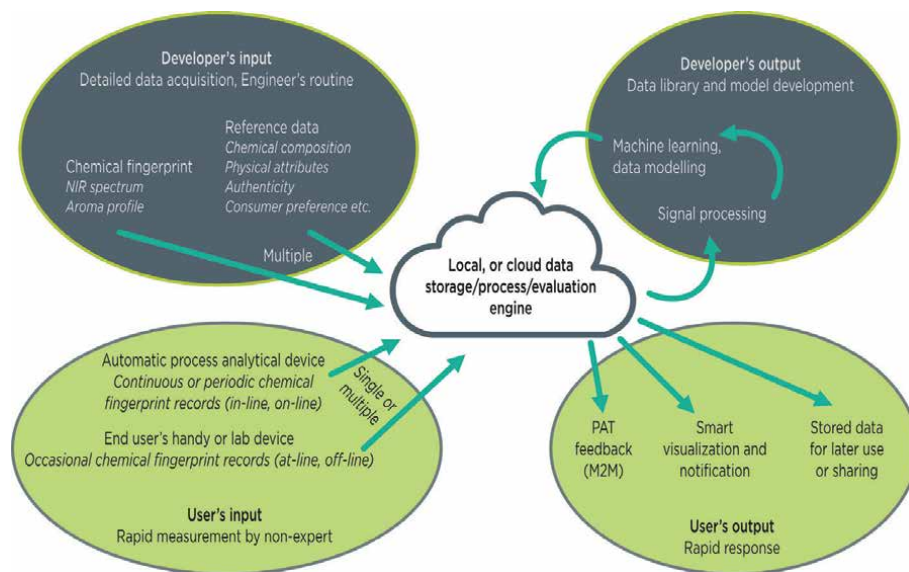


Figure 1.
Schematic flow chart of the development and application of sustainable analytical methods.

processing to enhance or reduce various signals, reducing the dimensions of multivariate data, and exploring basic variations. Then, multivariate data analysis is done using linear and non-linear calibration or classification modellings [22]. Both the raw data and the developed mathematical calibration and prediction models can be stored on local computers or in cloud servers. Users will then measure their new samples with the fingerprinting SAM technology and have the recorded chemical fingerprint evaluated by the previously developed quantitative or qualitative models, predicting the compositional variables, physical or sensory attributes, or group identities. With most SAM technologies, the whole process of data recording and prediction can happen in fractions of the time normally needed for reference measurements. The aim is to get accurate approximations and to exploit short response time. Many of the instant decisions taken based on information gathered from applications of SAMs could never be taken with conventional analytical methods since those measurements require considerable time, not considering the transportation and sample handling issues.

Since SAMs are correlative technologies, the accuracy of both the fingerprint and the reference data is crucial to improving prediction reliability. Fingerprints do not measure chemical compounds directly; instead, these are interpreted by mathematical models derived from the training dataset. Based on the previously experienced patterns of relation of fingerprint and reference data of the training database, predictions on quantitative or qualitative measures can be given for the new samples based on their fingerprints only. Due to the correlative approach, the training database must contain the sample types and variables of interest that may appear in the future. Additionally, to avoid inaccuracies arising from interpolative predictions, future samples to be measured and predicted must fall within the variance of the training database.

Contrary to targeted conventional chemical or physical methods, when one single variable is determined by one measurement, SIM technologies allow non-targeted

analysis of samples through complex chemical fingerprints. This also means that one measurement can hold a wealth of information, and a holistic description of samples can be achieved: multiple compounds or both qualitative and quantitative measures can be determined simultaneously. Due to the non-targeted approach, SIM technologies are also excellent in monitoring and warning systems when the users do not know exactly what property of the product will change in the future. The general screening of the chemical fingerprint may reveal unexpected differences, drawing attention to errors or even excellence during product development.

The complex digital fingerprint, like the predicted variables, can be easily transferred and interpreted by various automated systems. Interestingly, unlike conventional targeted analytical methods, the archived fingerprints can be reassessed even when the sample does not exist anymore. For example, new information gathered in production recently may lead to the requirement of finding certain clusters amongst samples scanned long ago and describe patterns related to technological conditions in the production based on archived data – such recalls of saved data can assist in the refurbishment of technological lines, or identification of the period or cause of errors. Therefore, SAMs may provide data for high-quality assurance when the digital fingerprints of a batch can be recorded along the product chain. With blockchain technologies [23], these can be stored in a secure way and used for the benefit of the producer, processor, trader, and consumer.

Violating the basics described above would lead to challenged results and obscure conclusions; therefore, decent knowledge is required both in the case of the development and application of SAMs technologies. Besides the careful use of the technology and the results provided, users must always pay attention to the theory and practice of representative sampling [24]. Even the most precise technologies and most accurate calibrations can give false results on the investigated batches.

3. Some key GAT applications

3.1 Unmanned aerial vehicles (UAV) or drones in animal production systems

Unmanned aerial vehicles (UAVs) equipped with digital, satellite, or computer vision imaging technologies have been used extensively by ecologists and animal behaviour researchers to study the movement and habits of grazing animals in pasture and silvopasture systems, as well as in pastoral livestock production [25]. Drones with high-resolution or infrared cameras have been used for animal population count, tracking of group or herd movement and isolated animals on grazing fields (**Figure 2a**) [26, 27]. The technology has been used to study animal-preferred grazing plants on pasture fields with multiple or mixed crops [28]. In the application of fertiliser (foliar system) and pesticides to pasture crops at required dosages and times, drone technology has been very useful [29]. Natural mating behaviour amongst farm animals and conserved game animals has been successfully monitored with drones equipped with computer vision technology [30]. In recent years, drone and computer vision technology has been employed to identify sick, injured and springing heifers or pregnant cows that need to be assisted [31]. However, the technological challenges associated with UAVs include the high initial cost of purchase, adverse weather interference, especially on foggy days, and regulatory compliance or security clearance, which is mostly required before flying the drone [29].

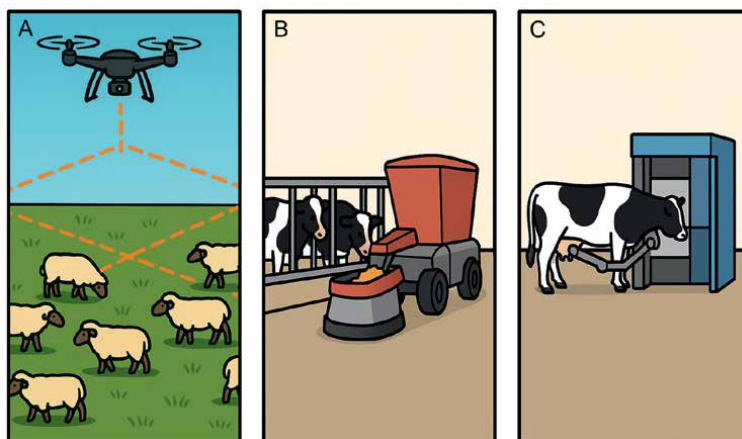


Figure 2. Schematic representation of green agricultural technologies (GAT): (A) unmanned aerial vehicles, (B) automated feeding, and (C) automated milking.

3.2 Automated or robotic animal feeding

The provision of sufficient and timely feeding, along with the genetic makeup of the animal and a good environment, form the basis for animal growth and development [32]. Before the invention of smart or intelligent feeding, manual feeding was the primary method of delivering feed to farming animals [33]. However, emerging challenges in the so-called “Global North”, such as an ageing population, labour shortages, and the liberalisation of agricultural markets, have led to the fast adaptation of intelligent or smart farming technologies in animal agriculture [34]. For example, manual feeding systems are challenged with high labour costs, contamination, and inefficient feed management or handling [33]. Smart engineering has given rise to automated or robotic smart feeding systems designed to improve feeding efficiency [35]. The technology consists of an automatic feed dispensing system, an unmanned ground robotic vehicle, and an embedded vision technology that delivers feed to animals within specified time intervals (**Figure 2b**). The ground robotic vehicle receives feeds from the dispensing system for delivery at the animal pen house in real time [36].

Sinnott et al. reported that when the manual feeding system was compared with the robotic system in a calf feeding trial, the automated system was 39% more efficient than the manual system [33]. Muir et al. [37] reported an improvement in recent robotic systems that have the technology to measure animal feed intake. Recent technologies have added water delivery components to the known feeding systems for multipurpose delivery [38]. Despite their usefulness, most smart feeding technologies are not yet fully automated, as human intervention is still required to load feed into the robotic system. Furthermore, the designs of most farms make it difficult for the robot to navigate successfully [39], thus requiring costly infrastructure modifications to meet the needs of modern technology.

Again, in novel combined systems, the technology can check the animals’ behaviour and the rearing and feeding conditions continuously. Big data systems equipped with AI technologies are evaluating the effect of various conditions on animal behaviour, physiology, and production. When a physiological or production deficit is

detected, the system modifies the conditions to achieve optimal values in the control criteria. The method mimics the good farmer's approach, when the conditions of the farm animals are evaluated very often before feeding, that is, during manual feeding [40]. Despite their advantages, these novel systems must be populated with appropriate input data and trained by experts to recognise patterns indicative of preclinical health issues and emerging problems in livestock.

3.3 Automated milking systems in dairy production

Milking technologies have also evolved from when a handheld pump was used, starting in the 1860s, to the automatic milking systems that appeared on the scene in the 1990s [41]. Current engineering advances have developed more robust and intelligent systems that can handle milk interval regularity and teat cup failures (**Figure 2c**) [42]. Robotic or automated milking systems help reduce bacterial contamination that may result from human contact, thus ensuring cleaner and safer milk [43]. Automated milking systems also ensure the maximum yield of milk harvested from large herds. It also eases the drudgery that is mostly associated with hand or conventional milking systems [44]. Some of the milking robots have embedded quality testing devices that enable the continuous monitoring of milk quality parameters or metrics, enabling early quality problems [45]. Again, the design of this technology is mostly done having the comfort or welfare of the dairy cow in mind, thus reducing emotional stress that is mostly associated with the process of manual milking [46, 47]. The challenges with the system are the initial cost of installation and the frequent engineering challenges that may require the presence of maintenance personnel from the source company [48]. There are also challenges with animals' body size or confirmation score, udder shape and size, since the lack of homogeneous herds increases the chances of technological flaws [49]. This leads to the need for investment to improve genetics and rearing conditions.

4. Some key SAM applications

The evolution of biometric sensors and big data in precision livestock farming has been phenomenal. Digital sensor technologies (DSTs) are mostly non-destructive and, in animal agriculture, may be used to monitor animals' health and behaviour in real-time rapidly, which enables farmer managers to integrate the acquired data for population-level management decision-making [16] through big data analytics systems. DSTs are mostly applied in SAM to ensure real-time results' precision and accuracy. This section will focus on the applications of digital sensors such as NIR spectroscopy and hyperspectral imaging and machine olfaction or volatiles-sensitive sensor technology (**Figure 3**).

4.1 The applications of NIR spectroscopy in precision animal farming

One of the widely used or applied DSTs is the NIR spectroscopy. NIR is a correlative rapid analytical method that utilises the NIR region (780–2500 nm) of the electromagnetic spectrum to evaluate the nutritive qualities of animal feed and products such as meat, milk and its derivatives and egg [19]. The interaction of the NIR light with the organic bonds present in feed or animal products [50, 51] provides essential quality information about the investigated substance [52]. The NIR

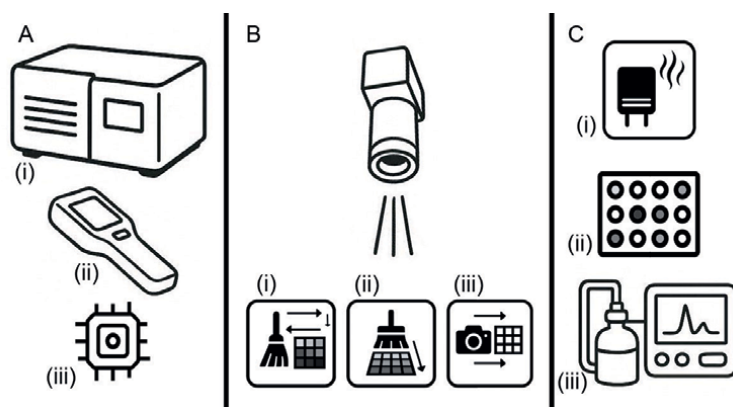


Figure 3.

Examples of sustainable analytical methods: (A) near-infrared spectroscopy: (i) benchtop, (ii) portable or handheld, (iii) NIR-on-chip spectrometers; (B) hyperspectral imaging: (i) whisk broom or point scanning, (ii) push broom or line scanning, (iii) snapshot imaging; (C) machine olfaction: (i) gas sensor array, (ii) biomimetic optoelectronic e-nose, (iii) gas chromatography-based virtual sensor array technology.

technique has evolved from benchtop devices to handheld and now pocket-sized or chip-embedded devices (**Figure 3a**) [53]. The application of the NIR technology in agriculture has been largely credited to Karl Norris [54, 55] for his role in the first analysis of egg quality and protein contents in soybean and wheat. Since then, NIR has been used for instant analysis of the nutritive value of feedstuffs such as corn [56], mixed crop silages [57], and soybean [58], and complete feed or total mixed ration [59], very essential for precision animal feeding. The output or product quality analysis with NIR not only allows for the nutritive evaluation of animal products but also gives valuable insight into product quality that is essential in grading and sorting for various market demands. The integration of NIR in grading systems allows for the sorting of eggs, for example, [60] reported the success of sorting double-yolk eggs from single yolks using NIR spectroscopy. Wold et al. reported the application of NIR to sort chicken breast meat into classes (normal fillets, wooden and spaghetti) based on breast muscle quality [61]. The evaluation of milk quality based on protein and fat levels [62] and bacterial spores' presentation in the milk of dairy cows suffering from mastitis [63] have been extensively studied using NIR spectroscopy.

4.2 Hyperspectral imaging (HSI) and precision animal agriculture

The HSI technique combines spectroscopy with high-resolution imaging, which allows the collection of detailed information about the composition and characteristics of materials across the electromagnetic spectrum to acquire the spectrum for each pixel in the form of an image, which is mostly difficult with conventional imaging technology [64]. The technology has evolved with different miniature and low-cost hyperspectral sensors, such as Headwall Micro-Hyperspec, Cubert UHD 185-Firefly, and sophisticated hyperspectral sensors, such as PRISMA, DESIS, EnMAP, and HypsIRI [65]. Spatial and spectral resolutions may differ, while differences in the imaging technologies (e.g., snapshot, push broom scanning, and whisk broom scanning) may also lead to differences in the recorded data (**Figure 3b**) [66].

In precision animal agriculture, HSI technology has been used to assess pasture seed quality [67], to map nutrient concentration and deficiency in pasture fields [68,

69] to evaluate pasture quality and degradation status [70, 71] and to predict the nutritive and digestibility components of grass pasture [72]. In the area of animal product quality analysis and assurance, HSI has been used to analyse meat quality parameters [73], for example, for in-line sorting of red meat based on colour [74] for the classification of meat from different animals [75], monitoring of meat water holding capacity (WHC) [76], and identifying microbial-infected meat [38].

Though HSI has enormous potential in precision animal farming, the complexity of the technology is derailing its adoption even at the top industrial level. More effort is needed to simplify its application to the basic level of the agriculture value chain.

4.3 Machine olfaction: A promising tool for the rapid evaluation of animal feed and products

Another digital sensor technology with enormous potential in precision animal farming is machine olfaction, also known as volatiles-sensitive sensor array technology and popularly referred to as the electronic nose (e-nose) system. E-nose systems are mostly made of metal oxide semiconductor sensors (MOS), metal oxide semiconductor field-effect transistors (MOSFET), conducting polymer composites and quartz microbalance (QMB), biomimetic optoelectronics with colorimetric sensor array, and gas separation technologies combined with flame ionisation detectors (FID) (**Figure 3c**) [21]. The interaction between volatiles from feed and animal products with the sensors provides signals or smell fingerprints that are informative enough for quality evaluation based on the aroma pattern. The smell or odour of feed influences the feed intake of an animal [77]. Therefore, in recent years, attempts have been made by silage scientists to screen silages based on the smell pattern generated because of fermentation [78, 79]. The discrimination of bovine milk as affected by feeding using e-nose has also been well documented [80–82]. The technology has also been used to study the shelf life of milk [83, 84]. Meat quality analysis as influenced by feeding has also been comprehensively studied [65, 85, 86]. The technology is still developing, and hopefully, the invention of portable e-noses by industrial experts will help in the advancement of the technology in precision animal farming [87]. **Table 1** shows a summary of some of the most applied GAT and SAM technologies in the advancement of precision animal agriculture.

Technology	Type	Application	Author
GAT	UAV	For animal population count, tracking herd movement and isolated animals on grazing fields	[26, 27]
	UAV	For monitoring animal-preferred grazing plants on pasture fields with multiple crops	[28]
	UAV	In the application of fertiliser (foliar system) and pesticides to pasture crops at the required dosages and times	[29]
	UAV	For monitoring natural mating behaviour amongst farm animals and conserved game animals	[30]
	UAV	To identify sick, injured and springing heifers or pregnant cows that need to be assisted	[31]
	Smart feeding	Robotic system applied in precision calf feeding	[33]

Technology	Type	Application	Author
GAT	Smart feeding	A recent robotic system to measure animal feed intake	[37]
	Smart feeding	Recent technologies have added water delivery components	[38]
	Smart milking	Automated milking systems for maximum yield and to reduce bacterial contamination of milk	[43, 44]
	NIRS	Instant analysis of the nutritive value of feedstuffs (corn, soybean, and silages)	[56–58]
	NIRS	Integration of NIR in grading systems allows for the sorting of eggs	[60]
SAM	NIRS	The application of NIR to sort chicken breast meat into classes (normal fillets, wooden, and spaghetti)	[61]
	NIRS	Evaluation of milk quality based on protein and fat levels	[62]
	NIRS	Detecting bacterial spores' presentation in the milk of dairy cows suffering from mastitis	[63]
	HSI	In assessing pasture seed quality	[67]
SAM	HSI	In the mapping of the nutrient concentration and the deficiency in the pasture fields, the pasture quality and the degradation status	[68–70]
	HSI	To analyse meat quality parameters, such as in-line sorting of red meat based on colour,	[74, 75]
		classification of meat from different animals, monitoring of meat water holding capacity, and identifying the microbial-infected meat	[38, 76]
	e-nose	Screening silages based on the smell pattern generated because of fermentation	[78, 88]
	e-nose	Discrimination of bovine milk quality as affected by feeding	[80–82]
SAM	e-nose	To study meat quality (odour specific) analysis as influenced by feeding	[65, 85, 86]

GAT: green agricultural technologies; **SAM:** sustainable analytical methods; **UAV:** unmanned aerial vehicle; **NIRS:** near-infrared spectroscopy; **HSI:** hyperspectral imaging.

Table 1.

Summary of some of the most applied GAT and SAM technologies in the advancement of precision animal agriculture.

5. Conclusion and prospects of GAT and SAM

Based on the literature cited in this chapter, the following key conclusions can be drawn:

- The application of GAT and SAM has improved the efficiency of animal farms, enhanced safer food through quality assurance, improved animal welfare and physiological conditions, and increased the profitability of farmers and the protection of the agricultural ecosystem.
- Current GAT and SAM technologies are expensive for low-income farmers, making it very difficult to adopt in low-income countries.

- Though efficient and effective technologies come with high costs, experts must focus on producing relatively cheaper technologies with the same level of efficiency for low-income countries to enable the continuous supply of food to their populations, preventing starvation and preserving ecosystems.
- Stakeholders involved in the promotion of GAT and SAM must influence policy-makers to adopt these technologies within the framework of sustainable animal agriculture.
- The practical application of GAT and SAM in animal production can sometimes be very complex, especially in remote areas where the technology may need network connectivity to work efficiently. Though some of the portable technologies are currently efficient in offline mode, some require network connectivity (online) for efficient operation.
- Manufacturers and users of GAT and SAM must consistently review the performance of these technologies for effective design and development of future generations of the devices.
- An example is hyperspectral imaging (HIS) technology: more needs to be done to improve the easy applicability of HIS in the animal product quality testing field.

Conflict of interest

The authors declare no conflict of interest.

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Sustainable Poultry Production: Impact of Alternative Feed Ingredients, Litter Types, and Phytogenics on the Performance of Broiler Chicken

Emmanuel K. Asaniyan

Abstract

Due to the diversity of production systems, production environment, competition for conventional resources, and the challenges of current livestock production system, there has been increasing need to find alternative. Therefore, this chapter discusses the multifaceted approaches of enhancing the sustainability of broiler chicken production. It examines how alternative feed ingredients, such as plant-based proteins and by-products, can improve feed efficiency and animal performance while reducing environmental impact. The role of different litter types, including eco-friendly options, is explored for their effects on bird welfare, biosecurity, and overall poultry farm sustainability. Phytogenic feed additives such as herbs like dried roselle calyx, and seeds like pawpaw seeds, mustard seeds, and black cumin seeds promote health and growth. Phytogenic supports enhanced gut health, boosting immunity and optimizing nutrient absorption. By integrating these innovative practices, the article illustrates how the poultry industry can achieve better health outcomes for broilers while minimizing ecological footprints. In conclusion, this chapter shows that the use of alternatives like cockroach and bambara nut, sand, and herbs and seeds like pawpaw seeds, mustard seeds, and black cumin seeds can serve as alternative source of protein, alternative litter, and alternative to antibiotics.

Keywords: alternative feed ingredients, broiler welfare, biosecurity, gut health, nutrient absorption, environmental safety

1. Introduction

The broiler chicken production is at the forefront in the fastest-growing poultry industry sector of animal agriculture. Global broiler meat production reached approximately 103.5 million metric tons in 2023 and was projected to rise to around 104.2 million metric tons by 2024 [1]. Hence, as the global demand for poultry meat continues to rise, there is increasing pressure to make production practices more

sustainable. Sustainable poultry production encompasses a variety of practices aimed at minimizing environmental impact, improving animal welfare, and enhancing economic profitability. This necessitates a focus on alternative feed ingredients, innovative litter management strategies, and the use of natural supplements like phytochemicals to improve broiler chicken performance.

The corn that serves as the major source of energy, soybeans and fish meal that serve, respectively, as sources of plant and animal proteins in poultry diets are being competed with poultry by the increased human consumption of the ingredients. Also, the existing crisis between herders and crop farmers in Nigeria and other parts of West African Countries coupled with ongoing Russia-Ukraine war affected local availability and importation of these ingredients to meet poultry industry demand. Hence, the need for the alternative feed ingredients. Alternative feed ingredients, such as insects, algae, and agricultural by-products, offer promising solutions by reducing dependency on conventional feed ingredients and promoting circular economy principles. Incorporating such ingredients into poultry diets could also enhance the sustainability of the industry by decreasing feed costs and lowering the carbon footprint associated with feed production.

The proper handling or management of poultry wastes, droppings or feces, enhances sustainable poultry production and environmental integrity. Traditional bedding materials, such as wood shavings and straw, may not always be the most sustainable options. Therefore, the development of alternative litter types that are effective in waste management, health, and improved well-being of broiler chickens is a key area of interest in sustainable poultry production. Another promising avenue in sustainable poultry production is the incorporation of phytochemicals into broiler diets. The combined impact of alternative feed ingredients, innovative litter types, and phytochemicals can significantly improve the overall performance of broiler chickens. The objective of this chapter is to evaluate resources that can be used as alternative feed ingredients, litter materials, and phytochemicals in Broiler chicken.

2. Sustainable poultry production practices

Sustainable poultry production practices are various poultry production activities that aim at meeting the current food demand for poultry products while ensuring that future generations can also enjoy the poultry products. Sustainability in poultry farming embodies a holistic approach that encompasses environmental stewardship, economic viability, and social responsibility [2]. However, Valentin and Spangenberg [3] introduced a fourth essential dimension of sustainability: “Institutional sustainability.” This aspect focuses on the management and governance of global systems, highlighting the importance of transparent, accountability, and inclusive institutions that actively engage with their stakeholders [4]. Sustainable poultry farming embraces the interconnectedness of these dimensions, emphasizing that progress in one area should not compromise the others [5]. Therefore, the concept of sustainable poultry farming is the determinant of adoptable sustainable poultry production practices; alternative feed ingredients, litter types, and phytochemicals.

2.1 Alternative feed ingredients

These are nontraditional ingredients used in the manufacture of poultry feeds. They either replace or supplement conventional ingredients. Prominent conventional

feed ingredients of concern for alternatives due to their prevailing high cost are maize, soybeans, and fish meal. However, the alternative feed ingredients in the poultry industry had been categorized into insect-based, single-cell, algae and seaweeds and by-products and food wastes [5]. *Insect-based ingredient*: Scientific evidence suggests that edible insects provide a complete source of animal protein, containing all essential amino acids. As a result, they can be incorporated into poultry diets [6]. Researchers have identified and confirmed 13 insect species suitable for poultry feed. Among these, eight insects (black soldier fly, housefly, beetle, mealworms, silkworms, desert locust, crickets, and grasshoppers) have been approved for use as both food and feed by European Union (EU) regulations [6]. Insect-based protein offers several advantages over traditional sources like soybean and fish meal [6]. These advantages include significantly lowering greenhouse gas emissions and water footprints, thereby reducing environmental impact [7]. Moreover, insect farming is highly resource-efficient, requiring considerably less water and land than traditional feed production, thereby significantly lowering its environmental impact. Additionally, insects can be sustainably raised on organic waste, supporting the principles of a circular economy [6, 8]. Incorporating insects into poultry diets aligns with their natural feeding habits, promoting advantages such as accelerated growth and improved feed conversion efficiency [6, 8], superior meat quality, and the supply of essential nutrients such as methionine [9]. Most research has predominantly concentrated on the black soldier fly. However, other insects, including houseflies, mealworms, beetles, locusts, silkworms, and cockroaches, have also been explored as viable protein sources for poultry nutrition [5]. Some of these insects are available all year round [10], with the potential of being farmed [11]. Ross 308 male broiler chickens fed a diet containing up to 15% black soldier fly meal for 35 days exhibited heavier carcasses compared to those on a soybean meal-based diet [12]. Additionally, a diet with 5% black soldier fly meal led to a reduction in abdominal fat percentage, while a 10% inclusion resulted in increased carcass weight and a higher breast percentage [13]. Similarly, carcass composition improved in Hubbard S757 broilers when fed a diet containing 7.8% black soldier fly meal combined with 5.2% alfalfa meal [14]. Hwangbo et al. [15] reported that growth performance was enhanced when supplementing broiler feed with 10–15% housefly larvae. Similarly, chickens fed 20 and 30% of housefly maggot meal registered the best body weight compared with control group [16]. Mealworm, once incorporated in the broiler diets up to 10%, has no negative effects on the body weight, feed intake, and feed conversion ratio (FCR) [6]. Feed conversion ratio and dressing percentage were not affected by increasing levels of silkworm meal (25–100% in replacement of Soybean meal) in broilers [17]. Therefore, silkworm meal can be used to substitute fish meal or soya bean meal without adverse effects on broiler performances, carcass traits, and profitability [6]. Replacing up to 50% of fish meal with German cockroach (*Blattella germanica*) meal does not affect meat quality, meat sensory attributes, and consumers' acceptability of chicken [18]. [6] reported that insect meals used in broiler chicken diets have the potential to produce meat with chemical composition and quality traits comparable to those obtained from conventional feed ingredients. It corroborated the report that several studies agreed that insect meal feed did not have any negative effect on poultry products (**Table 1**) [22].

Single-cell proteins (SCPs): These are microbial proteins derived from microorganisms like algae, bacteria, fungi, and yeasts [23]. Single-cell protein production efficiently repurposes waste streams, helping to minimize waste and environmental pollution, while also reducing dependence on arable land and freshwater resources [24]. Several research papers discuss the use of single-cell proteins in sustainable

Component	Black soldier fly larvae (BSFL)	Mealworms (<i>Tenebrio molitor</i>)	Crickets (<i>Acheta domesticus</i>)	Housefly larvae (<i>Musca domestica</i>)
Crude protein (%)	35–50	45–55	55–70	40–55
Ether extract (fat, %)	20–35	30–40	10–25	15–30
Crude fiber (%)	5–15	5–10	8–12	6–10
Ash (%)	5–15	3–5	3–6	5–12
Calcium (%)	5–8	0.1–0.3	0.1–0.3	2–5
Phosphorus (%)	0.6–1.5	0.5–0.8	0.5–1.2	0.7–1.5
Chitin (%)	5–10	6–10	6–9	6–12

Makker et al. [19], van Huis et al. [20], and Oonincx et al. [21].

Table 1.
Chemical composition of insect-based ingredients (dry matter basis).

poultry farming [5]. The 5 and 10% inclusion levels of single-cell protein derived from yeast in broiler chicken diet improved the body weight gain and feed conversion ratio [25]. Inclusion of single-cell protein replacing up to 5% of soybean meal in broiler diets can be beneficial for enhancing growth rate, breast yield, and gut health [26]. The high nucleic acid content of SCPs increases the amount of uric acid in the body. This leads to the formation of stones in the kidneys and other organs. Single-cell proteins obtained from algae, bacteria, and fungi contain a large amount of nucleic acids.

Algae and seaweeds: Algae are a diverse group of photosynthetic organisms that inhabit various aquatic environments, including both freshwater and marine ecosystems [27]. Seaweeds are macroscopic marine algae. Algae and seaweeds are increasingly recognized as sustainable feed supplements for poultry, valued for their abundance, renewability, and eco-friendly properties [28]. The brown seaweed (*Turbinaria murayana*) in broiler diets significantly reduced abdominal fat content by suppressing lipogenesis in the liver [29]. Also, incorporating brown seaweed (*Sargassum wightii*) at a dietary level of 0.13% significantly enhanced growth performance, carcass characteristics, cellular immunity, and total viable count [30]. The extract of *Ascophyllum nodosum*, which is a kind of brown seaweed, promoted and enhanced growth performance and reduced fat deposition in broiler chickens [31]. *Aristolochia indica* leaf meal can be included up to 400 g in the diet of broilers without compromising their performance and health status [32]. However, further research is needed to assess the impact of algae and seaweed on poultry health and performance under different conditions, ensuring their full potential in poultry nutrition is realized [5].

By-products and food waste utilization: By-products comprised of agro-industrial by-products (AIBPs) and animal by-products (inedible parts of slaughtered animals) that are not purposed for human consumption. Similarly, food wastes are remnants from the food production, processing, distribution, and consumption chain. They are often considered unsuitable for use. However, they can serve as alternatives to conventional feedstuffs in animal nutrition, enabling the production of animal products without competing for land or contributing to food-feed competition, thereby promoting environmental, social, and economic sustainability [33]. For instance, by-products from the fruit juice industry are rich in dietary fiber, antioxidants,

vitamins, minerals, and phytochemicals, all of which can support poultry health [33]. Likewise, residues from the oilseed industry, including soybean, canola, sunflower, cottonseed, and flaxseed meals or cakes, offer essential nutrients such as protein, amino acids, fatty acids, and minerals, making them valuable for poultry nutrition [33]. Distillers' grain by-products (dried grains with solubles and wet grains) from corn or wheat ethanol production [34] provide essential nutrients like protein, energy, fiber, and phosphorus. Animal by-products include rumen contents (undigested and partially digested food), blood, bone, feathers, hair, horn, hoofs, skin, hides, fat, offal, and eggshell.

Bambarra groundnut (*Voandzia subterranean* (L.) *thouars*) offal is a by-product of bambarra groundnut seeds processing. It is the sieveate after the flour extraction. Broiler chickens can be fed up to 45% heat-treated bambarra groundnut (*Voandzia subterranean* (L.) *thouars*) offal [35] and 20% inclusion level of enzyme-treated bambarra groundnut offal can be fed to broiler chicken without adverse effect on hematology and for increased carcass weight [36]. Dietary inclusion of 3–6% dried apple pomace in broiler chicken feed did not impact growth performance, gut morphology, or histopathology but led to an increase in ileum and ceca weight, ileum digesta viscosity, and influenced the activity of certain bacterial enzymes in the ileum [37]. Incorporating dried sweet orange (*Citrus sinensis*) peel (DCSP) into broiler diets at levels of 0.5–2% resulted in reduced liver and abdominal fat as well as lower serum triglycerides, without negatively affecting feed conversion ratio (FCR) [38]. Similarly, in another study, the inclusion of 0.8% DCSP powder in the diet lowered certain blood biochemical parameters, such as cholesterol, without compromising growth performance or carcass traits [39]. Including 15% sunflower meal (SFM) in diets formulated based on digestible amino acids enhanced broiler performance without affecting carcass and cut yields, though it led to an increase in digesta viscosity [40]. The incorporation of 8, 16, and 24% dried distillers' grain with solubles (DDGS) in broiler diets led to increased body weight gain without any adverse effects [41]. Inclusion levels of up to 160 g/kg in broiler diets from 22 to 42 days had no impact on performance, carcass and cut yields, meat quality, or litter characteristics [42]. Additionally, incorporating 5% tomato pomace (TP) helped mitigate the negative effects of heat stress in broilers [43]. Moreover, the supplementation of tomato waste juice at up to 120 mL/day in broiler diets was found to support the development of internal organs [44]. Brewery by-products are unpopular in poultry diets due to the high level of the fiber fraction [45]. The nutrient composition of agro-industrial by-products' availability and composition may vary based on region, climate, and season, which can restrict their use in animal diets [46]. Nutrient variability can be reduced by the processing of agro-industrial by-products (AIBPs) to produce a uniform feed with consistent nutrient composition, while nutrient supplementation is necessary [47]. The most commonly used animal by-products in broiler diets include meat and bone meal, blood meal, feather meal, and poultry offal meal. These protein-rich feed ingredients can partially substitute soybean meal [48]. The individual inclusion of 5% meat and bone meal or poultry offal meal into broiler diets did not negatively impact live performance or carcass yield while contributing to a reduction in feed costs [48]. However, equal replacement of fish meal with blood meal in the diet of broiler chicken did not support good performance [49]. Blood meal inclusion of up to 3% in broiler diets can be recommended, as it does not negatively affect production parameters during both the starter and finisher growth stages [50]. Broiler chicken fed a diet where fish meal was entirely replaced with 100% feather meal were raised most economically, without any adverse effects on their performance [51].

Diet	Soya bean meal	Fish meal	Yellow meal worm
Soybean meal	150	0	0
Fish meal	0	50	0
<i>Tenebrio molitor</i> meal	0	0	60
Bran wheat	78	68	69
Corn grain	250	300	300
Barley hay	250	300	300
Triticale whole grain	250	250	250
Chemical composition (g/kg)			
Dry matter	903.6	892	886.2
Organic matter	949.7	943.8	957.8
Crude protein	197.2	200.4	197.2
Ether extract	88.6	104.2	86.8
Nonfibrous carbohydrate	319.8	344.8	252
Neutral detergent fiber	360.1	394.4	326.8
Acid detergent fiber	170.3	164.9	146.4
Acid detergent lignin	29.8	26.9	23.7

Robles-Jimenez et al. [52].

Table 2.

*Yellow mealworm (*Tenebrio molitor*) as a novel protein feed ingredient comparable to soya bean and fish meal.*

Fish meal is widely used as an animal source protein in broiler diet but its high cost necessitated alternatives. Also, the increasing cost of grains especially maize, the major source of energy in broiler chicken feed, now required more attention on seeking alternative for maize. By this, low-cost feed will be realized to particularly propel sustainable broiler chicken production and poultry industry in general (**Table 2**).

2.2 Litter types

Litter is generally a bedding material on which chickens are reared under deep litter system of poultry management. The litter is a good absorbent of moisture that supports good performance of broiler chickens, through enhanced exhibition of welfare behaviors like dustbathing, scratching, and preening. Litter management in terms of litter depth, number of birds per square meter area, frequency of litter replacement, good ventilation, and consciousness of keeping litter dry has contributory roles in the performance of broiler chickens. Environmental conditions and the quality of litter materials are key factors influencing the growth rate and carcass quality of broiler chickens [53]. Various materials, including wood shavings, hazelnut husk, ground corn cobs, paper pieces, rice hulls, volcanic ash, and perlite, are used as litter in broiler production, with thick wood chips being the most preferred option [54]. A study using wood shavings or sand at different depths found that neither the type of litter material nor its depth significantly affected average body weight gain [55]. Likewise, the use of thick sawdust, fine sawdust, or rice hulls as litter materials showed no significant impact on broiler body weight gain [56]. Chickens generally prefer fresh and loose litter to perform active behaviors like dustbathing

and scratching. Different litter materials or litter types might influence how often chickens perform the welfare behaviors. Litter materials differing in type, particle size distribution, and freshness were preferred to varying degrees for different behaviors [57]. Fine-grained litter materials like sand support dustbathing [57, 58]. Broiler chickens show a preference for fresh litter over used material for active behaviors like ground scratching and dustbathing. Regularly replenishing fresh materials in the environment can enhance activity levels and support better health in broiler chickens [57]. Sand can serve as an alternative to straw- and rice husk-based litter for broiler chickens without negatively affecting their performance or welfare [59]. Therefore, sand can be used as litter material in coastal areas and areas of limited vegetation (arid and semi-arid regions). Broiler chickens through ground scratching regularly peck on litter; and by this consumed litter particles. Fibrous litter materials like wood shavings can contribute to muscular development of the gizzard. Physiologically, gizzard functions as grinding (reducing feed particle for ease of digestion) organ in chickens. This can enhance rate of feed conversion efficiency (feed utilization) and muscle development in broiler chicken. Anupoju [60] reported that when chicken droppings mix with litter, chemical and bacterial processes synthesize Riboflavin (Vitamin B2) and Vitamin B12. Additionally, built-up litter contains essential nutrients, such as niacin, phosphorus, potassium, magnesium, sodium, and calcium. Broilers raised on deep litter often peck and consume small amounts of litter material, providing them with these vitamins and minerals. Therefore, broiler chicken on litter is naturally shielded from some nutrient deficiencies through nutrient recycling. The gathered information on litter types indicated that broiler chicken can be reared on any available litter materials with tolerable shortcomings for good performance under good management systems. However, farmers need to put in place proper biosecurity measures that will secure flock immunity and prevent importation of pathogens.

2.3 Phyto-genics

The primary essence of feeding broiler chickens is to achieve wholesome performance. Reaching expected table size or weight at scheduled age is the major concern of the farmer. However, efforts should be geared toward providing broiler chickens with balance diets, rich in necessary nutrients and items that enhance well-being. In addition to the feed ingredients (maize/corn, soya bean meal, groundnut cake meal, fish meal, and others) that constitute the major components of broiler feed, feed supplements and feed additives are essential in balance diets for broiler chickens. Feed supplements provide the essential nutrients that may be lacking or deficient in the feed ingredients. The feed supplements are usually in the form of vitamin and mineral premixes and essential amino acids (lysine and methionine). On the other hand, feed additives are non-nutritional substances added to broiler chicken feed to improve feed quality, ensure broiler health, and enhance good performance. Feed additives do not directly supply essential nutrients; however, they play a vital role in overcoming specific challenges, including disease prevention, digestion enhancement, and growth rate optimization. Feed additives include antibiotics/synthetic compounds, antioxidants (tocopherols), binders, enzymes, probiotics, prebiotics, and organic acids. The use of feed additives, especially synthetic antibiotics, is under strict regulation and even banned in some part of the world due to antibiotics resistance and residual constituents in meat product with potential of compromising human health. Consequently, focus and attention are shifted to phyto-genics. Phyto-genics are natural or nonantibiotic growth promoters used as feed additives, derived from herbs, spices,

or other plant sources [61]. Similarly, phytogenic feed additives, also known as phyto-biotics or phytochemicals, are plant-derived natural compounds, herbal formulations, plant extracts, or bioactive substances that enhance feed properties, support animal growth performance, and improve the quality of animal products [62]. Phytogenics, as a valuable component of comprehensive disease prevention strategies, align with the One Health Initiative, which promotes the well-being of humans, animals, and the environment [63]. A broad range of plant-derived products may fall under the category of phytogenic feed additives [64]. Phytogenic feed additives positively impact animal performance by enhancing body weight, feed conversion ratio, and meat quality. Further research has revealed their antimicrobial, antiviral, antifungal, antioxidant, and anti-inflammatory properties, which contribute to these benefits [65]. Herbs used in animal production are generally nontoxic, cost-effective, and environmentally friendly, highlighting their broad application potential. Currently, feed manufacturers incorporate phytogenic additives into broiler, pig, and ruminant feed products [65]. The supplementation of phytogenic feed additives in broiler diets positively influences growth performance, biochemical parameters, and economic efficiency by maximizing returns and gross margin. Additionally, it enhances the gene expression profile of antioxidant enzymes [66]. Hematological and serum biochemistry analyses indicate that the aqueous extract of dried roselle calyx supports the health and well-being of broiler chickens [67]. Dietary inclusion of lemon peel and orange peel had positive influence on gut morphology, red blood cell production,

Parameters	Function in poultry
Enhancing growth performance	• Improve body weight gain. • Optimize feed conversion ratio (FCR). • Enhance overall growth performance when used as an alternative to antibiotic growth promoters (e.g., black cumin, mustard, and pawpaw seeds).
Promoting health and well-being	• Support gut health and morphology (e.g., positive effects on ileum and cecum microflora). • Use lemon and orange peel to improve gut morphology. • Boost red blood cell production and plasma protein reserves. • Improve hematological and serum biochemical parameters (e.g., aqueous extract of dried roselle calyx).
Disease prevention and immune support	• Exhibit antimicrobial, antiviral, antifungal, antioxidant, and anti-inflammatory properties. • Align with disease prevention strategies under the One Health Initiative.
Improving meat quality	• Enhance meat physicochemical properties. • Enhance meat quality and reduce cholesterol levels. • Improve consumer acceptability (e.g., black cumin and mustard seeds influence meat taste preferences).
Economic and environmental benefits	• Maximize economic efficiency by improving returns and gross margins. • Make them economical, eco-friendly, and derived from natural sources. • Promote sustainable farming practices by reducing reliance on synthetic antibiotics.

Wang et al. [65], Shahin et al. [66].

Table 3.
Impact of phytogenic feed additives on production parameters of poultry.

plasma protein reserves, and lipid profile of broiler chickens [68]. Phytogenic feed supplementation with 15 g/kg of pawpaw seed meal, mustard seed meal, and black cumin seed meal enhances the body weight gain and supports the normal ileum and cecum microflora of broiler chicken [69]. However, Pawpaw (*Carica papaya*), Mustard (*Brassica juncea*), and Black cumin seeds as feed additives in the diets of broiler chicken enhanced performance, with the meat under the black cumin and mustard seeds being the most and least acceptable, respectively [70]. Phytogenic feed additive in broiler chickens' diet as alternative to antibiotics growth promoters can enhance broiler chicken production and meat physicochemical properties when used in appropriate doses and proportions [71]. Consequently, phytogenic feed additive is readily available to promote sustainable safety in the consumption of broiler chicken meat and associated products. However, processing and extraction techniques need to be standardized to ensure the potency of the realized phytochemicals (**Table 3**).

3. Conclusion

Based on the literature cited in this chapter, the following key conclusions can be drawn:

- Alternative feed ingredients:
 - i. Insect-based proteins (e.g., black soldier fly, housefly, mealworms) are viable replacements for conventional feed ingredients like soybean and fish meal, offering high nutritional value, improved feed conversion ratios, and environmental benefits.
 - ii. Single-cell proteins derived from microorganisms can supplement poultry diets, improving growth performance and reducing dependency on traditional protein sources.
 - iii. Algae and seaweeds contribute to poultry nutrition by enhancing growth, meat quality, and immunity while offering an eco-friendly alternative to conventional feed.
 - iv. By-products and food waste (e.g., fruit peels, oilseed meals, distillers' grains, and animal by-products) can be efficiently utilized in poultry diets, reducing food-feed competition and feed costs without negatively affecting growth or meat quality.
- Litter types:
 - i. Various materials, including wood shavings, sand, and rice hulls, can serve as effective litter in poultry farming.
 - ii. Proper litter management enhances bird welfare, promotes natural behaviors, and contributes to nutrient recycling.
 - iii. Some litter materials, such as sand, aid gizzard development, improving feed utilization and digestion.

- Phytochemicals as feed additives:
 - i. Phytochemical feed additives, derived from plants, improve poultry performance, gut health, and immune function while reducing reliance on antibiotics.
 - ii. They possess antimicrobial, antioxidant, and anti-inflammatory properties, supporting sustainable poultry production.
 - iii. Standardization of processing and extraction methods is necessary to optimize their efficacy.

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Conflict of interest

The authors declare no conflict of interest.

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Practical Implementation of Precision Livestock Farming Concept in Cattle, Pig and Poultry Breeding

Stephen Foluso Ayanleye

Abstract

Due to inefficiencies in animal husbandry and the stress in manual handling of animals in the farm, this paper evaluated practical implementation of precision livestock farming concept in cattle, pig, and poultry breeding. All the references used in this study were selected from local and international articles that majored in precision livestock farming, and a total of 28 references were used for this study. This report outlines precision livestock farming in the global setting. Based on the findings from this study, the precision livestock technologies being used in cattle farming were ruminant collars and reticulum rumen boluses and that in pig farming were real-time sound analysis, and poultry farming had automatic body weight estimation. The benefits of precision livestock farming were efficient use of resources, reduction of harmful emissions per unit of product, and reduction of drug use through early detection of pathology. In addition, the findings from this study showed that majority of the farmers were skeptical toward adopting precision livestock farming due to the absence of information transfer, support systems, and a reliable service provider for farmers. The opportunities available for farmers toward adoption of precision livestock farming were efficient use of resources in the farmland, increase in the production capacity, and reduction in the mortality rate of animals, hence leading to increased profitability and yield of farmers, ease of sorting animals for treatment or medications, and improved feeding and water intake of animals in the farm.

Keywords: precision livestock farming, cattle farming, pig farming, poultry farming, technology

1. Introduction

The application of information and communication technologies for enhanced control of fine-scale animal and physical resource variability to optimize economic, social, and environmental dairy farm performance is the definition of precision livestock farming [1]. Regarding the most recent EU-funded initiative for precision livestock farming, the EU-PLF project, there is another definition that is somewhat comparable.

“Intelligent management and care of (individual) animals in livestock farming by continuous automated monitoring/controlling of the production/reproduction, health and welfare of (individual) animals, thereby allowing quick corrections when deviations from normal are monitored,” is how precision livestock farming (PLF) is defined, according to recent EU-PLF research (Available from: <http://www.eu-plf.eu/>).

With the use of precision livestock farming, a farmer can secure better animal health, welfare, yields, and environmental impact while also gaining the ability to manage their livestock automatically and add value. Precision livestock farming is a method that uses sensor-based monitoring systems to integrate health, genetics, feed, social behavior, and resource availability with the goal of meeting the needs of each individual animal in larger herds [2].

However, it should be noted that precision animal nutrition (PAN) is an integral part of precision livestock farming (PLF). In other words, PLF cannot be imagined without precision animal nutrition. One of the most important reasons for this is that, for example, in Europe and the USA, feeding costs account for 65–75% of the total production costs. It is also important to emphasize that the concept of PAN does not only mean applying high-tech in animal husbandry but also mean feeding farm animals with the most biologically effective and safe diets. To the end, we use the latest scientific findings of related sciences (biology, biochemistry, molecular biology, microbiology, physiology, informatics, etc.). The purpose of this chapter is to evaluate the practical implementation of precision livestock farming concept in cattle, pig, and poultry breeding.

2. Available precision livestock farming technologies

The PLF technologies are available in dairy farming, piggery farming, and poultry farming. This will be discussed extensively below;

2.1 Precision technologies in dairy farming

According to Eastwood *et al.* [1], precision dairy farming is the application of information and communication technology to enhance the management of animal and physical resource variability at the fine scale and to maximize farm performance in terms of the economy, society, and environment. The dairy industry has embraced the following technologies among others.

2.1.1 Biometric-based identification

One of the main animal biometric traits used to identify individual cattle is the muzzle point picture pattern. It is like the fingerprint of a human. In ruminants, every individual animal has a different vascular pattern. A retinal image is captured once the eye is scanned [3].

2.1.2 Automatic milking system

The fact that cows can choose to visit the milking robot is one of the features of autonomous milking. According to Hogeveen *et al.* [4], this causes a significant variance in the frequency of visits to the milking robot, which in turn causes a significant difference in the length of milking intervals. The milking stall itself, the teat cleaning and detection systems, the robotic arm device for connecting the teat cups, the control system with

sensors and software, and the milking machine are the key parts of an automatic milking system. More frequent milking yields a higher milk yield when automatic milking is used [5]. Pedometers, automatic temperature recorders, milk conductivity indicators, automatic estrus detection monitors, daily body weight measurements, daily milk yield recording, monitoring of milk components (fat, protein, and SCC), and many other precision dairy farming technologies are employed [6]. A sophisticated milk analysis instrument called Herd Navigator (DeLaval, Sweden) was created in 2008 to measure progesterone for heat detection, lactate dehydrogenase (LDH) for mastitis detection, and betahydroxybutyrate (BHB) for ketosis detection. The parameters are measured when the animals arrive at the milking parlor. This technology automatically gathers representative milk samples of individual cows from particular milking sites during milking and automatically picks using a particular algorithm known as the “biomodel” [7].

2.1.3 Activity monitoring

The identification of behavioral estrus remains a crucial component of the overall reproductive management program, even with the increasing use of hormonal synchronization techniques that enable timed artificial insemination (TAI) [8]. New electronic devices that integrate activity monitoring as a way to link increased physical activity with estrous behavior in cattle have been developed in response to the effects of AI service rate on reproductive performance and the challenges associated with visual estrus identification on farms. During estrus, there was a noticeable increase in restlessness and general physical activity [9]. Subsequent research has verified that estrus may be detected with the use of the measurement of the rise in steps, particularly when it is linked to a particular algorithm [10]. An example of monitoring system in dairy cattle can be seen in **Figure 1**.

Examples of PLT tools used for activity monitoring of farm animals in dairy cattle are:

- *Rumination collars*: When rumination collars are used, ruminating is identified by identifying the sounds made while chewing and omitting those associated with



Figure 1.
Delaval software for monitoring dairy cow. Source: Matthews et al. [11].

eating. The ruminating time parameter might be useful in two contexts: health and welfare sensors for cows and nutrition management. The scientific literature has recognized that dairy cows ruminate for approximately 35–40% of the day on average [12]. An example of rumination collar is shown in **Figure 2**.

- *Reticulo-rumen boluses*: These boluses evaluate rumen function using certain sensors (temperature, pH, pressure, etc.) that may be connected to feeding and drinking habits and rumen pH for the identification of SARA (Sub Acute Ruminal Acidosis). The development of automated weighing, body condition score (BCS) using picture capture, and rumen wireless telemetry to detect sub-acute ruminal acidosis have all improved metabolic disease monitoring [14].

2.2 Precision technologies in pig farming

Precision technologies in pig farming include image analysis for automatic body weight estimate, sound analysis for welfare assessment, behavior monitoring, waste monitoring on the farm, and abattoir registration systems.

2.2.1 Real-time sound analysis

In intensive pig farms, respiratory diseases are common, with high incidence and prevalence rates, with coughing being the main clinical symptom. Pig vocalization has been demonstrated to be directly correlated with pain, and attempts have been made to categorize these noises [15]. Veterinarians also frequently evaluate cough



Figure 2.
Rumination collar for a dairy cow. Source: EU-PLF [13].

noises in pig houses in order to make diagnostics. In this context, efforts have been undertaken to determine the features of animal coughing [16]. Cough noises can only be evaluated on a farm visit, and using an automated cough monitoring system for animals can help improve farm management by providing the right care [17]. A typical example of precision livestock technology tool is shown in **Figure 3**, as this equipment monitors the animals and detects when it needs attention.

2.2.2 Monitoring of drinking behavior

It is possible to use drinking behavior as a predictor of productivity or health issues if there is a pattern of drinking and the behavior is specific. Monitoring the water consumption of developing pigs in real time appears to be a potential means of enhancing management [18].

2.2.3 Body weight estimation by image analysis

Every pen was under surveillance by a top-view camera. Using shape recognition techniques, individual pigs were automatically recognized by their distinctive painting patterns. The following is how the weight estimation procedure evolved: First, an elliptical fitting method was used to locate the pigs in the image. Second, the pig's area inside the ellipse was computed. Lastly, dynamic modeling was used to estimate the weight of the pigs. After that, the constructed model was verified by contrasting the estimated weight with twice-weekly manual measurements of each individual pig's actual weight [19].

2.3 Precision technologies in poultry farming

Farmers that own grill houses are forced to grow more birds in order to turn a profit from this enterprise. It gets quite difficult to view such a large number of birds on grill farms with lakhs of birds. The farmer can automatically keep an eye on every bird with the aid of these precision technologies. This is illustrated in **Figure 4** using eYeNamic System.



Figure 3.
Monitoring device for pig. Source: EU-PLF [13].



Figure 4.
Precision technology in poultry (eYeNamic System). Source: EU-PLF [13].

2.3.1 The system for real-time monitoring of the eggshell temperature and weight loss of eggs

The embryo, which is changing from an endothermic to an exothermic living entity, depends on the regulation of its microenvironment, which includes temperature, humidity, and gas concentration. Real-time monitoring techniques have been developed to measure the temperature of the eggshell and the weight loss of the eggs throughout the incubation period, allowing the climate control to be adjusted continually. A more effective method of controlling the incubation process is based on this knowledge. Reducing the hatch window and improving hatching outcomes are the objectives [20].

2.3.2 Continuous automated monitoring of feed intake of broilers by sound technology

It has been demonstrated that selecting pecking behaviors where the birds actually take food to consume may be done with a microphone placed within the grill feeder pan by keeping an eye on how much food the bird is losing after consuming it. Less than 1% is the measuring technology's inaccuracy [21].

2.3.3 Automatic body weight estimation

Grill weights are measured using a model-based weighing technique. A fixed, population-based statistical connection is typically utilized to relate the weight of the birds to the voltage or pressure that the weighing scale measures. Another issue is that the heavier birds are jumping lower on the moving scale as the fattening stage comes to a close. To address this issue, software is available [22].

The most important precision livestock technical equipment of all the mentioned equipment above for cattle, pig, and poultry breeding are automatic milking system, rumination collars, reticulum boluses, and real-time sound technology. These available technologies are the most important due to their necessity toward ensuring precision feeding among farm animals.

3. Associated benefits of precision livestock farming

Reducing the emission intensity is facilitated by more efficient use of resources. Thus, it has been shown that precision livestock farming, especially with regard to dairy cattle, increases farm productivity. PLF has been, however, tried little with development for beef cattle. These days, the management of grazing is the main application of technology. Satellite remote sensing is a potentially useful technology for managing grasslands effectively in terms of animal production and ecosystem conservation, as evaluated by Ali *et al.* [23]. Current focus in animal management is on telemetry technologies, specifically GPS use. This makes it possible to automatically record activity, especially foraging, which, when paired with the features of the pasture, may make it possible to determine animal consumption more precisely and give decision-makers tools [24, 25]. Lastly, grazing animal emissions have also been estimated using GPS position and inverse modeling [26]. Precision feeding appears to have a direct bearing on reducing emissions. It is anticipated, therefore, that in the near future, clever ventilation systems and ideal barn climate will also be able to reduce emissions.

Other benefits of precision livestock farming are:

- i. More efficient use of resources
- ii. Reduction of harmful emissions per unit of product
- iii. Reduction of drug use through early detection of pathology
- iv. Complete traceability of livestock through food chain.
- v. Reduction of workload through automation
- vi. Management of animal welfare
- vii. Automatic control of product quality.

4. Status of farmers toward adoption of PLF

The tools offered by precision farming and other information technology have not yet been incorporated into mainstream livestock management, despite the fact that the majority of farmers recognize the advantages of employing a more focused strategy to manage their livestock output with greater information. The systems' increased complexity prevents simple adoption and introduces uncertainty into the financial benefit calculations. Numerous specialists in pasture farming have stated that the primary obstacle to the quick commercialization and adoption of PLF systems in the cattle production chain is the absence of information transfer, support systems, and a reliable service provider for farmers. Experts emphasize the necessity of having a service sector capable of sensitizing the farmers towards adopting PLF [27].

Appropriate business structures that spare farmers from large initial investment costs would be necessary in this service sector. The second significant barrier restricting the rate of adoption of PLF technology is the lack of coordination among academics, developers, the market, and farmers. Although it would be extremely difficult,

improving coordination between PLF tool vendors and developers would lead to the development of better integrated systems. As a result, PLF systems would become more commercialized as integrated systems to better serve farmers [27].

A producer has a big financial commitment when deciding which precision dairy equipment to buy and use, and it can be difficult to select one that will meet their demands for a number of years. Among other things, a recent study sought to find out what parameters are currently tracked on farms, what factors farmers take into account when choosing precision dairy farming technologies, and which parameters producers thought would be most helpful [28]. Due to several technologies being capable of monitoring multiple factors, producers were able to choose from a variety of options. Furthermore, producers may be able to utilize many technologies. According to producer replies, the most often measured parameters using already-adopted technologies were mastitis (25.7%), cow activity (41.3%), daily milk yield (52.3%), and not applicable (31.2%). Rumen pH (0.9%), respiration rate (1.8%), methane emissions (1.8%), bodily condition score (2.8%), and heart rate (3.7%) were the least used technology [28].

An attempt was made to quantify the factors that farmers deemed more significant when purchasing PLF technology in the same study [28]. The farmers ranked the benefit-to-cost ratio as the most crucial factor, followed by the overall cost of the investment, simplicity and convenience of use, performance that has been independently verified through research, and the availability of local assistance.

Hence, the status of farmers toward PLF is uncertain, as some of the farmers feel there is no need to replace human handling of animals with technology, and they do not have the conviction that PLF could increase the production capacity. Another factor that made the status of farmers toward precision agriculture to be uncertain is the cost in implementing this technology.

According to the study conducted by Wang *et al.* [29] on challenges faced by U.S farmers to adopting precision agriculture farming, many of the farmers were concerned with the cost of maintenance.

Producers agreed that cost concerns, including initial investment costs; annual subscription costs for software and maintenance; and operating costs, were the top issue in regard to PA technology adoption. Many of the farmers opined that precision agriculture or precision livestock farming equipment and services were too high, which made cost the most significant challenge for farmers in adopting precision livestock farming. The study of Wang *et al.* [29] also shows that farmers experienced with PA technologies stated that brand compatibility and data privacy were challenges in adopting PLF.

5. Opportunities for farmers toward adoption of precision livestock farming

The opportunities for farmers toward adopting PLF include: decreased fuel use, lower greenhouse gas emissions, and better water quality in the nearby streams as a result of pesticide and fertilizer use that is more efficient.

Other opportunities available for farmers toward adoption are:

- Efficient use of resources in the farmland
- Increase in the production capacity

- Reduction in the mortality rate of animals, hence increasing profitability and yield of farmers.
- Ease of sorting animals for treatment or medications
- Improved feeding and water intake of animals in the farm

6. Conclusion

Based on the literature cited in this chapter, the following key conclusions can be drawn:

1. Precision livestock farming has its origin from Europe, but many countries are now interested in precision livestock farming due to its advantages in the food/agricultural industry.
2. Precision livestock farming has its challenges to farmers, which has hindered many farmers to be skeptical in its adoption.
3. The benefits of precision livestock farming outweigh its challenges, and The stakeholders in the agricultural sector and other sectors in every country across the world should support researchers in funding/conferences/workshops in enhancing the adoption of precision agriculture by farmers in every part of the world.

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Cattle Instance Segmentation by Transfer Learning Approach Using Deep Learning Models for Sustainable Livestock Farming

Rotimi-Williams Bello, Pius A. Owolawi, Etienne A. van Wyk and Chunling Tu

Abstract

Image segmentation of animal instances is among the applications of artificial intelligence that recently emerged for sustainable livestock farming. This approach to sustainable livestock farming has become a practical avenue which several precision livestock farming researchers are utilizing to achieve their aims. Artificial intelligence involves several complex tasks including video and image processing. Moreover, the large volume of data required to train deep learning models makes these tasks more complex. However, with the emerging technology of transfer learning, these challenges have been remarkably mitigated. In this study, a system suitable for sustainable livestock farming is proposed using techniques of transfer learning and deep learning models for animal detection and recognition in a farm environment. We evaluated the proposed transfer learning method of the Enhanced Mask R-Convolution Neural Networks (CNN) by comparing it to other two deep learning models, namely Mask R-CNN and Faster R-CNN, on the same dataset using evaluation metric. The Enhanced Mask R-CNN obtained promising results of 0.2 s (computing time) and 97% (mAP), higher than the results obtained by the other two deep learning models. The findings in this study reveal the capacity of transfer learning as an approach for addressing the challenges in segmenting cattle images needed to improve precision livestock farming for sustainable agriculture.

Keywords: artificial intelligence, Enhanced Mask R-CNN, instance segmentation, precision livestock farming, transfer learning approach

1. Introduction

Image segmentation of animal instances is among the applications of artificial intelligence (AI) that recently emerged for sustainable livestock farming. This approach to sustainable livestock farming has become a practical avenue that many

precision livestock farming (PLF) researchers are utilizing to achieve their aims. Artificial intelligence involves several complex tasks including video and image processing. The large volume of data required to train deep learning models makes these tasks more complex. However, with the emerging technology of transfer learning, these challenges have been remarkably mitigated. There are many applications of instance segmentation in livestock farming suitable for sustainable agriculture. Among the applications is a behavioral understanding of animal posture or gesture, which is critical for the health and welfare analysis of the animal for prompt action by the farmer. Other problems that apply instance segmentation for their solutions are estimation of farmer pose [1], detection of plant leaf disease, etc. [2]. Animal activities are recognized for individual instance segmentation by two primary feature representation techniques, namely handcrafted and deep learning.

Feature representation by handcrafted technique has notable challenges associated with it; for example, sentiment, bias, and subjectivity are some of the notable challenges. On many occasions, to handle complex tasks, new data are generalized by models, which allows them to perform on unfamiliar data. This condition for creating and maintaining these representations is difficult and consumes time, thereby adding to the challenges confronting feature representation by handcrafted technique. To address the challenges of feature representation by handcrafted technique, feature representation by deep learning technique was introduced. Deep learning is a method of artificial intelligence that instructs computers how data should be processed, to a certain extent, by mimicking the human brain. The models of deep learning have the capacity to recognize complex images, audio, videos, and several other patterns in data to produce high-precision predictions and insights. Complex patterns in data are recognized and captured by deep learning-based representation by using a feature extraction method that is based on Convolution Neural Networks (CNNs). The application of this model allows the generalization of new data and high-performing transfer learning. On many occasions, there is a problem with interpreting the hierarchies of the intrinsic features, which allow the comprehension of intricate connections [3, 4]. Many segmentations that involve individual animal instances can be carried out on large and heterogeneous datasets by applying any deep learning techniques [5–7]; however, making large datasets and other resources available for the training of deep learning models is a perpetual challenge [8].

While humans depend on information and datasets collected in their small quantity, spanning a specific time frame, to learn uncountable classes of new objects, deep learning models have the capability of transferring what they learn of a specific task to another task by using transfer learning method, which involves either a fine-tuning approach or a feature extraction approach [9–11]. By applying animal instance segmentation, activities among farm animals, such as eating, drinking, standing, lying down, and mating, can be recognized, which are necessary for their welfare and health monitoring to ensure productivity and sustainable livestock farming. The ability to recognize activities among farm animals facilitates understanding of suitable methods to apply in livestock management, especially should there be any disaster. Moreover, recognition of activities among farm animals enables tailored farming practices and decisions that are data-driven for the overall sustenance of PLF.

The detection of farm animal activities has been done using audio sources and multi-modal sources, for example, modalities based on vocal and language [12, 13]. However, little research has been carried out on using video-generated images in recognizing farm animal activities. The aim of this study is to mitigate the abovementioned issues using a transfer learning approach with instance segmentation techniques of deep learning models to recognize farm animal activities. As said earlier, classifiers and feature extraction by

handcrafted methods have been employed in instance segmentation and recognition of farm animal activities with promising results [14]. A lot of time is consumed by employing highly skilled feature detectors and extractors for feature detection and extraction with the right techniques for their representation [15, 16]. The recognition of patterns in data and the extraction of features using automated methods for the recognition of activities among farm animals has popularized several models of deep learning and, thus, making the models gain wide acceptance.

Notable results have been obtained by using models that are based on CNNs for the recognition of behaviors of individual livestock [17]. Camera-captured data and CNNs have been employed for the recognition of behavioral activity and inactivity among farm animals [18]. As efficient as it is, LSTM (Long Short-Term Memory) models based on CNN, when applied for processing temporal sequences [19], do not have the capacity for extracting complex features. Two-dimensional CNNs and three-dimensional CNNs are not comparable. While it is possible for two-dimensional CNNs to produce only results that are remarkable, there is a limitation to the concurrency of spatial and temporal feature collections. On the other hand, in three-dimensional CNNs, extracted spatial features and temporal features are employed for improved identification of contextual patterns and dynamical patterns [20].

Machine vision techniques and deep learning models have been the frontiers as state-of-the-art technologies are applied to livestock farming [21–24]. However, due to the limitation of the cattle dataset, there is a need to develop a robust and reliable technique based on transfer learning, which, under less computational time, could accurately carry out instance segmentation of individual cattle using models of deep learning. This work is a step toward achieving sustainable agriculture through PLF. The contributions of this work are as follows:

1. Innovative application of transfer learning is demonstrated in this study by addressing the challenges in segmenting cattle images needed to improve PLF for sustainable agriculture.
2. Segmentation accuracy and processing time are optimized by training the target model with the existing model's knowledge that is previously trained on the same tasks.
3. Limitations in prior works, which employed static images, are addressed in this work by employing DJI Phantom 4 Rtk drones for the collection of data, thereby adding to the originality.
4. The methods used in (2) and (3) address limitations of data, which could drastically affect the proposed model accuracy.
5. The performance of the proposed model is improved by the transfer learning method by which overfitting is reduced, and pre-trained knowledge is leveraged.

2. Materials and methods

Drones, cattle videos, and cattle images are used for the experiments performed in this study. The experiment is performed and implemented in Jupiter Notebook, hosted by Google Colab with its parameters.

2.1 Collection of images and pre-processing

Suitable datasets are needed for accurate results to be obtained by deep learning models, however, due to limitations in open benchmark datasets, there is ineffectiveness and inefficiency in deep learning models performance when segmenting cattle instances. In addition, some of the publicly available datasets, such as Holstein Friesian Cattle datasets [25], though accessible, are unreliable. The unreliability of the Holstein Friesian Cattle datasets originated from the images, which are the same: blurred, distorted, sparse, etc. We optimize open datasets by applying a data collection method using drones to collect more farm animal images from the primary source, that is, the ranch. The ranch is in Nigeria, which has Keteku and Muturu cattle breeds, and is surrounded by a heterogenous environment. We collected 1200 images and used 1000 images for training the models and 200 images for testing the models. LabelMe [26] was applied to label each image ground-truth. **Figure 1** shows samples of the cattle images. We store the labeled data to conform to the format acceptable by the Enhanced Mask R-CNN framework [27] for image annotation.

Models of deep learning are used by the proposed transfer learning approach for individual cattle's activity detection and segmentation, which underscores proper monitoring of their health and welfare for improved productivity and sustainable



Figure 1.
Images showing a group of cattle at the ranch.

livestock farming. The proposed transfer learning approach for individual cattle’s activities detection and segmentation makes use of DJI Phantom 4 Rtk drones integrated with the Enhanced Mask R-CNN algorithm. A sample of the DJI Phantom 4 Rtk drone is shown in **Figure 2**.

The videos and the static images utilized in this study were captured by the camera, however, video recordings were preferred to static images because video recordings have good qualities that could facilitate the experiment’s accuracy. The acquired cattle images were stored in MOV format (as MPEG 4 video container file), and converted to JPEG format after cropping, as original images. Since it is easy to train deep learning models faster on small images, it is important to trim the input images to the same size. Therefore, trimming image datasets enables compatibility among deep learning models. In this study, at the pre-processing stage, the collected images were trimmed to $512 \times 512 \times 3$ pixels. An object detector is used in training the trimmed images to enable easy extraction of the features by CNNs and subsequently, target cattle detection. There are two reasons for reducing the size of the images: (1) image reduction guides against overfitting during training of networks and (2) image reduction increases the training speed of deep learning models. As shown in **Figure 3**, there are three main components in the proposed cattle instance segmentation model, namely backbone, neck, and head.



Figure 2.
DJI Phantom 4 Rtk drone.

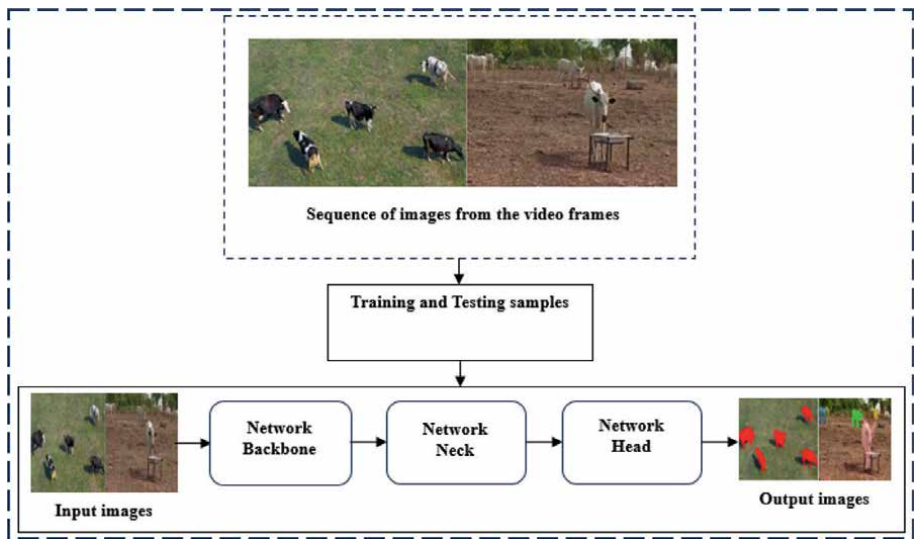


Figure 3.
Workflow of cattle instance segmentation.

A pre-trained network is defined by the backbone, meaning that the backbone oversees the activities of the pre-trained network. One of the pre-trained networks popular for its deep residual and thereby commonly employed as backbone is ResNet. The class of objects, the bounding box, and the mask are all handled by the head, which operates on one-stage object detection models, for example, YOLO (You Only Look Once), etc. or on two-stage object detection models, for example, Mask R-CNN [28], etc. The backbone and the head are connected by a layer called the neck, which operates on the FPN (Feature Pyramid Network) model.

2.2 Transfer learning

Large datasets are needed to obtain accurate results from deep learning model applications on difficult tasks; however, to train models with large datasets requires a lot of time and, thus, the reason for proposing a transfer learning approach in this study. **Figure 4** depicts the general idea behind the transfer learning approach.

Enhanced Mask R-CNN, Mask R-CNN, and Faster R-CNN [30] are compared in this study by employing them for the detection of activities among cattle. We re-applied Mask R-CNN's previously learned and acquired weights and biases. A large and standardized dataset was used for Mask R-CNN's training. The approach involved in re-applying the existing model to a new task is called transfer learning. In transfer learning, the training of fully connected layers (FCL) depends on the problem space,

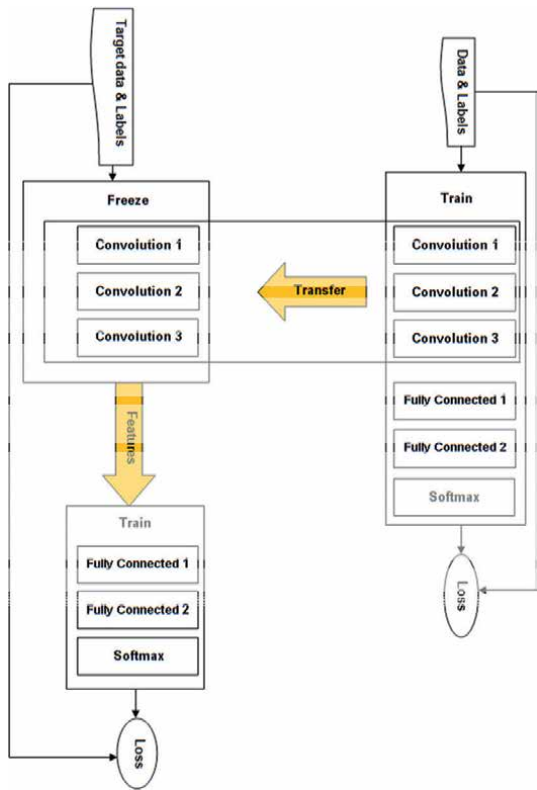


Figure 4. Workflow of transfer learning approach [29].

and this is by restraining some layers at the top of the pre-trained model. The problem space, which determines the training of fully connected layers, greatly depends on the availability of training images and the method of processing. To restrain the layers at the top of the pre-trained model, there is a need to freeze the updates on the weights and biases of layers at the lower part of the pre-trained model, based on the problem space. Using a small quantity of training images restrains the last fully connected layer. The abovementioned approach makes the old model perform feature extraction as an extractor, thereby optimizing the training time and increasing the detection accuracy.

2.3 The employed models of deep learning

The models of deep learning, Faster R-CNN, Mask R-CNN, and Enhanced Mask R-CNN, which are employed; in this study, are presented in this section.

2.3.1 Faster R-CNN model

For object locations to be hypothesized by state-of-the-art models for object detection, there is a need for algorithms that will handle the region proposal. Advancements in networks like SPPnet, and models like Fast R-CNN have optimized the processing time of the networks meant for detection tasks, revealing computation of region proposal as a constriction. A region proposal network (RPN) was introduced in [30] that has complete image convolutional features shared with the object's detection network, thereby allowing region proposals at little or no cost. A RPN is a fully convolutional network (FCN) that is responsible for concurrent prediction of bounds and scores for objects at each location. The training of RPN is end-to-end such that high-quality region proposals can be generated, which Fast R-CNN can later use for detection. Fast R-CNN and RPN were merged as a single network by jointly using the features of their convolutions. The component of RPN directs the integrated network on what to do by employing the attention mechanisms. The system has a 5 fps (frame per second) rate on a GPU with high object detection accuracy on PASCAL VOC and MS COCO datasets. **Figure 5** shows the framework of Faster R-CNN.

2.3.2 Mask R-CNN model

The framework of Mask R-CNN model is developed to facilitate the segmentation of object instances. Objects can be detected simultaneously in an image by the Mask R-CNN approach, and a high-quality mask is generated for each detected and segmented instance. **Figure 6** shows the Mask R-CNN framework, for instance, the segmentation of human beings in an image. Mask R-CNN extended the framework of Faster R-CNN model by adding a branch, known as mask prediction branch, in parallel to Faster R-CNN's branch, which recognizes box. The addition of small overhead to Faster R-CNN with 5 frame per second (fps) processing speed, ensures training speed of Mask R-CNN. In addition, it is easy to generalize Mask R-CNN to other tasks.

2.3.3 Enhanced Mask R-CNN model

The components of Enhanced Mask R-CNN are as follows: (a) A filter size (optimal), which is used for extracting features that are small in size and complex, (b) Region proposals, which are used for utilizing semantic features that are multi-scale,

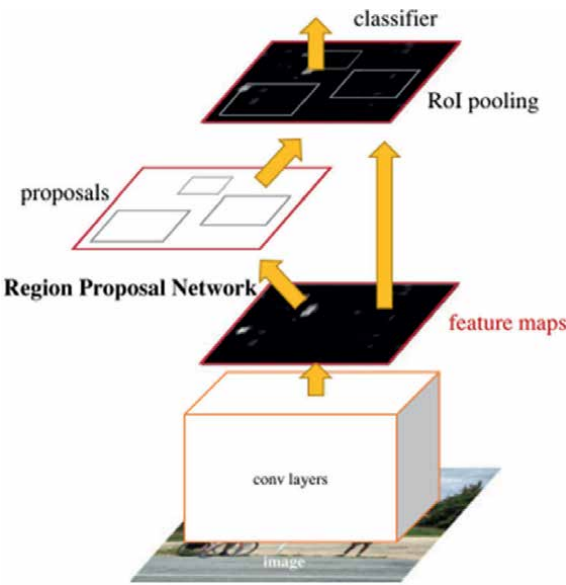


Figure 5.
Framework of Faster R-CNN [30].

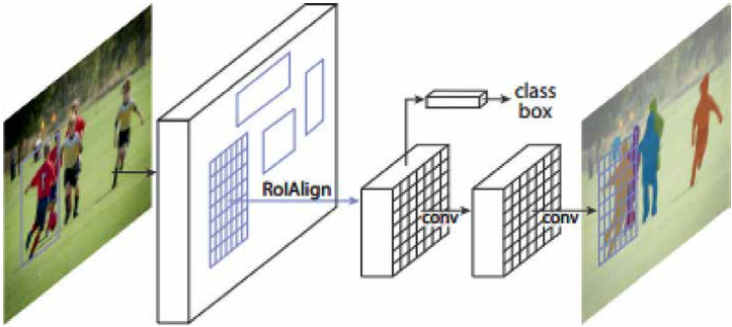


Figure 6.
Instance segmentation by Mask R-CNN [28].

and (c) FCL of Mask R-CNN, which subnetwork is integrated with, for enhanced segmentation of instances. Moreover, there is a structure in it that consists of three distinct branches, and the branches are as follows: (1) backbone branch, (2) ROIalign (ROI alignment) branch, and (3) mask generating branch. The purpose of FCL in the network is to generate mask, bounding box, and class for the target object, after all the feature maps (fixed-in-size) have been transmitted through it. There are many issues with ResNet, which Mask R-CNN uses for its backbone. These issues originate from activation layers skipping when performing backpropagation.

In addition, there is no formula to describe instability of ResNet parameters, thereby affecting the accuracy of gradient formula. Furthermore, there is no proper clarification in the training process about the layer that benefits more from training than another. To address the issues, a method based on an abridged ResNet model was proposed [6]. By applying new gradient formula, new rules consisting of different

parameters for ResNet were obtained. The architecture of the residual network and enhanced residual network is shown in **Figure 7a** and **b**, respectively. A smaller filter size (optimal) than the ResNet is provided by the solution for the extraction of features that are smaller and complex, thereby reducing the training parameters and increasing the computation efficiency.

ResNet improved its performance using a deep network comprising a set of blocks that were able to solve the issues surrounding gradient vanishing. **Figure 8** shows the block of residual networks. The formula for building the two-layer block is denoted by Eq. (1):

$$H(x) = F(x, \{W_i\}) + x \tag{1}$$

where x denotes the building block input; $H(x)$ denotes the building block output vectors, and $F(x, \{W_i\})$ denotes the learned residual mapping in the training process.

According to **Figure 7b**, the steps involved in training the best block convolutional layers are as follows: (1) not repeating more than once for convolution block that occupies the first position, (2) not repeating more than four times for convolution

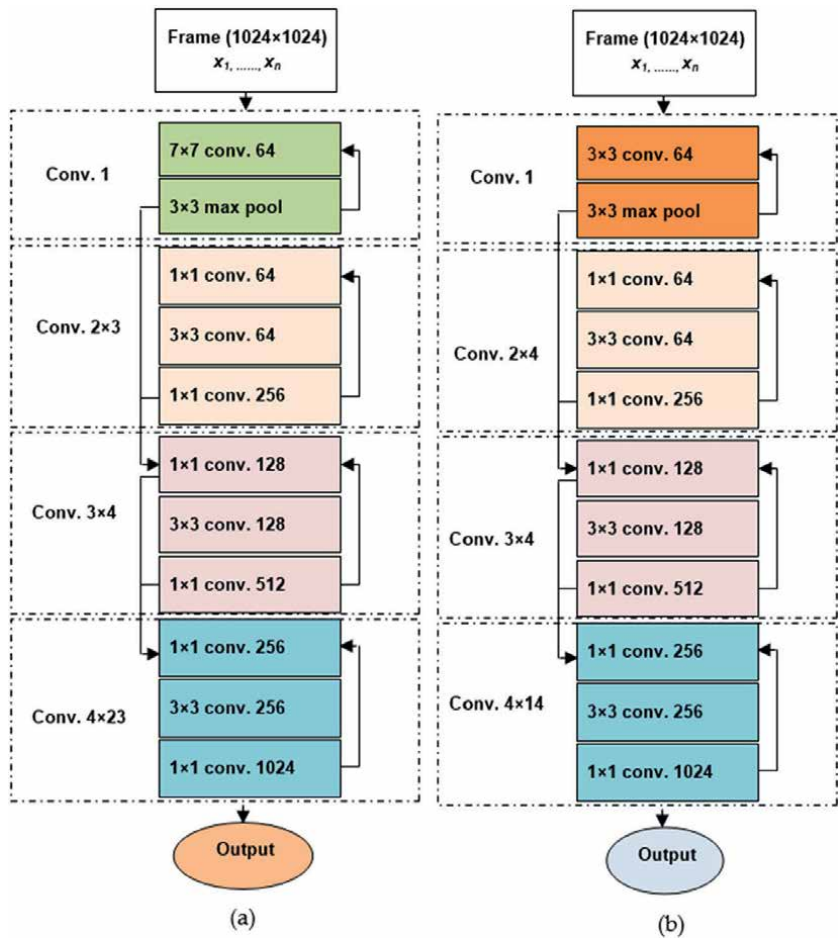


Figure 7.
Architecture of (a) residual network and (b) enhanced residual network.

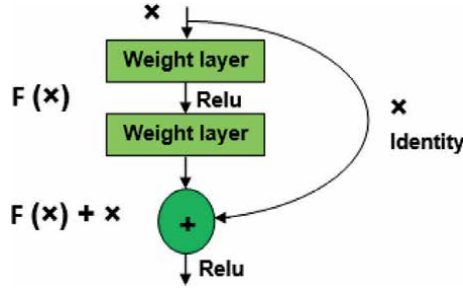


Figure 8.
Residual network block [31].

block that occupies the second position, (3) not repeating more than four times for convolution block that occupies the third position, and (4) not repeating more than 14 times for convolution block that occupies the fourth position.

2.3.4 Enhanced output

The Enhanced Mask R-CNN has an FCN, a regression, and a classification branch as its output module. The detection and segmentation of the input cattle images are accurately performed by the output module, including the computation of the object's pixel area, the location of the bounding box, and the class of object. For an enhanced output, the Enhanced Mask R-CNN's subnetwork is integrated with Mask R-CNN's FCL, as depicted in **Figure 9**.

The steps involved in the cattle detection is as follows: (a) at multi-scale, object's features map is estimated by FPN, and the proposed region's size for the target object is predicted by the ROI alignment, (b) to classify object, ROI alignment's generated features are fed into FCL, and min and max pool sizes are provided by ResNet-101 in addition to mask size, and (c) to calculate the weights of the features, object's standard deviation, and minimum value and maximum value were employed. The object predicted in the image is box-bounded, classified, and masked as output by the enhanced model immediately after the mask is fed into the layer activation, for example, the layers that are all-zeros or have noise as denoted in Eqs. (2)–(5):

$$y = az \text{ (linear activation)} \quad (2)$$

$$A(z) = \max(0, z) \text{ (rectified linear unit (ReLU))} \quad (3)$$

$$\sigma(Z)_i = \frac{e^{z_i}}{\sum_{j=1}^K e^{z_j}} \text{ (softmax)} \quad (4)$$

$$S(Z) = \frac{1}{1 + e^{-z}} \text{ (sigmoid to scrutinize)} \quad (5)$$

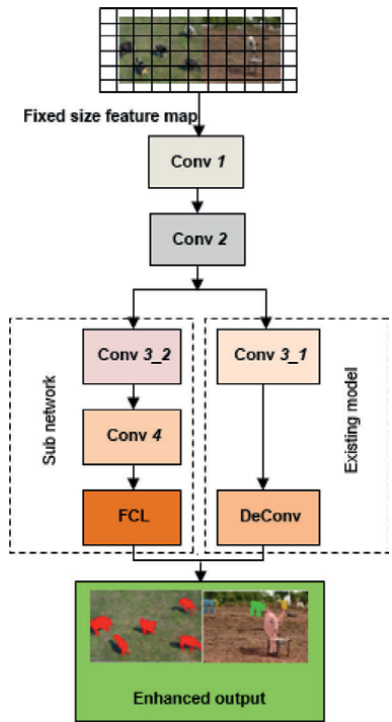


Figure 9.
For enhanced output, the Enhanced Mask R-CNN's subnetwork is integrated with Mask R-CNN's FCL.

where the co-efficient is denoted as a , the input feature in Eq. (2) is denoted as x . Training the Enhanced Mask R-CNN minimizes the loss function (L). Eq. (6) represents L:

$$L = L_{ce} + L_{be} + L_{me} \tag{6}$$

where the loss function is denoted as L , the classification error is denoted as L_{ce} , the bounding box regression error is denoted as L_{be} , and the mask error is denoted as L_{me} . The calculation of cross-entropy is in the binary mask loss function. Eq. (7) measures the accuracy of the segmentation:

$$IOU = \frac{A \cap B}{A \cup B} \tag{7}$$

where the extent of bounding boxes overlapping of predicted object and ground-truth object is denoted as IOU (Intersection Over Union), while the bounding box of predicted objects is denoted as A , the bounding box of their ground-truth is denoted as B . IOU values of 0.5 to 0.95 with mAP@X notation were used, the metric is computed by threshold value, X . To compute the precision-recall, the establishment of all matches for the image are followed. Precision (P) formula is used for calculating all the model's correctly produced instances:

$$P = \frac{\text{True Positive}}{\text{True Positive} + \text{False Positive}} \quad (8)$$

Recall (R) formula is used for calculating all the model's positively produced instances:

$$R = \frac{\text{True Positive}}{\text{True Positive} + \text{False Negative}} \quad (9)$$

where a positive instance correctly predicted is the True Positive; a positive instance incorrectly predicted is the False Positive; and a negative instance incorrectly predicted is the False Negative. Average precision (AP) is calculated as in Eq. (10):

$$AP = \sum_{n=1}^N [R(n) - R(n-1)] \cdot \max P(n) \quad (10)$$

where the number of points produced by Precision-Recall (PR) is denoted as N; in the PR space, value x and value y are assigned to PR point as Recall and Precision, respectively. The mean Average Precision (mAP) is calculated as in Eq. (11):

$$mAP = \frac{1}{n} \sum_{i=1}^n AP_i \quad (11)$$

where the class i 's AP is denoted as AP_i , and the number of classes is denoted as n .

3. Results and discussion

In this section, the emphasis is on the evaluation and validation of the capability of the proposed Enhanced Mask R-CNN model, which is built on the framework of

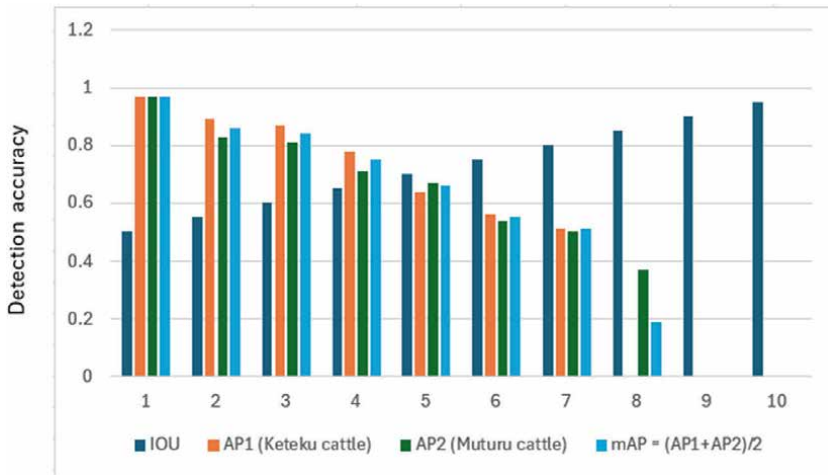


Figure 10. Analysis of Enhanced Mask R-CNN performance with evaluation metric based on the datasets of the two breeds of cattle.

Mask R-CNN, to classify objects by their type with precision, for sustainable livestock farming. The three models were tested with datasets comprising images of two breeds of cattle, namely Keteku and Muturu. The results of the Enhanced Mask R-CNN based on the experiment performed using the pre-processed datasets are shown in **Figure 10**. The results justify what is obtained in Eqs. (7)–(11), respectively. With IOU of 0.50, the results in **Figure 11** show the enhanced model obtained 0.97 mAP,

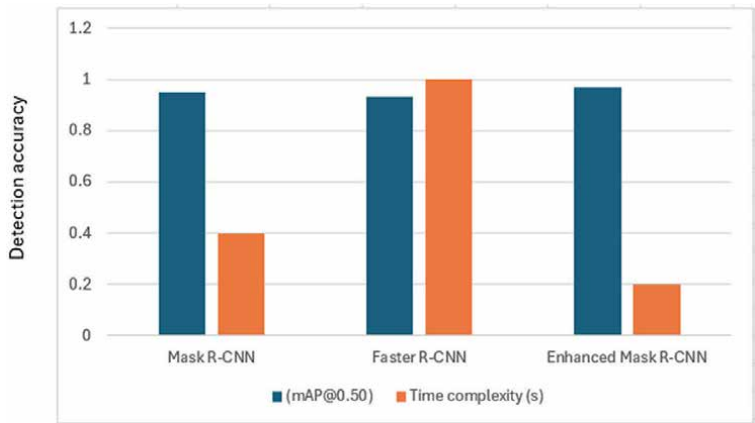


Figure 11.
Comparison of Enhanced Mask R-CNN with Faster R-CNN and Mask R-CNN.

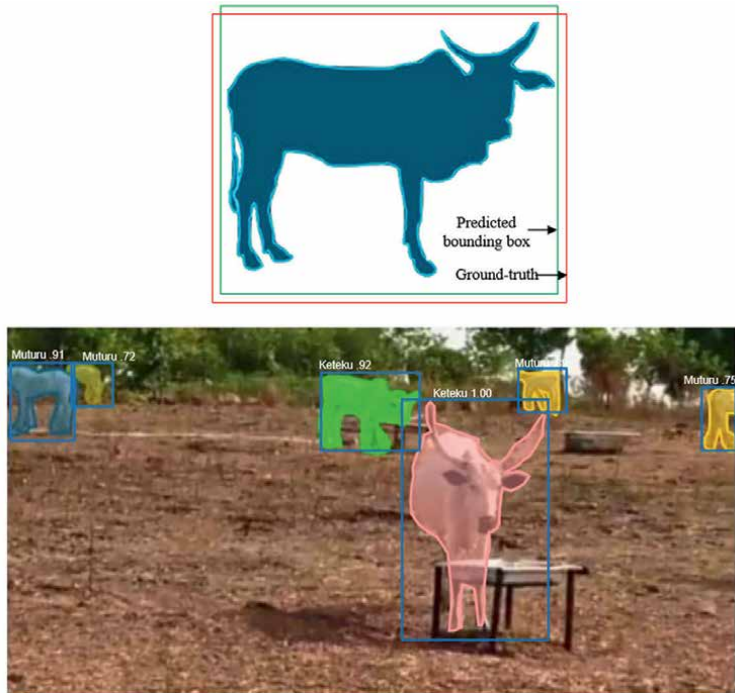


Figure 12.
Visual results of image segmentation of cattle instances by the Enhanced Mask R-CNN. The image above shows the mask, the predicted bounding box, and the ground truth. The image below shows the bounding boxes, objectness scores, masks, and cattle class by breed.

which is more accurate in precision than the results obtained by the other two models compared in this study, namely Faster R-CNN and Mask R-CNN, which obtained 0.93 mAP and 0.95 mAP, respectively, with the same IOU of 0.50. Moreover, the performance of the Enhanced Mask R-CNN model is evident in time complexity, with 0.2 s processing speed, compared to Faster R-CNN and Mask R-CNN, with 1 s and 0.4 s processing speed, respectively. **Figure 12** shows visual results of image segmentation of cattle instances by the Enhanced Mask R-CNN model.

3.1 Implications of the proposed technique and results

In addition to the contributions made by this work, as outlined in Section 1 of this chapter, the proposed technique and the results obtained in this study have long-term sustainability for PLF (animal husbandry). For example, this technique can be utilized in the livestock sector for animal recognition and thus greatly add to the accuracy and effectiveness of processes for managing livestock. Moreover, individual animals can be tracked and counted, and their health status can be determined, thereby helping farmers in the best possible way to manage their cattle, optimize rations and welfare, and boost productivity. The results achieved in this study can also contribute to the actualization of the sustainable development goals by strengthening the valuable quality used by rural households to attain the objectives of their livelihood.

4. Conclusions

The work carried out in this study presents an image segmentation of cattle instances with a transfer learning approach of deep learning models based on original datasets. The approach has the capacity for actualizing PLF for sustainable agriculture, especially whenever the need arises for automated animal inventory and monitoring, which is more than what traditional methods can handle. In this study, we re-applied Mask R-CNN's previously learned and acquired weights and biases. The Mask R-CNN model is trained on a large, standardized dataset, thereby optimizing the processing speed and boosting the enhanced model's performance and accuracy. The findings in this study reveal the capacity of transfer learning as an approach for addressing the challenges in segmenting cattle images needed to improve PLF for sustainable agriculture.

Conclusively, based on the results of this chapter, the following most important conclusions can be drawn:

1. The challenges in segmenting cattle images needed to improve PLF for sustainable agriculture are addressed by innovative application of transfer learning.
2. Segmentation accuracy and processing time are optimized by training the target model with the existing model's knowledge that is previously trained on the same tasks.
3. Employing drones such as DJI Phantom 4 Rtk drones, as employed in this study, for collection of data, facilitates model training and accuracy.
4. The methods used in (2) and (3) address limitations of data, which could drastically affect the proposed model accuracy.

5. The performance of the proposed model is improved by the transfer learning method by which overfitting is reduced, and pre-trained knowledge is leveraged.
6. Finally, the results of this chapter can strengthen the valuable quality used by the rural households to attain the objectives of their livelihood, thereby contributing to the sustainable development goals.

In our future work, we hope to improve and extend the approaches used in this study to the recognition of other animals for sustainable livestock farming.

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Conflict of interest

The authors declare no conflict of interest.

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The Wildlife-Livestock Interface: Implications on the Sustainability of Wildlife Populations, Pastoral Livestock Production Systems and Livelihoods

Oscar Madzingira, Michael Sinvula Lukubwe and Evans Simasiku

Abstract

The wildlife-livestock interface (WLI or interface) is a dynamic area in rangelands where wildlife and livestock habitats overlap. The development and geographical range of the interface is influenced primarily by forage and water resource distribution, climate change, and human, livestock, and wildlife population dynamics. The interaction between wildlife and livestock can have positive or negative consequences. Among other benefits, the interface provides safe areas for wildlife breeding and foraging. However, biodiversity and sustainability may be curtailed by poaching, habitat destruction by human activities, and human-backed competition with livestock for grazing and water resources. In livestock, the degraded interface range-land limits livestock productivity, while the close interaction with wildlife promotes the transmission of diseases. However, studies have shown that a properly managed WLI can improve livestock weight gains, mitigate bush encroachment, and facilitate the removal of diseased animals and pathogens from the environment by predators and scavengers. Human-wildlife conflict (HWC) arising from property and crop field damage by elephants and buffalo, and human anxiety, injuries, and deaths from predator attacks, is the major negative impact of WLI areas on livelihoods. Harnessing wildlife as an economic resource for the community through legalised community participation in wildlife conservation, and in economic benefits such as tourism, trophy hunting, and game meat harvesting can ameliorate HWC, and promote the sustainable utilisation and conservation of wildlife. In this chapter, the authors discuss the effects of the wildlife-livestock interface on the sustainability of wildlife populations, pastoral livestock production systems, and rural livelihoods.

Keywords: wildlife-livestock-interface, sustainability, human-wildlife conflict, conservation, rural livelihoods, pastoral production system

1. Introduction

The wildlife-livestock interface (WLI) (also referred to as the “interface”) is a network of ecological and epidemiological interactions that occur between livestock and wildlife in the intersecting geographical space that they share [1]. Interfaces are transition areas between specialised wildlife areas, such as national parks and game reserves, and human-settled areas where agropastoralism is practiced.

Wildlife, livestock, and pastoralists have co-existed for many years in many rangelands around the world. However, the exponential growth of the human population on a fixed land mass in the communal areas, the encroachment by pastoralists and agro-pastoralists into historically protected areas, and the climate change-driven competition for limited grazing and water resources have brought livestock and wildlife closer to each other, particularly in Southern African savannah biomes [2]. As a result, wildlife habitats have fragmented rapidly, forcing wildlife into pockets of land at the boundaries of human habitation, such as the forest patches, wetlands, and arid rangelands that are less attractive to human habitation and agriculture. However, because the human-settled land has historically been used by wildlife, frequent incursions of wildlife into areas of human habitation and conflict are inevitable.

Besides human encroachment, some interface areas were created by wildlife encroaching into domestic animal and human settlements in search of scarce feed or water resources. For example, the rapid increases in populations of wild boars (*Sus scrofa*) resulted in increased contacts with domestic pigs [3]. In southern Africa, the recovery of wild herbivore populations in protected areas [4] through conservation practices has been noted as one of the drivers of their movement out of the protected areas into adjacent agricultural landscapes [5] in search of better grazing and water. Climatic (e.g., rainfall, temperature, and humidity) and environmental changes (e.g., land degradation, loss of habitat, and vegetation cover) driven by global warming [6] also play a role in bringing wildlife and livestock together in interface areas. The high densities of animal populations [7] that congregate around the areas with good grazing and water resources during the dry season or droughts [8, 9] increase the interfacing. The major wild animal species identified in interface areas in southern Africa are the large herbivore mammals, particularly ruminants [3].

In this chapter, the implications of wildlife-livestock interfacing on the sustainability of wildlife populations, pastoral livestock production, and rural livelihoods are discussed. This review is biased towards wild herbivores, carnivores, and livestock because they are the most common species at the interface. Approaches for promoting the sustainable coexistence of wildlife, livestock, and humans at the interface are highlighted.

2. Characteristics of the wildlife-livestock interface

In WLI areas, ecosystems and resources are shared. In the past, the interface was largely transient, with pastoralist livestock herded through wildlife areas in search of pasture and water. In the present context, interface areas are characterised by intermittent or continuous sharing of grazing and water resources during specific seasons of the year. The nature of interface areas varies with the landscapes and the extent of human intervention [10]. In some regions, interface areas have become more frequent, fragmented, or disconnected due to the expansion of human settlements towards protected areas.

The interaction between wildlife and livestock can be a direct physical interaction when sharing the same space at the same time (**Figure 1**). When wildlife species mix with domestic animals, the separation distance can be a matter of a few metres, close enough for the transmission of pathogens through aerosols, bodily fluids, contaminated grazing, or water [3]. In other cases, wildlife-livestock interfacing can be indirect with each group utilising the same space at different times. In this scenario, contact is incidental through forage, soil, or water contaminated by bodily discharges, such as urine, faeces, saliva, ocular or nasal discharge from another animal, shared insect vectors, or intermediate hosts [11]. Contact between wildlife and domestic animal species is more common in open habitats where plains species, such as wildebeest and zebra thrive, as observed in the Greater Serengeti system of East Africa [5, 12] and the Zambezi region of Namibia. The discrete forest, woodland, and bush species are the least likely to come into direct contact with other species.

Wildlife-livestock interfaces are dynamic, with their geographical range changing with seasonal ecological factors such as the availability of feeding resources, hunting, or poaching pressure. Seasonal wildlife movements result in constant interactions

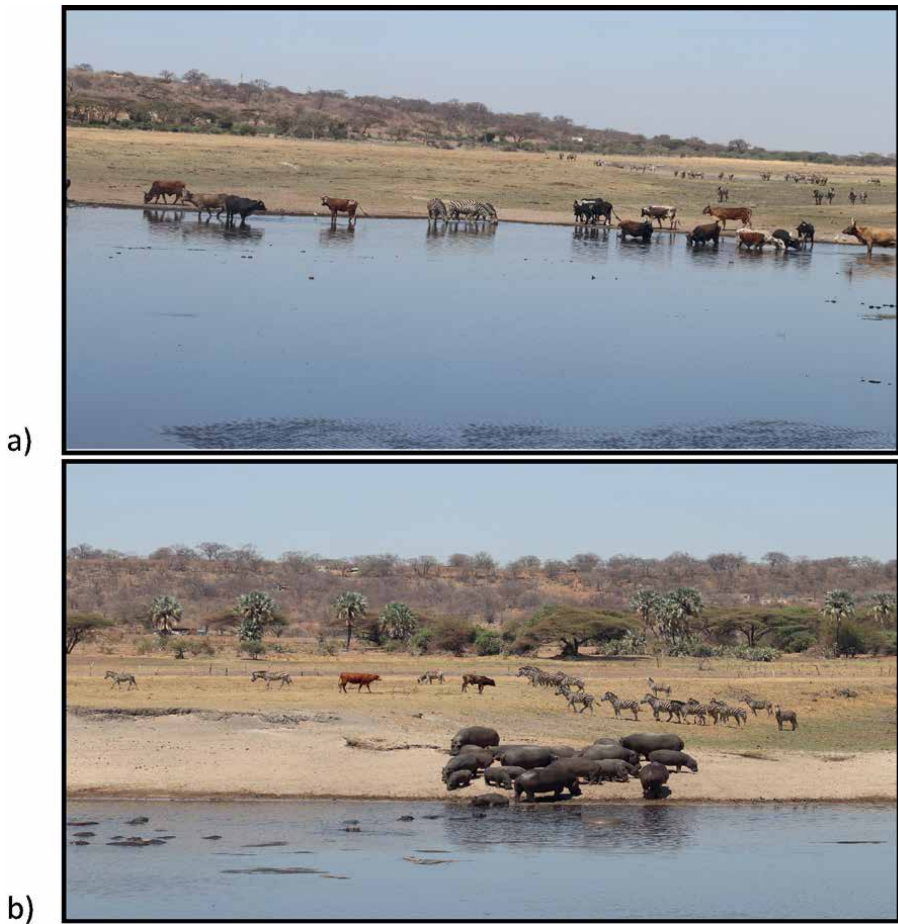


Figure 1.
(a) and (b): Livestock and wildlife congregate at a shrinking water source along the Chobe River on the Botswana-Namibia border during the dry season (Photo: MS Lukubwe, 2024).

with livestock and also increase the possibility of the occurrence of transboundary diseases [3]. During drought periods, the mixing of wild and domestic animals is higher at watering points and locations with abundant forage resources. The variability in the distribution of water sources on rangelands is a major factor influencing the interaction between wild and domestic herbivores. In savannah semi-arid landscapes, surface water sources contract during the dry season. The remaining permanent water bodies attract and concentrate a wide range of wild and domestic animal species [5]. In the wet season, when water resources are spread across landscapes, wild herbivores are distributed across the landscape [12] where they occupy and forage in their preferred habitats away from livestock. Man-made interfaces occur on private wildlife-livestock farms.

3. Implications of the wildlife-livestock interface on the sustainability of wildlife populations

The human-altered habitat at the interface can promote the proliferation of wildlife species that prefer feeding on open, grass-dominated habitats, such as the buffalo, wildebeest, and zebra. Moreover, the interface is often devoid of predators due to their persecution and elimination. Thus, it acts as a sanctuary for breeding, raising of offspring, and proliferation of wild herbivore populations. However, wildlife in the interface is vulnerable to the consequences of increasing human environmental degradation arising from the exploitation of resources such as groundwater, natural gas, and oil [13–15]. Nevertheless, wildlife has greater resilience to local environmental change than livestock, which makes it better able to thrive even in the face of degradation.

Most protected areas' forage resources are degraded. The rangeland management practices in the interface, such as the provision of water and the use of fires to improve grazing quality [16], can attract and benefit a variety of wild herbivores in the long term. Thus, interfaces are areas where wildlife can find better forage resources during seasons of shortage and are important areas for wildlife conservation [17]. However, if wildlife is constantly persecuted, livestock may eventually replace wildlife [17]. For example, the activities of herders (and their dogs) around watering points often discourage wild ungulates from sharing watering points with livestock [18]. As a result, wild animals are often pushed away from areas used by livestock. The narrowing of wildlife areas due to human encroachment and persecution can result in the loss of biodiversity, as the available land can no longer support the same numbers as before [19], and habitats and niches have been modified or destroyed.

Changes in vegetation structure in degraded interface rangelands reduce habitat quality for certain wildlife species, thereby impacting their ability to thrive, avoid predators, and reproduce and ultimately affecting the potential biodiversity of the area [16, 20]. Overall, the combined effect of all aspects of livestock production across most rangelands worldwide is that high densities of livestock are maintained, and the rangeland is degraded, because the farmers are slow or never adopt destocking as a response. Indigenous large wild herbivores and their predators are pushed to isolated and narrowing habitat refugia and protected reserves [8, 17, 21] where only a few can be sustained. Restoring the wildlife community would require a disproportionate pull-back in agricultural production, with exorbitant opportunity costs.

In many rangelands near wildlife areas, global demand for animal protein and the attractive prices offered for livestock [17], coupled with improved livestock breeding

systems, have driven the expansion of livestock production into wildlife areas, reducing wildlife habitats and biodiversity. Even dry rangelands are increasingly being converted to livestock and crop production to meet human food needs at the expense of wildlife habitat [17]. Wildlife communities, particularly the large vertebrate species, are incompatible with crop production because the opportunity costs of wildlife conservation are too expensive [17]. The economic competition relegates wildlife to the very arid side of rangelands, where opportunity costs are low, but only a few animals can be sustained.

Wildlife migration corridors are increasingly being blocked by permanent settlements from the ever-increasing human population, which exacerbates conflict, persecution, and illegal poaching of wildlife, reducing their numbers (**Figure 2**).

The persecution of large carnivores due to their depredation of livestock (**Figure 3**) has led to the virtual eradication of apex predators from most rangelands [17]. Predator conflict and persecution often occur because the wildlife management authority conducts limited surveillance and control of predatory behaviours at the interface [22, 23]. The geographic expansion of human activities has resulted in large predator populations such as the African lion *Panthera leo* [24] becoming increasingly fragmented [25] and threatened worldwide [26]. Apex predators have been extirpated from most rangelands [17] through retaliatory killings or attacks on observation, as they are a threat to livestock and humans.

The African lion has lost approximately 85% of its range in the last 500 years [27]. Conflict mitigation requires a balance of practical solutions, outreach, and the best available information on both the ecology of the carnivore species concerned and the human dimensions of the problem. In some regions of the world, the eradication of large predators has resulted in problematically high densities of wild herbivores, with associated impacts on biodiversity [28]. Abundant wild ungulate populations in the absence of apex predators can create political tensions and socioeconomic costs on rangelands, as demonstrated by elk and feral horse populations in the western United



Figure 2.
Fencing obstructing a migration wildlife corridor. Such barriers limit animal movements, disrupt seasonal migrations, and increase the risk of human-wildlife conflict in shared landscapes (Photo: MS Lukubwe, 2024).

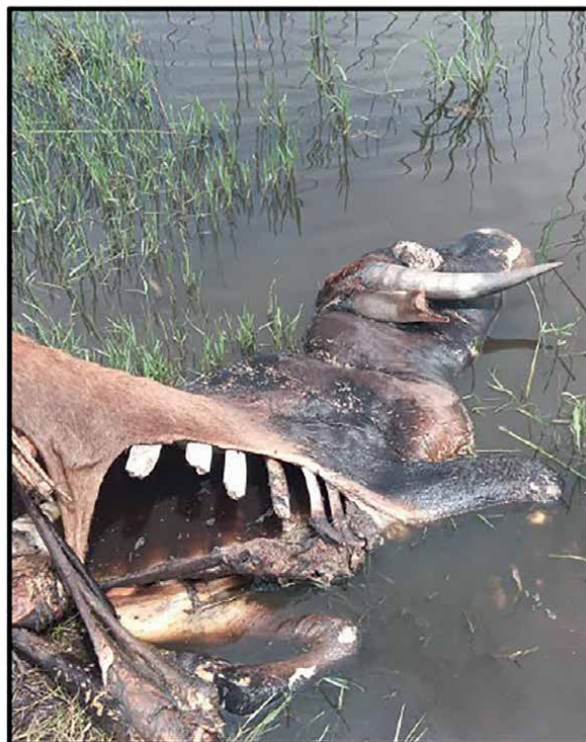


Figure 3.

A cow killed by a lion in the Salambala Conservancy, north-eastern Namibia. Farmers may apply for “offset compensation” through the Ministry of Environment, Forestry and Tourism, which dispatches a verification team to assess the claim. Under the revised policy, the compensation is set at N\$8000 (=USD 440) (Photo: contributed, 2025).

States of America [29]. Wildlife in interface areas is exposed to poisoning (deliberate or unintentional) or retaliatory killings with the potential to decimate their numbers (**Figure 4**).

Wild animals, especially ungulates, often face competition from their domestic counterparts because humans facilitate conditions that enable livestock to flourish by persecuting wildlife, transforming, and fragmenting their natural habitats [17]. Competition between wildlife and livestock can be actual or perceived. Perceived competition prevails where livestock owners have negative attitudes towards wildlife because they do not derive any tangible benefits from it [30], most frequently due to prohibitive policies and legislation. This is especially the case in many areas around the world, where wildlife is held in trust by the government for the public. Such a model often results in illegal overexploitation of wildlife on rangelands [31]. In the case of herbivores, poaching can cause the numbers to decline, forcing predator species to target livestock as easy prey [32].

WLI rangelands can be successfully managed for both livestock and wildlife if the costs of competition, predation, and disease can be offset by mixed revenue streams and facilitated grazing. Communal pastoralists around the world, including Namibia, have now adopted the ‘Conservancy’ concept to sustainably manage wildlife and generate revenue at the WLI to alleviate poverty. This concept involves the zoning of the landscape for natural resources management (example in **Figure 5**).



Figure 4.
An elephant and a lion killed in communal farming areas; stark examples of escalating human–wildlife conflict (Photos credit: <https://neweralive.na/elephant-tussle-turns-wild/> and Kwando Carnivore Project respectively).

The conservancy is divided into exclusive wildlife areas, multiple use areas (grazing and conservation), and settlement and cropping areas to accommodate wildlife as a resource.

Several community-based wildlife management projects in southern Africa have successfully integrated wildlife conservation and sustainable utilisation of wildlife at the interface. The success of these projects has been attributed to the autonomy and authority given to local communities to manage their wildlife resources. In conservancies, tourism, regulated hunting for trophies and meat add to the rangeland's output. The income generated is used to improve infrastructure (waterpoints, access roads, and clinics) that is beneficial to the sustainable utilisation of wildlife [17] and the community. Namibia's conservancy system is internationally commended as one of the leading models of community-based natural resource management [33, 34]. In this system, registered community members participate in wildlife conservation, land management, and community development projects under the leadership of a conservancy management committee [34]. In Zimbabwe, the Communal Areas Management Programme for Indigenous Resources (CAMPFIRE) project is another example of how communities empowered with self-governance and technical know-how can successfully manage and sustainably utilise wildlife resources [35]. The CAMPFIRE project contributed to the resilience of social-ecological systems in rangelands [36].

4. Implications of the interface on livestock production

Wildlife, particularly herbivores, compete with livestock for forage and water resources on shared rangelands, thereby reducing rangeland carrying capacity and productivity [16]. On the contrary, a study in East Africa demonstrated that the weight gains of cattle reared on pastures shared with wild ungulates during the wet season was significantly higher (0.32 kg/animal/day) than that of cattle raised on pastures where wild ungulates were excluded (0.25 kg/animal/day) [37]. This facilitative interaction was attributed to the role of zebras (*Equus quagga*) in reducing the stem

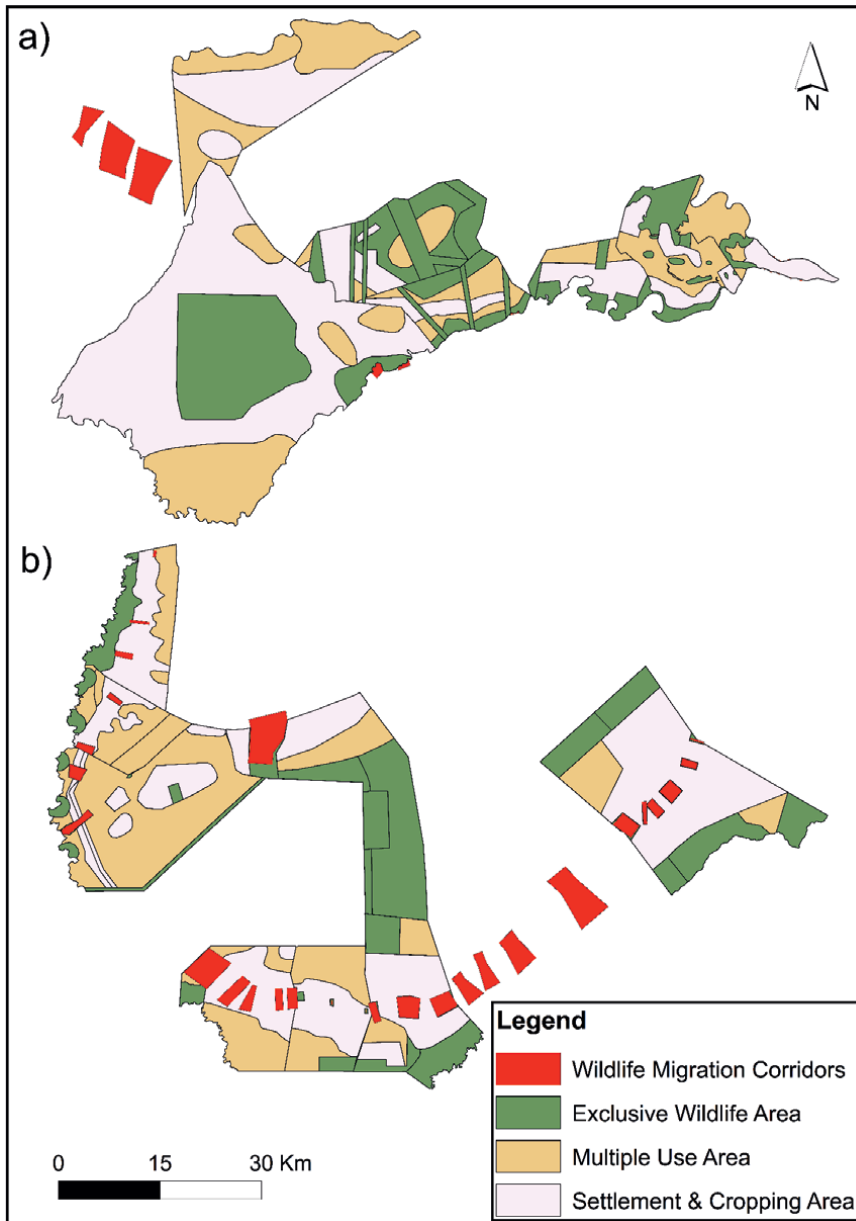


Figure 5. Land-use zoning maps of conservancies in the Zambezi Region, Namibia, showing the distribution of wildlife migration corridors (red), exclusive wildlife areas (dark green), multiple-use areas (light brown), and settlement and cropping zones (light pink). (a) Eastern Zambezi region. (b) Northeastern Zambezi region. These zoning schemes support land-use planning and aim to reduce human-wildlife conflict (Source: authors' compilation).

to leaf ratio in the grass sward and creating conditions for ruminants such as cattle to thrive [17]. Browsing on seedlings and saplings by wildlife is reported to mitigate bush encroachment on degraded rangelands [38, 39], thereby conserving them for livestock production.

The wildlife-livestock interface inevitably precipitates human-wildlife conflict with pastoralists, particularly in communal areas adjacent to protected areas in many

parts of Africa [40]. The conflict is at a local-level and is linked to forage resources [41–43], depredation, and disease transmission to livestock [17, 44–48].

Depredation of livestock species by wild carnivores such as lions (*Panthera leo*) and jackals (*Canis mesomelas*) negatively impacts livestock numbers on rangelands, causing economic losses [49] for the farmers, human-wildlife conflict, and negative impacts on food security and livelihoods. For livestock on rangelands, the indirect effects of predators include decreased conception rates and weight gains [50, 51] through the effects of stress [52, 53]. In territorial carnivore species such as lions, the elimination of a problem territory holder creates a vacuum that is rapidly filled by neighbouring individuals or dispersers, as demonstrated in lions in Zimbabwe [54]. In most cases, the vacant territory is filled by immature adults that are less efficient hunters and competitors and more likely to invade human settled areas [55] for easier livestock prey [56]. Therefore, retaliatory killings compromise the viability of some carnivore populations [57] and are counterproductive for mitigating human-carnivore conflicts. One way of reducing the conflict associated with depredation is to herd the livestock and avoid the areas frequented by wildlife. Wildlife-livestock conflict can also be mitigated through regular monitoring to institute pre-emptive control measures; positioning of anthropogenic resources evenly across the rangeland to prevent the congregation of livestock and wildlife; recreational and subsistence hunting which benefits the community; the thinning of vegetation cover near livestock can reduce local populations of wildlife; and rearing of livestock near human settlements can prevent depredation.

Of great importance at the interface is the role of wildlife as reservoirs of several zoonotic and non-zoonotic pathogens of livestock [58], which complicate the control of such infections in livestock populations. The wildlife species most often implicated in disease transmission are the ungulates from the family Bovidae, of which the buffalo and bovine antelopes are the most prominent [3]. The role of wildlife as disease reservoirs has, in some cases, been overemphasised due to human bias towards livestock, while overlooking the value of wildlife and the role of livestock in spillback infections [59–61]. Many diseases of livestock, such as bovine tuberculosis (BTB) and brucellosis, initially spread to wildlife as animal agriculture expanded and subsequently recirculated back into livestock [10]. More realistically, bidirectional transmission of pathogens occurs freely between wildlife and livestock species [59–61], but disease transmission from wildlife to livestock has the greatest economic impact [62]. Viewed this way, it becomes clear that human-induced shifts in farming practices and land use changes, such as encroachment into wildlife habitats, deforestation, and intensification of agriculture, also play a role in the observed disease epidemiological patterns [63–66]. Political and social controversies regarding wild animal conservation at the wildlife-livestock interface in rangelands almost always include concerns about disease transmission [67]. Such controversies emanate primarily from the poor success rate of controlling diseases in wildlife reservoirs [68]. Additionally, most protected areas are located in remote regions with limited access to veterinary services, resulting in the persistence of preventable diseases [3]. Culling and increased hunting of wildlife to reduce host density and disease transmission are often proposed to control wildlife diseases, but they are impractical and rarely effective [69]. Active and passive surveillance of wildlife and livestock diseases at the interface is necessary for early detection and control of emerging or re-emerging infections before they cause devastating effects in the livestock population. On a positive note, predators at the interface regulate ungulate populations and take out weak individuals and the sick, thereby contributing to animal health in rangelands. Additionally, predators

provide carrion for scavengers such as vultures [70], which remove pathogens from the environment and curb the spread of diseases [71].

5. Implications of the wildlife-livestock interface on pastoral livestock production and livelihoods

In WLI areas, community members' options for continued movement of their livestock to seek better foraging areas have declined as corridors to distant pastures are blocked by settlements and fencing. As a result, communities have adopted sedentary pastoralism, which has led to overstocking and its consequences, including diseases and parasite burdens. As a result, many communities in WLI areas embraced ecotourism to generate income from wildlife resources to better their livelihoods [72]. Integrating wildlife bolsters the adaptive capacity of a rangeland by providing communities with options for coping with the unpredictable environmental change [17] brought about by climate change. Adaptation is contingent upon local communities being empowered to benefit directly from their wildlife resources [17].

Wildlife that frequent interface areas can be harnessed for the economic benefit of the communities through consumptive and non-consumptive use including trophy hunting, ecotourism, and controlled harvesting for meat [17]. Ecosystem services can be provisioning, regulating, cultural, and supporting services [73]. For rural communities, the provisioning services are the most valued, with wildlife acting as a source of commodities that include meat and skins and reducing dependence on livestock. In the African tradition, game meat has always been a source of food over the years. Therefore, it is inevitable that some degree of illegal hunting occurs in the interface to maintain livelihoods, which may threaten the conservation status of some wildlife species, particularly where efficient modern ways of hunting, such as rifle hunting, are employed. Other wildlife ecosystem services, such as regulating, cultural, and supporting services, are difficult to ascribe a market value [73], but can improve livelihoods.

Human-wildlife conflict (HWC) is a major issue arising at the interface [17]. Even on the best-managed rangelands, HWC has negative implications on livelihoods. Predators such as lions and hyenas (*Crocuta crocuta*), and large herbivores, including elephants and buffalo, are the major species involved in this conflict, as is the case in the Zambezi region of Namibia. Lions and hyenas impact livelihoods through instilling fear and distress, and the killing of vulnerable livestock at the interface (Figures 6 and 7), reducing farmers' financial and food security.

As a result, the affected communities often adopt continuous herding of their livestock during the day, avoidance of wildlife areas, guarding livestock at night, or the use of predator-free pens. Even in seasons where grazing is available, the large herbivores raid and trample the palatable crops, discouraging agricultural production and impacting food security. The only way livelihoods can be maintained in such scenarios is to integrate wildlife and livestock on rangelands and utilise the wildlife resource for the benefit of communities. In Namibia, community conservancies conduct game meat harvesting under regulated quotas, providing both community benefits and supporting sustainable wildlife management. The high stocking rates at the wildlife-livestock interface can lead to overgrazing and degradation of rangelands. The degraded landscape negatively impacts the sustainability of livestock grazing systems, reduces agricultural crop productivity, and is linked to increasing poverty. Affected farmers may be forced to exploit wildlife for consumption and income.

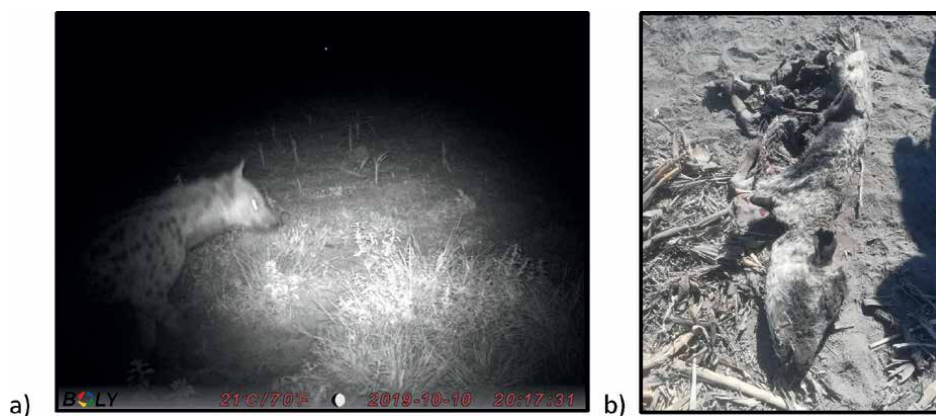


Figure 6.
 (a) A spotted hyena captured by a camera trap while stalking cattle near a kraal in the floodplains of northeastern Namibia (Photo: Lukubwe, 2019). (b) Despite being under the supervision of a herder during daytime grazing, this calf was attacked and killed by a hyena in broad daylight (Photo: contributed, 2025).



Figure 7.
 Hyena attacks on livestock in the Zambezi Region, Namibia — a common source of human–wildlife conflict that threatens rural livelihoods and livestock security (Photo: contributed, 2025).

Livestock raised on degraded rangelands exhibit poor body condition and fetch low prices on the market, reducing household income. Livelihoods are also affected by the high prevalence of livestock diseases from wildlife reservoirs, property damage, community nuisance, and human deaths and injuries [32] arising from lion, hyena, buffalo, elephant, and hippopotamus attacks. The threat of zoonosis always looms at the WLI from diseases such as brucellosis and Rift Valley fever that have been reported to occur in livestock in interface areas [74].

Traditional deterrent techniques, including the guarding of crop fields, continuous checks on problem animals along the periphery of the interface, shouting, beating drums, hurling rocks, use of strong kraals and dogs (**Figure 8**) to herd livestock, are used by communities as deterrents of HWC [32]. In some areas, improvised modern methods such as burning chilli bombs and blowing vuvuzelas are also used to deter wildlife. Chilli bombs, a mixture of elephant dung and crushed chilli, are burned to release a pungent smoke that acts like tear gas—effectively deterring elephants and



Figure 8.
One of the dog breeds (Anatolian Shepherd) used for guarding livestock against predators in Namibia (Source: <https://cheetah.org>).

other wildlife. The vuvuzela, a loud noise-making instrument popularised during the 2010 FIFA World Cup in South Africa, is traditionally used by soccer fans. In north-western Namibia, however, its loud sound is repurposed by communities to scare off elephants.

Exposure of wildlife to traces of veterinary drugs may facilitate the development of antimicrobial-resistant pathogens [49, 75], including parasites and bacteria, that may be transmitted back to livestock and humans, complicating the treatment of infections. Studies have shown that wild animals that share rangeland with cattle can harbour and act as reservoirs of antibiotic-resistant microorganisms and antibiotic-resistant genes [76, 77]. Therefore, to curtail the spread of antimicrobial resistant pathogens, a One Health approach is required. Since interfaces are here to stay, there is a need to manage wildlife and livestock in ways that are sustainable, taking into account the changing climate and one-health principles [1, 78].

6. Conclusions

Based on the literature cited in this chapter, the following key conclusions can be drawn:

- The wildlife-livestock interface presents both positive and negative impacts on the sustainability of wildlife populations, livelihoods, and the pastoral system.
- Expanding human and livestock populations and the increasing demand for agricultural land pose significant threats to biodiversity and wildlife populations at the interface.
- Human-wildlife conflicts due to depredation and the trampling of crop fields are common at the interface.

- Shared use of ecological resources between large densities of wildlife and livestock promotes rangeland degradation, reduced productivity, and can precipitate disease outbreaks in livestock and zoonosis in humans.
- Adopting a One Health approach is essential for managing disease risks at the interface and ensuring the health of humans, animals, and ecosystems.
- Human livelihoods are impacted by fear, injuries, and deaths caused by predators, property damage, and the threat of antimicrobial-resistant (AMR) pathogens from wildlife reservoirs.
- The sustainability of livelihoods can be enhanced by integrating and making use of wildlife as a resource to promote resilience, especially in the face of climate change effects.
- Community-based conservancy projects that empower local populations with autonomy and technical capacity are the most effective in integrating and sustainably managing the interface, reducing conflict, and improving livelihoods.

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Nowadays, and even more so in the future, society's demand for sustainable animal agriculture will increase, ensuring that the human population has access to sufficient quantities of safe, healthy, and environmentally friendly foodstuffs of animal origin. This book summarizes the latest scientific findings in sustainable animal agriculture (cattle, pigs, and poultry) and their practical applications. Moreover, it presents the role of the "One Health" concept in sustainable livestock farming. The authors of the book's chapters are internationally recognized experts in their respective fields.

Therefore, we hope readers will find valuable information they can apply in their everyday professional activities. We recommend this book to researchers, university lecturers, Ph.D. students, and all those involved in the practice of animal agriculture.

W. James Grichar, Agricultural Sciences Series Editor

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